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Hydrological change detection using modeling: Half a century of runoff from four rivers in the Blue Nile Basin

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[1] Land cover changes can have significant impacts on hydrological regime. The objective of this study was to detect possible hydrological changes of four watersheds in the Blue Nile Basin using a model-based method for hydrological change detection. The four watersheds, Birr, Upper-Didesa, Gilgel Abbay, and Koga range in size from 260 to 1800 km^2. The changes were assessed based on model parameters, model residuals, and in the overall function of the watersheds in transferring rainfall into runoff. The entire time series (1960–2004) was divided into three periods based on political and land management policy changes. A conceptual rainfall-runoff model, the HBV (Hydrologiska Byråns Vattenbalansavdelning) model, was used for the analysis, and suitable parameter sets for each period were found based on a Monte Carlo approach. The values of six out of nine parameters changed significantly between the periods. Model residuals also showed significant changes between the three periods in three of the four watersheds. On the other hand, the overall functioning of the watersheds in processing rainfall to runoff changed little. So even though the individual parameters and model residuals were changing, the integrated functioning of the watersheds showed minimal changes. This study demonstrated the value of using different approaches for detecting hydrological change and highlighted the sensitivity of the outcome to the applied modeling and statistical methods.

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1. Introduction

[2] Changes in watershed characteristics and climate are the main drivers of hydrological change [*Kundzwicz*, 2004; *Kundzwicz and Robson*, 2004]. Watershed characteristics like geomorphology, land cover, soil, and geology influence the hydrological regime. Knowing the role of watershed characteristics for hydrological change is fundamental for the planning of watershed management to address problems like drought flooding and increasing food production with available water.

[3] The Blue Nile Basin is characterized by severe degradation for many decades. Soil and land use degradation have been problems for more than half a century in the Blue Nile Basin [*Gete and Hurni*, 2001; *Bekele*, 2003]. This degradation has been hypothesized to result in hydrological changes. It is believed that this degradation history has had a major impact on the water resources of the region. The livelihood of the people in the region is highly dependent on rain-fed agriculture which is very sensitive to such changes. The agriculture productivity has failed during the recurrent drought and subsequent water availability problem in the region [*Rahmato*, 2009]. Spatial differences in the hydrology of watersheds in the basin have been linked to differences in watershed characteristics [*Gebrehiwot et al*., 2011]. *Gebrehiwot et al*. [2011] found that dry season flows benefited from the existence of woodland and grassland in the watersheds; these land covers are common in southwest part of the basin. The dry season flow is also less in the watershed with mainly tuff/basalts bedrocks. Linking hydrological change and change of watershed characteristics has been a topic of debate in the tropics and elsewhere in the world [*Bruijnzeel*, 2004; *Calder*, 2005]. Knowing how much change in the hydrological regime can be expected and attributed to the changes in the characteristics of watersheds is of value for sustainable land management and climate change adaptation in the basin.

[4] Statistical methods were widely used to detect hydrological changes. In addition, models are also being used in different ways. For example, models have been used for hydrological change detection using paired watershed

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studies [*Zerge et al*., 2010]. Models can also be applied to a single watershed to analyze the hydrological changes over time [*Seibert and McDonnell*, 2010]. The model approach eliminates the need for a control watershed and can also be used in situations where such a control is missing [*Mishra et al*., 2010]. *Seibert et al*. [2010] used a modeling approach to detect hydrological changes caused by land cover change resulting from a wild fire. Evaluation of residuals, changes in parameter values, and simulations based on different parameter sets are three ways in which models can be used to detect hydrological changes in a single watershed over time [*Seibert and McDonnell*, 2010]. Hydrological models can elucidate both the cause and the potential effect of changes; they are capable of quantifying the links between hydrological changes and changes in watershed characteristics [*Le Lay et al*., 2007]. Modeling approaches have the advantage of being able to show the integrated effect of how watersheds process precipitation into discharge.

[5] There is a clear difference between modeling approaches for change detection and change prediction. For the latter there is a need for a physically based model which allows parameterization of land use changes for simulations under changed conditions. For change detection, on the other hand, a model is needed that reliably reproduces the runoff series, which would have been observed if there had been no change. Here conceptual models are a suitable choice; it has been often shown that for situations with calibration, these models perform equally well or even better than more complex models [e.g., *Breuer et al*., 2009]. Furthermore, for conceptual models it is possible to obtain model parameters by calibration, and these model parameters can then also be used to investigate hydrological changes. Therefore, conceptual models with less parameters are more suitable for change detection than physical-based models.

[6] In our study of the Blue Nile Basin, we used modeling to detect whether the hydrological regime has changed between three 15 year periods of the 45 years' observed record (1960–2004). We did this in three separate ways, (i) testing changes in model parameters between the three periods; (ii) analyzing the changes in model residuals between the periods; and (iii) comparing the runoff simulations produced by the parameters from the different periods when used with the climate input of the entire time series. This study also aimed to evaluate model-based hydrological change detection methods.

2. Studied Watersheds

2.1. Blue Nile Basin and Study Watersheds

[7] The Blue Nile Basin, also called the *Abbay* in Ethiopia, is the part of the Nile Basin that flows from the northwest of Ethiopia. It covers an area of about 200,000 km^2 area within Ethiopia. The Blue Nile lies between 34.5–39.7 dd (decimal degrees) E longitude and 7.8–12.7 dd N latitude. This basin comprises 6.7% of the whole Nile Basin surface area; yet it produces 62% (51×10^9 m^3 yr^{-1}) of the Nile River flow, at Aswan in Egypt [*Ministry of Water Resources*, 1999]. The Blue Nile's flow is characterized by seasonal variability; with 82% of the annual flow occurring during the rainy period July−October. The mean annual rainfall in the basin ranges from 800 to 2200 mm [*Ministry of Water Resources*, 1998].

[8] Four watersheds from different parts of the basin were considered in this study; Birr, Upper-Didesa, Gilgel Abbay, and Koga (Figure 1). Three of them, Birr, Gilgel Abbay, and Koga, are located in the north-central part of the basin, while Upper-Didesa is in the south. These watersheds have distinct watershed characteristics, especially with regard to land cover change history during 1960−2001 (Table 1). In particular, the degradation of the natural forest started earlier in the north than the south [*Bekele*, 2003]. The northern watersheds had lost much of their forests already in 1960, while there is still a significant amount of natural forest in the south. The watersheds are also characterized by differences in size, climate, and geology.

2.2. Data

2.2.1. Hydrometeorological *D*ata

[9] Daily rainfall, daily mean air temperature, mean daily potential evapotranspiration (PET) for each month, and daily stream flow data were used in the modeling. Rainfall and temperature data were provided by the National Meteorological Service Agency of Ethiopia. As there are no meteorological stations located within the study watersheds, data from neighboring stations were used to estimate watershed rainfall. Eight stations were used, and there were two to four stations for each watershed; *Debre Markos* and *Feres Bet* for Birr; *Arjo*, *Bedele*, *Chira*, and *Gatira* for Upper-Didesa; *Bahir Dar*, *Dangila*, *Debre Markos*, and *Feres Bet* for Gilgel Abbay; and *Bahir Dar* and *Dangila* for Koga (Figure 1). These stations were selected based on consistency of the data availability since 1960. The areal rainfall was calculated as a weighted mean where the weights were determined by the Thiesen polygon method. Missing data from some stations were filled in based on nearby stations and a correlation analysis between individual stations [*Mellander et al*., 2013].

[10] Temperature data were taken directly from the nearest station. Long-term mean daily PET for each month was estimated from monthly minimum, maximum, and mean temperatures using the Hargreaves method [*Belete*, 2002]. The Hargreaves method was chosen as this method of several tested methods best could reflect the mean daily Penman-Monteith values given for six of the eight stations in the Abby Master Plan document [*Ministry of Water Resources*, 1998]. The PET values produced using the Hargreaves method were calibrated to the mean PET value extracted from the Master Plan document.

[11] Hydrological data were collected and processed by the Ministry of Water Resources, Ethiopia. Manual staff gauge readings were performed twice a day and converted to discharge using rating curves. These rating curves were constructed based on three to four current meter readings per year and annual surveys of the channel cross section [*Dahmen and Hall*, 1990; *Wijeserkera and Perera*, 2012].

2.2.2. Data *Q*uality

[12] Meteorological and hydrological data were checked using different plots and identifying changes existing in the

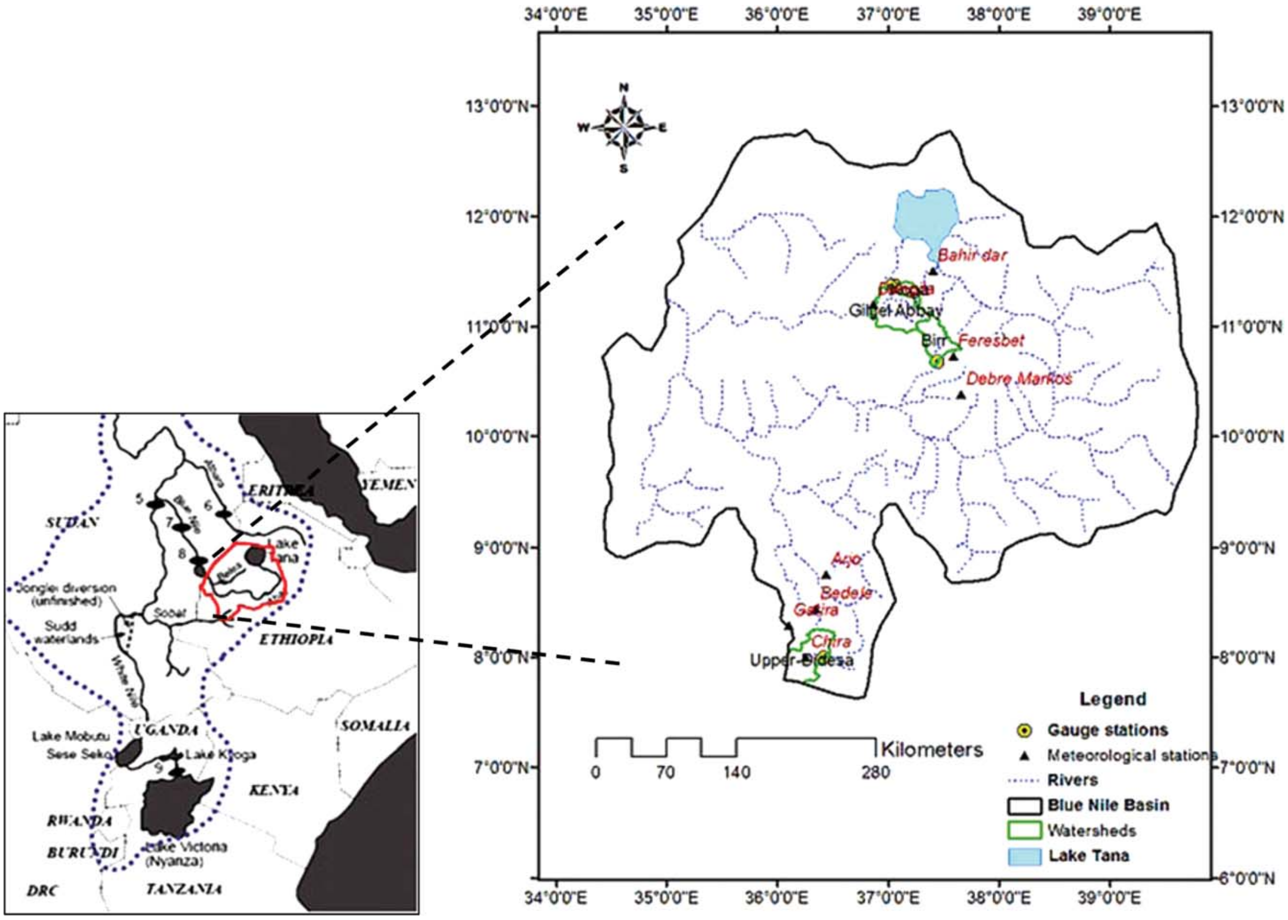

Figure 1. Location of the Blue Nile Basin, the study watersheds, gauge, and meteorological stations. (left) The broken line represents the Nile Basin.

data series as described by *Dahmen and Hall* [1990]. The annual water balance was checked for outliers and for shifts as well.

[13] Outliers (unexpectedly high or low), missing values, and offsets in runoff from the rainfall season were identified. These were cross-checked with the original data, looking for arithmetic or literal errors during data processing, and some errors were corrected based on this cross-checking. Unrealistic data figures were excluded as outliers after all the process of data quality assessment. These excluded values accounted for 3% of the data. Original data were missing for another 3.5% of the days. Thus, the missing values comprised 6% of the total data set.

3. Model Parameters and Change Detection

3.1. Model Description

[14] The HBV (Hydrologiska Byråns Vattenbalansavdelning) model [*Lindström et al.*, 1997], a conceptual rainfall-runoff model, was used to detect changes in the hydrological regime. HBV has been used worldwide at different scales ranging from plot to regional scale and in different climatic regions from the tropics to snow-dominated regions [*Lidén and Harlin*, 2000]. In this study, the version *HBV light* was used [e.g., *Seibert*, 1999], which is basically similar with the version described by *Lindström et al.* [1997].

[15] HBV simulates runoff using daily rainfall, temperature, and mean monthly PET as input [*Lindström et al.*, 1997]. The model includes different routines for evapotranspiration, soil moisture accounting, runoff generation, and snow (Figure 2). There are 14 parameters in HBV light of which 9 parameters were used in this study (the five snow parameters were not used) (Table 2 and Figure 2).

3.2. Parameter Selection

[16] Ranges of parameter values for calibration were generated in two steps. First, the initial ranges were selected based on literature [*Ashenafi*, 2007; *Merz and Blöschl*, 2004; *Muli*, 2007; *Seibert*, 1999; *Yeshewatesfa and Bardossy*, 2004]. Second, the initial ranges of parameters were adjusted based on the results of 10,000 Monte Carlo simulations. By assessing the distribution of the parameter values along the ranges, either constricted or maintained or relaxed [*Bardossy and Singh*, 2008].

[17] Best parameter values for runoff simulations were generated using Monte Carlo run with the identified ranges of each parameter. Two hundred fifty thousand runs were used to generate 50 best parameter sets [*Seibert and Vis*, 2012]. The 50 best parameter sets were selected based on highest Nash-Sutcliffe model efficiency values (R_{eff}) [*Nash*

Table 1. Geographical, Hydrometeorological, and Land Resource Description of Study Watersheds

	Area (km^2)	Altitude (m)	Annual Rainfall (mm)			Mean Daily PET (mm)			Annual Discharge (mm)			Land Cover Status[a]			Soil and Geology[b]
			P1	P2	P3	P1	P2	P3	P1	P2	P3	P1	P2	P3	
Birr	980	1790	1790	1569	1833	16	16	16	508	419	560	>20% covered with forests	15%–20% covered with forests	<15% covered with forests	Haplic luvisols, deep alisols, and dominated by tuff basalt rocks
Upper-Didesa	1806	1480		1995	2013	–	19	19	–	507	474	~90% covered with forests	60%–80% covered with forests	~50% covered with forests	Regosols and calcic vertisols, with volcanic rocks and basalts
Gilgel Abbay	1660	1900	1615	1483	1569	18	19	20	1068	1097	1131	~7% covered with forests	1%–4% covered with forests	~5% covered with forests	Luvisols, and geology is dominated by tuff basalts
Koga	260	1890	1546	1510	1588	18	19	20	576	497	673	>20% covered with forests	2%–5% covered with forests	~1% covered with forests	Luvisols, and geology is dominated by tuff basalts

[a] Sources for land cover status were *Gebrehiwot et al.* [2010] and *Gebrehiwot* [2012].

[b] Sources for soil and geology were *Ministry of Water Resources* [1999] and *Gebrehiwot et al.* [2011].

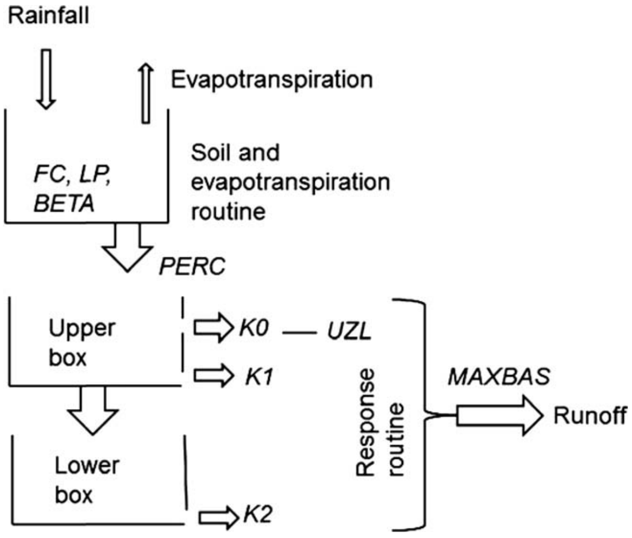

Figure 2. Representation of the HBV-model structure with routines in regular font and parameter names in italic [*Lindström et al.*, 1997].

and Sutcliffe, 1970]. The efficiency values were computed for 7 day intervals instead of daily values to reduce the effect of possible timing errors of the daily rainfall and discharge data, especially for cases with extreme weather [*Krause et al.*, 2005].

4. Change Detection

4.1. Parameter Comparison

[18] Changes were detected in three different ways: comparing parameter set values, comparing model residuals, and comparing simulated runoff using parameters selected for three different periods. The best 50 parameter sets were selected for each of the three periods, which were 1960–1975 (P1), 1976–1990 (P2), and 1991–2004 (P3). The periods were selected based on breaks in political regimes in 1975 and 1991 that were associated with changes in the land management [*Gebrehiwot et al.*, 2010; *Rahmato*, 2009]. Data series were classified into two equal ranges (two periods, P2: 1985–1994 and P3: 1995–2004) for Upper-Didesa as data from this watershed were available only from 1985 onward. The annual flow refers to the Gregorian calendar year-flow since that suits as the water (or hydrological) year in the study area.

[19] R_{eff} values were plotted against parameter values to study parameter identifiability. In R_{eff} versus parameter value plot, a parameter was deemed identifiable for a period if high R_{eff} values could only be achieved along a small interval of the parameter value range in at least one of the three periods. In the further analysis we focused on the identifiable parameters, as change can only be detected with them.

[20] The distributions of the 50 best parameter sets for each period were compared. The significance of the differences between parameter distributions were tested using the nonparametric Wilcoxon signed-rank test (with $\rho \leq 0.05$) [*Zar*, 1999].

[21] It is also possible that parameters compensate for each other and/or changes could be correlated in ways that

Table 2. Parameters of HBV and the Ranges Used in the Monte Carlo Approach and Identifiability of Parameters

	Description	Model Routine	Tested Parameter Range	Identifiable in ... Watersheds
FC	Maximum soil moisture storage, similar to field capacity but merely a model parameter	Soil routine	50–1800 mm	All
LP	Soil moisture value above which actual evapotranspiration reaches PET (mm)	Soil and evapotranspiration routine	0.01–1 mm	All
BETA	A coefficient which determines the portion of water contributed to evaporation	Soil and evapotranspiration routine	1–7	All
PERC	Maximum percolation from upper to lower box	Response function	0–6 mm d^{-1}	Upper-Didesa and Koga
UZL	Maximum threshold parameter at which water retained in the upper box	Response function	0–100 mm	All except Birr
K0	Recession coefficient for peak flow	Response function	0.05–0.5 d^{-1}	Birr and Upper-Didesa
K1	Recession coefficient for subsurface flow	Response function	0.001–0.4 d^{-1}	All
K2	Recession coefficient for base flow	Response function	0.0005–0.25 d^{-1}	All except Gilgel Abbay
MAXBAS	A parameter function for equilateral triangular weighting function	Routing routine	1–8 days	All

offset the effects on model performance. A principal component analysis (PCA) was conducted on the parameter sets to check this. PCA identifies different linear axes that represent relationships between variables (parameters in this case). The first four axes were considered for analyzing the expressed variance [*Eriksson et al*., 2001]. Parameters are assumed to be compensating for each other if they are far apart along an axis. SIMCA 12.0.1 [*UMETRICS AB*, 2009], a multivariate analysis software, was used for the PCA. Parameters with a strong nonlinear behavior (FC, LP, BETA, and MAXBAS in all watersheds) were log-transformed before running the PCA.

4.2. Residual Analysis

[22] The model residuals of the three periods were compared. The residual analysis allows for evaluating influence of the watershed characteristics on the flow regime relative to a reference period [*Seibert and McDonnell*, 2010]. In this case the 50 best parameter sets calibrated to P1 were used to simulate all three periods. Relative residuals were calculated using the mean annual observed (Q_{obs}) and simulated discharge (Q_{sim}) as $(Q_{obs} - Q_{sim})/Q_{obs}$. The simulation was generated with the specific period climate using parameter sets selected based on P1. The median relative residual to each of the 50 simulations was calculated after computing annual means of the daily discharge.

[23] In calculating the relative residuals, the possible effect of climate factors were constrained, so that the changes could be attributed to changes in watershed characteristics. Relative residual values that differ significantly from zero were considered to have larger changes in the watershed characteristics since the reference period, P1. Larger positive residuals' mean Q_{sim} was lower than the observed discharge in the respective period, i.e., that parameters from P1 underestimate the runoff in the respective period. Negative residual values mean that the parameters from P1 resulted in less runoff than the actual observed runoff. The significance of differences in residuals for the different periods was evaluated using the Wilcoxon signed-rank test [*Zar*, 1999].

4.3. Comparison of Runoff Simulation Using Different Parameter Sets

[24] The 50 best model calibrations from each period were used to simulate the runoff using the entire climate time series and compared. This comparison of simulated runoff allows identification of the combined effect of different parameters. This is a way to quantify watershed functioning. The significance of differences between the runoff simulations was compared using Wilcoxon signed-rank test [*Zar*, 1999]. The dry and wet years' simulations were used for illustration (Figure 4). Presentation of dry and wet years' simulation is to see how much the relative changes of flow driven by extreme climate events [*Croke et al*., 2004].

5. Results

[25] HBV performed well in simulating each period for each watershed (Table 3). The model efficiency of the 50 best parameter sets was higher than 0.65 in all cases when looking at 7 day intervals and higher than 0.6 when evaluated on a daily time step. In Birr and Upper-Didesa, the model efficiencies were greater in the earlier period, whereas in Gilgel Abbay and Koga, a better model performance was observed for the later periods. The model performance was best in Gilgel Abbay throughout.

5.1. Identifiability Analysis

[26] The parameters FC, LP, BETA, K1, and MAXBAS were found to be identifiable in all watersheds (Table 2). UZL and K2 were identifiable in three of the four watersheds, whereas PERC and K0 were identifiable only in two watersheds. So PERC and K0 were not emphasized in the subsequent analysis.

5.2. Change Detection Analyses

[27] Six parameters among the nine were significantly changing from period to period for Upper-Didesa and Gilgel Abbay, whereas five for Koga, and four parameters for Birr (Table 3). FC was significantly changing from period to period in all watersheds. The highest median value of FC was 1670 mm for Koga P3, and the lowest median was 196 mm for Gilgel Abbay in P1. LP, BETA, K1, and MAXBAS were significantly changing for Gilgel Abbay and Koga. K2 was significantly changing for Upper-Didesa and Koga. The highest median value of K2 was 0.13 d^{-1} for Birr in P1, and the lowest median value was 0.05 d^{-1} in Koga P3. UZL was significantly changing in Gilgel Abbay.

[28] The PCA analysis revealed some correlations between the parameters, which might indicate that parameter changes could compensate each other. The total

Table 3. Medians of the 50 Best Parameter Values and Maximum Model Efficiency[a]

	FC	LP	BETA	PERC	UZL	K0	K1	K2	MAX	R_{eff}-7	R_{eff}-1
Birr											
P1	**1208**^{a}	**0.21**^{a}	1.15	–	–	0.24	0.22	0.13	**1.96**^{a}	0.73	0.65
P2	**1387**^{b}	**0.17**^{b}	1.10	–	–	0.28	0.25	0.12	**2.41**^{b}	0.70	0.62
P3	**1605**^{c}	**0.28**^{c}	1.10	–	–	0.24	0.21	0.12	**2.73**^{b}	0.70	0.61
Upper-Didesa											
P2	**773**^{a}	0.31	**3.25**^{a}	**1.32**^{a}	63.7	**0.09**^{a}	**0.06**^{a}	**0.08**^{a}	2.21	0.80	0.75
P3	**715**^{b}	0.22	**1.54**^{b}	**4.28**^{b}	60.0	**0.21**^{b}	**0.14**^{b}	**0.06**^{b}	3.04	0.70	0.66
Gilgel Abbay											
P1	**196**^{a}	**0.86**^{a}	**2.40**^{a}	–	**75.5**^{a}	–	**0.05**^{a}	–	**2.24**^{a}	0.82	0.79
P2	**227**^{b}	**0.94**^{b}	**1.68**^{b}	–	**73.9**^{b}	–	**0.08**^{b}	–	**2.54**^{a}	0.83	0.79
P3	**217**^{b}	**0.95**^{b}	**1.80**^{b}	–	**76.8**^{c}	–	**0.09**^{b}	–	**1.89**^{b}	0.87	0.80
Koga											
P1	**1413**^{a}	**0.36**^{a}	1.15	3.59	62.5	–	**0.14**^{a}	**0.06**^{a}	**2.19**^{a}	0.68	0.63
P2	**1637**^{b}	**0.44**^{b}	1.22	2.24	56.0	–	**0.15**^{a}	**0.08**^{a}	**2.17**^{a}	0.72	0.65
P3	**1670**^{b}	**0.50**^{b}	1.28	1.69	52.7	–	**0.11**^{b}	**0.05**^{b}	**3.07**^{b}	0.71	0.64

[a] Values in a column which are indicated with bold and similar letters are significantly different at $\rho \leq 0.05$ with Wilcoxon signed-rank test. "–" shows that the parameters respective to each watershed were nonidentifiable (Table 2).

variance explained by four axes of the PCA was 54% for Birr, 67% for Upper-Didesa, 48% for Gilgel Abbay, and 55% for Koga. Soil routine parameters (FC, LP, and BETA) were positively correlated to each other and negatively correlated with subsurface recession coefficients (K1 and K2) in P1 for Birr. The same type of correlation was seen in P2 for Upper-Didesa. Apart from these, there were not any particularly strong positive or negative correlations seen in the PCA analysis, but rather many moderately correlated parameters.

[29] The annual variation and median of residuals in the different watersheds and period classes showed that model residuals were significantly changing in four of seven possible cases (Figure 3). The model efficiencies (R_{eff}) of the

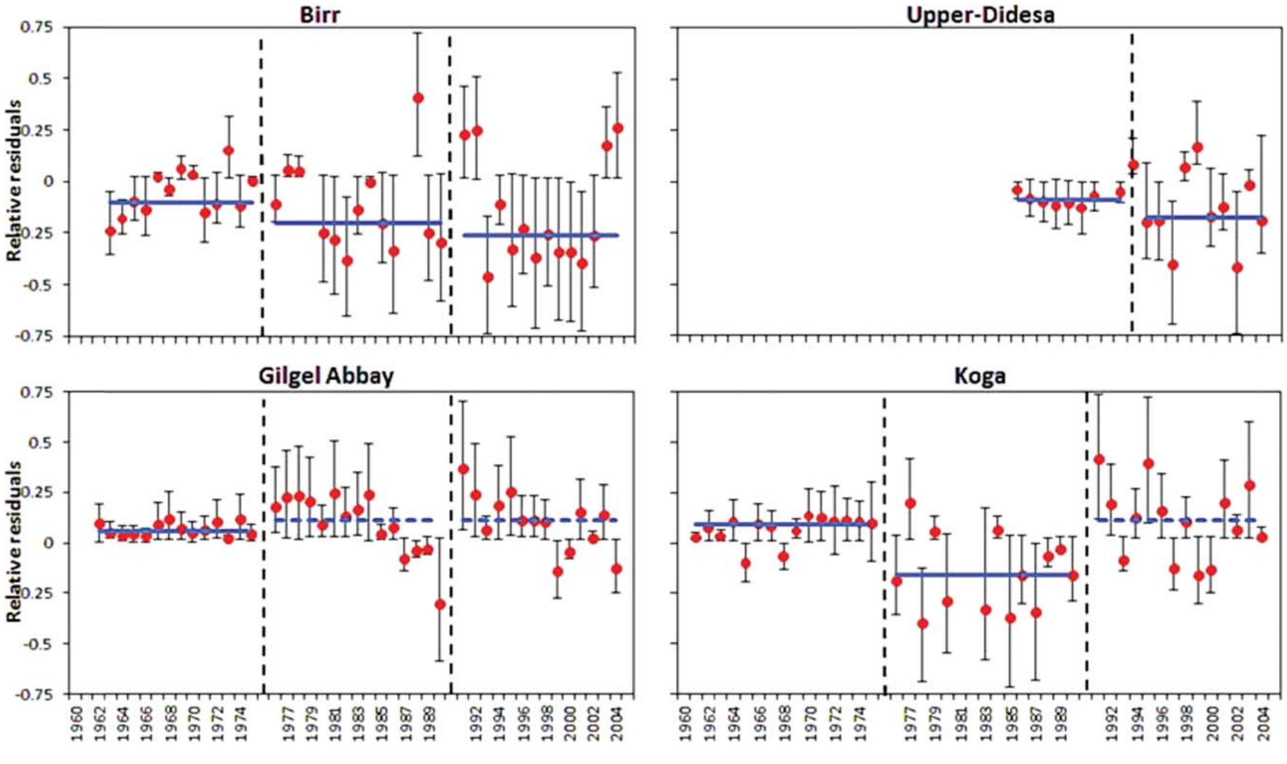

Figure 3. Medians and 75 percentile interval of the relative residuals of 50 best parameter sets simulations in four watersheds in the Blue Nile basin. Relative residual calculated as $(Q_{obs} - Q_{sim})/Q_{obs}$, where Q_{obs} refers to the observed discharge of the respective period and Q_{sim} refers to the simulation generated with the respective period climate using parameter sets from P1. Vertical broken lines divide the study periods into 1960–1975 [P1], 1976–1991 [P2], and 1992–2004 [P3] (except for Upper-Didesa where there are two periods—before and after 1994). The medians for each period are indicated with horizontal lines; solid lines indicate significant differences relative to the reference period (P1); while dashed lines indicate nonsignificant difference from P1.

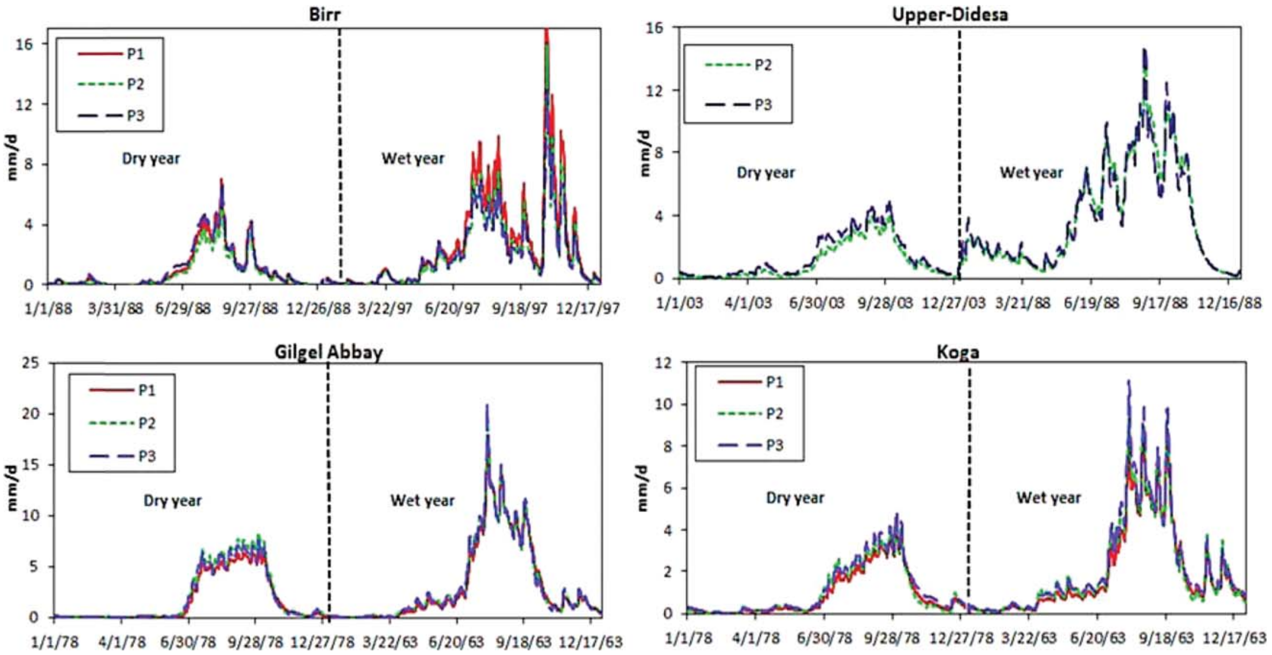

Figure 4. Daily runoff simulation results in the four watersheds using the parameter sets from the different periods (P1, P2, and P3) for the dry and wet year climate inputs.

residual analysis were greater than 0.58 in all cases. Subdividing the different periods and performing split-sample tests indicated that model performances for independent periods were in general not much poorer than those obtained for calibration periods. This indicated that the model was suitable to reconstruct runoff time series for (hypothetically) unchanged conditions. There were significant changes of residuals from the reference period, P1 in all watersheds, except for Gilgel Abbay. Residuals in P3 of Koga were not statistically different from those in P1. More negative relative residuals were observed in P3 of Birr and Upper-Didesa and in P2 of Koga (Figure 3); indicating a decrease in discharge.

[30] Ten cases were compared for runoff simulation (between the three periods for Birr, Gilgel Abbay, and Koga, as well as between two periods for Upper-Didesa). Among the 10 test cases, there was no significant change (Wilcoxon signed-rank test, $\rho \leq 0.05$) between runoff simulations. There was, however, a 15% increment of Q_{sim} for P3 in Upper-Didesa and Gilgel Abbay (Figure 5), although this was not significant according to the statistical test. The least percentage change was 3% increment in Gilgel Abbay from P1 to P2. The highest mean simulated discharge was 2.4 mm d^{-1} in Gilgel Abbay in P3. The lowest mean simulated discharge was 1.1 mm d^{-1} in Upper-Didesa in P2. The biggest relative change was in Gilgel Abbay from 2.1 mm d^{-1} in P1 to 2.4 mm d^{-1} in P3, while the least relative change was in Birr from 1.5 mm d^{-1} in P1 to 1.4 mm d^{-1} in P3.

6. Discussion

[31] Hydrological change studies are of a great value in the Blue Nile Basin, as impacts of such environmental change [*Baldassarre et al.*, 2011; *Bekele*, 2003; *Gete and Hurni*, 2001] and population pressure are escalating [*Food and Agriculture Organization*, 2000]. This study has addressing hydrological change detection using a modeling approach in four watersheds of the Blue Nile Basin. The modeling approach was used to find patterns that could be missed by the statistical analysis [*Gebrehiwot*, 2012]. Even though one must be cautious in ascribing specific meaning of changes in model parameters to watershed characteristics, especially when model parameters rather represent more conceptual than physical features [*Xu*, 1999]. There could be also a case where model performance decreased in the validation periods, but this did not affect the overall results as performance differences between calibration and validation were generally small with the median difference in R_{eff}-daily being 0.05 and 0.04 for R_{eff}-7-day with the split-sample test.

6.1. Model Parameters

[32] Model parameters were changing significantly from period to period. Soil routine, evapotranspiration routine, and subsurface response function parameters (FC, LP, BETA, K1, K2, and MAXBAS) changed most between the three periods. This might suggest that watershed characteristics related to soil moisture, evapotranspiration, and subsurface flow were changing. It is also noted that ranges of parameter values were different among watersheds. FC and LP were higher for Birr and Koga, while FC was lowest for Gilgel Abbay (Table 2). This implies that there are difference watershed characteristics among watersheds which are represented by the model parameters. This hypothesis is supported by the results presented by *Gebrehiwot et al*. [2011] where spatial differences in hydrological regime were attributed to differences in geology, soils, and land use.

[33] The change of FC could be related to changes in soil moisture retention capacity of the watersheds.

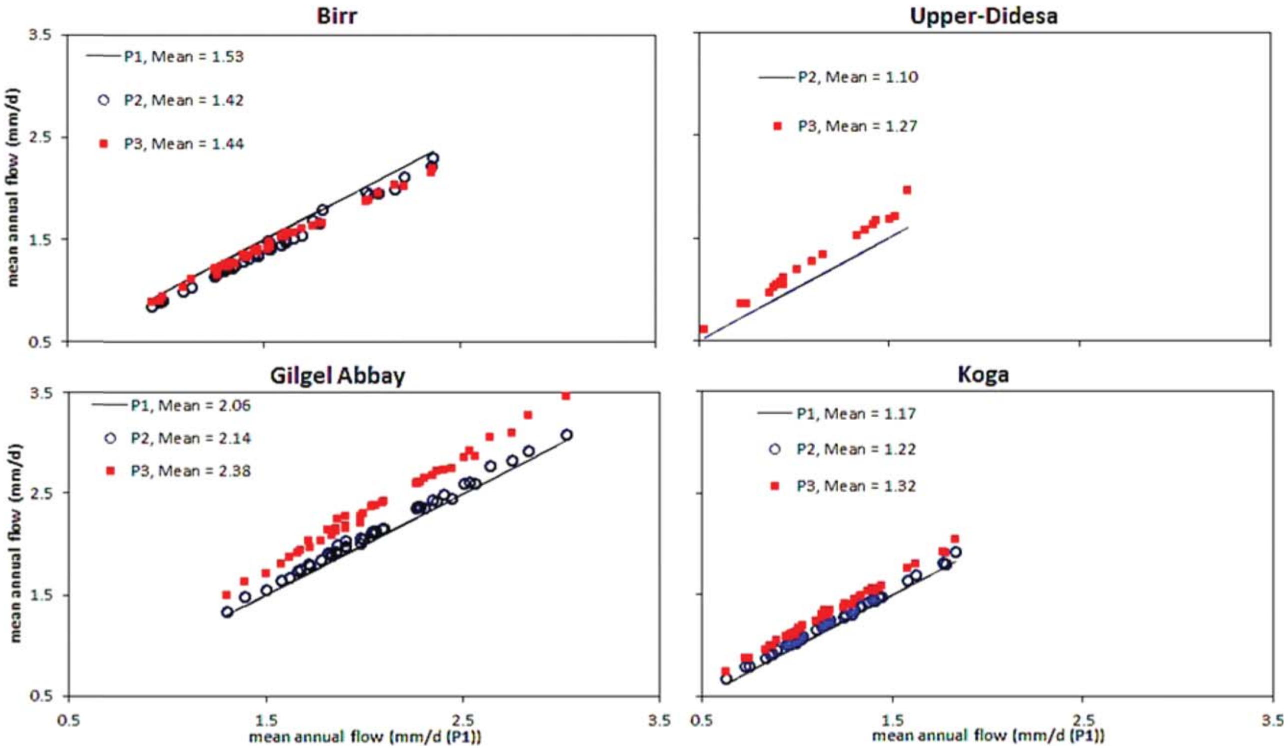

Figure 5. Comparison of the mean daily runoff simulation of the entire time series climate input produced with the parameter sets from the three different periods.

LP was increasing in Birr, Gilgel Abbay, and Koga; while BETA was decreasing in Upper-Didesa. This might mean that the amount of soil moisture contributing to PET was becoming higher in the former watersheds and the fraction of water which could contribute to evaporation became less in the later. However, a change in one parameter, such as FC, representing storage of soil water could be compensated by another parameter, such as K2 giving less base flow. The likelihood of compensation between parameter changes was supported by the PCA which showed some correlation between the different parameters. The three adjacent watersheds (Gilgel Abbay, Birr, and Upper-Didesa) showed difference in parameter changes; this implies that the status and change of soil water availability are watershed specific. Changes in soil moisture are crucial as they are the constraining factors for the small-scale farming systems in the study area [*Anderson et al.*, 2012].

6.2. Residuals

[34] The residuals were becoming more negative toward recent years in Birr and in Upper-Didesa, as well as in P2 in Koga. More negative relative residuals indicated that simulated runoff for that specific period was overestimated when using parameters from P1. Residuals were becoming more positive in Gilgel Abbay in P1 and P2 and during P3 in Koga, which indicated that more runoff was produced with a greater amount of rainfall over time in these watersheds. This indicates that watershed characteristics are playing fewer roles in processing the rainfall water into runoff. However, there were changes in watershed characteristics, especially in forest cover, and almost no change in rainfall [*Gebrehiwot*, 2012; *Gebrehiwot et al*., 2010].

6.3. Runoff Simulations

[35] Simulations showed the integrated effect of the nine parameters on how the watersheds generate runoff. The significant changes in the parameters and residuals were not associated with significant changes in runoff simulations (Table 3 and Figures 4 and 5). There was no significant change according to the Wilcoxon signed-rank test but a 15% of daily runoff change in P3 of Upper-Didesa and Gilgel Abbay; this might be related with a change of more parameters (6) in these two watersheds than the others. The lack of significant change in the runoff simulation between the three periods was consistent with the statistical hydrological change analysis where not many hydrological changes were seen in the observed discharge over the same time series [*Gebrehiwot*, 2012]. The statistical analysis was done for 12 watersheds including those in this study. Indeed, there was much similarity in the response of runoff to rainfall whether observed or simulated over the 45 year study period.

[36] One possible reason for not seeing significant differences between runoff simulations, even though there were changes in parameter sets, is that the changes of individual parameters could compensate for each other [*Beven*, 2006]. Parameter relationships revealed by the PCA analysis indicate that compensation could have masked the cumulative effect of changing parameters in Birr and Upper-Didesa. There were correlations between parameters, but the relationships were not clear enough

to say explicitly that compensation was occurring. The variability and inconsistencies of results among watersheds indicate the specificness of the watersheds in hydrological responses.

[37] All results are indicating each watershed need specifically tailored water and land resources management. Yet, there is a need for further investigation of how well model parameters reflect differences in the characteristics of watersheds, especially for soil and land use resources, since the region is known to have an extensive soil degradation history [*Gebrehiwot et al*., 2010; *Birru*, 2007; *Hurni et al*., 2005; *Bekele*, 2003; *Gete and Hurni*, 2001]. There is no clear generalization that can be made about the relation of these degradations to the flow processes at the watershed scale of thousands of square kilometers. This does not mean that degradation has not been affecting the subsistence farming in the region which is dependent on the limited water availability, but there is not strong evidence that hydrological change is detectable at this scale of large watersheds. Scale is another issue in watershed-based development. In a study by *Hurni et al*. [2005], land use differences highly influenced hydrological responses at plot scale. There are differences in hydrological response to land use and climate changes at different scales [*Ellison et al*., 2012]. This study finds that the hydrological regimes of the rivers were changing across the Blue Nile Basin in different ways.

7. Conclusion

[38] Significant changes in model parameter values and model residuals were found, though the changes were not consistent across the four watersheds studied. There were however little changes in actual runoff simulations. This means that even though parameters and residuals changed over the past 45 years, they have little impact on the modeled hydrological responses seen at the scale of rivers. The small change of runoff in the last 45 years was also reflected in the statistical analysis of the hydrological regime.

[39] This study reveals the need to consider the possibilities for compensation between parameters in hydrological change detection work. There is also a need for further research to clarify which parameters specifically represent which watershed characteristics and how far the soil and vegetation degradation can be related to changes in parameter values at large (>100 km^2) scale. In the Blue Nile, this entails showing how the soil degradation history affects the flow processes in the basin. There were bigger differences between watersheds than temporal differences within a watershed. Thus, there is also a need to account for the spatial differences when searching for temporal differences in parameter changes.

[40] This study showed that change detection analysis with only parameters can be misleading. We recommend that change detection modeling should include comparisons of simulations using the different parameter sets to see the overall changes of the simulated hydrological regime, and not just analyzing individual parameter value changes. In general, our study highlights the fact that the choice of the modeling and statistical methodology can have important influences on the outcome.

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