Application of the HEC-HMS Model for Runoff Simulation of Upper Blue Nile River Basin

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Abstract

Hydrological models have been used in different River basins across the world for better understanding of the hydrological processes and the water resources availability. It is important to use hydrological model today to assess and predict the water availability of river basins due to climate change to develop a strategies in order to cope up with the changing environment. It is very crucial to properly calibrate and validate models to give confidence to model users in prediction of stream flow. In this study HEC-HMS 3.5 hydrologic model (Developed by US Hydrologic Engineering Center-SMA (with Soil moisture Accounting Algorithm) has been used to calibrate (from 1988-2000) and validate (from 2001-2005) the upper Blue Nile River Basin (Gilgel Abay, Gumera, Ribb and Megech catchment).

The model performance tested for each catchment in simulation the runoff flow during calibration and validation period, The Nash-Sutcliff (ENS) and Coefficient of determination (R^2) used to evaluate the performance of the model. The results obtained are satisfactory and accepted for simulation of runoff. The deficit and constant loss method, synder unit hydrograph method and exponential recession method, are the best fit performed methods of the hydrological processes of infiltration loss, direct runoff transformation and base flow part respectively. Thus, this study shows that HEC-HMS hydrological model can be used to model the upper Blue Nile River basin catchments for better assessment and prediction of simulation of the hydrological responses. The study recommends further studies which incorporate the land use change of the basin in the model.

Keywords: Blue Nile; HEC-HMS; Modelling

Introduction

Climate change is threatening the normal hydrological cycle of River basins, due to rising in temperature because of the global warming effect which is associated in disturbing the frequency and intensity of precipitation a given climatic condition [1]. This has an implication on the hydrologic events and the water resources availability [2]. The upper Blue Nile River basin is the main sources for economic and social welfare of the people living on the River basin. This is so because the majority of the people rely on climate sensitive sectors like agricultural productivity, fishery, and hydropower power sources [3]. The impacts of climate change have been noticed and discussed in different research studies [4]. In order clearly understand the reality and predict the future water availability of different catchments, it is a must to use a mathematical hydrological modelling [5]. According to Lastoria [6] and Xu [7] on the basis of process description, the hydrological models can be classified in to three main categories. Lumped, distributed and semi distributed models. Lumped models; parameters of lumped hydrologic models do not vary spatially within the basin and thus, basin response is evaluated only at the outlet, without explicitly accounting for the response of individual sub-basins [6]. Most of the time these models are not good for event scale hydrological processes. If the interest is primarily in the discharge prediction only, then these models can provide just as good simulations as complex physically based models [8,9]. The other one is Distributed models, parameters can easily vary in space at the desired resolution based on the preference of the user. Distributed modeling approach attempts to incorporate data concerning the spatial distribution of parameter variations together with computational algorithms to evaluate the influence of this distribution on simulated precipitation-runoff behavior. Distributed models generally require large amount of (often unavailable) data [8]. However, the governing physical processes are modelled in detail, and if properly applied, they can provide the highest degree of accuracy [9]. The last one is Semi-distributed models. Parameters of semi-distributed (simplified distributed) models are partially allowed to vary in space by dividing the basin in to a number of smaller sub-basins. The main advantage of these models is that their structure is more physically-based than the structure of lumped models, and they are less demanding on input data than fully distributed models [10]. HEC-HMS [11], SWAT [12], HBV [13], are some examples of semi-distributed models.

In this study we use a semi distributed hydrologic model of HEC-HMS. HEC-HMS 3.5 (developed by USA Hydraulic Engineering center-Hydrologic Modelling System–Soil Moisture Accounting Algorithm, HEC [14] is used to model four catchments in the Upper Blue Nile River basin (Gilgel Abay, Gumera, Ribb and Megech catchments). HECH-HMS model is capable of simulating rain fall-runoff relation for dendritic watershed in space and time [15]. HEC-HMS model has been used successfully in different parts of the world River basins for catchment modeling [16,17]. HEC-HMS Soil Moisture Accounting (SMA) algorithm has been used to analyze the long term impacts of climate change on water resources availability of the Blue Nile [18,19]. Hence a proper understanding of the rainfall- runoff relation at different small scale watershed level of the upper blue Nile River basin help to study water balance, water resources management

and flooding control of the basin. In this study in order to clearly understands the hydrologic characteristics of each catchments, we will calibrate rainfall-runoff relation of the basin using HEC-HMS 3.5 model from 1988-2000. After calibration the model will be validated from 2001-2005.Moreover, the basic sensitive parameters and the good modeling methods for each process part will be identified for assessment of runoff simulation.
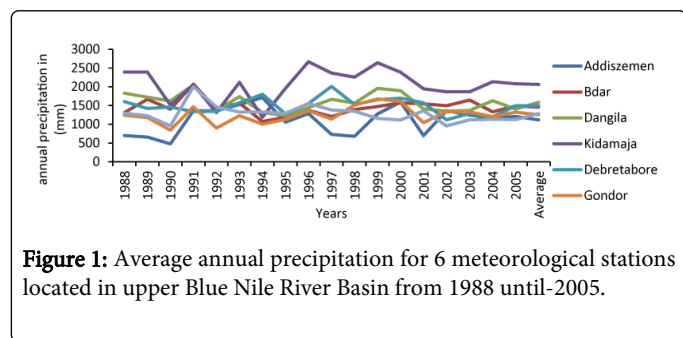
Materials and Methods

Description of the study area

The upper Blue Nile River Basin which is located in the Ethiopian Highlands. The Blue Nile River runs from its origin, Lake Tana, to the Sudanese border and eventually meets the White Nile River at Khartoum, Sudan. The Lake Tana Basin is located in north-western Ethiopia (latitude 10.95° and 12.78°N, and longitude 36.89° and 38.25°E) with a drainage area of about 15,000 km^2 [3]. The Lake Tana, the largest lake in Ethiopia and the third largest in the Nile Basin, is located in this basin. The major rivers feeding the Lake Tana are Gilgel Abay, Gumera, Ribb, and Megech. These rivers contribute more than 93% of the flow to the Lake [20,21].

Hydro climatic characteristics of upper blue Nile basin

The climate of upper Blue Nile River Basin (Tana Basin) is dominated by highland tropical monsoon. The basin is located in the high land of the country, Ethiopia. The mean annual rainfall of the area is about 1465 mm even with significant spatial variation and The average annual maximum temperature is 25.5°C and mean annual minimum temperature is 10.8°C from 1988-2005 for the study area (Figure 1).

Figure 1: Average annual precipitation for 6 meteorological stations located in upper Blue Nile River Basin from 1988 until-2005.

Hydrology of the basin

Lake Tana has more than forty tributaries, but the major rivers feeding the Lake are Gilgelabay (the largest river from the south direction), Gumera, and Ribb from the east and Megech from the north, these four main rivers accounts about 93% of inflow. The only river flowing out of the Lake Tana is the Blue Nile River (Abay River). The Blue Nile flow approximately reaches annually about 4 billion cubic metric at the out let of the LakeTana. From the Lake Tana, the Blue Nile travels around 35 Kms and reaches to a fountain place so called Tisesat which is 50 meter high, then flows in gorges towards the Sudan border. The Blue Nile flow at the Ethio-Sudan border annually reaches about 50 billion cubic meters (Figure 2). In the mean while major tributary rivers joins the Blue Nile, like Beles, Didessa, Fincha, Guder, Muger, Wenchit, Jemma, Beshilo and Temcha. The Blue Nile contributes two third of the Nile River Basin flow [22].

Figure 2: Map of weather and gauging stations on upper Blue Nile River basin (Lake Tana basin).
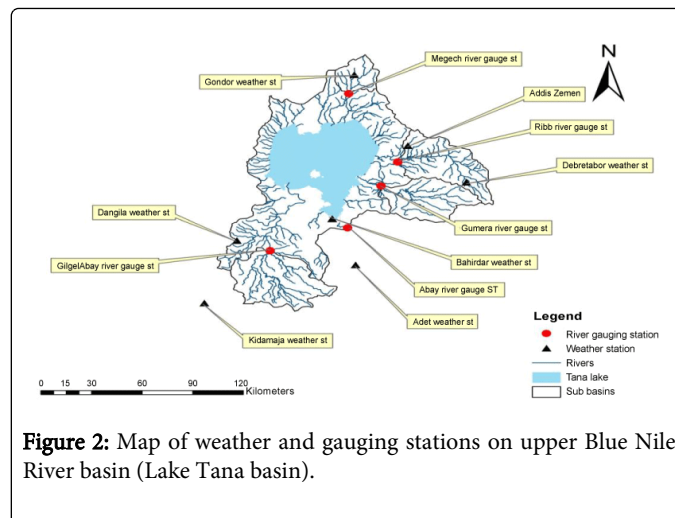
Topography of upper blue Nile (Lake Tana basin)

The upper Blue Nile area is high land area where the source of Blue Nile originates. In the peripheral part of South, East, and Northern directions, there are high mountains which reach up to 4000 m above sea level (Figure 3).

Figure 3: Map of digital elevation of upper blue Nile river basin.
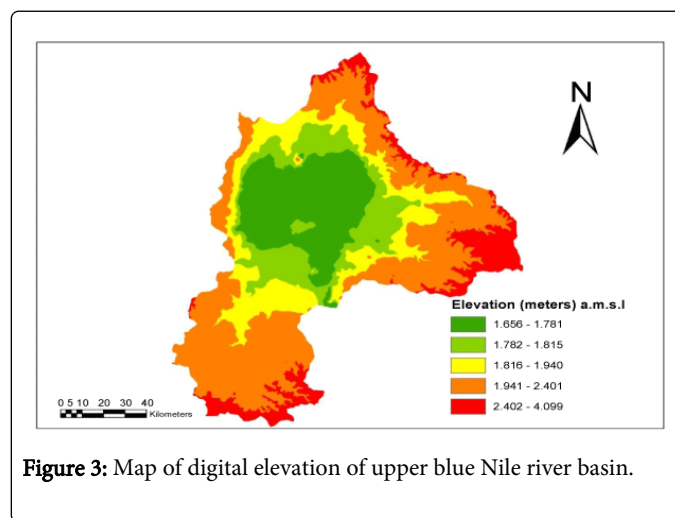
Land use of blue Nile basin

The land use data was obtained from the Ministry of Energy and Water of Ethiopia. Since land cover is the major factor that affects runoff, evpotranspiration, and soil erosion characteristics of the basin. The total area of the basin covers about 15,000 Km^2, more than 90% of the area is covered with dominantly and moderately cultivated land (Figure 4).

Soil type of blue Nile basin

The other major factor of the basin property is the soil type. The soil data of FAO (1988) calssification is obtained from Ministry of Energy and water of Ethiopia. The main dominant soil in the basin is Eutric Leptosols (54.56%), Haplic Alisols (14.23%) and Eutric Cambisols (7.71%). The rest are in minor proportion like, Chromic Luvisols,

Eutric Fluvisols, Eutric Regosols, Eutric Vertisols, Haplic Nitisols and Lithic Leptosols (Figure 5).
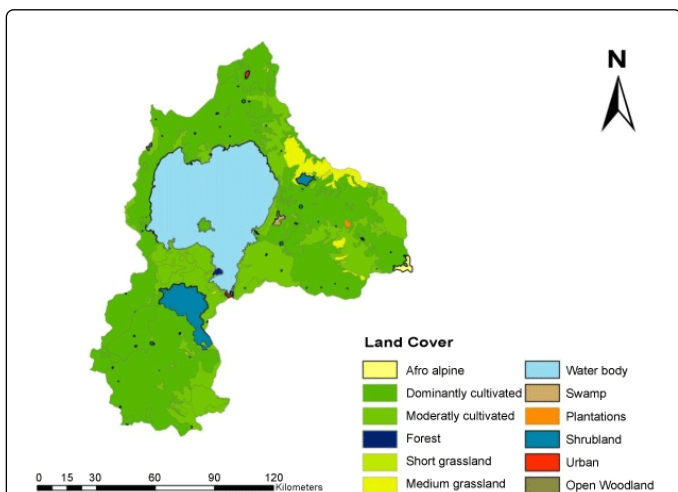

Figure 4: Map of land use of upper blue Nile river basin.
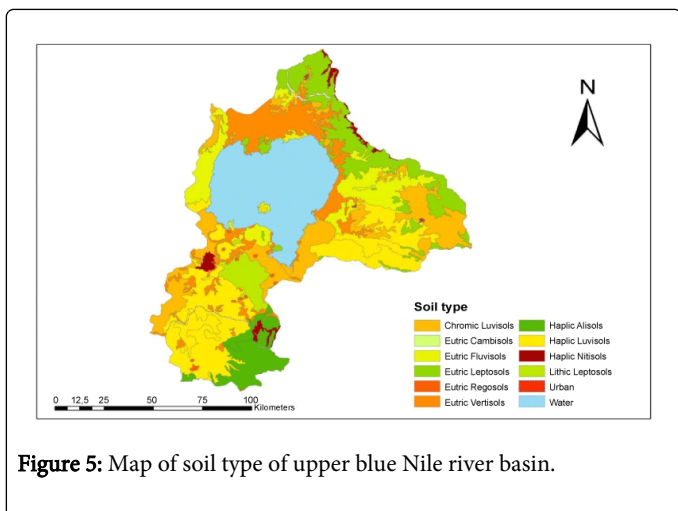

Figure 5: Map of soil type of upper blue Nile river basin.

Geology of the blue Nile basin

The basin composed of different geological consituents. More than 87% of the area is covered by Termaber basalt (71.86%) and Basaltic volcano (15.82%). The other perecent filled with, Alluvium, Ashangi basalt, Colluvium, Lacustrine and Amiba aiba basalt (Figure 6).

Materials

Topography data of 90 m resolution was used for catchment delination and catchment characteristics using Arc GIS software, soil, land use and geological data used to better understand the nature the ctachments. Stream flow from 1988-2005 for each catchment also collected for calibration and validation of the hydrological model. All the data collected from Ethiopian Ministry of Water and Energy. Meteorological data also collected from Ethiopian Meteorological Station Agency (NMSA), which used for used as input to hydrological model for catchment simulation (Table 1).
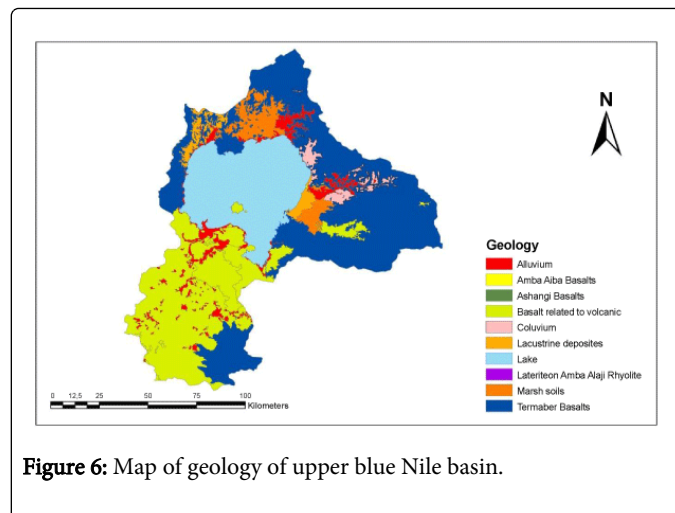

Figure 6: Map of geology of upper blue Nile basin.

Names	Area size (KM^2)	Weather stations inside the catchment
Gilgel Abay	1664	Kidamaja, Adet and Dangila
Gumera	1335	Addis Zemen, DebreTabore and Bahirdar
Ribb	1595	Addis Zemen and DebreTabore
Megech	531	Gondor

Table 1: Area size and weather stations of each catchment in upper blue Nile river basin.

For each catchment areal precipitation was prepared using Thiessen polygon techniques. The number of observed weather station which contributes for each catchment presented (Figure 7).
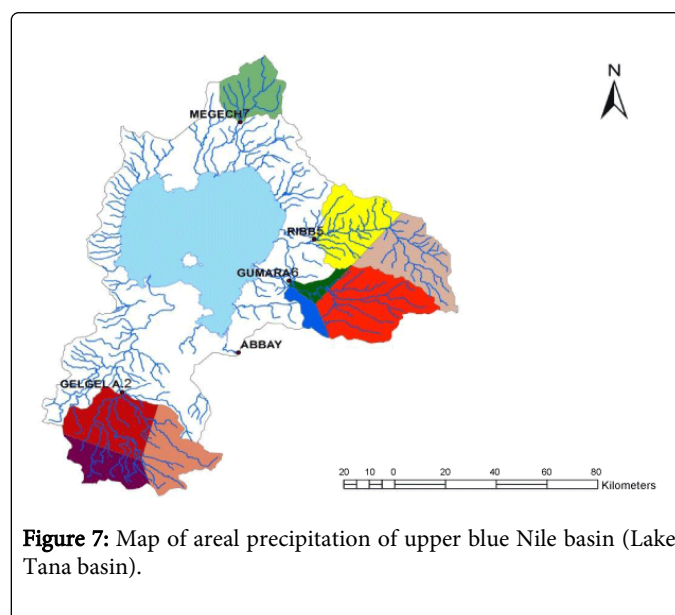

Figure 7: Map of areal precipitation of upper blue Nile basin (Lake Tana basin).

Potential Evapotranspiration (PET)

There are a number of methods to estimate potential evapotranspiration. However, the methods vary based on climatic

variables required for calculation. The temperature based method uses only temperature and day length; the radiation based method uses net radiation and air temperature and some other formula like, Penman requires a combination of the above net radiation, air temperature, wind speed, and relative humidity.

The FAO Penman-Monteith method is recommended as the sole ET0 method for determining reference evapotranspiration when the standard meteorological variables including air temperature, relative humidity, and sunshine hours are available [23]. In this study the potential evapotranspiration of the observed weather stations for each catchment was computed by FAO Penman-Monteith method.

Methods

Arc GIS 10.2 was used to delineate the catchment area. The watershed and sub basins delineation was carried out based on an automatic delineation procedure using a Digital Elevation Model (DEM) and digitized stream networks.

HEC-HMS

The model that will be used in this study is, HEC-HMS 3.5, which is developed by the United States Army Corps of Engineers, and is designed to simulate the precipitation–runoff processes of dendritic watershed systems [14].

HEC-HMS is a semi -distributed conceptual hydrological model which simulates run off. It requires daily precipitation, long term average monthly potential evapotranspiration, runoff flow of the basin (for calibration and validation), and geographical information of the basin to get the simulated runoff as output [24]. HEC-HMS model setup consists of a basin model, meteorological model, control specifications, and input data (time series data) [14].

In HEC-HMS basin model the surface and ground water flow is computed using soil moisture accounting (SMA). The SMA model accounts for evapotranspiration and percolation between rainfall events as well as infiltration and other losses during rainfall events. Modelling of snowpack accumulation and snowmelt is optional. HEC-HMS generates a continuous stream flow record for the sub basin from the direct-runoff and base flow records [15]. Direct runoff is transformed to stream flow by a user-selected transform method. The transform options include several unit-hydrograph methods, the Clark time-area method, and a kinematic wave method. The model also computes downstream processes such as channel routing and reservoir routing [14].

Soil moisture accounting method (SMA)

Water is stored in canopy of leaves, in soil profile, in surface depression, and in two ground layers. Canopy losses are considered as initial loss, infiltration is subtracted from precipitation that exceeds from canopy storage. Infiltration that is not infiltrated accounts into depression storage. Over flow from the depression storage is considered as surface flow (Direct runoff, stream flow). Canopy interception is computed in the same way for the pervious and impervious parts of the sub basin. Water is removed from the canopy through evaporation. Water in the impervious parts of the basin considering as there is no infiltration and deep storage losses in that area. Water is removed from depression storage through evaporation and infiltration. The two ground water storage layers serve as for shallow surface drainage and deep aquifer hydraulically connected to

stream flow. Lateral flow from the ground surface contributes to stream base flow. The rate of evaporation depends on the weather condition, canopy vegetation type, amount of water in surface depression, canopy and in soil profile. The user can input monthly average values of potential ET, or the HEC HMS model can compute potential ET from user-input net radiation and temperature data using the Priestly-Taylor method [14].
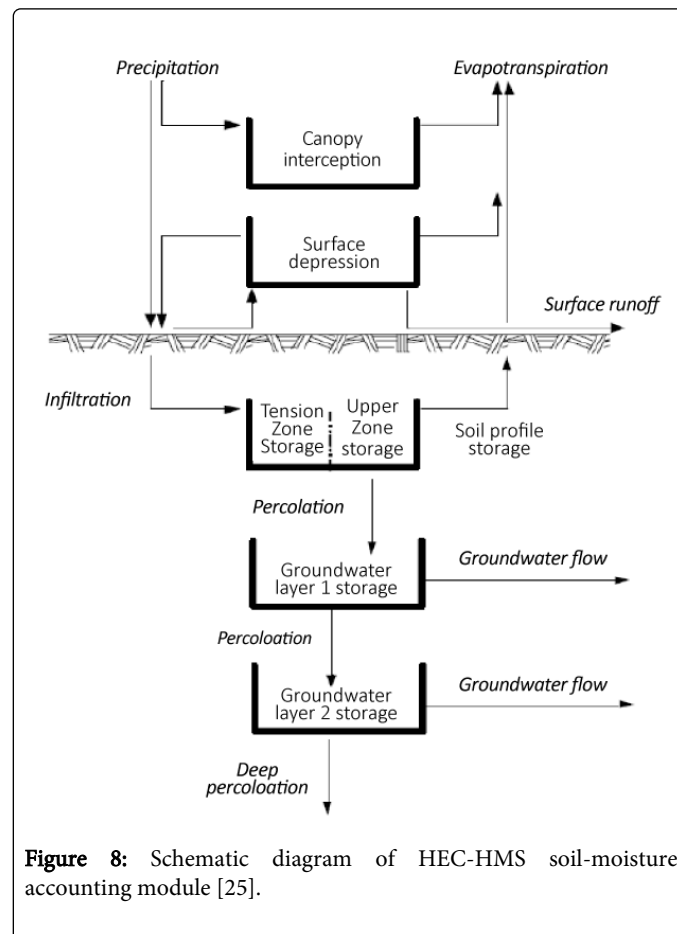

Figure 8: Schematic diagram of HEC-HMS soil-moisture accounting module [25].

HEC-HMS model setup

HEC-HMS Model setup consists of four main model components: basin model, meteorological model, control specifications, and input data (time series, paired data, and gridded data).The Basin model for instance, contains the hydrologic element and their connectivity that represent the movement of water through the drainage system [14].

The meteorological component is also the first computational element by means of which precipitation input is spatially and temporally distributed over the river basin [15]. The spatio-temporal precipitation distribution was accomplished by the gauge weight method. The Thiessen polygon technique used to determine the gauge weights and the following input data used like daily precipitation, daily temperature, elevation, and long term mean monthly actual potential evapotranspiration. Areal Precipitation of the four catchments was prepared for model input accordingly (Figure 8).

Catchment division for modelling

In order to increase for better performance of modelling, the catchment is sub divided into sub basin to use the model as semi-distributed. All are divided except Megech catchment due to its small size of the catchment. Gilgel Abay catchment divided in to three sub basins, Gumera in to three sub basins and Ribb in to two sub basins (Figure 9).
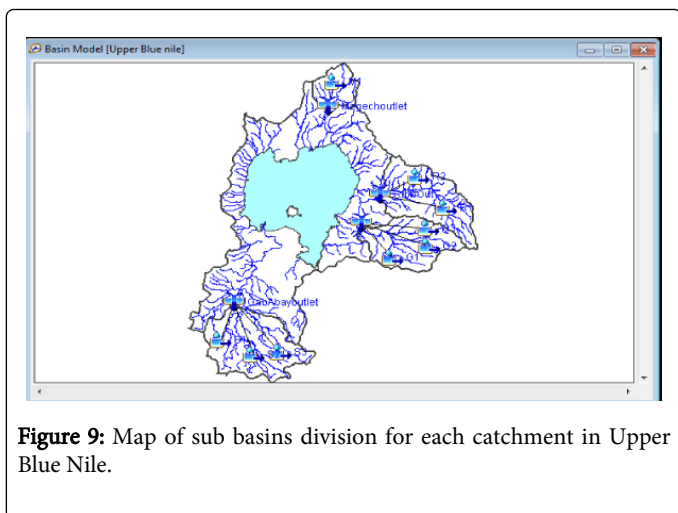

Figure 9: Map of sub basins division for each catchment in Upper Blue Nile.

HEC-HMS calibration and validation

The deficit and constant loss method used to model infiltration loss. For the transformation of precipitation excess into direct surface runoff, synder unit hydrograph method was used and for the base flow recession method was employed to model base flow. These methods selected based on checking up of every methods for the best fit options. In HEC-HMS modeling of each method, each method needs parameters and values as an input to obtain simulated runoff hydrographs. The values of the parameters estimated by observation and measurement of stream and basin characteristics, but some of them cannot be estimated. When the required parameters cannot be estimated precisely, the parameters are calibrated. By systematic search of the best fit of the observed and simulated stream flow hydrograph, the calibrated values were determined for each sub basin of upper Blue Nile basin. In order to get the optimum parameter values after manually calibrating the model, an automatic trial and error method applied [15]. The Nelder and Mead optimization method used than the univarient method. The reason behind is, the Nelder and Mead method uses downhill simplex to evaluate all parameters simultaneously and which parameters to adjust. This automatic calibration processes uses in order to minimize a specific objective function, such as sum of the absolute error, sum of the squared error, percent error in peak, and peak weighted root mean square error [14]. In our study the sum of squared error objective function used because it gives large weight to large error and less weight to small error [26]. Therefore, automated calibration in conjunction with manual calibration was used to determine a practical range of the parameter values preserving the hydrograph shape and minimum error in volume. The calibration from (1988-2000) and validation from (2001-2005) period used. Validation is the key criteria to test hydrological model performance with independent data serious [27]. During validation period, the calibrated model without changing the parameters, the goodness fit statics also computed (Table 2).

Modelling	Model	Parameter	Unit	Minimum	Maximum
Runoff Volume	Deficit and constant loss	Initial deficit	MM	0	500
		Maximum deficit	MM	0	500
		Constant rate	MM/HR	0.1	5
Direct runoff transformation	Snyder's UH	Lag time	HR	0.1	500
		Peaking coefficient	-	0.1	0.1
Base flow	Exponential Recession	Initial base flow	$m^{3/s}$	0	100000
		Recession factor		0.000011	-
		Flow to peak flow ratio		0	1

Table 2: Modeling methods and Calibration parameters constraints [14].

Model performance criteria

Finally the model performance was evaluated for both calibration and validation in different ways including coefficient of determination (R^2) and Nash-Sutcliffe efficiency [28] and MBE.MBE, ENS, and R^2 [29] are used to assess the hydrological modeling performance.

1. By visually inspecting and comparing the calculated and observed hydrograph

2. Coefficient of correlation (R^2)

$$R^2 = \left(\frac{\Sigma\left(Qobs - \overline{Qobs}\right)^2 - \Sigma\left(Qsim - \overline{Qsim}\right)^2}{\Sigma\left(Qobs - \overline{Qobs}\right)^2} \right)$$

Where:

Qobs=observed discharge

Qsim=simulated discharge

obs=mean of observed discharge

sim=mean of simulated discharge

R^2 is indicates how the simulated data correlates to the observed values of data. The range of R^2 is extends from 0 (Unacceptable) to 1(best).

3. Nash-Sutcliffe efficiencies (ENS) [28].

$$E_{NS}=1-\frac{\sum(Qobs-Qsim)^2}{\sum(Qobs-\overline{Qobs})}*100$$

Where:

Qobs=observed discharge

Qsim=simulated discharge

obs=mean of observed discharge

sim=mean of simulated discharge

Nash-Sutcliffe efficiencies can range from $-\infty$ to 1.

An efficiency of ENS=1 corresponds to a perfect match of modelled discharge to the observed data. An efficiency of ENS=0 indicates that the model predictions are as accurate as the mean of the observed data, whereas an efficiency less than zero ($-\infty<ENS<0$) occurs when the observed mean is a better predictor than the model. The closer the model efficiency is to 1, the more accurate the model is [30].

4. Mass Balance error

$$MBE=1-\frac{\sum(Qobs-Qsim)^2}{\sum(Qobs)}*100$$

This Mass balance error can vary between ∞ and $-\infty$. The model performs best when the value of zero is attained. This M.B.E tells us how much direct runoff moved in to the out let.

Result and Discussion

HEC-HMS hydrological modelling of the upper blue Nile river basin

The HEC HMS hydrological model has been calibrated manually and automatically to optimize to obtain the best possible option fit. Initial deficit constant loss, Snyder unit hydrograph transform, and recession base flow method used. The calibration and validation performance of the HEC-HMS 3.5 is carried out by comparing of the daily simulated runoff with the observed stream flow at the out let of the catchments. To assess the performance of the model predictability of representing the hydrological simulation of the reality of the basin. Three basic statistical hydrological model performance check used. The ENs (Nash Sutcliffe efficiency), R^2 (Relation coefficient) and MBE (Mass balance error).

### Hydrological modelling of catchments

A semi-distributed hydrological modelling technique applied for Gilgel Abay, Gumera, and Ribb catchments in order to increase the performance of the model. However a lumped system applied for Megech catchment due to its small area size. The catchments are classified into sub basins and each sub basin parameters manually adjusted by trial and error method and automatically optimized to get the best fit.

In Figure 10, the daily hydrograph of the simulated runoff caught the observed flow during calibration period (1/1/1988-1/12/2000), it is

well simulated, but the peak flow is under predicted in the model. Based on the calibrated parameters and values the model is validated from (1//1/2001-31/12/2005), and the performance a little bit improved. As you can see, the daily hydrograph well simulated with observed stream flow, however as like calibration period, there is also under prediction in the peak flow. The model performance was checked using ENS, R^2 and MBE, the result obtained are satisfactory and acceptable to simulate the basin runoff for future projection (Table 3). The deficit and constant loss method, synder unit hydrograph method and exponential recession method, are the best fit performed methods of the hydrological processes of infiltration loss, direct runoff transformation and base flow part of the model. Yilma H, et al. [31] has also indicated that synder unit hydrograph method and exponential recession method are the best fit.

Calibration and validation HEC-HMS

Calibration and validation HEC-HMS is given in Figure 10.
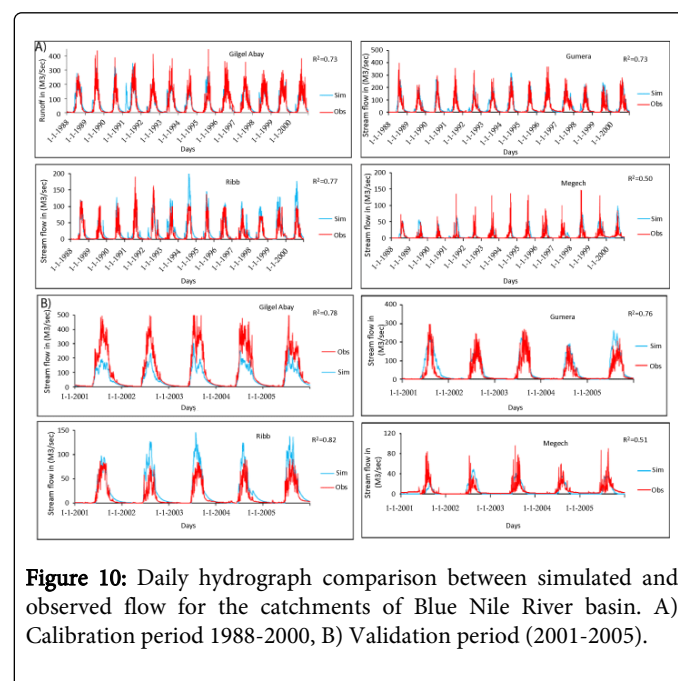
Figure 10: Daily hydrograph comparison between simulated and observed flow for the catchments of Blue Nile River basin. A) Calibration period 1988-2000, B) Validation period (2001-2005).

Conclusion

HEC-HMS (Soil Moisture Algorithm SMA) hydrological catchment simulation model calibrated and validated for each catchments. The soil moisture storage coefficient and the base flow coefficients are the most sensitive parameters for simulation of runoff. This also has been noted by Flemming and Nearby (for Dale Hollow watershed located within the Cumberland River basin in USA).The daily Nash and Sutcliffe efficiency (E_{NS}) and coefficient of determination (R^2) of model performance criterion used to evaluate the model applicability for different catchments. The model well simulated the daily stream flow at the out let of the catchment, however there is a slight under and over prediction of the high flows; this is the common draw backs of hydrological models [32]. The results obtained are satisfactory and acceptable. The applicability of the model is also ensured by Yilma and Moges [31], the difference is that they studied only Gilgel Abay catchment of the Upper Blue Nile River basin. Therefore, we assured in this study, HEC-HMS model can be used for modelling and

projection of future impacts of climate changes on runoff for upper Blue Nile River basin and can be applied to other catchments with similar hydro meteorological and land use characteristics. However the result of this study has been carefully noticed. Since HEC-HMS hydrological model assumed that the land use has been unchanged during modeling period, in reality the land use may change. In the future, we recommend further studies which incorporate the land use change of the basin [32].

Catchment name	Performance factor	Calibration period	Validation period
Gilgel Abay	E_{Ns}(Nash-Sutcliffe Efficiency)	0.71	0.77
	R^2(Relation coefficient)	0.73	0.78
	MBE(Mass balance Error)	12.3%	7.49%
Gumera	E_{Ns}(Nash-Sutcliffe Efficiency)	0.52	0.567
	R^2(Relation coefficient)	0.724	0.76
	MBE(Mass balance Error)	51.2%	42%
Ribb	E_{Ns}(Nash-Sutcliffe Efficiency)	0.52	0.53
	R^2(Relation coefficient)	0.77	0.78
	MBE(Mass balance Error)	47.1%	46.2%
Megech	E_{Ns}(Nash-Sutcliffe Efficiency)	0.49	0.5
	R^2(Relation coefficient)	0.5	0.51
	MBE(Mass balance Error)	15%	9%

Table 3: Calibration and validation performance values of upper Blue Nile basin.

Acknowledgments

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