Year: 2013

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

Gebrehiwot, Solomon Gebreyohannis; Seibert, Jan; Gärdenäs, Annemieke I; Mellander, Per-Erik; Bishop, Kevin

Abstract: 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 km². 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.

DOI: https://doi.org/10.1002/wrcr.20319

Posted at the Zurich Open Repository and Archive, University of Zurich
ZORA URL: https://doi.org/10.5167/uzh-83877

Published Version

Originally published at:
DOI: https://doi.org/10.1002/wrcr.20319
Hydrological change detection using modeling: Half a century of runoff from four rivers in the Blue Nile Basin

Solomon Gebrehiwot,1,2 Jan Seibert,3,4 Annemieke I. Gärdenäs,5 Per-Erik Mellander,6 and Kevin Bishop1,4

Received 8 May 2012; revised 13 May 2013; accepted 17 May 2013; published 27 June 2013.

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 km². 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 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.


1. Introduction

2 Changes in watershed characteristics and climate are the main drivers of hydrological change [Kundzewicz, 2004; Kundzewicz 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
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.

2.2. Data

2.2.1. Hydrometeorological Data

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 Abbey; 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 Thiessen 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].

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 Abay 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.

2.2.2. Data Quality

Meteorological and hydrological data were checked using different plots and identifying changes existing in the
data series as described by Dahmen and Hall [1990]. The annual water balance was checked for outliers and for shifts as well.

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

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].

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

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].

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...
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

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.

$R_{eff}$ 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.

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].

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

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Annual Rainfall (mm)</th>
<th>Mean Daily PET (mm)</th>
<th>Annual Discharge (mm)</th>
<th>Land Cover Status</th>
<th>Soil and Geology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Birr</td>
<td>980</td>
<td>1790</td>
<td>1790</td>
<td>&gt;20% covered</td>
<td>Haplic luvisols, deep alluvial and deposits, and deposits with volcanic rocks and basalt.</td>
</tr>
<tr>
<td>Upper-Didesa</td>
<td>1806</td>
<td>1599</td>
<td>2013</td>
<td>15%–20% covered</td>
<td>Regosols and calcic vertisols, with forests and with peat deposits.</td>
</tr>
<tr>
<td>Gilgel</td>
<td>1660</td>
<td>1483</td>
<td>2015</td>
<td>2%–5% covered</td>
<td>Luvisols, and geology is dominated by tuff basalts.</td>
</tr>
<tr>
<td>Koga</td>
<td>260</td>
<td>1546</td>
<td>1510</td>
<td>&lt;5% covered</td>
<td>Luvisols, and geology is dominated by tuff basalts.</td>
</tr>
</tbody>
</table>

Sources for land cover status were Gebrehiwot et al. [2010] and Gebrehiwot et al. [2011].

Sources for soil and geology were Ministry of Water Resources [1999] and Gebrehiwot et al. [2012].
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

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 parameter sets selected based on P1. The median relative relation was generated with the specific period climate using MAXBAS A parameter function for equilateral triangular routing routine 1–8 days All except Gilgel Abbay

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

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

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

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

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.

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

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](image.png)

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.

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

<table>
<thead>
<tr>
<th>Watershed</th>
<th>FC</th>
<th>LP</th>
<th>BETA</th>
<th>PERC</th>
<th>UZL</th>
<th>K0</th>
<th>K1</th>
<th>K2</th>
<th>MAX</th>
<th>$R_{eff}$ P1</th>
<th>$R_{eff}$ P2</th>
<th>$R_{eff}$ P3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Birr</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P1</td>
<td>1208</td>
<td>0.21</td>
<td>1.15</td>
<td>–</td>
<td>–</td>
<td>0.24</td>
<td>0.22</td>
<td>0.13</td>
<td>1.96</td>
<td>0.73</td>
<td>0.65</td>
<td></td>
</tr>
<tr>
<td>P2</td>
<td>1387</td>
<td>0.17</td>
<td>1.10</td>
<td>–</td>
<td>–</td>
<td>0.28</td>
<td>0.25</td>
<td>0.12</td>
<td>2.41</td>
<td>0.70</td>
<td>0.62</td>
<td></td>
</tr>
<tr>
<td>P3</td>
<td>1605</td>
<td>0.28</td>
<td>1.10</td>
<td>–</td>
<td>–</td>
<td>0.24</td>
<td>0.21</td>
<td>0.12</td>
<td>2.73</td>
<td>0.70</td>
<td>0.61</td>
<td></td>
</tr>
<tr>
<td>Upper-Didesa</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P1</td>
<td>773</td>
<td>0.31</td>
<td>3.25</td>
<td>1.32</td>
<td>63.7</td>
<td>0.09</td>
<td>0.06</td>
<td>0.08</td>
<td>2.21</td>
<td>0.80</td>
<td>0.75</td>
<td></td>
</tr>
<tr>
<td>P2</td>
<td>715</td>
<td>0.22</td>
<td>1.54</td>
<td>4.28</td>
<td>60.0</td>
<td>0.21</td>
<td>0.14</td>
<td>0.06</td>
<td>3.04</td>
<td>0.70</td>
<td>0.66</td>
<td></td>
</tr>
<tr>
<td>P3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gilgel Abbay</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P1</td>
<td>196</td>
<td>0.86</td>
<td>2.40</td>
<td>–</td>
<td>75.5</td>
<td>–</td>
<td>0.05</td>
<td>–</td>
<td>2.24</td>
<td>0.82</td>
<td>0.79</td>
<td></td>
</tr>
<tr>
<td>P2</td>
<td>227</td>
<td>0.94</td>
<td>1.68</td>
<td>–</td>
<td>73.6</td>
<td>–</td>
<td>0.08</td>
<td>–</td>
<td>2.54</td>
<td>0.83</td>
<td>0.79</td>
<td></td>
</tr>
<tr>
<td>P3</td>
<td>211</td>
<td>0.95</td>
<td>1.80</td>
<td>–</td>
<td>76.8</td>
<td>–</td>
<td>0.09</td>
<td>–</td>
<td>1.89</td>
<td>0.87</td>
<td>0.80</td>
<td></td>
</tr>
<tr>
<td>Koga</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P1</td>
<td>1413</td>
<td>0.36</td>
<td>1.15</td>
<td>3.59</td>
<td>62.5</td>
<td>–</td>
<td>0.14</td>
<td>0.06</td>
<td>2.19</td>
<td>0.68</td>
<td>0.63</td>
<td></td>
</tr>
<tr>
<td>P2</td>
<td>1637</td>
<td>0.44</td>
<td>1.22</td>
<td>2.24</td>
<td>56.0</td>
<td>–</td>
<td>0.15</td>
<td>0.08</td>
<td>2.17</td>
<td>0.72</td>
<td>0.65</td>
<td></td>
</tr>
<tr>
<td>P3</td>
<td>1670</td>
<td>0.50</td>
<td>1.28</td>
<td>1.69</td>
<td>52.7</td>
<td>–</td>
<td>0.11</td>
<td>0.05</td>
<td>3.07</td>
<td>0.71</td>
<td>0.64</td>
<td></td>
</tr>
</tbody>
</table>

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

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, \( p \leq 0.05 \)) between runoff simulations. There was, however, a 15% increment of \( Q_{\text{sim}} \) 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

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 \( R_{\text{eff}} \)-daily being 0.05 and 0.04 for \( R_{\text{eff}} \)-7-day with the split-sample test.

6.1. Model Parameters

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.

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

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.
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

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

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.

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 km²) 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.

[41] Acknowledgments. This paper was produced as a part of the research project funded by Swedish International Development Agency (SIDA) and the Swedish Foreign Affairs Office project “Soil and water management in agricultural production.”

References


