Predicting Runoff Yield using SWAT Model and Evaluation of Boru Dodota Spate Irrigation Scheme, Arsi Zone, Southeastern Ethiopia

Ehitaferahu Teso,[1] Tena Alamirew[2] and Megersa Olumana[3]
[1]*East Shoa Zone Irrigation Development Authority, Adama, Ethiopia*
E-mail ehitaferahuteso@gmail.com, +251-911-88-91-17
[2]*Water and Land Resource Center (WLRC), P.O. Box 8707, Addis Ababa, Ethiopia*
E-mail: tena.a@wlrc-eth.org +251-922-47-01-13
[3]*Tshwane University of Technology p/Bag X68, Pretoria 0001, South Africa*
E-mail: DinkaMO@tut.ac.za

Abstract

For strategic planning and decision making on water-related development projects systematic assessment of the availability of water resources is imperative. Nevertheless, such information is rarely available for many of the subbasins in Ethiopia. Hence, ungauged catchments need to be modeled using hydrologic models. This study was initiated with the objective of calibrating and validating SWAT model on Keleta River gauged watershed (about 761.89 km^2) so that it can be used to predict runoff on a monthly, seasonal and annual basis, and evaluate the Boru Dodota spate irrigation scheme that has a similar hydrometeorological condition with the Keleta Watershed. Keleta River's observed flow data were used for sensitivity analysis, model calibration and validation. The result of model performance analysis demonstrated a good agreement between the average monthly simulated and measured values: Nash-Sutcliffe model efficiencies (NSE) of 0.71 for calibration and 0.73 for validation periods. Moreover, the coefficients of determination (R^2), 0.73 and 0.76, were obtained during the same period. The calibrated parameter on the gauged catchment was in turn used to estimate runoff yield of the ungauged catchment. The simulated mean monthly and average annual water yields of the Boru River Watershed were found to be 0.53 and 6.4 m^3s^{-1}, respectively. The 70% dependable wet season water yield of the catchment was 3.41 m^3s^{-1}, and crop water requirement of the command area was 1.2 $ls^{-1}ha^{-1}$. The water yield from the catchment can irrigate only 2,842 ha of land out of the pre-designed 5,000 ha of land of the Boru Dodota spate irrigation scheme. In conclusion the SWAT model can be used to analyze ungauged watershed runoff yield in areas that have similar hydrometeorological characteristics as those of the Keleta Watershed in the region. The information obtained can then be used to redesign the spate system or a conventional irrigation system.

Key words: *SWAT, spate irrigation, PUB, ungauged catchment, runoff prediction*

1. Introduction

Water is a key driver of sustainable development and poverty alleviation. It is an input to almost all production in agriculture, industry, energy and transport. Ethiopia has nine wet and three dry river basins. The annual runoff and groundwater potential from nine river basins are estimated to be 122 BM^3 and 40 BM^3, respectively. The Awash River Basin is among the nine river basins which cover a total drainage area of 110,000 km^2 and contribute 4.6 BM^3 of annual runoff (Getaneh 2011).

Most water-scarce (the semiarid, arid and desert) areas in Ethiopia are crossed at least with ephemeral rivers. In addition, some such areas are neighborhoods of highlands with enormous but unpredictable runoff. Making use of such disastrous, unreliable and erratic floods in conjunction with the rainfall on the agricultural fields is challenging. An initiative is needed to efficiently utilize the flood resource from the upper land to supplement the rain-fed agriculture on the lower land (Demissie et al. 2010), i.e., the development of spate irrigation. In developing spate systems, it is important to understand the entire hydrology of the system: the baseflow, subsurface flow and groundwater and the pattern of spate floods. This will dictate the potential yield of the area to be irrigated. However, spate floods can have very high peak discharges generated in wadi catchments through localized storms. The extreme characteristics of wadi hydrology make it very difficult to determine the volume of water that will be diverted to fields and hence the potential cropped areas (Steenbergen et al. 2010).

One of the challenges in water resources development in Ethiopia has been the paucity of hydrological and meteorological data. On top of this, analyzing the historical events is difficult because of a lack of historical runoff records from the ephemeral rivers. In the absence of measured data, watershed models serve as a means of organizing and interpreting research data while also providing continuous water-quality predictions that are economically feasible and time-efficient.

Although empirical formulas are adopted, this simply simulates rainfall-runoff relationships developed not exactly in the same agroclimatic zones. There is great uncertainty on the estimation for it does not consider the complex interactions that take place in the watershed.

A comprehensive understanding of hydrological processes in the watershed is the prerequisite for successful water resources management and environmental restoration. Due to the spatial and temporal heterogeneity in soil properties, vegetation and land use practices, a hydrologic cycle is a complex system. As a result, mathematical models and geospatial analysis tools are required for studying hydrological processes and hydrological responses to land use and climatic changes. The Soil and Water Assessment Tool (SWAT), a physically based semi-distributed model, was selected to analyze the yield of the ungauged Boru River Watershed with respect to quantity of runoff. SWAT has the ability to characterize complex, watershed representations to explicitly account for spatial variability of soils, rainfall distribution, and vegetation heterogeneity and shows the effects of different land management practices on surface runoff and sediment yield (Arnold et al. 1998).

The Boru Dodota Spate Irrigation Scheme is one of the areas with a semiarid climate in the Oromia Regional State Arsi Zone, Dodota District. The area faces frequent crop failure due to the erratic nature of rainfall. Boru Dodota uses spate irrigation to divert floods up to 6 m^3s^{-1} of the ephemeral Boru River to supplement the rain-fed agriculture on 5,000 ha (Aman 2007). In the Boru Dodota irrigation scheme the periods of flood and crop production coincide. However, due to the unpredictable nature of the flood from the subbasins and the rainfall on the scheme, a substantial size of the command area is left without irrigation (Demissie 2010). The hydrologic processes of the watershed were not analyzed because of the absence of hydrologic information, such as surface runoff, baseflow, seasonal water yield, the magnitude and return period of extreme events. Farmers' indigenous knowledge, visual observation and empirical formulas were used to estimate peak flows and baseflow, which are the basis for structural design and used for deciding the supplemented area (Aman 2007). This study was initiated to triangulate the assumption adopted in estimating the surface runoff, baseflow, and seasonal water yield upon the system design development.

The general objective of this study is to create an understanding of how hydrological models can be utilized to solve challenges on catchments characterized in the absence of hydrological data. The runoff yield of the ungauged Boru River Watershed was estimated and the parameters used for the Boru Dodota spate irrigation scheme evaluated. The specific objectives were to calibrate and validate a SWAT model on monthly time step at gauged Keleta River Watershed; estimate monthly, seasonal and annual runoff yields and water balance of the ungauged Boru River Watershed using the SWAT model at the headwork, and evaluate Boru Dodota Spate Irrigation Scheme.

2. Materials and Methods

2.1. Description of the Study Area

The Keleta-gauged and Boru-ungauged river watersheds are found in the southeastern part of Ethiopia in the Arsi Zone of Oromia Regional State. The watersheds originate from the Chilalo Mountain situated in the upper Awash River Basin. Boru (Wadi) River drains to Keleta River below the gauging station as shown in Figure 6.1. The watersheds are geographically situated between 7°55 - 8°16′ N latitude and 39°17′ - 39°34′ E longitude and 7°55′ - 8°11′ N latitude and 39°16′ - 39°22′ E longitude, respectively. They cover a total drainage area of 761.9 km^2 and 74.8 km^2, respectively. The minimum and maximum elevations of the watersheds are 1,600 m, 4,183 m, 4,039 m and 1,865 m, amsl, respectively. Rainfall in the downstream of the Boru Watershed (Boru Dodota Spate Irrigation Scheme) is erratic and dry for much of the year (Aman 2007). Boru Dodota Spate Irrigation Project was designed to provide supplemental irrigation water for about 5,000 ha of potential irrigable land using the 6 m^3s^{-1} designed flood generated from Boru and other micro watersheds (Aman 2007).

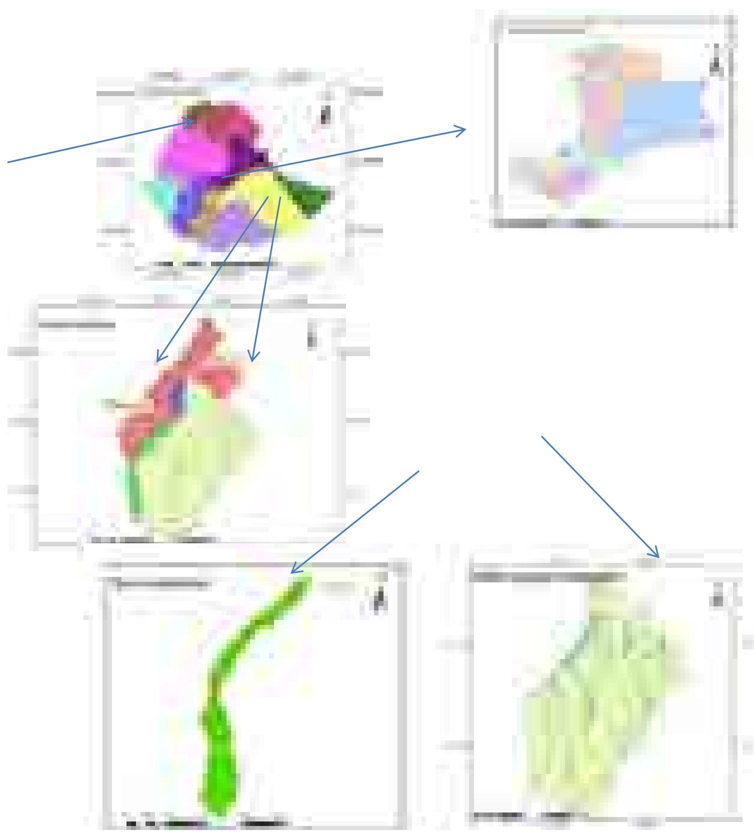
2.2. Description of the SWAT Model

SWAT was developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large, complex watersheds with varying soils, land use and management conditions over long periods. The model is a basin-scale, continuous-time model that operates on a daily time step. It is physically based, computationally efficient, and capable of continuous simulation over long periods (Gassman et al. 2007). In SWAT, a watershed is divided into multiple sub-watersheds, which are then further subdivided into hydrologic response units (HRUs) that consist of homogeneous land use, management, and soil characteristics. The HRUs represent percentages of the sub-watershed area and are not identified spatially within a SWAT simulation. Alternatively, a watershed can be subdivided into only sub-watersheds that are characterized by dominant land use, soil type, and management (ibid). The review of SWAT model applicability to the local situation indicated that the model is capable of simulating hydrological processes with reasonable accuracy and can be applied to large ungauged watersheds (Kebede et al. 2006). SWAT is currently applied worldwide and is considered as a versatile model that can be used to integrate multiple environmental processes, which support more effective watershed management and the development of better-informed policy decisions (Gassman et al. 2005). The simulation of the hydrology of a watershed is classified as the routing phase and the land phase of the hydrological cycle that controls the amount of water, sediment, nutrient and pesticide loadings to the main channel in each subbasin and simulates the hydrologic cycle based on the water balance equation (equ. 1) of Arnold et al. (1998) and Neitsch et al. (2005)

$$SW_t = SW_o + \sum \left(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw} \right) \quad (1)$$

where, SWt is the final soil water content (mm), SWo is the initial soil water content on day i (mm), t is the time (days), R_{day} is the amount of precipitation on day i (mm), Q_{surf} is the amount of surface runoff on day i (mm), E_a is the amount of evapotranspiration on day i (mm), W_{seep} is the amount of water entering the vadose zone from the soil profile on day i (mm), and Q_{gw} is the amount of return flow on day i (mm).

Figure 6.1. Major river basins of Ethiopia and location map of Boru and Keleta sub-wateshed.



2.3 SWAT Model Inputs

2.3.1. Digital Elevation Model (DEM)

DEM was used to delineate the watershed and analyze the drainage pattern of the land surface terrain and subbasin parameters, such as slope gradient, slope length of the terrain and the stream network characteristics, such as canal slope length and width. The DEM with a resolution of 30 m was downloaded from Advanced Space Borne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER GDEM) of the official website (http://www.gdem.aster.ersdac. or.jp/download.jsp) released by Earth Remote Sensing Data Analysis Center (ERSDAC) in collaboration with National Aeronautics and Space Administration (NASA) of the United States.

2.3.2. Land use and land cover (LULC)

The land use map and all datasets of the study area were obtained from the Ministry of Water and Energy (MoWE) of Ethiopia derived from satellite imagery and field data collection from 2004 to 2007. The reclassification of the land use map was made to represent the land use according to the specific land cover types. A look-up table that identifies the SWAT code for the different categories of LULC was prepared to relate the grid values to SWAT LULC classes. The major land uses of the study areas are illustrated in Figure 6.2.

2.3.3. Soil properties

A soil map and datasets on basic soil physico-chemical properties may be obtained from the Ministry of Water and Energy (MoWE 2007), Soil and Terrain Database for north-eastern Africa CDROM (FAO 1998), Harmonized World Soil Database (HWSD) and different irrigation design documents around the study area. Soils in the study watersheds are classified based on the revised FAO/UNESCO-ISWC (1998) classification system (Tables 6.1, 6.2 and 6.3).

2.3.4. Meteorological data

The SWAT model requires meteorological data such as precipitation, maximum and minimum air temperatures, sunshine hours, wind speed and relative humidity; these were collected from the National Meteorological Services Agency (NMSA) of Ethiopia for Kulumsa, Sire, Diksis, Huruta and Melkasa. Among these stations, the model used only Kulumsa, Melkasa and Huruta stations for the Boru Watershed (Figures in the Annex). All weather stations provided precipitation and minimum and maximum temperatures, whereas daily sunshine hours, wind speed and relative humidity were obtained from Melkasa and Kulumsa weather stations. Although much of the data had missing values, the SWAT model fills the gap by the weather generator model WXGEN embedded in Arc SWAT interface. The Penman-Monteith method, which utilizes the solar radiation, relative humidity and wind speed data records, was employed for estimation of potential evapotranspiration.

Finally, the quality of rainfall data was checked by cross correlating between the stations on a monthly basis. The correlation coefficient (r^2) ranges from 0.86 to 0.98. The result of the correlation coefficient (r^2) implied that all stations were positively and strongly correlated and there were consistent records among the stations.

2.3.5. Hydrological data

The only hydrological data required for sensitivity analysis, calibration and validation of the model, and the daily Keleta River discharge, were obtained from the Hydrology Department of the Ministry of Water and Energy of Ethiopia. The homogeneity of average annual daily flow data was tested using RAINBOW, which uses past flow data for analysis. The total daily discharge data of the Keleta River were separated into surface runoff and baseflow by using an automated baseflow separation and recession analysis technique (Arnold et al. 1999). The output was used to test whether the SWAT model reflects the basic observed water balance components (surface runoff and baseflow) at the gauging station or otherwise.

Table 6.1. Major soil classes of Keleta River and Boru River watersheds.

Name of soil unit	Code of the soil unit	Keleta Watershed		Boru Watershed	
		Area [ha]	[%] in weight	Area [ha]	[%] In weight
Chromic Luvisol	LVx	8,143.17	10.69	1,161.95	15.14
Chromic Vertisol	Vc	9,540.65	12.52	214.66	2.87
Dystric Nitosol	Nd	1,817.55	2.39	*	*
Eutric Cambisol	CMe	11,629.20	15.26	427.82	5.72
Eutric Nitosol	Ne	4,317.98	5.67	377.05	5.04
Eutric Rigosol	RGe	*	*	182.55	2.44
Eutric Vertisol	VRe	29,898.20	39.24	822.98	11.01
Lithic Leptosol	LPq	1,142.33	1.50	*	*
Orthic Luvisol	Lo	9,530.98	12.51	1,585.30	21.20
Vertic Cambisol	CMv	168.73	0.22	2,705.25	36.18

Table 6.2. Land use, SWAT codes and area coverage in Keleta and Boru watersheds.

Land use	SWAT code	Keleta Watershed		Boru Watershed	
		Area [ha]	[%] in weight	Area [ha]	[%] in weight
Forest -- Deciduous	FRSD	10,454.45	13.72	1115.38	14.92
Forest -- Evergreen	FRSE	5,658.80	7.43	815.14	10.90
Agric. Land – Generic (Mixed Farming)	AGRL	59,107.05	77.58	5547.04	74.18
Range – Brush (woodland)	RNGB	968.48	*	1.27	*

NB: * indicates soil type and land use not found in that specific area.

Table 6.3. Slope classes and percentage area coverage of Keleta and Boru watersheds.

Slope class	Keleta Watershed		Boru Watershed	
	Slope (%)	Area coverage (%)	Slope (%)	Area coverage (%)
I	0-10	43.13	0 – 10	39.8
II	10-20	37.57	10 – 25	43.33
II	20-30	12.44	25 – 40	10.18
IV	30-9999	6.86	40 - 9999	6.69

Figure 6.2. Soil map and its spatial distribution over (A) Keleta and (B) Boru watersheds.

A

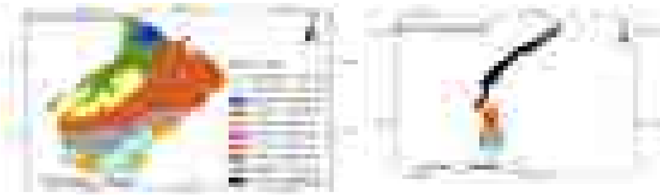
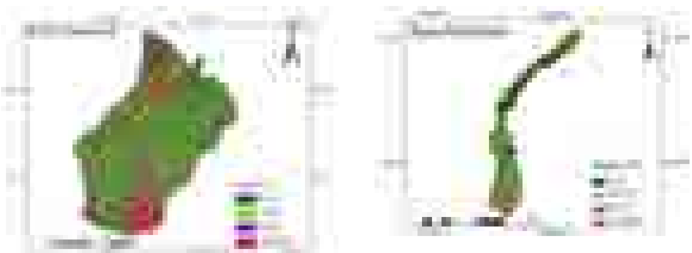


Figure 6.3. Land use map and its spatial distribution over (A) Keleta and (B) Boru watersheds.

A B

Figure 6.4. Land slope map and its spatial distribution over (A) Keleta and (B) Boru watersheds.

A B



2.4 Model Setup

2.4.1. Watershed delineation

Automated watershed delineation embedded in Arc SWAT interface was used to delineate the watershed. Delineation of the watershed and sub-watershed was done using Digital Elevation Model (DEM) data. DEM was imported into the SWAT model and projected to UTM zone 37, projection area of Ethiopia. A mask was manually delineated over the DEM in order to extract the specific area, to delineate the boundary of the watershed and digitize the stream networks in the study area, which reduce the time of processing and burn-in a polyline stream dataset that in turn helps the subbasin reach to follow the known stream reach. In this study, the minimum threshold area of 1,522 ha and 233.4 ha were used to define the stream network for Keleta and Boru watersheds, respectively. This threshold area was used to define the minimum drainage area required to form the origin of a stream and to decide the number of subbasins within the watershed. Lastly, watershed outlet and inlet definition, watershed outlet or gauged point location and calculation of subbasin parameter were made.

2.4.2. Hydrological response units

After watershed delineation, subbasins were subdivided into areas having unique land use, soil and slope so-called hydrologic response units (HRUs). Even if the individual fields with specific land use, soil and slope were scattered over the subbasin, when lumped together they form HRUs. The land use, soil and slope datasets were projected into the same projection as DEM. After projection of the land use, soil and slope datasets were reclassified, overlaid and linked with the SWAT databases and ready for HRU definition. To define the distribution of HRUs, multiple HRU definition options were selected. The threshold level set for land use, soil and slope was used to define the number of HRUs within the subbasin as well as the watershed. In addition to land use and soil, HRUs were also classified based on slope classes. For these specific areas, multiple slope classification was used and the classifications were made based on the suggested minimum, maximum, mean and median slope statistics of the watershed. The minimum threshold area of 5% for land use over the subbasin area, 10% for soil class over the land use area and 10% for slope over the soil area were used. The land use, soil and slopes percentage areas covering less than the threshold area level were eliminated, and then the remaining areas were reclassified so that 100% of the land area in the subbasin could be used in the simulation.

2.4.3. Sensitivity analysis

After all the input (temporal and spatial) data required for the SWAT model were properly loaded, the parameter sensitivity analysis was done using the Arc SWAT interface for the whole catchment (Van Griensven et al. 2006). Twenty-six hydrological parameters were tested for sensitivity analysis for the simulation of the streamflow in the study area. Here, almost all the default lower and upper bound parameter values were used. In addition to hydrologic parameters, observed monthly flow values of Keleta River were used. The sensitivity analysis was made using a built-in SWAT sensitivity analysis tool that uses the Latin Hypercube One-factor-At-a-Time (LH-OAT) algorithm (Van Griensven 2005). After running a sensitivity analysis, the sensitivity parameters were categorized into four classes based on their mean relative sensitivity from very high to low.

2.4.4. Calibration and validation

During the calibration process, model parameters were subjected to adjustments in order to obtain model results that correspond better to the measured datasets. After the sensitive parameters were selected, the model simulates the stream flow using default parameter values for the years 1990-1995. The default simulation outputs were compared with the observed stream flow data on Keleta River. In this study, manual calibration followed by automatic calibration were made on a monthly basis from January 1, 1992 to December 31, 1995 until the average simulated value came closer to the measured value. Periods from 1990 to 1991 were used as warm-up periods. Automatic calibration makes use of a numerical algorithm to increase the performance of the model and to optimize the numerical objective functions. In manual calibration for each simulation result and parameter change, the corresponding performance evaluation criteria were compared against the preset values. This procedure continued until the acceptable calibration model performance statics $r^2 > 0.6$, ENS > 0.5 and D >±15 (Santhi et al. 2001; Moriasi et al. 2007) were achieved. After the simulation result for the calibration period had fulfilled the above statistical criteria, validation was performed for an independent period of records from January 1, 1996 to December 31, 1998. This period was preferred for validation due to better quality of data records. Therefore, the results were compared against an independent set of measured Keleta River discharge.

2.4.5. Model performance evaluation

In order to evaluate the model performance relative to the observed data, the following three performance measures were used during the calibration and validation periods: Percent difference between simulated and observed data (D), Coefficient of determination (R^2) equation (2) and Nash and Sutcliffe simulation efficiency (ENS) equation (3).

$$r^2 = \frac{\left(\sum [X_i - X_{av}][Y_i - Y_{av}]\right)^2}{\sum [X_i - X_{av}]^2 \sum [Y_i - Y_{av}]^2} \qquad (2)$$

where, X_i is measured value, X_{av} is average measured value, Y_i is simulated value, and Y_{av} is average simulated value.

The r^2 value measures how well the simulated versus observed regression line approaches an ideal match and ranges from 0 to 1, with a value of 0 indicating no correlation and a value of 1 representing that the predicted dispersion equals the measured dispersion (Krause et al. 2005).

Nash and Sutcliffe simulation efficiency (ENS) indicates the degree of fitness of observed and simulated data, given in equation (2).

$$E_{NS} = 1 - \frac{\sum_{i=1}^{n} (X_i - Y_i)^2}{\sum_{i=1}^{n} (X_i - X_{av})^2} \qquad (3)$$

where, X_i is measured value, X_{av} is average measured value, Y_i is simulated value, and Y_{av} is average simulated value.

The value of ENS ranges from one to negative infinity. The ENS indicates how well the plot of observed versus simulated value fits the 1:1 line. The closer the model efficiency is to 1, the more accurate the model and if it is between 0 and 1, it indicates deviations between measured and predicted values. If ENS is negative, predictions are very poor, and the average value of output is a better estimate than the model prediction (Nash and Sutcliffe 1970).

The percent difference (D) measures the average difference between the simulated and measured values for a given quantity over a specified period (usually the entire calibration or validation period) and it is calculated using equation (4).

$$D = 100\left(\frac{\sum Yi - \sum X_i}{\sum Xi}\right) \quad (4)$$

where, X_i is measured value and Y_i is simulated value. A value close to 0% is best for percent difference (D).

2.5 Transferring calibrated parameters of gauged catchments for ungauged catchments

After thorough calibration and validation of the SWAT model for the gauged Keleta River Watershed, the final calibrated parameter was used to predict runoff and water balance component of the ungauged Boru Watershed, which have similar hydrometeorological conditions. The Keleta River gauged watershed and Boru River ungauged watershed had the same HRUs definition from the minimum threshold level of 5% land use, 10% soil unit and 10% slope. The calibrated hydrologic parameters for the gauged Keleta Watershed were used to change the hydrological parameters in the SWAT model to correctly estimate runoff for the ungauged Boru River Watershed.

3. Results and Discussion

3.1. Watershed Delineations

The gauged Keleta River and the ungauged Boru River watersheds, as shown in Figure 6.3, covered the total drainage area of 761.9 km^2 and 74.8 km^2 and subdivided into 29 and 15 subbasins based on the minimum threshold area of 1,522 ha and 233.4 ha, respectively. Multiple HRUs were defined based on the minimum threshold level of 5% LULC, 10% soil unit, and 10% slope classes. The overlaid land use soil and slopes form 165 and 96 HRUs for Keleta and Boru watersheds, respectively.

3.2. Baseflow Separation

Baseflow separation result using the baseflow filter program by Arnold and Allen 1999 on an annual basis indicated that about 58% of the observed Keleta River discharge was contributed from the subsurface flow. The contribution of baseflow to Keleta River discharge exceeds the surface runoff. In contrast, the simulated flow at Keleta River is estimated as 61.3% of baseflow over the calibration period, whereas it is 60.9% over the validation period. Since the simulated baseflow had agreed with the estimated measured value with little deviation given different uncertainty, the model properly reflected the basic water balance components, such as baseflow and surface runoff.

3.3. Sensitivity Analysis

Among the 26 hydrological parameters selected for sensitivity analysis for simulation of streamflow in the study area, 18 were found relatively sensitive. Accordingly, the more sensitive parameters considered for calibration were: Baseflow alpha factor (Alpha-BF), Curve number (CN2), Threshold depth of water in the shallow aquifer (GWQMN), Effective hydraulic conductivity in the main channel (CH-K2), Plant evaporation compensation factor (ESCO), Available water capacity (SOL_AWC), Soil depth (Sol_Z), Leaf area index for crop (Blai), Deep aquifer percolation fraction (Rchrg-Dp), Maximum canopy index (Canmax), Threshold water depth in shallow aquifer (Revapmn) and Surface runoff lag time (Surlag). Among the baseflow parameters, baseflow alpha factor (Alpha-BF) is the most sensitive over the surface runoff parameter Curve number (CN2) (Table 6.4).

3.4. Model Calibration and Validation

For the calibration period of 4 years (1992 -1995) the simulated monthly flows showed good agreement with the observed monthly Keleta River discharge with a coefficient of determination (R^2 = 0.73), Nash Suttcliffe model efficiency (ENS = 0.71), and percent difference (D = -13.32%). However, the model underestimated the peak monthly flow for the whole calibration period; it followed the trend of observed monthly Keleta River discharge and gave a good response to extreme rainfall events, which resulted in high runoff volume. Table 6.4 illustrates the final calibrated parameter values. The hydrographs of simulated and observed flow values on a monthly basis are shown in Figures 5 and 6.

The SWAT model also successfully validated streamflow for an independent period (1996 – 1998). The model has strong predictive capability with R^2=0.76, ENS=0.73 and D =13.19; the values fulfilled the statistical model performance criteria $R^2 > 0.6$ and ENS > 0.5 recommended by SWAT developer (Santhi et al. 2001).

Generally, the above information showed that the performance of the model increased during the validation period more than during the calibration period. Even though the model underestimated the peak monthly flow for 1997 and overestimated it during 1998, the shape of the hydrograph of simulated flow was the same as the shape of hydrograph of measured monthly Keleta River discharge. The peak values gave a good response to extreme rainfall for the validation period. The hydrograph and the scattered plot of simulated and observed monthly flow values associated with rainfall for the validation period are illustrated in Figures 6.5 and 6.6, respectively.

Table 6.4. Sensitivity flow parameters and final calibrated fitted values.

Flow parameter	Sensitivity rank	Upper and lower bounds	Calibrated value
Alpha BF	1	0.0 to 1.0	0.5274
CN2	2	±25	-0.92491
Gwqmn	3	0.0 to 1000	-82.374
Ch-K2	4	0.0 to 150	93.043
Esco	5	0.0 to 1.0	0.21964
Sol_Awc	6	±25	19.176
Soil_Z	7	±25	9.993
Blai	8	0.0 to 1	0.45106
Canmax	9	0.0 to 1.0	1.569
Rech_Dep	10	0.0 to 1.0	0.0043145
Gw-Revmn	11	0.0 to 100	42.3420
Surlag	12	0.0 to 10	0.6709

Table 6.5. Summary of model performance evaluation for calibration and validation period on monthly time steps.

Mean annual water yield (mm)			Monthly model efficiency measures		
Period	Observed	Simulated	r^2	ENS	D (%)
Calibration	300.82	262.74	0.73	0.72	-13.32
Validation	234.13	267.31	0.76	0.73	13.91

Figure 6.5. Hydrograph of simulated and observed average monthly flow overlaid with monthly rainfall for the calibration period.

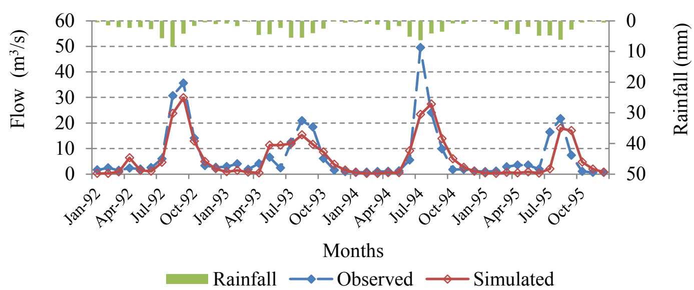
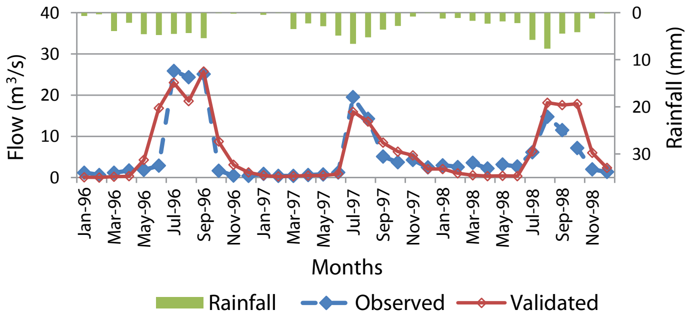


Figure 6.6 Hydrograph of simulated and observed monthly flow overlaid with monthly rainfall for the validation period.



3.5. Boru Dodota Water Yield Simulation

3.5.1. Monthly and seasonal water yield simulation

SWAT water yield simulation result for the period (1994 – 2010) showed 0.53 m^3s^{-1} and 6.4 m^3s^{-1} of mean monthly and annual average water yield, respectively. The result is summarized on a monthly and seasonal basis (dry, wet and intermediate season). The 70% dependable water yield indicated 0.28, 1.01, 3.4 and 5.14 m^3s^{-1} for dry, intermediate, wet seasons and annual basis, respectively. Therefore, among the dependable water yield for the above season, the water yield estimated during wet seasons was important for the spate irrigation scheme.

3.5.2. Average annual water balance components of ungauged Boru River Watershed

The SWAT model can also estimate average annual basin values for different water balance components of the ungauged Boru Watershed. Precipitation was the input, whereas surface runoff, lateral soil flow, groundwater flow, shallow aquifer recharge, deep aquifer recharge and actual evapotranspiration were outputs. The sum of surface runoff, lateral soil flow and groundwater contributions minus transmission loss (water lost from tributary channels in the HRU via transmission through the bed and becomes recharge for the shallow aquifer during the time step) is the total water yield or streamflow that reaches the headwork, whereas the change in soil water storage is the difference between inflow and outflow. The simulated annual water balance components of the Boru catchment are indicated in Table 6.6; 73.9% of the annual precipitation is lost through evapotranspiration from the watershed for the respective period.

Table 6.6. Average annual simulated hydrologic component for the Boru Watershed (1994-2010).

Water balance components	Amount in (mm)
Precipitation; Precip	868.40
Surface runoff; Sur_Q	57.91
Lateral soil flow contribution; Lat_Q	24.78
Ground water contribution to stream flow; Gw_Q	146.05
Revap or shallow aquifer recharges	0.00
Deep aquifer recharges, Rchg-Deep	0.63
Total water yield; Twyld	228.01
Percolation out of soil; Perc	145.92
Actual evapotranspiration; ET	641.60
Potential evapotranspiration; PET	1085.20
Transmission losses; Tloss	0.73
Change in soil water storage	-2.57

Table 6.7 and Figure 6.6 indicate the variability of simulated monthly water yield across subbasins for different land use, soil and slope classes. Subbasin 4 and subbasin 5 with agricultural land generic, Vertic Cambisol, and 10-25% slope, and subbasin 13 and subbasin 15 with forest deciduous and forest evergreen land use, Chromic Luvisol and Orthic Luvisol soil types and 0-10 and 10-25% slopes were estimated to have a high average water yield. This was because subbasins 4 and 5 are cultivated lands. Nevertheless, subbasins 13 and 15 were covered by forest; the area received a high amount of rainfall and generated more water than others could generate. In contrast, subbasins 4 and 5 (slope 10-25 %) had similar soil type and land use, but different slope from that of subbasin 1 and subbasin 3 (slope 0-10 %), which had contributed the least amount of water yield.

Figure 6.7. Estimated average monthly water yield across each subbasin.

Table 6.7. Variation of monthly water yield across subbasins for the period (1994-2010).

Subbasin	Area coverage (km^2)	Water yield (mm)	Subbasin	Area coverage (km^2)	Water yield (mm)
1	2.34	14.13	9	2.99	15.24
2	10.00	15.59	10	4.06	15.79
3	5.58	14.17	11	4.85	17.05
4	4.51	33.68	12	2.08	14.57
5	6.45	33.69	13	2.34	19.51
6	0.23	14.89	14	18.98	16.97
7	1.93	14.88	15	5.31	20.04
8	3.13	15.83			

3.6. Evaluation of Boru Dodota Spate Irrigation Scheme

Results of the SWAT model showed that the drainage area covered by the ungauged Boru River Watershed up to the headwork is 74.8 km^2; the watershed covered 50 km^2 as indicated in the design documents. In Boru Dodota Spate Irrigation Scheme, since the periods of flood and crop production coincide, the wet season (June-September) dependable water yield (3.41 m^3s^{-1}) was an important yield compared to yields in other seasons. The peak discharge and design discharge were 112 and 3.41 m^3s^{-1}, respectively, whereas these were 100 and 6 m^3s^{-1} in the previous design (Aman 2007). The crop water requirement of the command area is 1.2 $ls^{-1}ha^{-1}$ (Aman 2007), whereas 3.41 m^3s^{-1} discharges can only fulfill the crop water requirement of 0.68 $ls^{-1}ha^{-1}$, to supplement rain-fed agriculture on 5,000 ha of land. The remaining 0.52 $ls^{-1}ha^{-1}$ was expected from the precipitation on the command area. However, the precipitation of the area is so erratic in nature that it should have been given less consideration so that the 3.41 m^3s^{-1} discharge for 1.2 $ls^{-1}ha^{-1}$ can irrigate only 2,842 ha of land. The irrigable area of Boru Dodota Spate Irrigation Scheme covers 5,000 ha of land (Aman 2007), whereas the Boru River water yield should irrigate 2,842 ha of land. According to Demissie et al. (2010), information from Dodota District discloses that in 2008 and 2009, 1,821 ha and 1,686 ha of land were irrigated, respectively. The output of the model and the pre-designed discharge (Aman 2007) were different in the drainage area, peak and design discharge, canal capacity, irrigable area and in different hydrologic parameters of Boru River watershed.

Therefore, a great variation in canal capacity such as canal width, canal depth, canal hydraulic radius, canal width over depth ratio, wetted perimeter and all other design parameters were changed because of variation between the pre-designed discharge (6 m^3s^{-1}) and the model output (3.41 m^3s^{-1}). Therefore, all other irrigation structures incorporated in the project should have been redesigned based on the model output.

4. Summary and Conclusion

A comprehensive understanding of hydrological process in the watershed is the prerequisite for successful water resources management and environmental restoration. To analyze the yield of the ungauged Boru River watershed with respect to quantity of runoff yield, the SWAT model was selected. The performance and applicability of the SWAT model were evaluated through a sensitivity analysis, model calibration and validation. After modeling the gauged Keleta River watershed, calibrated parameters were transferred to the ungauged Boru River watershed by lumping the parameters having the same hydrologic response unit (HRUs) to predict runoff for Boru Dodota Spate Irrigation Scheme.

The SWAT model performs well in predicting runoff yield if properly calibrated and validated for the gauged river catchment and transferring the calibrated parameters to the ungauged catchment. Therefore, despite the data scarcity, the SWAT model is a potential tool to simulate the hydrology of ungauged watersheds in Ethiopia that have similar hydrometeorological conditions with those of the gauged watershed. The calibrated parameter values of Keleta watershed can be considered for further hydrologic simulation of the watershed and in developing neighboring catchments. All irrigation structures in Boru Dodota Spate Irrigation Scheme should have been redesigned and reconstructed based on the model output. In order to irrigate the remaining area, a storage reservoir is recommended. Future studies on Boru watershed modeling for the Boru Dodota Spate Irrigation Scheme should address the issues related to sedimentation. Accurate sampling and measurement of sedimentation parameters need to be addressed by responsible bodies to evaluate best management practices and climate change impacts on the availability of water resources.

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Appendix

Table A1. Mean monthly-observed discharge (mm) at gauged Keleta River Watershed.

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
1992	5.6	8.1	5.1	7.9	6.9	8.5	20.9	107.7	121	49.4	11.4	9.2	362
1993	10	13	6.5	14	23.0	8.1	43.8	73.5	62.5	21.5	5.3	3.2	284.0
1994	2.6	2.3	3.4	3.5	4.3	19	174	84.4	33.3	6.1	6.3	4.1	343.0
1995	3.3	3.6	10	12	12.2	6.5	57.6	76.1	25.1	3.8	2.1	2.3	214.7
1996	4.1	2.0	4.1	5.9	6.4	9.8	90.9	85.5	89.3	5.8	1.7	1.4	307.0
1997	3.1	1.2	1.4	2.0	2.7	4.3	68.6	50.1	17.3	13.0	14.9	8.6	187.2
1998	10.4	8.1	12.6	7.4	11.1	9.1	21.5	51.8	39.2	25.1	7.0	4.8	208.2
Mean	5.6	5.4	6.1	7.5	9.5	9.3	68.2	75.6	55.4	17.8	7.0	4.8	272.2

Table A2. Simulated average monthly water yield (mm) of gauged Keleta River watershed.

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
1992	0.8	1.7	4.0	28.0	5.0	3.5	13.5	69.0	89.3	37.1	12.4	5.1	269.3
1993	2.5	8.5	2.5	2.6	49.7	33.5	40.6	47.7	35.7	27.2	10.6	4.1	265.0
1994	1.6	0.6	1.4	1.6	2.0	33.6	78.3	87.5	39.6	16.4	6.6	2.7	271.7
1995	1.0	0.9	2.6	2.8	1.9	1.1	5.7	62.2	39.3	12.0	4.3	1.9	135.6
1996	0.1	0.0	0.7	1.0	15.1	57.1	80.9	65.2	93.12	30.7	10.8	4.3	357.2
1997	1.8	0.8	1.2	1.6	1.8	2.9	56.0	47.7	28.7	22.0	18.9	7.3	190.5
1998	7.2	3.3	1.9	1.2	1.5	1.2	22.3	63.8	59.8	62.8	21.0	8.1	254.2
Mean	2.2	2.2	2.0	5.5	11.0	19.0	42.5	63.3	54.8	29.7	12.1	4.8	249.1

Table A3. Indices for sensitivity classes.

Class	Index (I)	Sensitivity
I	|I| 1.00	Very high
II	0.20 |I| < 1.00	High
III	0.05 |I| < 0.20	Medium
IV	0.00 |I| < 0.05	Small to negligible

Source: Lenhart et al. (2002).

Table A4. General performance ratings of flow on a monthly time step.

Performance rating	ENS	D
Very good	0.75 <ENS< 1.00	D< ±10
Good	0.65 <ENS<0.75	±10 < D < ±15
Satisfactory	0.50 <ENS<0.65	±15 < D < ±25
Unsatisfactory	ENS <0.50	D > ±25

Source: Moriasi et al. (2007).

Figure A1. Average monthly rainfall distributions in gauged Keleta watershed.

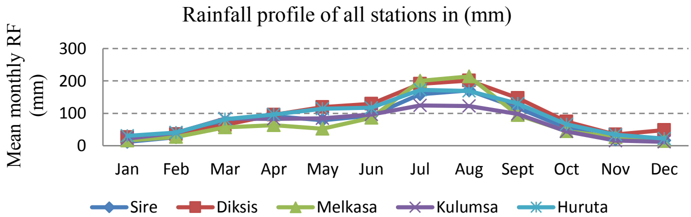

Figure A2. Mean monthly minimum and maximum temperature profile.

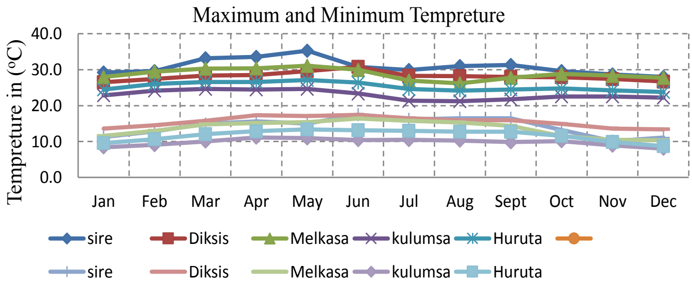

Figure A3. Mean monthly runoff at the gauging station of Keleta River.

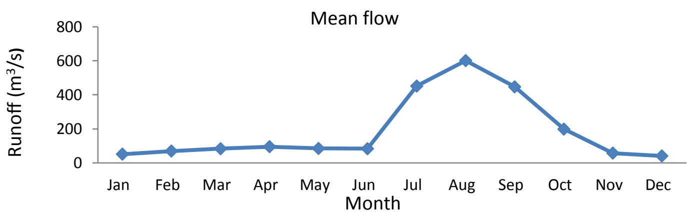

Figure A4. Rescaled cumulative deviations from the mean for the total annual flow of Keleta River.