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Testing the WEAP Hydrologic Model for Awash Basin, Ethiopia
"Soil Moisture Module with Watershed Demand Approach"

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Abstract

Currently, there are several hydrological simulation models in use worldwide. Prior to adoption of a model to a specific basin, its feasibility and practicality should be tested. This study highlights on the application of Water Evaluation and Planning system (WEAP) model for hydrologic simulation of Awash river basin in Ethiopia. A monthly time step hydrologic model was developed using the soil moisture rainfall-runoff method incorporated in WEAP with an aim to check the suitability of the model for Awash river basin. For this purpose five selected flow gauge stations located at the upper, middle and lower Awash basin were used as control stations. The model is configured taking into account the effects of development and hence the water abstractions, storage, loss rate, etc. are estimated using the data provided through various kinds of research and survey in Ethiopia. Standard methods are also used to prepare the hydro-metrological and landuse input data for each sub-catchment. Based on data availability, the time period 1986-2005 was selected for the hydrologic simulation. The observed data were split for calibration (1986–1995) and validation (1996–2005) purposes. Initially, the model was set up using the default model parameters. Then, manual calibration is performed to reproduce the observed streamflow. The model-simulated values are compared with those obtained from observations using standard statistical tests on monthly and monthly average basis. From the performance test results, it is observed that the coefficient of determination (R^2) and the Index of Agreement (IA) show a good fit. Furthermore, the Nash-Sutcliffe Efficiency (NSE) and the Percent Bias (PBIAS) calibration and validation results show good performance for Upper Awash stations and satisfactory results for the middle and lower Awash control stations. As a conclusion, the main modelling constraints were discussed and possible solutions were also suggested in order to improve the performance of water resources simulation models for the Awash basin.

Keywords: Awash Basin, Hydrologic Simulation, Calibration, Validation, Model Performance, WEAP

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1. Introduction

The Awash River originates from the high plateau to the west of Addis Ababa at an elevation of about 3,000 m above mean sea level (a.m.s.l.) in the central Ethiopian highlands. It then flows eastwards along the Rift Valley and terminates in saline Lake Abe at elevation of 250 a.m.s.l. at the border with Democratic Republic of Djibouti. The annual runoff within the basin is estimated at 4.9 Bm^3 (Halcrow, 1989). It has a total area of 114, 000 km^2 with a total length of 1,200 km. The landscape of the basin comprises highlands, escarpment and rift valley.

Awash river basin is the most developed and utilized basin in the country (Awulachew et al., 2007). The water demand in the basin is expanding due to population growth, rapid socio-economic development and increased irrigation expansion activities. On the other hand, the supply resources of basin are shrinking due to reservoir sedimentation, pollution and climate change impacts. The cumulative impact of these factors is leading the basin to water scarcity and water use conflicts among different water use sectors (Parker et al., 2016). In order to address these problems and improve the water resources management practices, the current and future water availability in terms of quantity, quality and spatial occurrence should be studied in depth in the first place. Then, an efficient water allocation mechanism should be established taking into account the different water use sectors including the environment. This can be realized manly through employing water resources simulation and planning models which are suitable for the basin.

The Water Evaluation and Planning System (WEAP) is an Integrated Water Resources Management (IWRM) model developed by the Stockholm Environmental Institute. WEAP has advantage over other simulation models in that it can be used for hydrologic simulation as well as scenario analysis and water allocation. WEAP can be considered as one of the potential modelling tools for the Awash river basin. However, prior to its adoption the suitability should be tested. Hence, the objective of this study is to develop a hydrologic model of the Awash basin using WEAP with the main goal of determining the feasibility and practicality of the WEAP hydrologic model for the entire Awash basin. Based on physical and socio-economic factors, Awash basin is divided into four distinct zones. These are Upper Awash (UA), Upper Valley (UV), Middle Valley (MV) and Lower Valley (LV). The location map of the study area is presented in Figure 1.

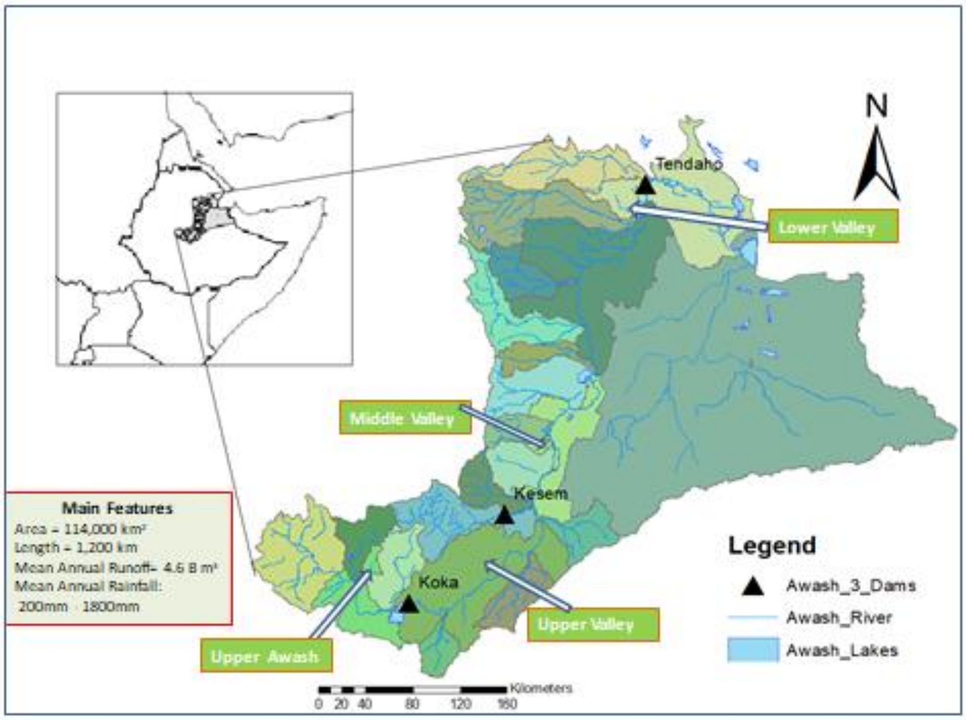


Figure1: Map of the Awash River Basin, Ethiopia

2. Materials and Methods

2.1. Model Description

There are three hydrologic modeling methods in WEAP (SEI, 2015). They are: 1) The Rainfall Runoff Method - Food and Agriculture Organization (FAO); 2) The FAO - Irrigation Demands Only, and 3) The Rainfall Runoff - Soil Moisture Method. For this study, the soil moisture rainfall-Runoff method is used for simulation of the hydrologic process of the Awash basin. The method is formulated based on an algorithm of one dimensional - two soil layer conceptual model for calculating surface runoff, evapotranspiration, deep percolation and sub-surface runoff for a defined unit area of land (Yates et al., 2005). The hydrologic process mass balances are described in Equation 1, and the corresponding conceptual model diagram is demonstrated using Figure 2 below.

The hydrologic process mass balance equation is written as:

$$Sw_j \frac{dz_{1,j}}{dt} = P_e(t) - PET(t)k_{c,j}(t)\left(\frac{5z_{1,j}-2z_{1,j}^2}{3}\right) - P_e(t)z_{1,j}^{RRF_j} - f_j k_{s,j} z_{1.j}^2 - (1-f_j)k_{s,j}z_{1.j}^2 \quad (1)$$

Where,
Sw_j = soil water holding capacity of area j (mm)
$z_{1,j}$ = relative water storage in the root zone layer in area j
$P_e(t)$ = effective precipitation at time t (mm)
PET (t) = reference potential evapotranspiration (mm/day)
$k_{c,j}$ = crop coefficient for area j
RRF_j = Runoff resistance factor for area j
f_j = horizontal and vertical flow partitioning coefficient
$k_{s,j}$ = saturated hydraulic conductivity of the root zone layer for area j (mm/time)

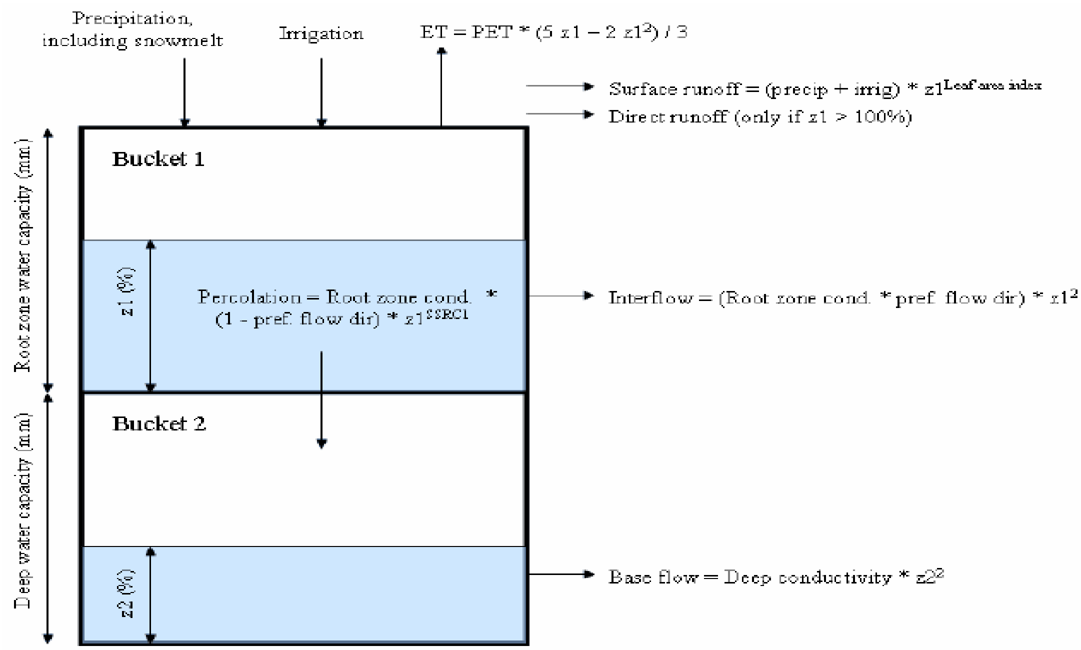


Figure 2: WEAP Soil Moisture Model (Source: SEI, 2015)

2.2. Study Definition

Several steps are included in the application of WEAP. The study definition sets up the time frame, spatial boundary, system components and configuration of the problem (SEI, 2015). In WEAP models are called ‘Areas’. Areas are limited by boundaries, which define the extent of the project area. Initially, the geographic area of the project is selected from the world map that is situated in the Schematic View. Once the Area is created the next step is to set the general parameters. This includes mainly the time frame and the time steps. For this study monthly time step is selected with the years 1986 and 2005 as the starting and end years of simulation period.

2.3. Input Data

The input data for WEAP hydrologic simulation modelling is comprised of two broad categories namely “Catchments & Demand Sites” and “Supplies & Resources”. The catchments & demand sites category includes user defined variables and default or calibratable parameters. The user defined parameters mainly include catchment area, landuse group, crop coefficient, precipitation, climate, water abstractions or demands and others. The default or calibratable parameters are those parameters which are used in the mass balance equation and derived from the landuse group and soil data. The supply & resources category consists of mainly user defined variable such as reservoirs, streamflow, flow requirements, transmission links, return flows and others. The data together with derived parameters and the input techniques employed are briefly discussed as follows.

2.4. Catchments and demand sites

2.4.1. Catchments

I. User defined variables

a) Catchment Area

The catchment area is a fundamental parameter of any hydrologic model (Amato et. al., 2006). ArcMap 10.3 software and STRM 90 DEM (Digital Elevation Model) were used to delineate twenty two sub-basins in the Awash basin river system. The shapefile of the sub-basins and the main rivers of Awash river basin were added to the WEAP schematic by first exporting the shapefile from the ArcMap and then adding them to WEAP as a vector layer of the basin. The rivers were then drawn in WEAP by tracing over the vector layer and the other schematic elements were placed using the "drag and drop" facility. The sub-basins, the corresponding areas and the resulting WEAP model schematic of Awash river basin is shown in Figure 3.

Nr.	Sub-Catchment Name	Area_Sq. km
1	Above_Melka_kuntre_st	4532.3
2	From_MK_st_to_Koka_dam	2548.4
3	From_Koka Dam_to Awash_st	7982.4
4	Awash_st_to_Ataye_Confl	3395.6
5	Akaki	1656.9
6	Mojo	2113.3
7	Keleta	1041.0
8	Arba	1797.8
9	Kesem	3535.3
10	Kebena	1553.2
11	Herdini	1687.2
12	Gaysene_Awara	1846.2
13	Najeso_Gera	3135.4
14	Awadi	1179.9
15	Ataye	1210.2
16	Borkena_Jara	3215.2
17	Cheleka	1819.0
18	Ataye_Mile_Conf	9231.6
19	Mille	4935.2
20	Logia	3791.0
21	Awash_Terminal	7036.2
22	Eastern_Catchment	44792.4
	Total	**114,035.44**

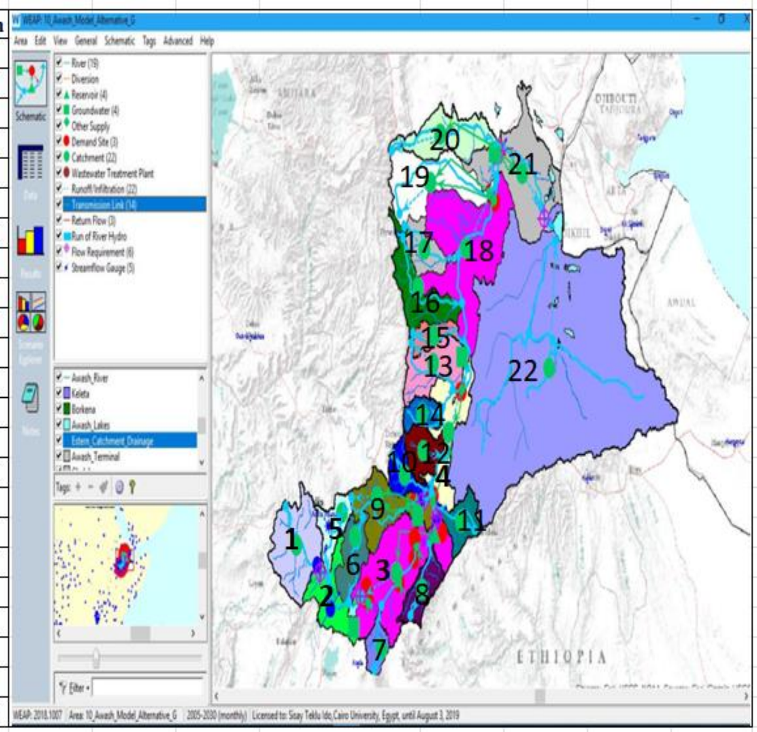


Figure 3: Awash Sub-Basins and WEAP Schematic View

b) Land Use Groups

Land use category sub divisions were created within the twenty two sub-basins. The land use classification is based on Globcover 2006 data as shown in Figure 4. The fourteen land use classes defined by Globcover were further modified and summarized to nine major classes for non-irrigated catchments. For irrigated catchments, the agriculture land use class was further divided to rainfed and irrigated agriculture based on the available irrigation data for the catchment. The area of each land use category within each sub-basin was determined as percentages of the total sub-basin area using Arc Toolbox and applied in the WEAP model as shown in Table 1 below.

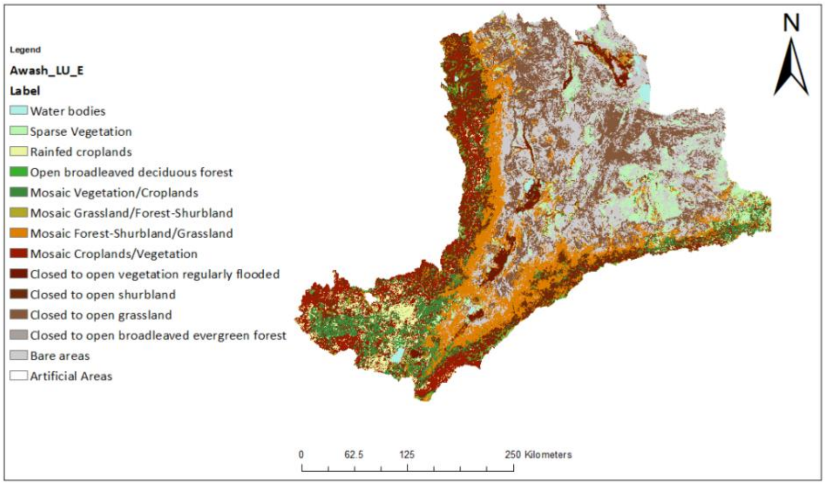


Figure 4: Awash Basin Landuse Category based on Globcover (2006)

Table 1: Landuse Category for Koka Dam to Awash Station Irrigated Catchment

Landuse Category	Area (sq km)	Percent Area
Shurbland	501.2	6.28
Agriculture/Rainfed	1138.0	14.26
Agriculture/Irrigated	235.04	2.94
Artificial/Urban	9.2	0.12
Bare areas	661.7	8.29
Forest	4428.3	55.48
Grassland	234.3	2.94
Sparse Vegetation	371.6	4.66
Water bodies	202.2	2.53
Wetland	198.3	2.48
Unknown	2.5	0.03
Total	**7982.4**	**100.00**

c) Crop coefficient, Kc

The crop coefficient Kc is a parameter that is used to expresses the relative evapotranspiration difference between the reference and the cropped surface. The Kc value is dependent on the type of land class. Crop evapotranspiration is calculated by multiplying the reference evapotranspiration (ETo) by Kc. For Awash river basin, Kc values for a total of twenty land use categories and crop types were determined from different previous studies (Allen et. al., 1998, Amato et. al., 2006, Tiruneh et al., 2013). For the Kc value of each land use category, a read from CSV files and a Key Assumptions were created and applied in the WEAP model as shown in Figure 5 below.

d) Precipitation

Monthly time series precipitation data was obtained from the National Meteorology Agency of Ethiopia (NMAE). The Theissen polygon spatial analysis method was applied to twenty one selected climate stations to determine the average monthly areal precipitation for each sub-basin for the period of 1986 to 2005. A read from CSV file monthly precipitation data for each sub-basin was created and applied in the WEAP model as shown in Figure 6 below.

e) Climate (Temperature, Wind , Humidity and Cloudiness Fraction)

The other climate parameters i.e., temperature, relative humidity and wind data are entered in degrees Celsius, as a percentage and in meters per second respectively. Monthly time series temperature and wind speed dataset in 0.25 degree raster format is obtained from Princeton University data portal (Terrestrial Hydrology Group, 2014). Theissen polygon spatially weighted relative humidity mean monthly values per sub-basin was estimated using data obtained from Food and Agriculture Organization (FAO) database (CLIMWAT, n.d.). One (1) month - Terra/MODIS cloudiness fraction data for five years from (2001-2005) was obtained from (NASA Earth Observations (NEO), n.d.). However, only average monthly cloudiness fraction and relative humidity data were available. Hence, the average monthly values were repeated for every corresponding month and read into WEAP as a time series expression from a CSV file.

f) Others

The other user defined parameters include the latitude at the centroid of each catchment expressed in Degree Decimal (DD) and Glacier and snow modelling parameters include melting point, freezing point, albedo with lower and upper bound. Glacier and snow modelling is not applicable for Awash river basin. Hence, WEAP default parameter values are used to run the model.

Landuse	Kc Values / months											
	1	2	3	4	5	6	7	8	9	10	11	12
Shrubland	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Artificial/Urban	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77
Bare areas	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Forest	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
Grassland	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53
Sparse Vegetation	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Water bodies	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05
Wetland	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Unknown	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Agriculture/Rainfed	0.05	0.05	0.05	0.05	0.05	0.57	0.57	0.57	0.57	0.57	0.57	0.57
Citrus	0.65	0.65	0.65	0.66	0.68	0.69	0.7	0.7	0.69	0.67	0.66	0.65
Vegetables	1	0.95	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.7	0.75	1.05
Sugar Cane	0.61	0.74	0.86	0.99	1.05	1.05	1.05	1.05	1.05	0.94	0.71	0.6
Cotton	1.15	1.11	0.85	0.05	0.05	0.05	0.05	0.05	0.3	0.35	0.6	1.05
Maize	1.13	0.81	0.62	0.05	0.05	0.05	0.05	0.05	0.3	0.4	0.99	1.2
Tobacco	0.35	0.75	1	1.1	1	0.9	0.05	0.05	0.05	0.05	0.05	0.3
Pasture	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46
Tree crops/Fruits	0.65	0.65	0.65	0.66	0.68	0.69	0.7	0.7	0.69	0.67	0.66	0.65
Banana	1.2	1.2	1.2	1.2	1.09	1	1	1	1.02	1.11	1.19	1.2

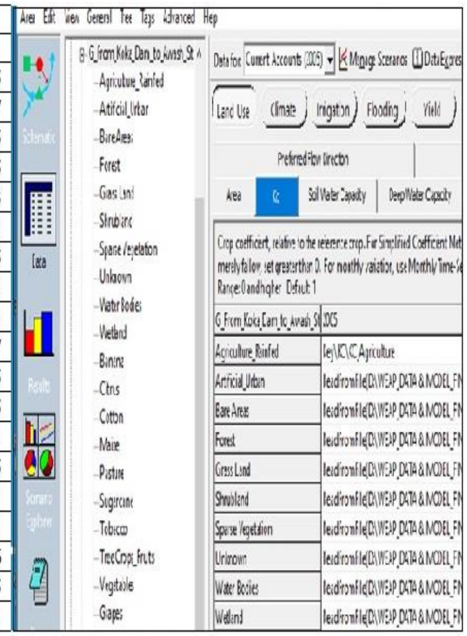


Figure 5: Crop coefficient (Kc) Values as applied in WEAP Model
(Source: Allen et. al., 1998, Amato et. al., 2006, Tiruneh et al., 2013)

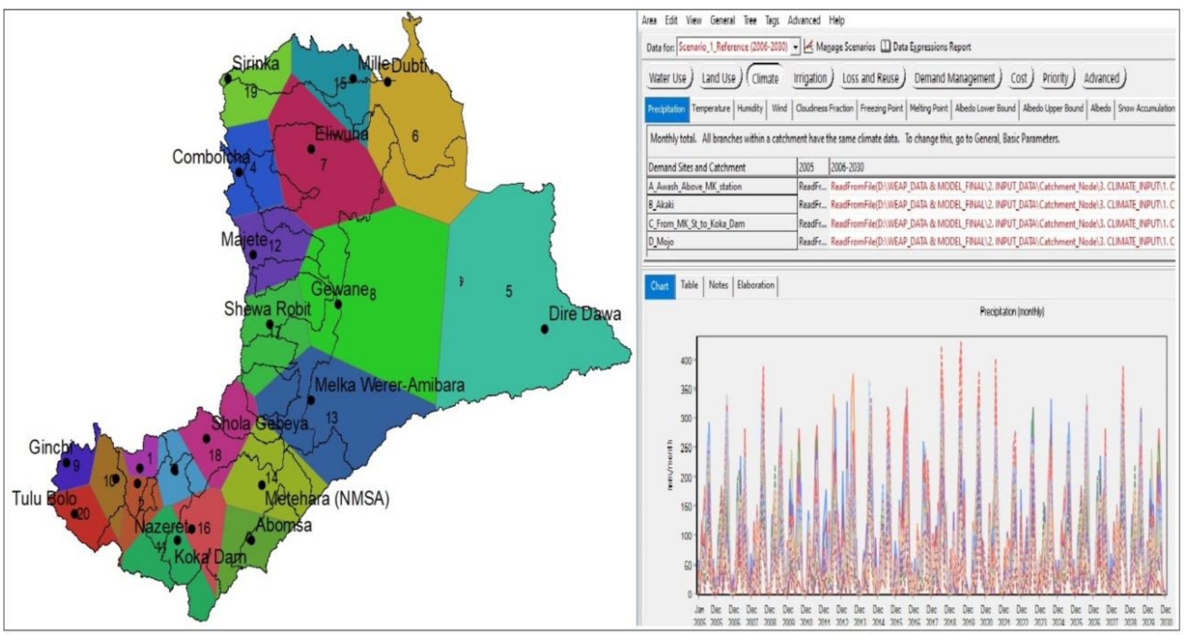


Figure 6: Theissen Polygon Weighted Precipitation and WEAP Time Series Expression

II. WEAP default and calibratable parameters

During WEAP modelling, the parameters and data are difficult to define with certainty. Initially, the setup of the model was established using a Key Assumption of the default values for each sub-basin and then the parameters were calibrated to fit with the physical characteristics of the basin. Descriptions of some of the parameters and the corresponding default values are summarized and presented in Table 2.

Table 2: WEAP Parameters and Ranges of Default Values

Nr.	Parameter	Unit	Range of Values		
			Minimum	Maximum	Default
1	Soil Water Capacity	mm	0	> 0	1000
2	Deep Water Capacity	mm	0	> 0	1000
3	Runoff Resistance Factor	-	0	1000	2
4	Root Zone Conductivity	mm/month	0	> 0	20
5	Deep Conductivity	mm/month	0.1	> 0.1	20
6	Preferred Flow Direction	-	0	1	0.15
7	Initial Z1	%	0	100	30
8	Initial Z2	%	0	100	30

2.4.2. Demand sites

a) Urban domestic demand

This study covers only the main towns namely Awash, Nazareth and Metehara which directly abstract water from the main Awash River. The total population of the three towns for hydrologic simulation starting year 1986 and end year (year 2005) was estimated about 99,268 and 235,354 respectively as indicated in Table 3. The annual rate of water use was estimated using a consumption rate of 100 LCD (Liter /Capita per Day). Based on the two national census data (CSA Census Report 1994, CSA Census Report 2007), the total population of the three towns is predicted to grow at a rate of 4.2 percent per annum.

Table 3: Population of Urban Domestic Demand Sites

Nr.	Demand Sites (Towns)	Population by year		
		1986	1994	2005
1	Nazareth/Adama	85481	127842	202917
2	Metehara	7980	11934	21,348
3	Awash	5807	8684	11053
Total		**99,268**	**148,460**	**235,354**

(Source: CSA Census Report, 1994 & 2007)

b) Irrigation demand

Irrigation water demands are modeled as a watershed demand. In this approach, the land cover in a sub-catchment has been designated as containing irrigated land cover fractions with lower and upper irrigation thresholds, Lj and Uj for crop j. These thresholds show both the quantity and timing of water needed for irrigation, as the water available in the storage of the upper level (Z1,j) depletes due to evapotranspiration and percolation. When the relative soil moisture, Z1,j drops below the lower threshold Lj, an irrigation demand will be triggered in the fractional area. The total irrigation demand for each sub-catchment is the sum of irrigation demand for the fractional areas found in the sub catchment (Yates et. al. 2005).

In the present study, irrigation water demand is estimated based on the existing and potential net irrigation areas (ha) data as proposed by Ministry of Water Resources (MoWR) and Halcrow (WWDSE and WAPCOS, 2005). According to this data, irrigation schemes are aggregated into three principal groups. They are: (I) Upper Valley (UV), (II) Middle Valley (MV), and (III) Lower Valley (LV) irrigation groups. The existing and proposed irrigation areas are presented in Table 4.

During the model application, the existing irrigation data in the years 1986-2005 are used for the hydrologic simulation in order to take into account the effects of development. In order to fit with the model input format, the data in Table 4 was rearranged and organized in a sub-catchment category as shown in Table 5. Within in each sub-catchment, the dominant crop types were identified and the data in Table 5 was further disaggregated based on irrigated crop area. Hence, for irrigated catchments, the irrigated crop areas were included as a component of agriculture landuse class. Like the others landuse classes, the area of each crop within each sub-catchment was determined as a percentage of the total sub-catchment area using Arc Toolbox and applied in the WEAP model. Table 6 demonstrates the input format used for the irrigation data at the year 1986. Similar procedures are also used for the year 2005.

Table 4: Existing and Potential Net Irrigation Areas (ha)

as Proposed by Halcrow and MoWR (Source: WWDSE and WAPCOS, 2005)

Irrigation Group	Existing		Expansion Proposed		Total	
	Halcrow 1989	MoWR 2005	Halcrow 1989	MoWR 2005	Halcrow 1989	MoWR 2005
Upper Valley	23284	23504	10626	17903	33910	41407
Middle Valley	21896	14591	36320	20000	58216	34591
Lower Valley	25600	11600	36900	48000	62500	59600
Total	**70,780**	**49,695**	**83,846**	**85,903**	**154,626**	**135,598**

Table 5: Existing Net Irrigation per Sub-catchments and Irrigation Groups

Irrigation Group	Irrigation Sub-Group	Sub-Catchments	Irrigation Area (ha)	
			1986/88	2005
Upper valley (UV)	(UV1)Upper Valley Irrigation_1	Koka Dam -Awash Station	7,001	8,203
	(UV2)Upper Valley Irrigation_2		7,323	5,083
	(UV3)Upper Valley Irrigation_3		8,960	10,218
	Total		**23,284**	**23,504**
Middle Valley (MV)	(MV1)Middle Valley_1	Kesem	1,915	1,915
	(MV2)Middle Valley_2	Awash St - Ataye Conflunce	17,410	8,590
	(MV3)Middle Valley_3		2,571	4,086
	Total		**21,896**	**14,591**
Lower Valley (LV)	(LV1)Lower Valley_1	Mille	1,440	1,440
		Logia	160	160
	(LV2)Lower Valley_2	Awash Terminal	15939	6000
	(LV3)Lower Valley_3		8,061	4,000
Total			**25,600**	**11,600**
Basin Total			**70,780**	**49,695**

2.5. Supply and resources

2.5.1. Reservoirs

The reservoir simulation in WEAP takes into account net evaporation on the reservoir, priorities of downstream requirements, hydropower energy demands, and the reservoir's operating rules. The only reservoir that is active during the simulation period is that of Koka dam. Koka dam is located in the upper valley region of the basin. It is a a multipurpose dam for hydropower production and flood regulation. The installed and firm capacity of Koka power house is 43.2 MW and 30 MW respectively (Halcrow, 1989). Initially, Koka dam was constructed and operated primarily for hydropower generation. Later on, the release from the dam has become the main source of water for the irrigation schemes downstream of the dam. During modelling the reservoir, the net evaporation, the reservoir elevation-area-capacity curve and other parameters data are adapted from previous researches (WWDSE and WAPCOS, 2005, Halcrow, 1989).

2.5.2. Streamflow gauges

Stream flow data was obtained from the hydrology department of Ministry of Water, Irrigation and Energy of Ethiopia. Five locations were selected as comparison points between the simulated and observed flows. Four out of five stations are located on the main Awash river and one station is located on the tributary Kesem river. These particular gauges were selected based on data availability and considering spatial distribution to cover the upper, middle and downstream reaches of the river basin as shown in Figure 7.

Table 6: Description of the Base-Year (1986) Landuse Categories for the Twenty Two SCs, Given as a Percentage of their Total Area, Where only SC5, SC7, SC11, SC20, SC21 and SC22 have Irrigated Land Cover Types

Catchment	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Landuse	Awash above Melka K.	Akaki	Mojo	Melka .K - Koka Dam	Kesem	Kebena	Koka dam to Awash st.	Keleta	Arba	Herdini	Awash st – Ataye Con.	Eastern Catchment	Ataye Mile Con.	Gaysen - Awara	Awadi	Najeso - Gera	Ataye	Cheleka	Awadi	Mille	Logia	Awash Terminal
Shrubland	10.8	9.91	6.1	6.0	19.97	25.6	6.3	6.7	25.2	31.5	2.1	4.2	1.6	11.7	26.0	18.7	8.1	32.0	21.4	22.70	5.45	1.9
Artificial/Urban		7.13					0.1					0.01										
Bare areas	0.4	0.69	0.1	0.1	4.44	6.9	8.3	0.1	2.3	5.0	28.7	36.3	39.4	11.4	8.4	18.0	19.0	10.2	13.8	12.81	28.35	49.2
Forest	28.0	24.93	25.9	33.8	39.75	31.6	55.5	33.2	36.5	55.5	25.0	15.7	15.9	48.4	39.3	27.3	29.4	28.2	23.8	21.04	15.10	5.5
Grassland	0.7	0.42	0.1	0.1	1.71	3.9	2.9	3.2	3.8	3.9	19.2	26.5	33.9	8.2	10.8	12.6	13.1	3.0	4.9	26.93	44.49	24.2
Sparse Vegetation	0.02	0.06	0.8	1.4	0.29	0.3	4.7	0.9	0.01		1.7	13.3	4.7	2.6	0.03	0.9	0.2		0.3	1.49	4.51	6.8
Water bodies		0.51	0.7	0.7			2.5				0.5	0.5	0.1	0.4		3.1			0.02	0.77		1.9
Wetland		0.22			0.51	3.8	2.5				16.6	0.01	2.7	6.3		2.9		0.2	0.5			6.0
Unknown	0.2	0.15	0.0	0.29	0.09	0.2	0.03	0.3	0.2	0.2	0.01	0.1	0.01	0.01	0.07	0.1	0.02	0.03	0.2	0.07	0.28	0.2
Agriculture/Rainfed	59.9	55.99	66.4	57.7	32.70	27.7	14.3	55.6	32.0	3.9	0.5	3.2	1.7	11.0	15.5	16.4	30.1	26.4	35.0	13.91	1.78	0.7
Agriculture/Irrigated					**0.54**		**2.92**				**5.9**									**0.29**	**0.04**	**3.4**
Citrus							0.03															
Vegetables							0.04															0.004
Sugar Cane							1.99															
Cotton					0.25		0.07				4.48										0.04	2.62
Maize							0.10				0.42									0.10		0.75
Tobacco					0.04		0.07															
Pasture											0.59											0.02
Tree crops/Fruits					0.25		0.63															
Banana											0.40									0.19		
Total (%)	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100.0**	**100.0**	**100.0**

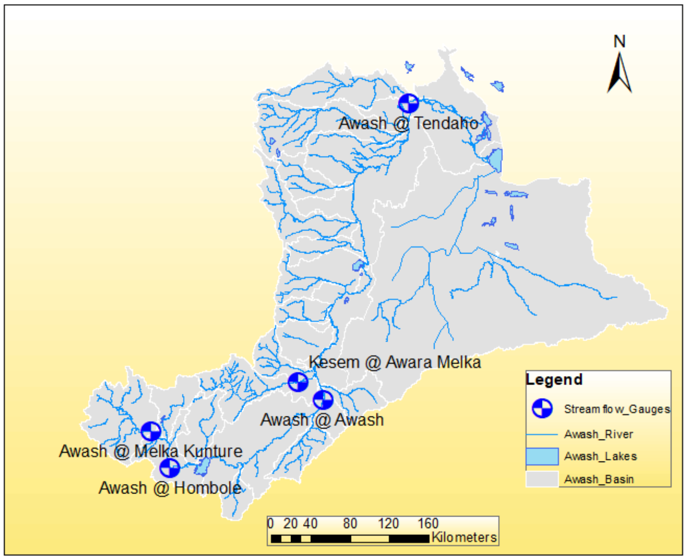


Figure 7: Location of Control Stations

2.5.3. Transmission links and return flows

Transmission links are used to connect the supply systems to each demand site. On the other hand, return flow links are used to connect the outflows from the demand sites back to the rivers. The return flow is determined as the balance between the inflow to a demand site and its consumption (the portion of the inflow that lost in the system). In this study, transmission links are established for all domestic demand sites and catchments. A 50 % return flow is also assumed for the three (3) urban domestic water demand site nodes.

2.6. Model calibration and validation

Initially, the default model parameters were used to set up the model. Based on data availability, the time period 1986-2005 was selected for the hydrologic simulation. The model was calibrated for the first 10 years period (1986-1995) and validated for the second 10 years period (1996-2005). However, the time span varies from one station to another depending on stream flow data availability as described in the results summary Table 8. The calibration and validation involved both quantitative and qualitative evaluation of the hydrologic response at the control stations. A Key Assumption of default parameter values was created for each sub-basin in the data entry view of the WEAP model as shown in Figure 8. The parameters were adjusted manually to reproduce the monthly and monthly average stream flow patterns.

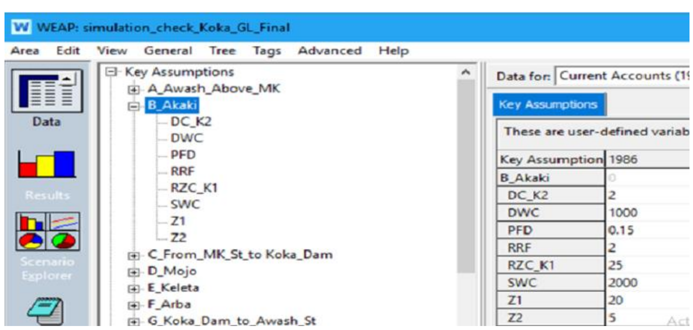


Figure 8: A Key Assumption Value of Parameters for Akaki Sub-catchment

2.7. Model Performance Tests

The performance of the hydrologic model was tested using standard statistical tests supported with visual inspection of the time series plots. The statistical parameters employed for the test include Coefficient of determination (R^2), Nash-Sutcliffe Coefficient (NSE), the Index of Agreement (IA) and the Percent BIAS (PBIAS). Details on efficiency criteria for the assessment of hydrological model are provided in Krause, et al. (2005). The model performance criteria employed in the present study are briefly described as follows:

2.7.1. Coefficient of Determination (R^2)

The coefficient of determination (R^2) is a measure of how well the regression model describes the observed data (Schneider et al., 2010). It is the square of the Pearson's coefficient of correlation (R) between two variables i.e., observed and simulated streamflows in our case. The closer R^2 to 1 indicates better fit or relationship, between the two variables.

$$R^2 = \left(\frac{\left(\sum_{i=1}^{n}(Q_{o_i}-\overline{Q_o})\,(Q_{s_i}-\overline{Q_s})\right)}{\sqrt{\sum_{i=1}^{n}(Q_{o_i}-\overline{Q_o})^2}\,\sqrt{\sum_{i=1}^{n}(Q_{s_i}-\overline{Q_s})^2}}\right)^2 \quad (2)$$

2.7.2. Index of Agreement (IA)

The index of agreement (IA) is used as a test of how well the simulated data fit with the observed one. It is a measure of the degree to which a model's predictions are error free (Cort J. W., 1981). Its value varies from 0 to 1; closer value to 1 indicates a better fit of simulated and observed stream flows.

$$IA = 1.0 - \left(\frac{\sum_{i=1}^{n}(Q_{o_i}-Q_{s_i})^2}{\sum_{i=1}^{n}\left(\left|(Q_{s_i}-\overline{Q_o})\right|-\left|(Q_{o_i}-\overline{Q_o})\right|\right)^2}\right) \quad (3)$$

2.7.3. Nash-Sutcliffe Coefficient (NSE)

Nash and Sutcliffe (1970) proposed an Efficiency Coefficient (NSE) as expressed in Eqn. 4 below. Its value ranges from minus infinity to 1.0, with high values indicating better agreement. An efficiency NSE= 1 indicates a perfect fit of simulated and observed data.

$$NSE = 1.0 - \left(\frac{\sum_{i=1}^{n}(Q_{o_i}-Q_{s_i})^2}{\sum_{i=1}^{n}(Q_{o_i}-\overline{Q_o})^2}\right) \quad (4)$$

2.7.4. Percent Bias (PBIAS)

PBIAS (%) measures the average tendency of the simulated flows to be larger or smaller than their corresponding observed values. The optimal value is 0. 0, positive and negative values indicate a model bias toward underestimation and overestimation respectively (Gupta et al., 1999). PBIAS is calculated as:

$$PBIAS = \left(\frac{\sum_{i=1}^{n}\,(Q_{o_i}-Q_{s_i})*100}{\sum_{i=1}^{n}(Q_{o_i})}\right) \quad (5)$$

Where:

$\overline{Q_o}$ ($\overline{Q_s}$) = Average observed (simulated) streamflow (m^3/s) Q_{S_i} = Simulated streamflow (m^3/s)

Q_{O_i} = Observed streamflow (m^3/s)   n = Number of data used in the analysis

2.7.5. Model Performance Ratings

The model performances with regard to the Nash-Sutcliffe Coefficient (NSE) and Percent Bias (PBIAS) tests are evaluated based on the general performance rating values Table 7 which is a result of the work of Moriasi et al. (2007).

Table 7: General Performance Ratings for Recommended Statistics for a Monthly Time Step

Performance Rating	RSR	NSE	PBIAS (%)		
			Streamflow	Sediment	N.P
Very good	0.00 < RSR ≤ 0.50	0.75 < NSE ≤ 1.00	PBIAS < ± 10	PBIAS < ± 15	PBIAS < ± 25
Good	0.50 < RSR ≤ 0.60	0.65 < NSE ≤ 0.75	± 10 ≤ PBIAS< ± 15	± 15 ≤ PBIAS < ± 30	± 25 ≤ PBIAS< ± 40
Satisfactory	0.60 < RSR ≤ 0.70	0.5 < NSE ≤ 0.65	± 15 ≤ PBIAS< ± 25	± 30 ≤ PBIAS < ± 55	± 40 ≤ PBIAS< ± 70
Unsatisfactory	RSR > 0.70	NSE ≤ 0.5	PBIAS ≥ ± 25	PBIAS ≥ ± 55	PBIAS ≥ ± 70

(Source: Moriasi et al. (2007))

3. Results and discussion

The monthly data calibration and validation statistics at each control station and the calibrated parameters for each sub-catchment are presented in Table 8 and Table 9 respectively. The calibration stage simulation and correlation plots are also demonstrated in Figure 9.

From Table 8, the Coefficient of Determination (R^2) values vary in the ranges of (0.59 - 0.88) and (0.60 - 0.93), and the Index of agreement (IA) values vary in the ranges of (0.83 - 0.96) and (0.86 - 0.98) for the calibration and validation stages respectively. In a similar manner, the Nash-Sutcliffe Efficiency (NSE) values vary in the ranges of (0.5 - 0.86) and (0.55 - 0.93) and the Percent BIAS (PBIAS) values vary in the ranges of (-0.34 – (-16.5)) and (-1.3 - (-20.1)) for the calibration and validation stages respectively. From the statistical analysis, it is also observed that the calibration and validation results fall within a more or less similar ranges. With regard to R^2 and NSE, the upstream stations (Melka kuntre, Hombole and Kesem) show very good performance results while the middle and lower valley stations (Awash Station and Tendaho respectively) show satisfactory results. With regard to IA, the upstream stations show very good performance results while the middle and lower valley stations show good results. With regard to PBIAS, the upstream stations (Melka kuntre and Hombole) and the Middle Valley (Awash Station) show very good performance results. Kesem station shows satisfactory result during calibration and very good result at validation. Similarly, Tendaho station shows good and satisfactory result during the calibration and validations stages respectively.

Table 8: Monthly Data Calibration and Validation Statistics

Nr.	Statistical Parameter	Gauge Station				
		Melka Kuntre	Hombole	Kesem	Awash Station	Tendaho
1	Calibration Duration	Jan/86 - Dec/95	Jan/86 - Dec/93	Jan/89 - Dec/97	Jan/86 - Dec/94	Jan/88 - Dec/94
2	Validation Duration	Jan/96 - Dec/2005	Jan/94 - Dec/2000	Jan/98 - Dec/2005	Jan/95 - Dec/2003	Jan/95 - Dec/2001
3	Nr. of Years	**10 (10)**	**8 (7)**	**9 (8)**	**9 (9)**	**7 (7)**
4	Nr. of Months	**120 (120)**	**96 (84)**	**108 (96)**	**108 (108)**	**84 (84)**
5	Coefficient of Determination (R^2)	0.88 (0.93)	0.86 (0.91)	0.8 (0.76)	0.6 (0.63)	0.59 (0.60)
7	Index of Agreement (IA)	0.96 (0.98)	0.96 (0.96)	0.94 (0.93)	0.87 (0.88)	0.83 (0.86)
6	Nash-Sutcliffe Efficiency (NSE)	0.82 (0.93)	0.86 (0.80)	0.78 (0.76)	0.5 (0.62)	0.55 (0.55)
8	Percent Bias (PBIAS) (%)	-5.8 (10.4)	-0.34 (-3.7)	-0.16.5 (-8.5)	-0.9.2 (-1.3)	11.4 (-20.1)

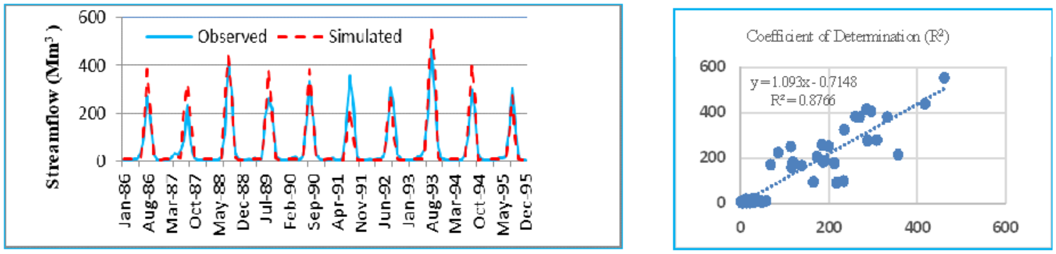
Table 9: Calibrated Parameters for each sub-catchment

Nr.	Parameter	Unit	Akaki	From MK st to Koka	Mojo	Keleta	Arba	Hendini	Kebena	Gayeen Awara	Awadi	Najeso Gera	Awash St to Ataye Conf.	Ataye	Borkena Jara	Chelekа	From Ataye Conf. to Mile Conf.	Mile	Logia	Awash Terminal	Eastern Catchment
1	Deep Conductivity	mm/month	2	2	35	2	2	10	10	10	20	20	20	20	0.1	20	0.1	100	100	20	20
2	Deep Water Capacity	mm	1000	10000	2000	1000	1000	1000	1000	1000	1000	1000	1000	5000	2000	2000	5000	1000	2000	2000	1000
3	Preferred Flow Direction	-	0.15	0.15	0.15	0.15	1	0.15	0.15	0.15	0.5	0.15	0	1	0.15	0.15	0.15	0.1	0.15	0.15	0.15
4	Runoff Resistance Factor	-	2	100	1000	10	2	1	1	4	4	5	10	20	25	100	20	10	3	2	2
5	Root Zone Conductivity	mm/month	25	75	15	100	55	20	100	1000	1000	75	75	1000	75	20	10	3	3	10	20
6	Soil Water Capacity	mm	2000	3500	5000	2000	500	1000	1000	1000	1000	500	500	500	1000	2000	1000	2000	2000	1000	1000
7	Initial Z1	%	20	10	0	30	30	60	30	30	30	60	100	0	60	30	30	95	65	78	30
8	Initial Z2	%	5	100	0	30	30	30	30	30	30	0	65	0	30	30	30	0	30	30	30
9	Irrigation Lower Threshold (LT)	%	-	-	-	-	-	-	-	-	-	-	82	-	-	-		93	87	70	-
10	Irrigation Upper Threshold (UT)	%	-	-	-	-	-	-	-	-	-	-	90	-	-	-		98	96	94	-

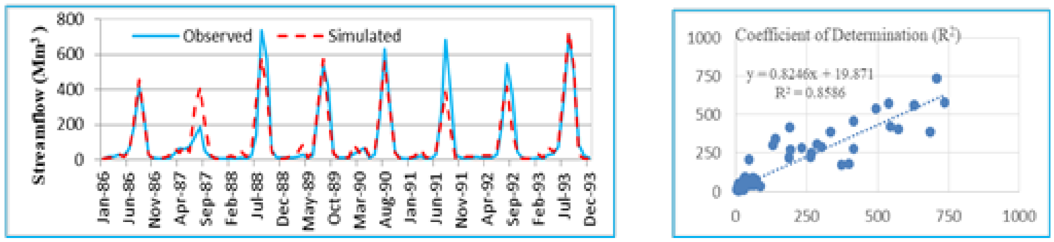
Nr.	Parameter	Unit	Months																	
			January			February			March			April			May			June		
	Sub-Catchments		a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
1	Deep Conductivity	mm/month	3	25	5	0.1	25	2	2	25	7	1	25	2	0.1	25	2	2	25	2
2	Deep Water Capacity	mm	3000	5000	1500	3000	5000	1500	3000	5000	1500	3000	5000	1500	3000	5000	1500	3000	5000	1500
3	Preferred Flow Direction	-	0.1	0.15	0.15	0.1	0.15	0.15	0.1	0.15	0.15	0.1	0.15	0.15	0.1	0.15	0.15	0.1	0.15	0.15
4	Runoff Resistance Factor	-	60	5	5	40	3	5	30	2.5	5	25	2	5	10	1.25	5	10	2	8
5	Root Zone Conductivity	mm/month	65	65	75	65	65	95	65	65	75	65	65	85	45	65	125	25	65	215
6	Soil Water Capacity	mm	1000	700	1380	2000	700	1380	1800	700	1380	1700	700	1380	1900	700	1380	4000	700	1380
7	Initial Z1	%	55	95	90	55	95	90	55	95	90	55	95	90	55	95	90	55	95	90
8	Initial Z2	%	1	94	0	1	94	0	1	94	0	1	94	0	1	94	0	1	94	0
9	Irrigation Lower Threshold (LT)	%		40	88		40	88		40	88		40	88		40	88		40	88
10	Irrigation Upper Threshold (UT)	%		95	100		95	100		95	100		95	100		95	100		95	100

Nr.	Parameter	Unit	Months																	
			July			August			September			October			November			December		
	Sub-Catchments		a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
1	Deep Conductivity	mm/month	2	25	35	1	25	70	1	25	25	2	1	15	3	20	10	3	20	10
2	Deep Water Capacity	mm	3000	5000	1500	3000	5000	1500	3000	5000	1500	3000	5000	1500	3000	5000	1500	3000	5000	1500
3	Preferred Flow Direction	-	1	0.15	0.15	1	0.15	0.15	1	0.15	0.15	0.1	0.15	0.15	0.1	0.15	0.15	0.1	0.15	0.15
4	Runoff Resistance Factor	-	3	3.5	3	2	4	3	2	5	3	5	265	3	5	150	8	5	100	8
5	Root Zone Conductivity	mm/month	1	65	75	5	65	25	15	65	10	25	65	5	25	65	1	25	65	1
6	Soil Water Capacity	mm	7000	700	1380	11000	700	1380	11000	700	1380	2000	700	1380	1100	700	1380	1100	700	1380
7	Initial Z1	%	55	95	90	55	95	90	55	95	90	55	95	90	55	95	90	55	95	90
8	Initial Z2	%	1	94	0	1	94	0	1	94	0	1	94	0	1	94	0	1	94	0
9	Irrigation Lower Threshold (LT)	%		40	88		40	88		40	88		40	88		40	88		40	88
10	Irrigation Upper Threshold (UT)	%		95	100		95	100		95	100		95	100		95	100		95	100

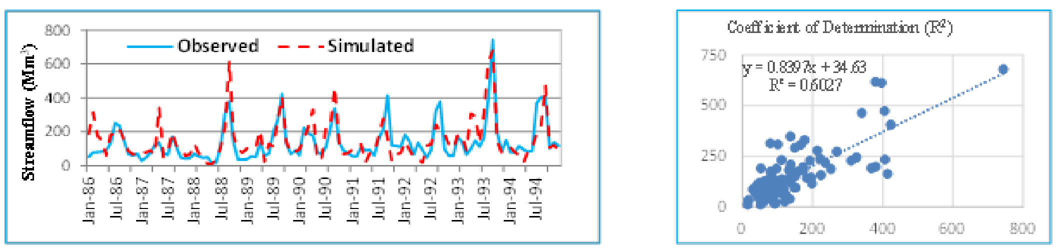
*For three Sub-catchments the calibrated parameters vary monthly. a = Awash above Melka kuntre station, b= Koka Dam - Awash station, , c= Kesem



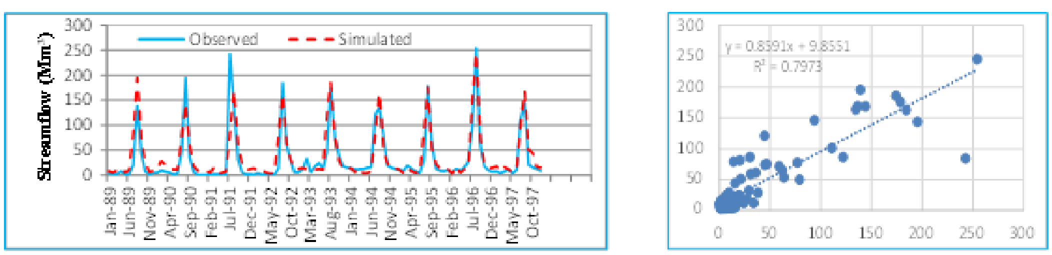
a) Awash @ Melka kuntre



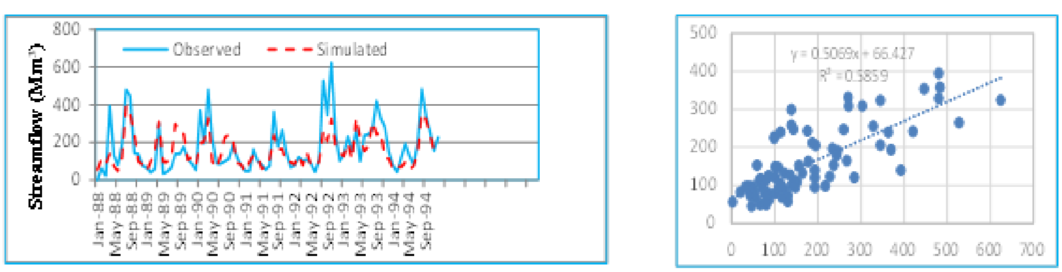
b) Awash @ Hombole



c) Awash @Awash Station



d) Kesem @Awara Melka



e) Awash @ Tendaho

Figure 9: Monthly Calibration and Correlation Plots

The calibration stage observed and simulated monthly flows for the control stations are shown in Figures 9 (a) through (e). Figure 9 (a) is a plot of the monthly observed and simulated stream flow for Melka kuntre station at the upper reach of Awash basin (period from Jan 1986 to Dec 1995). In this stream gauge, compared to the observed peak flows, the model simulated higher peaks in 60% of the total number of calibration months. However, the baseflows are well simulated in all calibration months.

Figure 9 (b) is a plot of the monthly observed and simulated stream flow for Hombole station at the upper reach of Awash basin (period from Jan 1986 to Dec 1993). In this stream gauge, the model underestimates peak flows in 37% of the total number of calibration months. 12% of the peak flow show over estimation. However, the observed and simulated baseflows are comparable in all calibration months.

Similar behavior is observed in Kesem gauge station whose tendency can be seen in Figure 9 (d). However, the differences between observed and simulated flows are more significant and noticeable in the Awash station and Tendaho gauge stations in Figure 9 (c) and Figure 9 (e) respectively. The low model performance at Awash station may be due to the impacts of the irrigation abstractions and Koka dam regulation effect at the upper and middle valley reaches of the basin. While, at Tendaho gauge station the low model performance may be due to the losses and regulation effect of the Gedebassa swamp.

4. Conclusions

Four model performance tests, namely, the Coefficient of Determination (R^2), the Index of Agreement (IA), the Nash-Sutcliffe Coefficient (NSE) and the Precinct Bias (PBIS) were used to evaluate the applicability of the WEAP hydrologic model for Awash river basin. Of the 5 control stations used for hydrologic simulation, three stations (Awash at Melka kuntre, Awash at Hombole and Kesem at Awara melka) show a good performance. While the other two control stations (Awash at Awash station and Awash at Tendaho) show satisfactory performance. The water resources system of the Awash basin is complex. The physical characteristic of the basin is comprised of the highlands and the rift valley system that results in a wide temporal and spatial variation of both climatic and hydrologic variables throughout the basin. The basin is also the most utilized basin in terms of irrigation development. The upper and middle valley reaches of the basin are highly impacted by the irrigation abstractions and Koka dam regulation. The lower valley reach flow is also significantly influenced by the losses at the Gedebassa swamp. However, the current understanding about the basin’s water resources is limited. The seepage and leakage of Koka dam, the surface-ground water interaction and the loss at the Gedebassa swamp system are not well understood. Moreover, lack of reliable quality stream flow record and water abstraction data is a main challenge. Under these circumstances, the modelling result obtained in this study is acceptable and can be used to reasonably simulate the water resources system of the river basin. Better understanding of the complex system of the Awash basin and improving the data quality can help to attain better model performance results.

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