Regionalization of Conceptual Rainfall-Runoff Model Parameters for Predicting Stream Flows of Ungauged Catchments in the Upper Blue Nile Basin

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ABSTRACT

Water resources development and research significantly suffered from lack of stream low data. Regionalization of model parameters was found very useful in filling such data gaps. We therefore regionalized the parameters of the HBV model so that the model could be used in ungauged catchments of the Upper Blue Nile (UBN) basin. Although we collected stream flow data for 76 stations from the Ministry of Water, Irrigation and Electricity, our data quality assessment indicated that only 20 stations were suitable for calibrating the HBV model. We calibrated the model using hydro-climate data of 6 years and validated the calibrated model for independent data of 4 years. The calibrated model reproduced the overall pattern and base flow of the catchments. However, it noticeably missed several peak flows. The values of the calibrated parameters varied with the characteristics of the catchments. We therefore developed a multiple regression relationship between the parameters and catchment characteristics for the basin. The relationship was statistically significant and therefore could be used to apply the HBV model for un-gauged catchments in UBN for water balance studies, climate change impact assessment, and recharge estimation. However, additional work specifically improved data sets were needed to improve the regionalization results for peak flows.

Key words: HBV; Prediction in ungauged catchment; regionalization; Upper Blue Nile.

1. INTRODUCTION

Stream flow data is a crucial input to water resources planning and management. These include assessment of water resources for different purpose, design of hydraulic structures, flood and drought assessment. However, stream flow data is often unavailable or has poor quality for most watersheds of the Upper Blue Nile (UBN). As a result, several water resources development projects are planned and managed based on limited data and this result in challenges in water resources planning and management and poor design of hydraulic structures. Therefore estimation of stream flow of ungauged catchments deserves a research attention.

Regionalization methods have been developed to estimate stream flow of un-gauged catchments. The common methods aim at transferring calibrated model parameter values to ungauged catchments through spatial proximity or similarity of catchment characteristics (Merz and Blöschl, 2004 and He et al., 2011).The basic assumption behind regionalization by spatial proximity is that catchments close in geographical location also behave similarly based on the idea that hydrological response is likely to vary gradually and smoothly in space (Blöschl, 2005). On the contrary, regionalization by similarity of catchments characteristics is based on the premise that optimized model parameters (MPs) are transferable to other catchments provided that physical catchment characteristics (PCCs) are comparable (Rientjes et al, 2011). Seibert (1999) reported that limited number of gauged catchments, model parameter uncertainty and problems related with manual calibration are the main challenges in regionalization of model parameters. Additional studies are needed to overcome the problems which are mentioned by Seibert (1999).

Stream flow provides the integrated response of catchments and hence is often strongly affected by catchment characteristics such as land cover, soil, climate and terrain characteristics. Hence, regionalization of stream flow can provide important information for hydro-climate–landscape co-dependence, and hydrologic forecast and water resource management in ungauged catchments (Gao et al. 2018). The existing observation networks across the world and in Africa cover few catchments. Many catchments are becoming practically ungauged due to lack of attention for hydrological observation. This increases the need for regionalization, which is also well recognized by the International Association of Hydrologic Sciences (IAHS). However, such efforts are very limited in number and extent across data scarce regions such as Ethiopia (e.g. Rientjes et al. 2011; and Kim and Kaluarachchi, 2008). We aim at providing additional study to the limited regionalization studies in the scientific literature.

The main objective of this study is to estimate HBV model parameters through regionalization procedure and predict stream flow at un-gauged catchments in the Upper Blue Nile Basin. We evaluate a regionalization technique to transfer HBV parameters of gauged watersheds to ungauged watersheds of UBN using the HBV-96 rainfall runoff model. The Blue Nile in the Ethiopian part is sub divided into 16 sub-basins but the regionalization in this study is done for 14 sub-basins. The HBV-96 model, which is a conceptual hydrological model, has received a wide range of application in different river basins worldwide because of its operational and strategic water management processes (SMHI, 2006). The model has also been applied in some sub-basins of UBN for climate change impact assessment, evaluation of rainfall runoff models and lake water balance studies (e.g. Rientjes et al., 2011and Uhlenbrook et. al., 2010). We believe that the established relationships between model parameters and chatchment characteristics may enhance applicability of the HBV model for assessment of water balance, climate change impact and flood and drought risk in UBN.

2. MATERIALS AND METHODS

2.1. Study area

The study area covers 171,529 km^2 considering the outlet at the Grand Ethiopian Renaissance Dam (GERD). The elevation ranges from 492m near the outlet to 4,257m at the upper most part of the study area. 25% of the country's population also resides in the study area. The area falls in three regional states of the country namely: Amhara, Oromia and Benishangul-Gumuz.

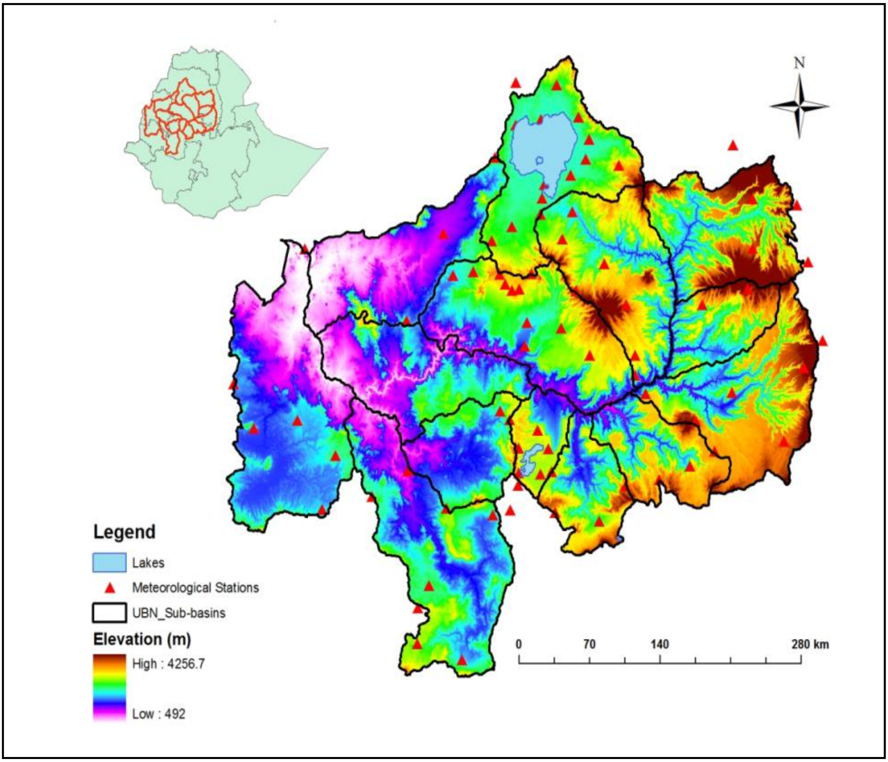


Figure 1: Location map of the study area. Note refer to Figure 2 and 3 for flow stations.

The basin possesses a highly seasonal flood regime. Our analysis shows that the mean annual rainfall of the area ranges from 967 mm to 2,059 mm and the mean annual potential evapotranspiration ranges from 1,279mm to 1,488mm from 1994 to 2002. In the study area, there are two commissioned dams and one hydropower plant (Finchaa and Koga dams, Arjo-Didessa and Tana Beles hydropower plant) and four under construction dams for irrigation and hydropower generation (Ribb, Megech, and GERD).

2.2. Datasets

Rainfall data is obtained for 80 rain gauges distributed across the UBN basin which are operated by the Ethiopian National Meteorological Agency (NMA). The rain gauge network is sparse and unevenly distributed with some missing data (Figure 1). The data for potential evapotranspiration (PET) estimation (daily maximum and minimum temperature, wind speed, relative humidity and sunshine hours) is collected for 33 stations from NMA. Haile et al. (2017); Haile and Rientjes (2015) have used the same dataset. For the sake of brevity, we prefer not to include description of the data quality assessment here. However, we will publish the data quality assessment report separately since it is a very intensive work which can be used as a base for future works.

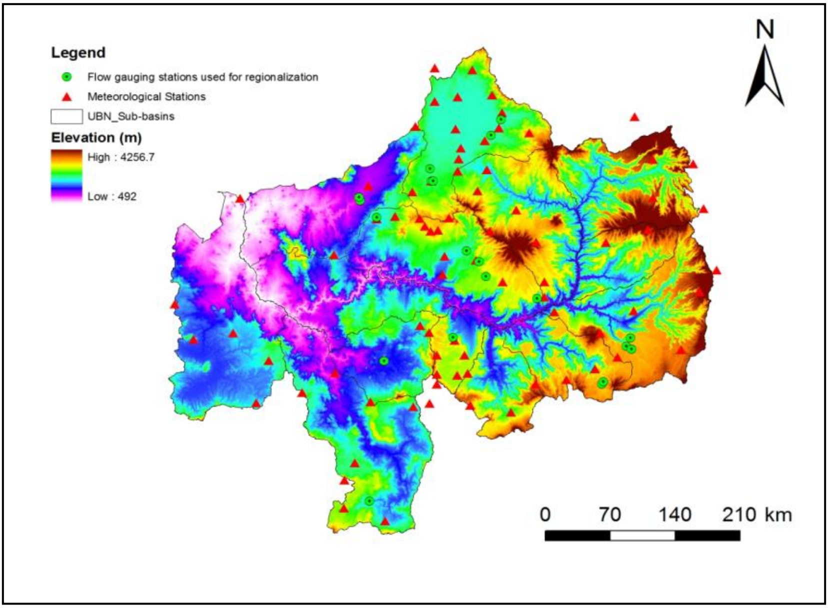


Figure 2: Distribution of selected meteorological and hydrological stations in Upper Blue Nile river basin

Daily stream flow data of 76 stations was collected from the Ministry of Water, Irrigation and Energy (MoWIE) of Ethiopia. The size of the gauged catchments varied between 20 and 65,784 km^2. Most stations had relatively complete data set for the years 1994 to 2002. After data quality assessments, the data of only 45 out of 76 stream flow stations were found reliable for HBV-96 model calibration.

Digital Elevation Model (DEM) with a resolution of 90m x 90m obtained from www.cgiar-csi.org/data/srtm-90m-digital-elevation-database-v4-1 and soil and land cover data were collected from MoWIE. We chose not to describe the soil and land cover as it was the case with several articles in the past.

2.3. Set-up of the HBV rainfall-runoff model

The HBV-96 (Hydrologiska Byråns Vattenbalansavdelning) rainfall-runoff model (Lindström et al., 1997) was used to perform the rainfall-runoff analysis. The model consisted of four routines (i) a precipitation accounting routine, (ii) a soil moisture routine, (iii) a quick runoff routine and (iv) a base flow routine. In addition, routing between sub-basins was possible using the Muskingum method or simple time lags. HBV simulated mass exchange across three stores: the soil moisture reservoir, the upper zone store, and the lower zone store. The equation for various routines of HBV had been described by many articles in the literature (e.g. Rientjes et al. 2011; Haile et al., 2017).

Inputs to HBV included daily rainfall and PET, Digital Elevation Model (DEM), and forested and non-forested catchment areas. Observed stream flow data was required as model calibration data. We initialized the model for two years (1991 and 1992) in order to reasonably reproduce antecedent conditions in the various model stores. The calibration period covered six years (1993 to 1998). During calibration, eight parameters were fine-tuned based on previous studies: FC, BETA, LP, ALPHA, Khq, K4, PERC and CFLUX. First, we fine-tuned the parameters that controlled base flow and annual stream flow volume. Next parameters that controlled the wet season stream flow dynamics, mainly stream flow peaks, were fine-tuned. The model was validated for independent data sets over a period of four years (1999 to 2002). Note that recent data set had not been reliable or complete for most stations since 2002.

The following two objective functions were used to assess performance of the HBV-96 rainfall-runoff model: Nash-Sutcliffe (*NS)* efficiency, which provided a measure of the match between the pattern of simulated and observed stream flows, and Relative Volume Error *(RVE),* which measured systematic differences (bias) in the simulated stream flow volumes. An NS value of 0.6 and 0.8 indicated fair to very good performance. An RVE value between +5% and −5% indicated a well performing model while error values between +5% and +10% or between −5% and −10% indicated reasonable performance.

2.4. Regional model development

Multiple regressions were used to establish relationships between hydrological model parameters (MPs) and physical catchment characteristics (PCCs). MPs were obtained from calibration of gauged catchments and PCCs that influenced the hydrological process were extracted from gauged and un-gauged catchments. About 49 PCCs had been selected and categorized into drainage network, basin geometry, drainage texture, relief characteristics, land cover, soil, and climate classes.

For selection of PCCs to be included in the multiple regression equation, correlation analysis was made for each MP with all PCCs (see ANNEX). We applied GIS operation to extract the PCCs. The PCCs having a higher correlation with the MP were selected for multiple regression entry. The PCC with the highest correlation with the MP were entered first and their statistical significance was checked to be selected as a potential candidate for the regional model. If the first PCCs was selected based on its statistical significance, the second highest correlated PCC would be entered in the multiple regression. We used significance level α =0.1. This step is repeated until the last PCC which adds the most significance. For details, reference is made to Rientjes et al. (2011).

3. RESULTS AND DISCUSSION

3.1. HBV model calibration and validation

Our data quality assessment revealed that the data of only 45 stream flow stations out of 76 stations were reliable for calibration. Hence, we were able to successfully calibrate 20 gauged watersheds for various reasons.

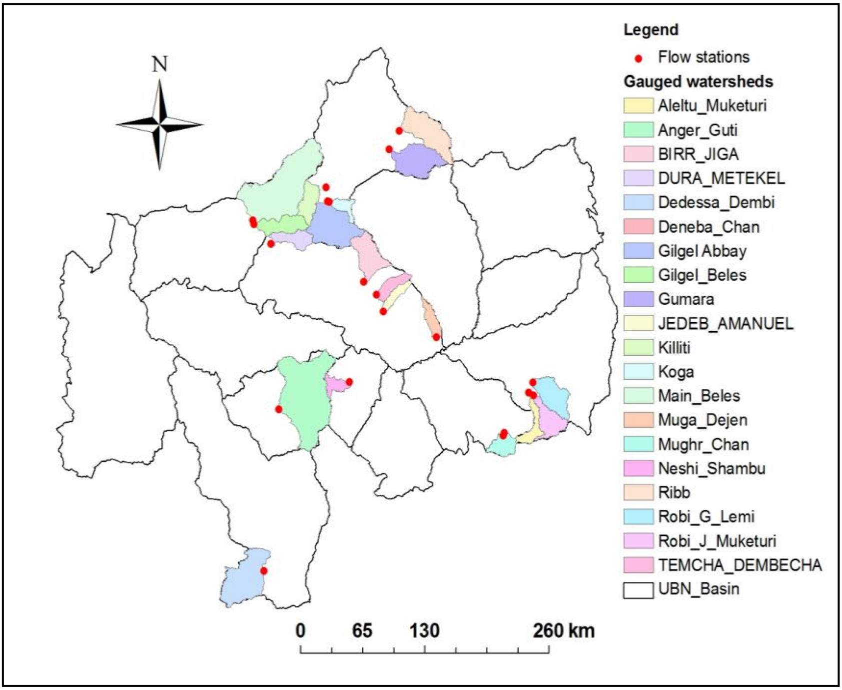


Figure 3: Distribution of gauged catchments used for developing regional models. The colors in the legend are overlapping but the reader can use the base names to differentiate catchments.

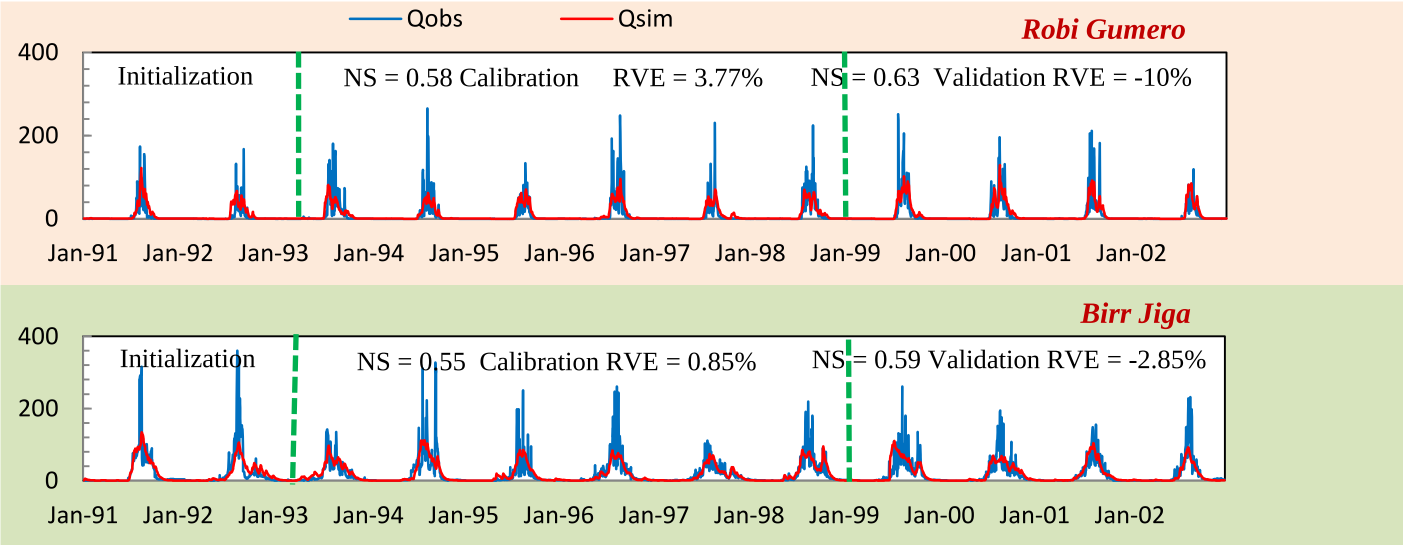
The calibration result showed that 50% of the 20 gauged watersheds had a NS value from 0.5 to 0.6 and the remaining 50% of the flow stations from 0.61 to 0.82. Similarly, 85% of the flow stations showed a RVE less than 5% and the remaining 15% fell in the range of 5 to 8.8%. Table 1 and Figure 4 showed the optimized model parameters value and their corresponding objective function values respectively for selected catchments.

Figure 4 showed the calibration and validation results for selected catchments. The model captured the overall pattern and base flow of the observed hydrograph. However, there was major limitation with capturing peak flows caused by inadequacy of stream flow observation interval (twice per day in Ethiopia) and limitation of the model to capture the more dynamic part of the hydrograph. We found the model performance still acceptable when evaluated outside the calibration period.

Table 1: Optimized model parameter for selected gauged catchments

Sub-Basin	Name	alfa	beta	cflux	FC	k4	khq	lp	perc	Hq
Anger	Anger_Guti	0.30	1.27	0.45	800	0.010	0.080	0.285	0.55	1.330
Beles	Gilgel_Beles	0.60	1.21	0.30	250	0.007	0.074	0.850	0.25	6.510
	Main_Beles	0.80	1.24	1.10	350	0.035	0.080	0.750	0.40	5.530
Didessa	Dedessa_Dembi	0.40	1.00	0.90	300	0.010	0.070	1.000	0.55	4.260
Finchaa	Neshi_Shambu	0.50	1.32	0.60	400	0.040	0.055	0.900	0.50	4.440
Jemma	Aleltu_Muketuri	0.50	1.24	1.35	150	0.080	0.100	1.000	0.12	4.960
	Robi_Gumero	1.00	1.16	1.50	300	0.010	0.120	1.000	0.10	3.950
	Robi_Jida	0.60	1.23	1.30	250	0.090	0.130	0.680	0.15	3.160
Muger	Deneba_Chan	0.20	1.00	0.10	110	0.005	0.090	1.000	0.10	14.760
	Mughr_Chan	0.30	1.00	1.00	210	0.080	0.060	0.850	0.10	5.460
South_	Birr_Jiga	0.25	1.11	0.90	150	0.060	0.070	0.900	0.25	5.930

Sub-Basin	Name	alfa	beta	cflux	FC	k4	khq	lp	perc	Hq
Gojam	Dura_Metekel	0.70	1.20	0.90	400	0.010	0.070	1.000	0.25	6.550
	Jedeb_Amanuel	0.50	1.00	0.20	180	0.030	0.060	1.000	1.10	6.430
	Muga_Dejen	0.10	1.10	0.90	250	0.060	0.150	0.800	0.90	6.200
	Temcha_Dembecha	0.20	1.10	0.40	200	0.030	0.070	1.000	0.70	5.350
Tana	Gilgel_Abbay	1.00	1.00	0.20	110	0.013	0.150	1.000	0.20	7.155
	Gumara	0.60	1.00	0.10	100	0.040	0.070	1.000	0.60	6.555
	Kiliti	1.00	1.55	0.20	620	0.100	0.150	0.410	0.20	4.665
	Koga	0.30	1.30	0.40	360	0.010	0.120	0.860	1.40	5.935
	Ribb	0.90	1.60	0.30	500	0.140	0.150	0.550	0.15	2.610


Qobs
Qsim
Robi Gumero
400
200
0
Initialization
NS = 0.58 Calibration
RVE = 3.77%
NS = 0.63 Validation RVE = -10%
Jan-91
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Birr Jiga
400
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Initialization
NS = 0.55 Calibration RVE = 0.85%
NS = 0.59 Validation RVE = -2.85%
Jan-91
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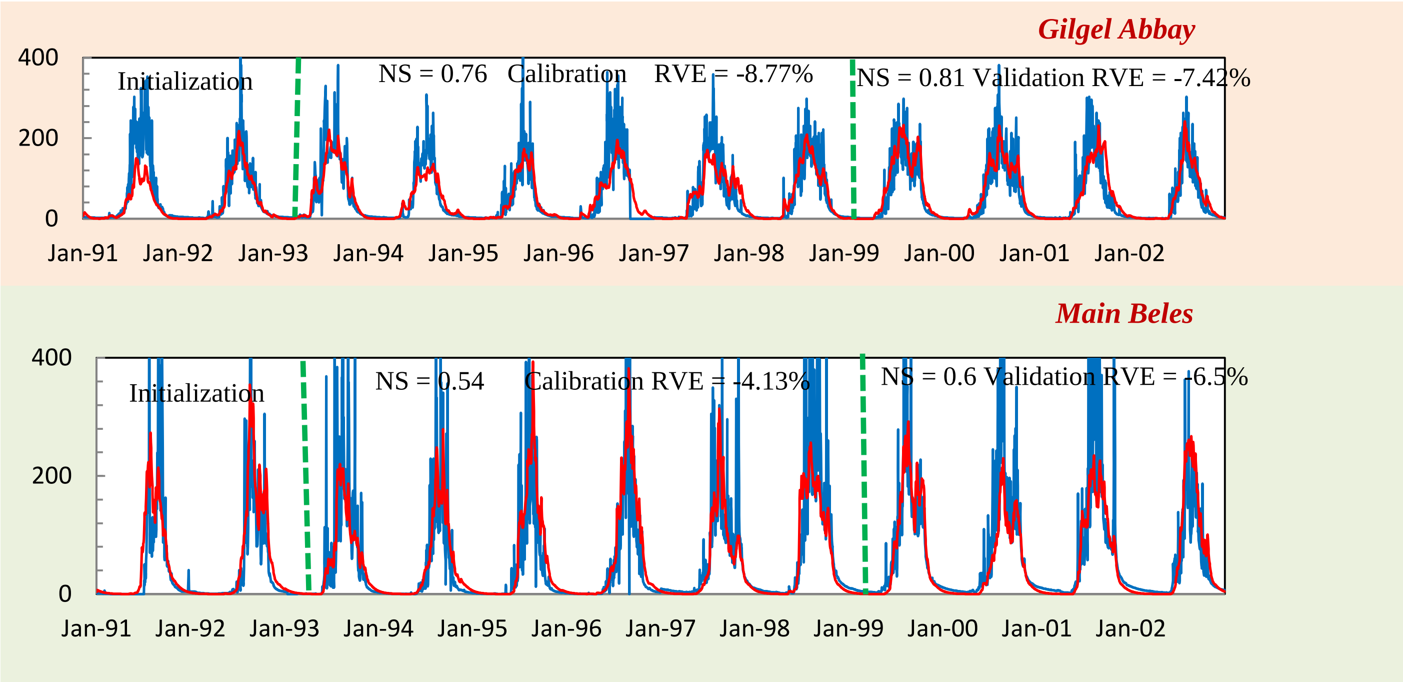

Figure 4: Observed and HBV simulated hydrograph for selected gauged catchments in the UBN. The Y-axis refers to stream flow in $m^3 s^{-1}$

3.2. Regionalization

The established regional models in Table 3 showed statistically significant regression equations. The results suggest that R^2 is found large for most of the equations.

Three groups of catchments (i.e. UBN, Tana-Beles and UBN excluding Tana-Beles) were considered. From the result, it could be seen that most regional models developed for the entire UBN showed a R2 from 0.28 to 0.55 compared to Tana-Beles with 0.67 to 0.93 and for UBN excluding Tana-Beles from 0.45 to 0.92. Thus, better models could result from considering small catchments size for regional model development. It could be observed that terrain aspect correlated to most model parameters in Tana-Beles sub-basin when compared to other physical catchment characteristics.

Table 3: Regional regression equations developed for the UBN, Tana-Beles and UBN excluding Tana-Beles.

	UBN		**Tana-Beles**		**UBN excluding Tana-Beles**	
	Coefficient	**R^2**	**Coefficient**	**R^2**	**Coefficient**	**R^2**
Alfa= $\beta_0+\beta_1\times$DD			Alfa= $\beta_0+\beta_1\times$Area+ $\beta_2\times$North_East		Alfa= $\beta_0+\beta_1\times$South_East + $\beta_2\times$GL	
β_0	-.918		.771		.957	
β_1	.002	0.30	9.490E-05	0.77	-.038	0.69
β_2	------		-.036		-.008	
Beta=$\beta_0+\beta_1\times$LFP+$\beta_2\times$CROPM			Beta=$\beta_0+\beta_1\times$North2		Beta=$\beta_0+\beta_1\times$LFP+$\beta_2\times$LUV	
β_0	1.158		3.800		.767	
β_1	.004	0.37	-.368	0.76	.006	0.68
β_2	-.005		------		.009	
****			Cflux=$\beta_0+\beta_1\times$North2+$\beta_2\times$Med E		Cflux=$\beta_0+\beta_1\times$South_East +$\beta_2\times$GL	
β_0	------		3.754		1.299	
β_1	------	------	-.331	0.86	-.050	0.53
β_2	------		-.001		-.014	
Fc=$\beta_0+\beta_1\times$MeaE			FC=$\beta_0+\beta_1\times$Slope(8-30)+$\beta_2\times$CROPM		Fc=$\beta_0+\beta_1\times$LFP	
β_0	614.803		588.480		78.408	
β_1	-.159	0.28	-4.937	0.83	2.160	0.45
β_2	------		-4.411		------	
K4=$\beta_0+\beta_1\times$CVDRY+$\beta_2\times$North_East			K4=$\beta_0+\beta_1\times$North_West		K4=$\beta_0+\beta_1\times$PWET+$\beta_2\times$South_East	
β_0	-.080		.300		.199	
β_1	.034	0.35	-.016	0.67	-.014	0.64
β_2	.004		------		-.003	
Khq=$\beta_0+\beta_1\times$ Slope(8-30)+$\beta_2\times$ALI			****		Khq=$\beta_0+\beta_1\times$ VER+$\beta_2\times$LUV	
β_0	.125	0.49	------	------	.073	0.92

	UBN		Tana-Beles		UBN excluding Tana-Beles	
	Coefficient	**R^2**	**Coefficient**	**R^2**	**Coefficient**	**R^2**
β_1	-.001		------		.001	
β_2	.000		------		-.001	
$Lp=\beta_0+\beta_1\times LFP+\beta_2\times CROPM$			$Lp=\beta_0+\beta_1\times North2+\beta_2\times ALI$		$Lp=\beta_0+\beta_1\times Area+\beta_2\times MBW$	
β_0	.932		-1.056		.847	
β_1	-.004	0.46	.273	0.90	.000	0.76
β_2	.004		------		28.468	
$Perc=\beta_0+\beta_1\times SHAPE+\beta_2\times LUV$			$Perc=\beta_0+\beta_1\times Flat+\beta_2\times CROPD$		$Perc=\beta_0+\beta_1\times North\_East+\beta_2\times URBAN$	
β_0	-.062		.126		.849	
β_1	.009	0.55	.625	0.85	-.060	0.67
β_2	.008		.008		2.867	
$Hq=\beta_0+\beta_1\times LFP$			$Hq=\beta_0+\beta_1\times North2+\beta_2\times LFP$		$Hq=\beta_0+\beta_1\times LFP$	
β_0	9.848		-1.527		11.987	
β_1	-.059	0.35	1.153	0.93	-.097	0.60
β_2	------		-.062		------	

**** Regional model couldn't be developed

The cross-validation result (not shown here) indicated that the regression equations resulted in successful application of the model for un-gauged catchments (Table 4). Particularly, HBV would successfully reproduce the pattern of hydrographs in all ungagged catchments as indicated by higher NS values. The regression equation could also be used to simulate stream flow hydrographs with few exceptions.

Table 4: Performance of Regional regression equations were developed for the UBN, excluding Tana-Beles. This was obtained from cross-validation (pretending data is not available for each gauged catchments)

UBN excluding Tana-Beles WS	Area (km^2)	Calibration		Validation	
		NS	**RVE (%)**	**NS**	**RVE (%)**
Anger Guti	3751	0.70	4.76	-1.28	95.50
Dedessa Dembi	1809	0.72	-2.21	0.66	-21.24
Neshi Shambu	326	0.70	-0.51	0.65	12.94
AleltuMuketuri	451	0.54	2.54	0.51	-19.68

UBN excluding Tana-Beles WS	Area (km^2)	Calibration		Validation	
		NS	**RVE (%)**	**NS**	**RVE (%)**
Robi Gumero	931	0.58	3.77	0.57	0.02
RobiJida	746	0.51	-0.79	0.47	29.96
Deneba Chan	87	0.55	-4.98	0.54	-13.93
Mughr Chan	494	0.56	2.24	0.55	18.04
Birr Jiga	976	0.55	0.85	0.54	3.82
Dura Metekel	546	0.82	-3.18	0.81	-7.97
Jedeb Amanuel	307	0.51	-4.42	0.49	-12.01
Muga Dejen	375	0.51	3.91	0.51	9.20
Temcha Dembecha	419	0.63	2.68	0.62	-2.51

4. CONCLUSIONS AND RECOMMENDATIONS

We applied the HBV-96 rainfall-runoff model and multiple regressions to transfer model parameters to ungauged watersheds of the UBN basin. Only 20 gauging stations out of 76 stations were found reliable for regionalization. The main reasons for excluding large number of stations were due to extensive missing data, large mismatch with catchment average rainfall data, incorrect latitude, longitude data of flow stations, difficulties with HBV calibrations, and small watershed size.

The HBV-model was well-performed in the 20 gauged watersheds with high NS and RVE values. The regionalization results were better when separate regressions equations were developed for the Tana-Beles sub-basin and the rest of UBN sub-basins. The established relationship between MPs and PCCs did not have strong hydrological explanation. For Tana-Beles, statistically significant relation was not found to establish the regionalization equation for the parameter which controlled the recession in the upper reservoir (Khq). For Tana-Beles, terrain aspect was the most commonly used for establishing the relation between MPs and PCCs because of its high correlation with calibrated parameter values. The regression equations developed here were different in terms of the PCCs from that developed by Rientjes et al. (2011) for Tana basin in Ethiopia.

Overall results found in this study could be used for further hydrological studies such as climate change impact assessment. Future studies should use regression equation and also explore the applicability of other regionalization methods.

Due attention should be given to improve monitoring network and data quality by increasing the number of gauging stations, extending monitoring to large catchment size, doing continuous flow data quality assessment mechanisms, and correcting coordinate of flow gauging stations.

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ANNEX

Physical Catchment Characteristics and Unit	Abbreviations
Longest flow path (km)	LFP (km)
Catchment Area (km2)	Area (km2)
Circularity index (-)	CI (-)
Elongation ratio (-)	ER (-)
Form factor (-)	FF (-)
Mean basin width (m)	MBW (m)
Relative perimeter (m)	RP (m)
Catchment shape (-)	SHAPE (-)
Drainage density (m Km-2)	DD (m Km-2)
Slope of catchment (%)	Slope (0-8) (%)
	Slope (8-30) (%)
	Slope (>30) (%)
Aspect (%)	North (%)
	North_East (%)
	East (%)

Physical Catchment Characteristics and Unit	**Abbreviations**
	South_East (%)
	South (%)
	South_West (%)
	West (%)
	North_West (%)
	North2 (%)
	flat (%)
Basin relief (m)	BR (m)
Hypsometric integral (-)	HI (-)
Latitude (m)	Lat (m)
Longitude (m)	Long (m)
Mean catchment elevation (m)	MeaE (m)
Median catchment elevation (m)	MedE (m)
Ruggedness number (-)	RN (-)
Relief ratio (-)	RR (-)
Cultivated Dominantly (%)	CROPD (%)
Cultivated Moderately (%)	CROPM (%)
Forest (%)	FOREST (%)
Grassland (%)	GL (%)
Urban (%)	URBAN (%)
Alisols area (%)	ALI (%)
Leptosol area (%)	LEP (%)
Luvisol area (%)	LUV (%)
Nitosol area (%)	NIT (%)
Vertisol area (%)	VER (%)
Aridity index	AI
Coefficient of variation of daily rainfall	CV
Coefficient of variation of wet season (Jun to Sep) daily rainfall	CVWET
Coefficient of variation of dry season (Oct to May) daily rainfall	CVDRY

Physical Catchment Characteristics and Unit	**Abbreviations**
Mean daily precipitation of wet season (Jun to Sep)	PWET (mm)
Mean daily precipitation of dry season (Oct to May)	PDRY (mm)
Mean annual evapotranspiration (mm)	PET (mm)
The difference of mean annual evapotranspiration and precipitation (mm)	PET-MAP (mm)
Mean annual precipitation (mm)	MAP (mm)