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Catchment modeling and model transferability in upper Blue Nile Basin, Lake Tana, Ethiopia

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Abstract

Understanding spatial and temporal distribution of water resources has an important role for water resource management. To understand water balance dynamics and runoff generation mechanisms at the Gilgel Abay catchment (a major tributary into lake Tana, source of Blue Nile, Ethiopia) and to evaluate model transferability, catchment modeling was conducted using the conceptual hydrological model HBV. The catchment of the Gigel Abay was sub-divided into two gauged sub-catchments (Upper Gilgel Abay, UGASC, and Koga, KSC) and one ungauged sub-catchment.

Manual calibration of the daily models for three different catchment representations (CRs): (i) lumped, (ii) lumped with multiple vegetation zones, and (iii) semi-distributed with vegetations zone and elevation zones, showed good to satisfactory model performance (Nash-Sutcliffe efficiency values, R_{eff}>0.75 and >0.6, respectively, for UGASC and KSC). The change of the time step to fifteen and thirty days resulted in very good model performances in both sub-catchments (R_{eff}>0.8). The model parameter transferability tests conducted on the daily models showed poor performance in both sub-catchments, whereas the fifteen and thirty days models yielded high R_{eff} values using transferred parameter sets. This together with the sensitivity analysis carried out after Monte Carlo simulations (1 000 000 model runs) per CR explained the reason behind the difference in hydrologic behaviors of the two sub-catchments UGASC and KSC. The dissimilarity in response pattern of the sub-catchments was caused by the presence of dambos in KSC and differences in the topography between UGASC and KSC. Hence, transferring model parameters from the view of describing hydrological process was found to be not feasible for all models. On the other hand, from a water resources management perspective the results obtained by transferring parameters of the larger time step model were acceptable.

1 Introduction

The Nile Basin is shared by ten riparian countries and is the life source for more than 160 million people living in the basin. The Blue Nile, originating from the Ethiopian Plateau, is the major source of the Nile water and contributes more than 80% of the Nile flow during the wet season (Conway and Hulme, 1993; Mishra et al., 2003) and 64% of the water at Aswan in Egypt (El-Khodan, 2003). Similar to other sub-basins, irrigation, hydropower power and flood management are the key water resource development needs in Ethiopia and in the Nile region in general. Therefore, understanding the water balance and its spatial and temporal dynamics in the headwaters is crucial.

A number of studies have been conducted on the Nile River; however, due to absence of data and other priorities, few of them covered the hydrology of the Upper Blue Nile. Most of the studies on the Blue Nile focus rather downstream, e.g., at Roseries dam in Sudan (Johnson and Curtis, 1994). In the past few decades, some research and development projects on the Upper Blue Nile were conducted (Lahmeyer, 1962; USBR, 1964; JICA, 1997; BCEOM, 1999; Conway and Hume, 1993; Mishra et al., 2003; Kebede et al., 2005). The runoff estimations of Lake Tana's sub-basin (source of Blue Nile) were computed backward using observed lake outflows. This contributes to the uncertainty of the runoff yield estimates into the Lake Tana (MoWR, 2005), and subsequently to the future generated downstream flows. Generally, little is known about the hydrology of the Gilgel Abay Catchment, one of the main tributaries of Lake Tana. The water balance studies of Lake Tana indicated that more than 93% of the inflow to Lake Tana originates from four main tributary rivers: Gilgel Abay, Gumera, Rib and Megech (Tarekegn and Tadege, 2005; Kebede et al., 2006). The Gilgel-Abay alone contributes about 60% of the inflow to the lake (Tessema, 2006).

From operational water resources management point of view, hydrological models are crucial for understanding and predicting the spatial and temporal distribution of water resources (e.g. Lidén and Harlin, 2000; Uhlenbrook et al., 2004). This includes predicting the future impacts of changes in the land use or the climate on hydrology.

Catchment scale studies of the Gilgel-Abay should help to identify the water balance dynamics, runoff generation processes and provide further insight on lake level fluctuations that are important for the use of the lake water resources and the lake's role in moderating the flow of the Blue Nile River. The objective of this paper is to conduct rainfall-runoff modeling, assess model complexity, and provide an overview on model transferability of the HBV model at different time-scale.

2 The study area

The Gilgel Abay catchment (GAC; 5000 km^2) is the largest of the four main sub-catchments of Lake Tana. It drains the southern part of the Lake Tana basin and has two gauged sub-catchments, namely the Upper Gilgel Abay (UGASC) and Koga (KSC) of 1654 km^2 and 307 km^2, respectively (Fig. 1). With elevation ranging from 1787 m to 3524 m a.m.s.l., rugged mountainous topography characterizes the southern part of the catchment and its periphery in the west and southeast, while the remaining part is a typical low lying plateau with gentle slopes. The geology is composed of quaternary basalts and alluviums. The soils are dominated by clays and clayey loams. The dominant land use units are agricultural (65.5%), agro-pastoral (33.4%), agro-sylvicultural (1%) and urban (0.1%). Among these, rainfed agriculture covers 65% of the GAC, and it amounts to 74% and 64% on the UGASC and KSC, respectively. Although there is no fixed dependence between the land use and elevation through out the basin, occurrence of seasonal wetlands (dambos) is observed mainly in the gentle slope areas (Fig. 1); compared to UGASC, the dambo covers a larger area in KSC. As described by von der Heyden and New (2003), the role of dambos in affecting catchment evapotranspiration, increasing base flow, and decreasing and retarding flood flow are not fully understood.

The rainfall over the Gigel Abay and Upper Blue Nile in general, originates from moist air coming from Atlantic and Indian oceans following the north-south movement of the Inter Tropical Convergence Zone (ITCZ). Different studies (e.g., Kebede et al., 2006; Tarekegn and Tadege, 2005) demonstrated that the study area has one main rainy season between June and September, in which 70% to 90% of the annual total rainfall occurs. Rainfall data from surrounding meteorological stations indicate significant spatial variations of rainfall in the GAC following the topography, with a decreasing trend from south to north. The temperature variations throughout the year are small (BCEOM, 1999). There are three discharge gauging stations (Fig. 1); all stations are equipped with staff gauges and readings have been taken twice a day (at 06:00 and 18:00 local time).

3 Materials and methods

3.1 Data screening and filling of gaps

The data to be used for hydrological simulations should be stationary, consistent and homogeneous (Dahmen and Hall, 1990). Therefore, we first screened the hydro-meteorological data in different steps: visual data screening and plausibility checks, comparison of monthly and annual totals for the hydrological years, tests for absence of trends, and split-record test for the stationarity of the mean and the variance. Records of nine rain gauges with various gaps were completed using regression and spatial interpolation techniques. Different combinations of stations have been attempted for filling the data gaps. After checking the quality of the point measurements and estimation of aerial mean values, total monthly and annual time series of the estimated rainfall, temperature and runoff data were tested for absence of trend, stability of variance and stability of mean. Names and locations of all flow and rain gauge stations used in this study, together with their respective lengths of data series and percentages of missing data can be found in Table 1.

3.2 The HBV model

3.2.1 Model description and input data

The widely used HBV model (Bergström, 1976) is a conceptual hydrological model, which simulates discharge using as input variables of rainfall, temperature and estimates of potential evaporation. The model consists of different routines representing snow accumulation and melt (not used for the study area), groundwater recharge and actual evaporation as functions of actual water storage in a soil box, three runoff components computed by three linear reservoir equations, and channel routing by a triangular weighting function. Detailed model descriptions can be found elsewhere (e.g. Bergström, 1995). The version of the model used in this study, “HBV light” (Seibert, 2002), corresponds to the version HBV-6 described by Bergström (1992).

The input data used are daily areal rainfall and temperature estimates as well as monthly estimates of potential evapotranspiration. Besides, in the absence of daily potential evapotranspiration data, long-term daily mean temperature data was used to adjust the long-term mean monthly evapotranspiration values to daily values (Lindstroem et al., 1996). Aerial estimates of rainfall and temperature for GAC, UGASC and KSC were calculated using the Thiessen polygon method. These values were distributed over elevation zones using elevation gradients (lapse rates). The estimation of the monthly potential evapotranspiration, E_O (mm/d), was done using the Penman-Monteith equation. While estimating the potential evaporation of GAC, UGASC and KSC existence of different land cover units were taken into account. As described by Chang (2003), when a grassland and forestland/woodland are subject to the same meteorological conditions, the latter transpires more. However, because of absence of data it was not possible to quantify the proportions of grassland and woodland, and they were mapped as mixed grassland (major land use unit) by BCEOM (1999). Hence, in determining E_O, the mixed grassland was considered to evaporate 10% more than computed E_O. Considering elevation zones and vegetation zones as primary hydrological units during the distributed modeling, the catchments were delineated into these different zones using ArcGIS.

Different model structures were applied to investigate the impact of the model structure on the hydrological simulations and the model transferability. Therefore, all input data were prepared for the following three catchment representations (CRs): (i) lumped model structure (CR I), (ii) lumped model structure with up to three vegetation zones (CR II), and (iii) semi-distributed model structure with multiple elevation zones and up to three vegetation zones per elevation zone (CR III). The catchment boundaries and elevation zones were estimated using a $90\times90\,m^2$ DEM and resulted in 18, 16 and 12 elevation zones of 100 m intervals for the GAC, UGASC and KSC, respectively.

3.2.2 Model calibration, validation and performance assessment

A manual model calibration was carried out, which was preceded by Monte Carlo simulations for every CR. However, quantifying the parameter uncertainty of the model, as extensively demonstrated e.g. by Seibert (1997) or Uhlenbrook et al. (1999) in other study areas, was beyond the scope of this paper. The model performance was assed visually and statistically; the objectives during calibration were to maximize the model efficiency according to Nash and Sutcliffe (1970) and to minimize the volume error (i.e. mean difference between simulated and observed runoff per year) at the same time. A simple sensitivity analysis to identify the most sensitive model parameters was carried out separately for each sub-catchment and CR. The number of model parameters used for model calibration varied for UGASC and KSC and also for the three CRs (Table 2). Validations of the models were done by following a split-record test using data of the periods 2000/2001 to 2004/2005 (UGASC) and 2001/2002 to 2004/2005 (KSC). By applying the best model parameter sets of one sub-catchment to the other sub-catchment allowed to test the parameter transferability. Finally, comparison made between most sensitive parameters of UGASC and KSC enabled differentiate hydrologic behaviors of the two sub-catchments.

4 Data analysis

4.1 Preparation of hydrometeorological input data

After checking of the data quality and completing of missing hydrometeorological and hydrological data, areal model input data were computed. The equations used for estimating areal rainfall and temperature values of GAC, UGASC and KSC using the Thiessen polygon method are as given in Eqs. (1)–(6). The potential evapotranspiration values calculated by considering the wighted mean values obtained for each land use according to the Penman-Monteith equation are given in Table 3.

$$P_{\mathrm{AGAC}} = 0.08P_Z + 0.17P_{AS} + 0.41P_{WA} + 0.08P_D + 0.16P_S + 0.1P_G \quad (1)$$

$$T_{\mathrm{AGAC}} = 0.07T_Z + 0.17T_{AS} + 0.43T_{WA} + 0.08T_D + 0.25T_G \quad (2)$$

$$P_{\mathrm{AUGASC}} = 0.17P_D + 0.21P_G + 0.33P_S + 0.29P_{WA} \quad (3)$$

$$T_{\mathrm{AUGASC}} = 0.36T_{WA} + 0.17T_D + 0.47P_G \quad (4)$$

$$P_{\mathrm{AKSC}} = 0.11P_K + 0.11P_S + 0.79P_{WA} \quad (5)$$

$$T_{\mathrm{AKSC}} = T_{WA} \quad (6)$$

The rainfall-elevation increases calculated based on long-term mean rainfall and elevation data were estimated to 2.3% per 100 m (GAC) and 2.4% per 100 m (UGASC and KSC). Similarly, the temperature-elevation lapse rate was determined to 0.14°C/100 m and is applicable to all study catchments. The corresponding reference elevations for the areal rainfall estimates were 2118 m (GAC), 2334 m (UGASC) and 2028 m (KSC). The elevations of the mean temperatures were estimated to 2088 m (GAC), 2240 m (UGASC) and 1900 m (KSC).

4.2 Statistical analysis

The time series analysis of the hydrometeorological data demonstrated inconsistencies, instationarities and inhomogeneities for several monthly values before 1993. For instance, the Pettitt test and F-test (significance level of 5%) applied to the monthly rainfall time series of GAC, UGASC and KSC identified two change points in June (1981 and 1988), and one change point for the March rainfall (1981). The conducted t-tests exhibited changes in most of the months except July, December, January and February in different years between 1981 and 1992. Similarly, annual aerial rainfall time series showed change points in 1981, 1987 and 1990 for all three investigated catchments (i.e. GAC, UGASC and KSC).

Similar observations could be made for the discharge time series: the monthly discharge revealed change points for the mean values in the years between 1981 and 1992 in all months except July and October (UGASC) and June, August and December (KSC). It was concluded that the change points and inconsistencies during the earlier parts of the time series are likely to be caused by the poor data quality. As all inconsistencies, instationarities and inhomogeneities were observed before 1993, data from the hydrologic year 1993/1994 onwards could be regarded as suitable for the hydrological modeling.

5 Hydrological modeling results and discussion

5.1 Model calibration and model validation

Manual adjustments of the model parameters followed carrying out of 1 000 000 Monte Carlo simulations per CR (for each catchment) with the objective to identify suitable parameter ranges and the sensitivity of parameters. Visual assessment of the hydrographs indicates generally good flow simulations in particular during the recession flows of each CR, but the short-term fluctuation during the high-flow season were not

modeled well, in particular in KSC (Fig. 2). Table 4 presents the best calibration parameter sets together with the corresponding statistical measures for model performance. For each CR the agreement between the observed and simulated runoff was good in the UGASC (R_{eff}>0.78) and satisfactory in the KSC (R_{eff}>0.6). The mean annual differences between the observed and simulated runoff (*meandiff*) were negligible, the agreement between simulated and observed low flows was good in the UGASC ($\log R_{\text{eff}}$>0.78) and acceptable in the KSC ($\log R_{\text{eff}}$>0.68).

Performance of the model during the validation period, i.e. 2000/2001–2004/2005 (for UGASC) and 2001/2002–2004/2005 (for KSC), indicated better efficiencies in the UGASC than during the calibration period. For all three CRs the model efficiencies were generally very good (R_{eff}>0.83), even though the model overestimated the observed discharge by about 52 mm/a. Its performance in simulating low flows was also very good ($\log R_{\text{eff}}$>0.84). In the KSC the achieved model performance was comparable to the results obtained during the model calibration. Yet, in the validation period, the model has shown better performance in simulating the low flows ($\log R_{\text{eff}}$>0.73). The reason that the model simulations during the validation period are tentatively better than during the model calibration period is likely to be caused by the better data quality (less missing values).

Good simulation results for all study catchments were achieved for longer modeling time step, i.e. 15- and 30-days (Fig. 3), as the large day-to-day fluctuations during the wet season were averaged out. The simulated average peak discharge was often higher than observed, except in the years 1999/2000 (Gilgel Abay) and 2002/2003 and 2004/2005 (Koga). The model efficiency values from the 15-daily model are greater than 0.80 and the water balance errors are low (<15 mm/yr). However, increasing the time step showed contrasting performances of the model in simulating low flows at both catchments. Compared to the results of the daily models, the $\log R_{\text{eff}}$ value has declined in the UGASC during both the calibration and validation of the model from 0.85 to 0.82 and from 0.91 to 0.74, respectively. On the other hand, with increased time step the $\log R_{\text{eff}}$ increased in the KSC from 0.68 to 0.85 during the calibration and from 0.74 to 0.88 during the validation.

5.2 Discussion of discharge modeling results

5.2.1 General

In the UGASC, the simulated discharge corresponded reasonably well to the observed river flow during the rising and falling limbs of the hydrograph (Fig. 2). The same is true but to less extent for the KSC. The high $\log R_{\mathrm{eff}}$ values obtained confirmed the model's efficiency in simulating low flows in both catchments. Regardless of the CR, discrepancies between simulated and observed discharges were noticed mostly during the rainy season. This can be related to the spiky runoff records that to some extent erratically vary on daily basis and most likely can be attributed to the data quality (see Sect. 3.2).

Well simulated recession flow has inference on good estimation of model parameters related to the catchment characteristics that govern water storage and delayed flow components. In this regard, the strengths of the HBV model's soil routine and runoff generation routine were revealed by their ability to produce good rainfall-runoff relation during mean and low flows and at least at the beginning of the rainy season, in a region where very intense short duration rainfall occurs. Nevertheless, compared to the UGASC the performance of the HBV model in the KSC was poorer. Although *meandiff* did not signify it during model calibration, over- and underestimations of Koga river flows were continuous in the wet season. The inability of the model to simulate the daily variable pattern of the observed flows may be caused by three factors. First, the spatio-temporal variability of the rainfall could not be observed with the given network (cf. Fig. 1) and errors in areal rainfall estimations translate more directly in poor runoff predictions in the smaller KSC than in the larger UGASC. Second, the limited frequency of flow observations (twice a day) at the gauge may cause that runoff peaks are missed. This problem is less tricky during recessions and low flow with more stable daily runoff. Third, the runoff generation mechanisms during flood generation are too complex for

the relatively simple conceptual model. This might be caused by temporary water storage in the catchment (i.e. at areas close to the channel network) and "overflow" of such areas if the storage capacity is exceeded. As estimated from the topographic map of the area (prepared by Ethiopian Mapping Authority EMA) areas close to the channel networks of about 56 km^2, 107 km^2 and 175 km^2 are subject to temporary inundation in KSC, UGASC and LGASC, respectively. The relatively larger inundated area in the KSC was confirmed by regional soil moisture mapping (Fig. 4), (Water Watch, 2006) using remote sensing data; the degree of soil moisture saturation on a scale between 0 to 1 was determined from a thermal infrared surface energy balance model (Bastiaanssen et al., 1998). This model computes latent and sensible heat fluxes, and their mutual magnitude is an indicator for soil moisture conditions integrated across the root zone (Scott et al., 2003). While wet soils will always have a latent heat flux that far exceeds sensible heat flux, dry soils will show the opposite behavior with sensible heat fluxes exceeding latent heat fluxes. The HBV model with the given model structure could not deal with such a complexity of hydrological processes. A more distributed and process-based model structure (e.g. Uhlenbrook et al., 2004; Wissmeier and Uhlenbrook, 2007) would be needed.

5.2.2 Effect of different catchment representations

In simulating the discharge of study catchments of Gilgel Abay, satisfactory model efficiencies could be achieved for all catchment representations (Fig. 5). The comparison of efficiency values for the three CRs during the calibration and validation periods shows that the semi-distributed simulations (CR III) resulted in a slightly better performance in the UGASC. While the model efficiency values at the KSC are the highest for the lumped representation of the model with multiple vegetation zones (CR II). The performance of CR II in the UGASC was comparable to the semi-distributed catchment representation (CR III).

Thus, it can be concluded that investigated model structures have only a minor relevance for the goodness of predictions of the catchment discharge. However, the distributed water balance predictions in the semi-distributed model version (CR III) vary significantly in time and space, and this makes sense from a process based point of view. But, this increased model complexity and larger variability of hydrological variables did not result in better predictions at catchment scale. As the increased degree of freedom through more model parameters for the more complex model structures (CR I<CR II<CR III) did not result in better model performance, one can conclude that information content available in the input and output data is already utilized in the simplest model structure (i.e. CR I).

5.2.3 Partitioning of flow hydrograph: direct runoff, interflow and base flow

The direct runoff (DR), interflow (IF) and base flow (BF) components computed by the HBV model showed that the IF and BF make the highest contributions to outflows of UGASC and KSC (Table 5). On a yearly basis, values acquired for CR III (UGASC) indicated that the proportion of direct surface runoff, interflow and base flow are 20, 47 and 33% of the annual flow. A similar computation in the KSC showed that 3, 46 and 51% of the annual runoff leave the sub-catchment by direct surface runoff, interflow and base flow, respectively. Similar results were obtained for other CRs. In particular the difference of the direct runoff components demonstrate the difference in the response pattern of the two sub-catchments which will be further explained in Sect. 5.2.5. Groundwater contributions of UGASC and KSC obtained in this study were compared with those of BCEOM (1999). The latter, using the hydric balance method determined contribution of the groundwater to Gilgel Abay and Koga rivers as 305 mm/yr and 203 mm/yr, respectively. Even though the results acquired by BCEOM (1999) appear to be somewhat higher than those obtained in this study, they are comparable.

5.2.4 Transferability of model parameters

As typical to other catchments of the Blue Nile, about half of the GAC is ungauged. We have carried out transferability tests of parameter sets before regionalizing results to other sub-catchments. This was done by applying the best set of calibration parameters obtained for one catchment to the other and vice versa. The sets of parameters selected for UGASC did not perform well in KSC on a daily base, whereas those of KSC yielded satisfactory performance on UGASC (Table 6). Poorer base flow simulations were also confirmed by the model efficiencies, which were lower in UGASC ($\log R_{\mathrm{eff}}$<0.67) and very poor in KSC ($\log R_{\mathrm{eff}}$<0). The observed high *meandiff* values corroborate that achieving good daily modeling results by transferring directly parameter sets within GAC is not possible.

Considering the importance of comparison of results at different time scales, transferability model parameters of the 15-days and 30-days time step models were also tested (cf. Hartmann and Bárdossy, 2005). These tests resulted in good performance in both catchments with R_{eff} of 0.86 and about 0.80 in UGASC and KSC for the 15-days model, respectively with low *meandiff* values in both catchments (Table 6). However, from visual evaluation of hydrographs it became apparent that the simulated discharge overestimated the recession flow of Gilgel Abay and underestimated that of Koga River. Attenuation of peak runoff was also noted in hydrographs of both rivers. Observations made from transferability test of the 30-day time step models of UGASC and KSC were similar: the objective functions (R_{eff} and *meandiff*) indicated good model performances (Table 6) whereas the visual evaluation revealed inaccuracies of the model in simulating different parts of the hydrographs. Hence, it was concluded that transferability of model parameters from hydrologic process point of view was not feasible both on the daily and increased time steps models. However, the tests demonstrated transferability of model parameters on longer time scales, which is very important from water resources management point of view.

5.2.5 Parameter sensitivity and its implication for the hydrologic process of the two sub-catchments

A sensitivity analysis was carried out to identify the sensitivity of model parameters and to associate them with the catchments' runoff generation characteristics. This was done by calculating 1 000 000 Monte Carlo Simulations (MCS; according to the approach of Beven and Binley 1992) for each CR of UGASC and KSC. The results obtained from the MCS varied for each CR; in UGASC 228 087, 158 954 and 95 043 simulations resulted in $R_{\text{eff}}>0.75$ (good performance) for CR1, CR2 and CR3, respectively; while 497, 202 and 1922 simulations yielded $R_{\text{eff}}>0.6$ (satisfactory performance) for CR1, CR2 and CR3 of KSC. The sensitivity analysis signified that the range of values for which the model parameters found to be highly sensitive vary between UGASC and KSC. This variation likely reflects different hydrological processes in the two sub-catchments and suggests the application of different runoff generation concepts of the HBV model as done by Uhlenbrook et al. (1999) in another study area. Please note a parameter, for which good model simulations were possible for a wide range of parameter values, can still be a significant parameter in a certain parameter set. In other words, changing the value of such a parameter and keeping the other parameter values constant can have an impact on the model performance. The analysis done in this approach using MCS identifies the range of parameter values over which good simulations were possible, by changing all parameter values per model run. The parameters for which the models were highly sensitive, i.e. good model simulations were obtained only for a comparable small interval (Fig. 6), are related to the soil moisture and runoff generation routine.

The most sensitive model parameter that determined amount of water storage in the sub-catchments was *FC*, which defines the amount of water stored in the soil routine and that can be emptied by evaporation. A good model performance was achieved in the UGASC with parameter values around the lower parts of the range of *FC* ($206<FC<285$ mm), whereas satisfactory model efficiencies were obtained in

the KSC for parameter values near the maximum of the range ($490<FC<599$ mm). The parameters β, Perc., and UZL were found to be the most sensitive ones only in UGASC, what might be explained through the more responsive behavior of this sub-catchment. The recession curve reflects the storage outflow relation and K2 appeared to be sensitive to high values in UGASC and low values in KSC.

This showed that the amount of water that can be stored (i.e. *FC*) in UGASC seems to be half the amount of water retained by the soils in KSC. Hence, a major portion of the rainfall received in UGASC leaves the catchment quickly as direct runoff. However, most of the rainfall falling in KSC is rather stored in the catchment and leaves the catchment later by evaporation and base flow, which is also demonstrated by water balance parameters (high actual evaporation and low discharge). In general, from the similarity of the inaccuracies induced by transferring the model parameters within its sub-catchments (which were mainly in the rising limb and recession curves of the hydrograph) together with the outcome of the parameter sensitivity analysis, it was concluded that the difference in hydrologic behavior in the two catchments hampered parameter transfer between the two sub-catchments. Therefore, with such significant differences in behavior of the sub-catchments, from a hydrologic process point of view parameter transfer cannot be done between UGASC and KSC. To obtain better results in regionalization of a hydrologic model as acquired elsewhere (e.g., Hundecha and Bárdossy, 2004; Seibert 1999) would need establishing functional relationships between catchment characteristics (land use, soil type, size, slope and shape) and model parameters. However, distribution and the limited number of meteorological and flow gauging stations did not allow such an approach in the GAC.

6 Conclusions

The runoff generation in the Upper Gilgel Abay sub-catchment (UGASC) is mainly dominated by quick flow while at the Koga sub-catchment (KSC) this component is of less importance; the water storage in this sub-catchment is larger. The presences of permanent marshland and dambos cannot be simulated well with present version of the HBV model. This resulted in poor simulation of the daily runoff in the KSC. The dissimilarities between the two sub-catchments have hampered transferability of model parameters between UGASC and KSC, and hence ultimately regionalization of the model parameters. However, a satisfactory performance of the models was noticed when transferring model parameters derived from increased simulation time steps. The computed direct runoff, interflow and base flow components by the HBV model were comparable to results from other studies (e.g, BCEOM, 1999). As perceived from this study, in GAC, runoff generation is dominated by interflow and base flow whereby the peaks of the hydrographs lag that of the rainfall because of storage of water in the catchment and adjoining wetland areas along the river course. Extrapolation of these observations to the ungauged gentle slope lower part of GAC signify temporary storage of water resulting in an increased lag-to-peak in the runoff which cause a delay between the time rainfall occurs in GAC and the time the peak runoff reaches Lake Tana.

The findings and limitations noted while doing this study lead to the following suggestions for future work. As the areal rainfall estimation has its clear limitation because of very few rain gauges, installation of many more stations maybe supported by a radar rainfall would improve the spatio-temporal capturing of rainfall variability. The presence of different landscape units in parts of the whole catchment (i.e. marshlands and dambos) that cause spatial and temporal variations in the runoff generation need to be better understood. Combined experimental and modeling studies, using recent techniques incl. tracers, geophysics and classical hydrometric approaches, could shed more light on the dominating processes. Increasing the number of discharge gauging stations in the catchment is as important as improving the accuracy of the existing gauging stations to finally understand the water balance dynamics of lake Tana better.

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Table 1. Available time series of meteorological and hydrological data; see Fig. 1 for the location of the stations.

	Station Name	Location	Altitude (m a.m.s.l.)	Data Series Length	Type	% Missing	Annual Mean
River gauging stations	Gilgel Abay*	11°22″ N, 37° 02″ E	–	1973–2005	Daily	0.3	19 997 m^3/a
	Koga*	11° 22″ N, 37° 03″ E	–	1973–2006	Daily	7.4	1975 m^3/a
Meteorological Stations	Abay Sheleko	11° 23″ N, 36° 52″ E	2000	1995–2005	Daily	3.1	1177 mm/a
	Bahir Dar	11° 36″ N, 37° 25″ E	1770	1996-2005	Daily	0.1	1571 mm/a
				1974–2004	Monthly	0.8	
	Dangila	11° 07″ N, 36° 25″ E	1290	1987-2004	Daily	10.2	1521 mm/a
				1987–2004	Monthly	–	
	Gundil	10° 57″ N, 37° 04″ E	2540	1996–2005	Daily	0.9	2093 mm/a
				1990–2005	Monthly	12.0	
	Kidamaja	11° 00″ N, 36° 48″ E	2450	1996–2005	Daily	6.7	2095 mm/a
				1981–2005	Monthly	7.7	
	Kimbaba	11° 33″ N, 37° 23″ E	1900	1988–2005	Daily	51.6	1385 mm/a
				1987–2005	Monthly	45.2	
	Sekela	10° 56″ N, 37° 10″ E	2690	1996–2005	Daily	3.3	1750 mm/a
				1988–2005	Monthly	47.7	
	Wetet Abay	11° 22″ N, 37° 03″ E	1900	1988–2005	Daily	47.0	1398 mm/a
				1987–2005	Monthly	45.2	
	Zege	11° 41″ N, 37° 19″ E	1800	1996–2005	Daily	1.9	1580 mm/a
				1975–2005	Monthly	17.7	

* Flow measurement at stations near Wetet Abay.

Table 2. Parameters and their ranges applied during the Monte Carlo simulations.

Parameter	Explanation	Unit	Minimum	Maximum
Soil and evaporation routine:				
FC	Maximum soil moisture storage	mm	200	600
LP	Soil Moisture threshold for reduction of evaporation	–	0.5	0.7
β	Shape coefficient	–	1	4
Groundwater and response routine:				
K0	Recession coefficient	d^{-1}	0.05	0.2
K1	Recession coefficient	d^{-1}	0.01	0.2
K2	Recession coefficient	d^{-1}	0.006	0.05
UZL	Threshold for K0-outflow	mm	10.2	25.6
PERC	Maximal flow from upper to lower GW-box	mm/d	1.4	2.8
Routing routine:				
MAXBAS	Routing, length of weighting function	d	1.5	2.9

Table 3. Monthly average potential evapotranspiration estimates for the period 1992–2004.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
E_O UGASC (mm)	105	113	138	148	136	107	92	88	101	115	106	104
E_O KSC (mm)	103	109	132	141	132	108	94	91	103	116	106	102
E_O GAC (mm)	105	112	136	146	134	107	92	89	102	115	106	104

Table 4. Best model calibration parameters (attained) and efficiency values for the three Catchment Representations (CRs) of UGASC and KSC.

Parameters	UGASC							KSC						
	CR I	CR II			CR III			CR I	CR II			CR III		
		Zone 1	Zone 2	Zone 3	Zone 1	Zone 2	Zone 3		Zone 1	Zone 2	Zone 3	Zone 1	Zone 2	Zone 3
FC [mm]	233	240	195	–	230	204	–	559	525	491	599	540	480	590
LP [–]	0.675	0.68	0.65	–	0.64	0.64	–	0.61	0.5	0.5	0.5	0.5	0.5	0.5
β [–]	1.4	1.45	1.35	–	1.35	1.1	–	2.0	2	1.7	1.8	2.1	1.89	2.11
K0 [d^{-1}]	0.055		0.056			0.057		0.15		0.14			0.11	
K1 [d^{-1}]	0.051		0.11			0.077		0.18		0.183			0.183	
K2 [d^{-1}]	0.047		0.04			0.037		0.014		0.014			0.014	
UZL [mm]	20.5		20.4			19.7		18.9		18.7			19.5	
PERC [mm/d]	1.7		2.1			1.96		2.48		2.2			2.23	
MAXBAS [d]	1.92		1.95			1.84		2.47		2.46			2.45	
R_{eff}[−]	0.7955		0.7822			0.7888		0.6155		0.6219			0.606	
log R_{eff}[−]	0.7756		0.8214			0.8495		0.7127		0.721			0.6772	
R^2[−]	0.7957		0.7838			0.7888		0.6257		0.6367			0.627	
meandiff [mm/a]	0		0			0		0		0			0	

Table 5. Statistics of direct runoff (DR), interflow (IR) and base flow (BF) components of the models for the period 1996/1997–2004/2005 using CR III.

	Variable	DR			IF			BF		
UGASC	Mean (mm/a)	320.9	155.3	221.0	453.4	586.5	513.4	313.9	346.7	352.2
	Mean (mm/d)	0.9	0.4	0.6	1.2	1.6	1.4	0.9	0.9	1.0
	Max. (mm/d)	6.981	4.77	5.69	7.52	11.42	9.21	1.7	2.0	1.96
	Stdv. (mm/d)	1.42	0.80	1.05	1.72	2.35	1.99	0.70	0.80	0.77
KSC	Mean (mm/a)	18.1	14.5	17.3	207.2	233.8	237.2	291.0	270.2	264.1
	Mean (mm/d)	0.0	0.0	0.0	0.6	0.6	0.6	0.8	0.7	0.7
	Max (mm/d)	5.6	3.7	4.6	10.2	10.7	11.3	2.2	2.0	2.0
	Stdv. (mm/d)	0.3	0.2	0.3	1.3	1.4	1.4	0.6	0.6	0.6
Catchment representation		CR1	CR2	CR3	CR1	CR2	CR3	CR1	CR2	CR3

Table 6. Results of the model simulations using transferred parameter sets for different modeling time steps.

Model	Catchment representation	R_{eff} [–]	$\log R_{eff}$ [–]	R^2 [–]	*meandiff* [mm/yr]	Remark
Daily	UGASC – CR3	0.7888	0.8495	0.7888	0	Calibration
	UGASC – CR3	0.8413	0.9072	0.8441	−51	Validation
	UGASC – CR3	0.6739	0.6543	0.7093	210	Transferred parameters
	KSC – CR3	0.6060	0.6772	0.6270	0	Calibration
	KSC – CR3	0.6035	0.7359	0.6142	6	Validation
	KSC – CR3	0.3303	−0.3411	0.6521	−211	Transferred parameters
Fiften days	UGASC – CR3	0.8417	0.8196	0.8657	0	Calibration
	UGASC – CR3	0.9292	0.744	0.9572	−7	Validation
	UGASC – CR3	0.8639	0.5773	0.9284	−12	Transferred parameters
	KSC – CR3	0.8134	0.8533	0.8308	0	Calibration
	KSC – CR3	0.8143	0.8771	0.8370	−12	Validation
	KSC – CR3	0.7978	0.3716	0.7994	−12	Transferred parameters
Thirty days	UGASC – CR3	0.8363	0.7298	0.8809	0	Calibration
	UGASC – CR3	0.8788	0.7411	0.916	−1	Validation
	UGASC – CR3	0.8398	0.7047	0.9103	57	Transferred parameters
	KSC – CR3	0.8473	0.8166	0.8506	0	Calibration
	KSC – CR3	0.8617	0.8527	0.8654	−7	Validation
	KSC – CR3	0.7762	0.2348	0.8530	−120	Transferred parameters

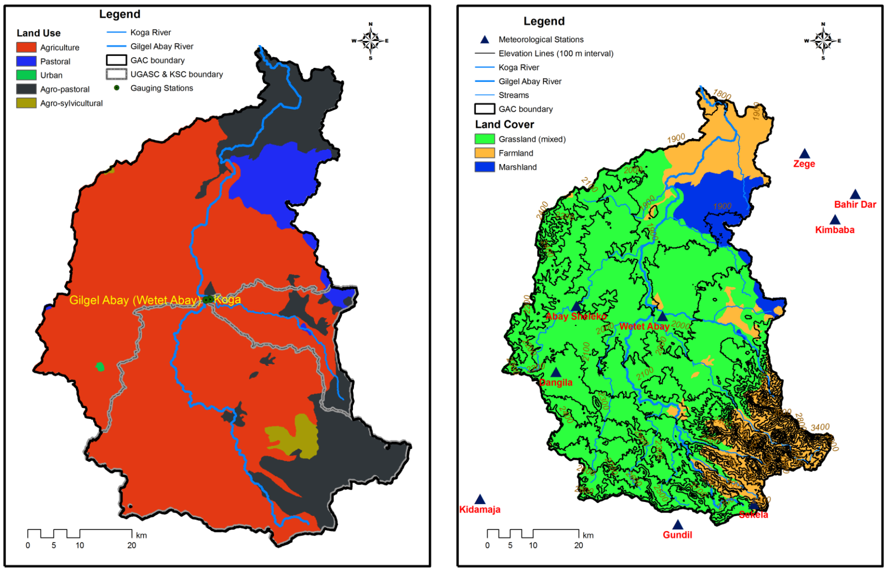

Fig. 1. Study area and instrumentation network: land use, gauging stations and boundaries of GAC, UGASC and KSC (left), and elevation lines, stream network, meteorological stations and land cover (right).

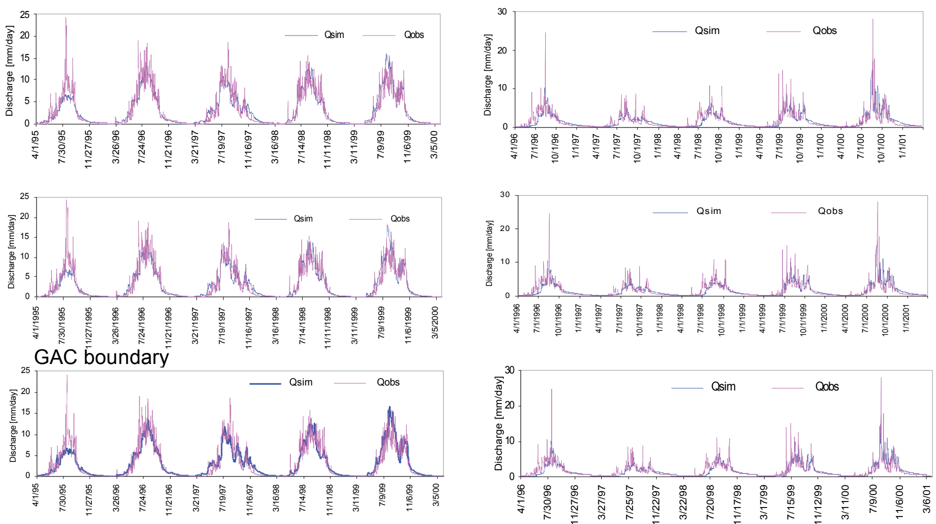

Fig. 2. Simulated and observed stream flows for CR I (upper), CR II (middle) and CR III (bottom) for the two sub-catchments UGASC (left) and KSC (right) for the calibration period.

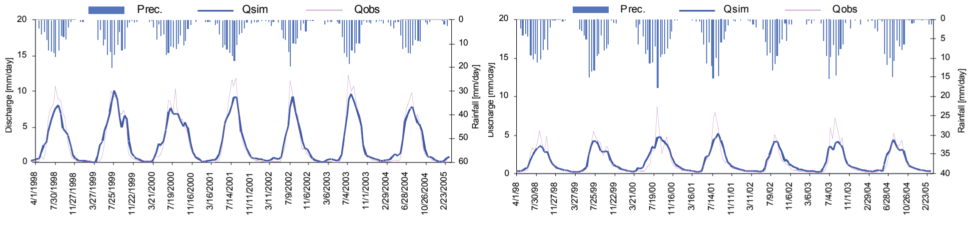

Fig. 3. Simulated and observed stream flow hydrographs for the15-days time step models (CR III).

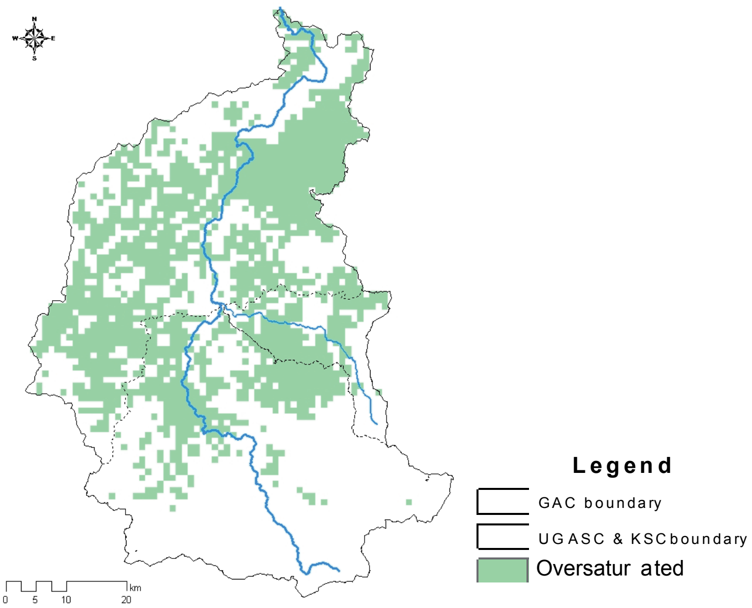

Fig. 4. Area with oversaturated soil moisture (August 2001) [Source: Water Watch, 2006].

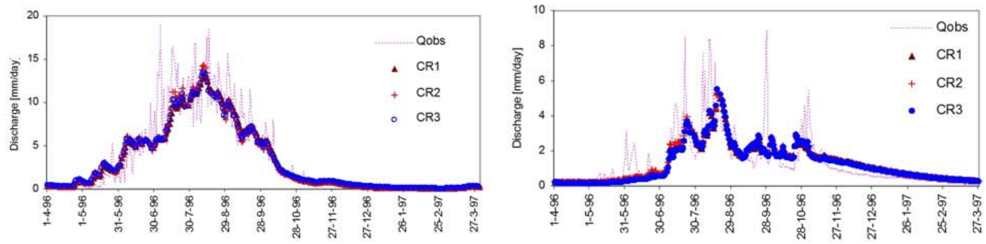

Fig. 5. Comparison of flow simulation of different CRs (Left figure: Gilgel Abay River; Right figure, Koga River) for the hydrological year 1996/1997.

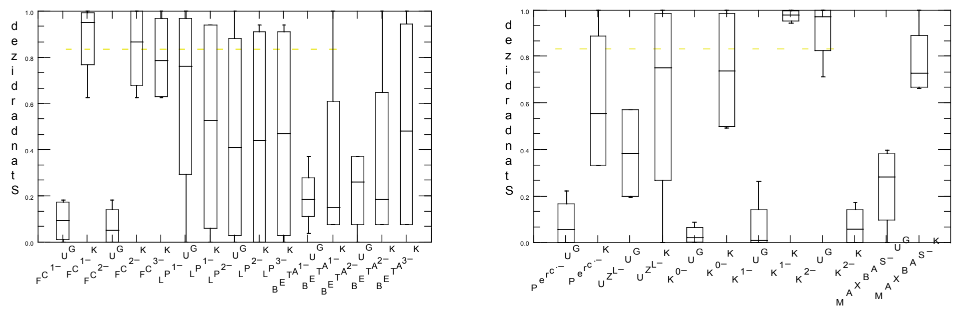

Fig. 6. Standardized sensitive parameter value ranges (see Table 2) of the soil and evaporation routine (left figure) and runoff, response and routing function model parameters (right figure); the suffixes UG and K stand for UGASC and KSC, respectively.