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Water Resources Allocation Systems under Irrigation Expansion and Climate Change Scenario in Awash River Basin of Ethiopia

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Abstract: Rational allocation of water resources is very essential to cope with water scarcity. The optimal allocation of limited water resources is required for various purposes to achieve sustainable development. The Awash River Basin is currently faced with a scarcity of water due to increasing demands, urbanization, irrigation expansion, and variability of climates. The excessive abstraction of water resources in the basin without proper assessing of the available water resources contributed to water scarcity. This paper aimed to develop a water evaluation and planning (WEAP) model to allocate the water supplies to demanding sectors based on an economic parameter to maximize the economic benefits. The water demands, water shortages, and supply alternatives were analyzed under different scenarios. Three scenarios were developed, namely reference (1981–2016), medium-term development (2017–2030), and long-term development (2031–2050) future scenarios with the baseline period (1980). The results of this study showed that the total quantity of water needed to meet the irrigation demands of all the stations was 306.96 MCM from 1980 to 2016. Seasonally, March, April, May, and June require the maximum irrigation water demand. However, July, August, and September require minimum demand for water because of the rainy season. The seasonal unmet demand is observed in all months, which ranged from 6×10^6 m^3 to 35.9×10^6 m^3 in August and May respectively. The trend of streamflow in Melka Kuntre was a statistically significant increasing trend after 2008 ($Z = 5.33$) whereas the trends in other gauge stations showed a relatively decreasing trend. The results also showed that future water consumption would greatly increase in the Awash River Basin. The prevention of future water shortages requires the implementation of water-saving measures and the use of new water supply technologies. The findings of this study will serve as a reference for water resources managers and policy and decision makers.

Keywords: water allocation; WEAP model; scenario; climate change; Awash River Basin

1. Introduction

The increasing demand of water resources in the world is the main problem for the sustainable utilization of water resources [1]. Water scarcity is mainly caused by over-exploitation of water resources, population growth, pollution, and increasing demand for economic development [2,3]. The ever-increasing population and economic development put more stress on the hydrological cycle and water resources, particularly in the river basin [1]. These pressures also cause the decline of available water resources in the basin. Climate change has also affected the hydrological cycles and water resources [4,5]. Recently, water resources allocation got much attention across the globe since climate change and population growth pushed to their natural limits [6]. Still, the scope of the problem becomes a research area in many regions of the world [7–16].

Efficient and optimal allocation of water resources plays a great role in balancing the demand and supply of water resources based on economic development [2]. However, the allocation fails to meet the acquired demand when the water demand exceeds the available water. The problems become worse with increasing water demand and economic growth.

The Awash River Basin is the most utilized basin in Ethiopia. It covers a total area of 114,123 km^2 that encompasses five regional states; Amhara, Oromia, Afar, SNNP, and Somali including two administrative councils, Addis Ababa and Dire Dawa [17]. The mean annual rainfall of the basin ranges from 100 to 1700 mm with great spatiotemporal variation. The basin also has a potential of 8.2 BCM and 10.3 BCM surface and groundwater, respectively, with 300 m exploration [18]. The temporal variation shares 71% and 29% of the rainy season (June to October) and dry season (November to May) respectively. The Awash River is the biggest contributor of water for the Awash River Basin. The river basin water is becoming scarce due to increasing demands and poor water resources management [19]. Hence, there is a need to allocate the water among the demanding sectors and to build water storage systems such as water harvesting, reservoirs, and dams. Water resources management models play a great role in addressing the water shortage of river basins by formulating prior allocation of water rights [20–22].

Nowadays, a water resource is modeled with various models such as MODSIM [23], WAS [20], CWAM [24], WEAP [25], and MOEA [6]. In this study, the water evaluation and planning (WEAP) model was chosen as it incorporates different hydrological components in data scarce areas, and because of its flexibility, simplicity, inclusiveness, and possibility of modeling the impact of climate change scenario on reservoirs and evaluating water resources using a scenario-based system. The model also simulated domestic, irrigation, and ecological water consumption in time and space as compared to other allocation models. The WEAP model resolves problems faced by water resources managers and planners using a scenario-based system by providing a set of objects and procedures which can be applied to reservoirs, river basins, and watersheds [19,26].

Previously, several distributed hydrological models have been applied to the Awash River Basin to model the hydrological characteristics. For example, Berhe et al. (2012), modeled the Awash River Basin using the MODSIM based allocation model under three different scenarios and the findings suggested that the model could be effective for water allocation [23]. Adeba et al. (2015), also tried to assess the water scarcity of the basin using the SWAT model [25]. Similarly, Mesfin et al. (2018), modeled the upper Awash River Basin using the SWAT model to evaluate the climate forecast system reanalysis weather data for watershed modeling [27]. Karimi, P., et al. (2015) [28], investigated the spatial evapotranspiration, rainfall, and land use data in water accounting that focused on the impact of the error in remote sensing measurements on water accounting and information provided to policymakers.

The studies done so far do not accurately model the water resources of the basin to allocate and address the water scarcity. Therefore, this study assessed the water scarcity of the basin under irrigation expansion and climate change scenarios for sustainable availability of water in the basin in the future. Furthermore, the study strengthened the concept that improving integrated water resources management through optimal and efficient water resources allocation is the key to overcoming the water shortage during dry periods.

Therefore, this paper aimed to develop a water allocation model to allocate the water supplies to demanding sectors based on an economic parameter to maximize the economic benefits.

2. Materials and Methods

2.1. Description of the Study Area

The Awash River Basin is one of the 12 river basins of Ethiopia which is found between latitudes of 7°53′ N and 12° N and longitudes of 37°57′ E and 43°25′ E [29]. The basin constitutes the central and northern part of the Rift Valley and is bounded to the west, southeast, and south by the Blue Nile, the Rift Valley lakes, and the Wabeshebele basins, respectively [17]. It covers a total area of 110,000 km^2, with a length of 1200 km [23]. The basin is a home of about 15 million inhabitants [17]. This basin has been the most highly utilized basin in Ethiopia since modern agriculture was introduced, as early as the 1950s [30]. The basin is divided into upper, middle, and lower valleys. The mean annual rainfall of the basin varies from 1600 mm northeast of Addis Ababa to 160 mm in the northern part of the basin (Figure 1). The distribution of rainfall is bimodal in the middle and lower parts of the basin and unimodal in the upper part [29]. The distribution of rainfall in the basin is influenced by the Inter Tropical Convergence Zone (ITCZ).

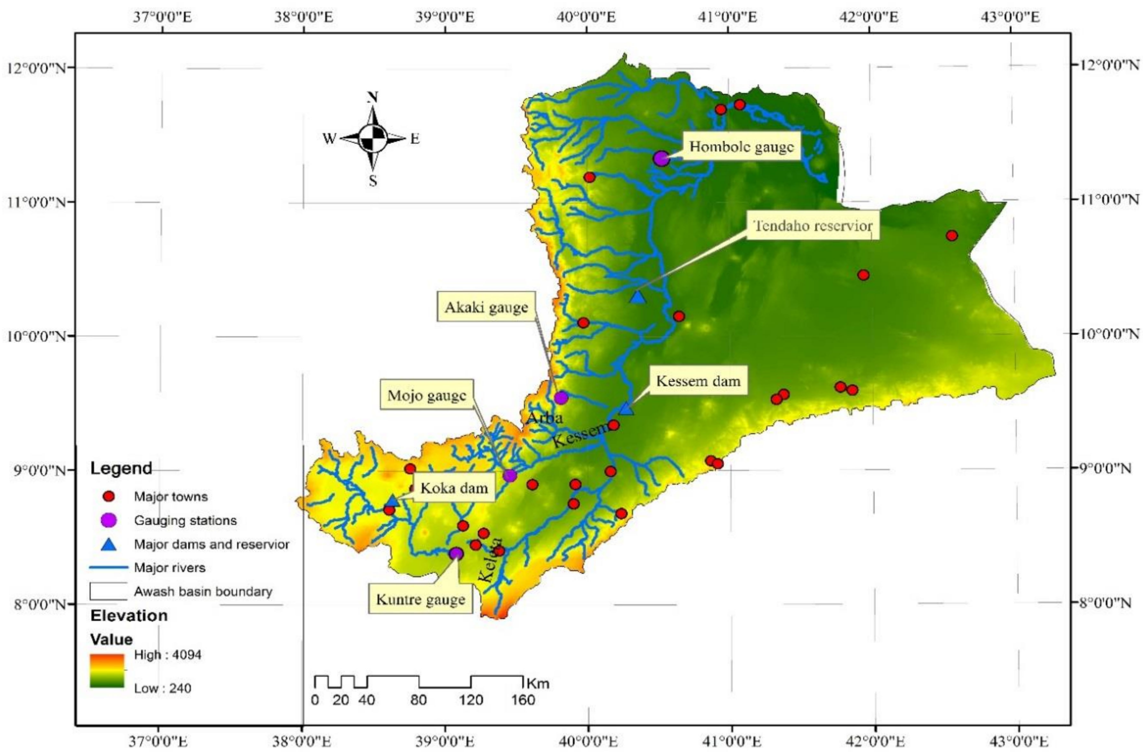

Figure 1. Location map of the Awash River Basin.

The mean surface water resource of the Awash River Basin is approximately 4.9×10^8 m^3 [31]. Irrigation used 44% from the surface water resources. More than 70% of large-scale irrigated agriculture in Ethiopia is found in this basin. The irrigation potential of the basin is estimated to be 206,000 ha as reported in the ministry of water and energy office. The total mean annual evaporation is 1810 mm and 2348 mm in the upper and lower parts of the basin [31]. The estimated mean annual runoff within the basin is about 4.6 km^3 [17]. Many rivers are functional only in rainy seasons (July to September) especially in lowland parts of the basin. However, the Mojo, Akaki, Kessem, Kebena, and Mile rivers are functional throughout the year. Since the population are highly dependent on rainfed agriculture, this has made the population and the economy vulnerable to impacts of climate change and droughts [32].

2.2. Sources of Data

Different datasets were used to establish the WEAP hydrological model for the study basin (Table 1). These data include the Digital Elevation Model (DEM) of the Awash River Basin, hydrological, climate, remote sensing, and water consumptions. All the necessary data for this manuscript were provided after quality control. The stations were also selected based on completeness of the data during the study periods. The land use data were obtained from the Awash River Basin master plan office. Previous studies also obtained the raw data from the same place for their research works.

Table 1. Input datasets of the water evaluation and planning (WEAP) modeling in the Awash River Basin.

Data Item	Description	Sources
Meteorological data (1980–2016)	Precipitation, temperature	National Meteorological Agency of Ethiopia
Hydrological data (1980–2014)	Reservoirs, data of Gauging stations	Department of water resources and hydrology of Ethiopia
Remote sensing data	Digital Elevation Model (DEM) of Awash River Basin	Department of GIS and Remote sensing
Water demand data	✓ Water use rate ✓ Population number ✓ Water consumption ✓ Agricultural sector ✓ Urban sector ✓ Land use data	Ministry of water resources and energy of Ethiopia

The climatic data such as precipitation, temperature, wind speed, and humidity were collected from the Ethiopian National Meteorological Agency (NMA). The streamflow/discharge data was acquired from the department of water resources and hydrology, which was used for calibration and validation of the basin. Water use, population, and other data were collected from various socioeconomic surveys and the statistical agency of Ethiopia, which are essential to analyze the water demand, water coverage, and unmet demand of water in the basin. The irrigation water demand of irrigated sites was also obtained from the basin authority office, as well as literature to compute the water requirement and water scarcity.

2.3. Methods

This study aims to develop the WEAP model for optimal allocation of water resources among competing sites. The WEAP model is one of the powerful tools used to evaluate the existing and planned water resources development in a given watershed. The model is used to identify water scarcity areas that cause conflict and can simulate a water allocation policy. Water allocation priority rules are set within the WEAP model based on either first come first served, or specific use or user, and/or making allocation proportional to demand. As it is generic, the model is not capable of capturing every fine distinction or detail of a water resource system and as such is best applied to scenario screening and pre and feasibility levels of analysis rather than to detailed design and permitting tasks. To allow simulation of water allocation, the elements that comprise the water demand–supply system and their spatial relationship are characterized for the catchment under consideration. It also helps to understand the available water resources demand for current and future development scenarios. The WEAP model also helps to provide a system for maintaining water demand and supply information in addition to the simulation of demand and flows. The hydrological systems in the WEAP model of Awash River Basin are depicted as nodes and links. The main river is drawn as a series of nodes, showing points of inflows from each catchment and river confluence linked to each other by river reaches.

It also calibrates and validates the streamflow in four gauging stations (Akaki, Hombole, Melka Kuntre, and Modjo) in the Awash River Basin. Three scenarios were established after developing the WEAP model to predict the water demands until 2050. The model was run on a monthly basis. The baseline or current scenario 1980–2016 was set to estimate the irrigation water demand. The WEAP model for the Awash River Basin was set up to simulate the current/base year (1980) condition and three subsequent scenarios: the reference scenario (1981–2016), the medium-term development (2017–2030), and the long-term development (2031–2050). For each development scenario, the outputs analyzed include the water demand satisfaction of the irrigation demanding sector and spatiotemporal variations in water shortage. The methodology of the study is shown in (Figure 2).

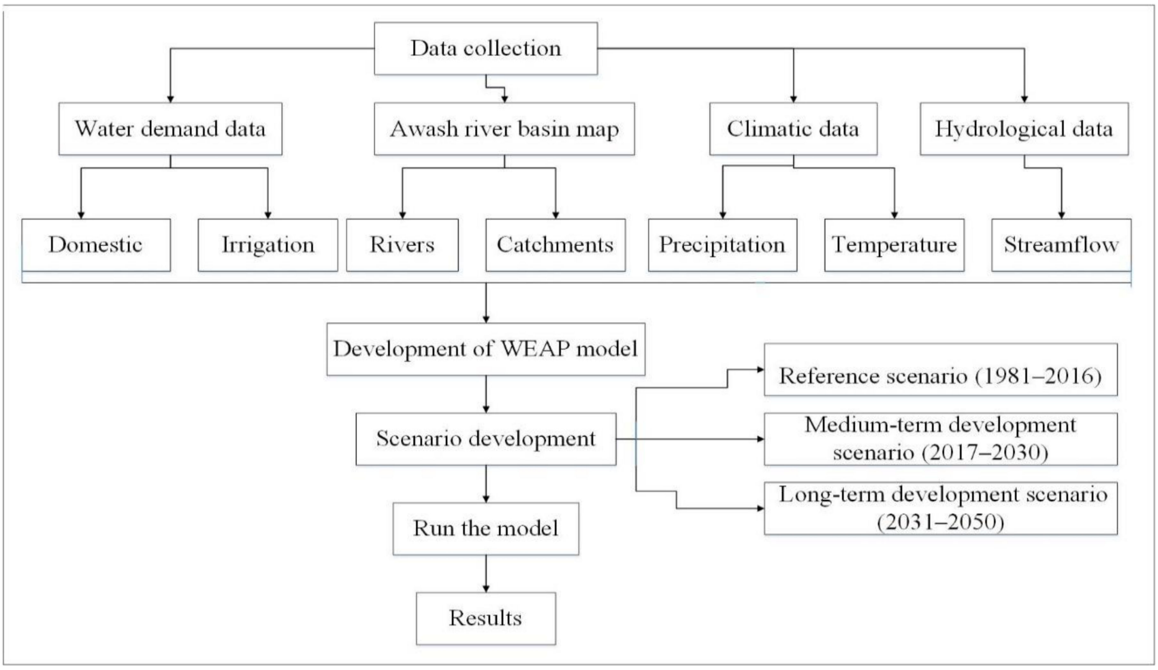

Figure 2. Methods of estimating water demands through the WEAP model.

The WEAP model provides an integrated assessment of climate, hydrology, water resources allocation, and watershed management [33]. It also addresses various issues such as water resources, water demands analysis in different sectors, provides priorities in water allocation, reservoir operation, and management. It solves the water allocation challenges at user-defined periods, either monthly or yearly based on linear programming structures [34].

2.4. Modeling Set up and Key Assumptions

1. All the demanding sites are given equal priority in the provision of water regardless of differences in financial returns expected from each scheme.
2. The model also contains four streamflow gauging stations, six transmission links, and six runoff/infiltration lines.
3. Six irrigation demand sites are also included in the model (Figure 3).
4. The model includes one main river (Awash River) and small tributary rivers (Figure 4).

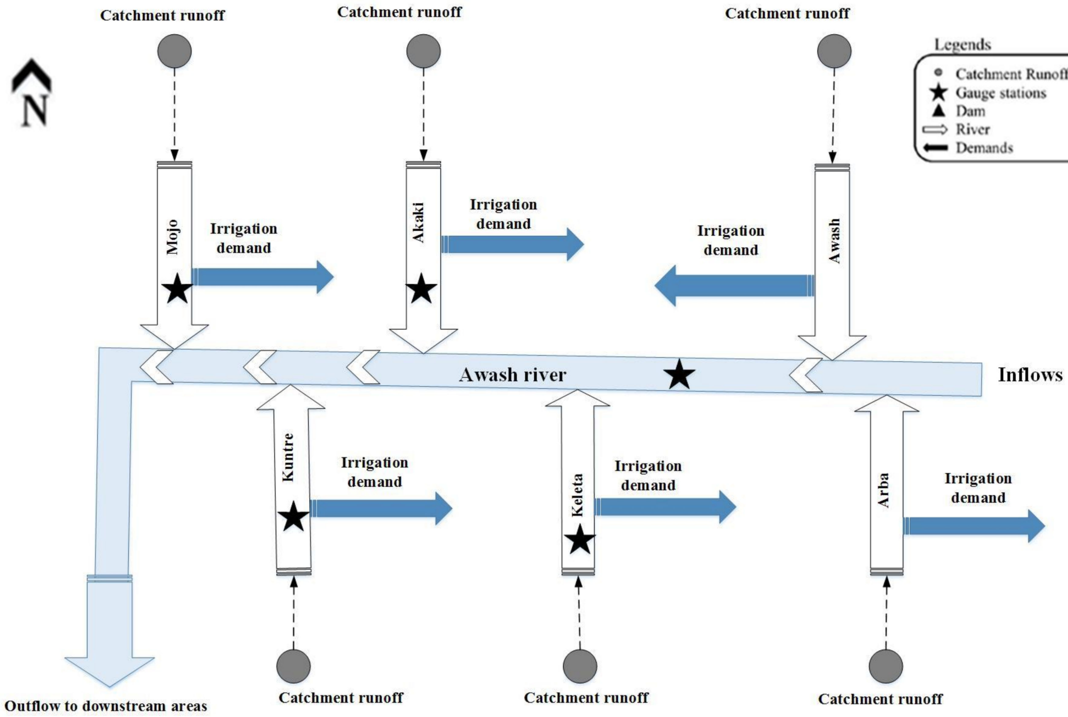

Figure 3. Water supply service structure and irrigation demands in the catchment.

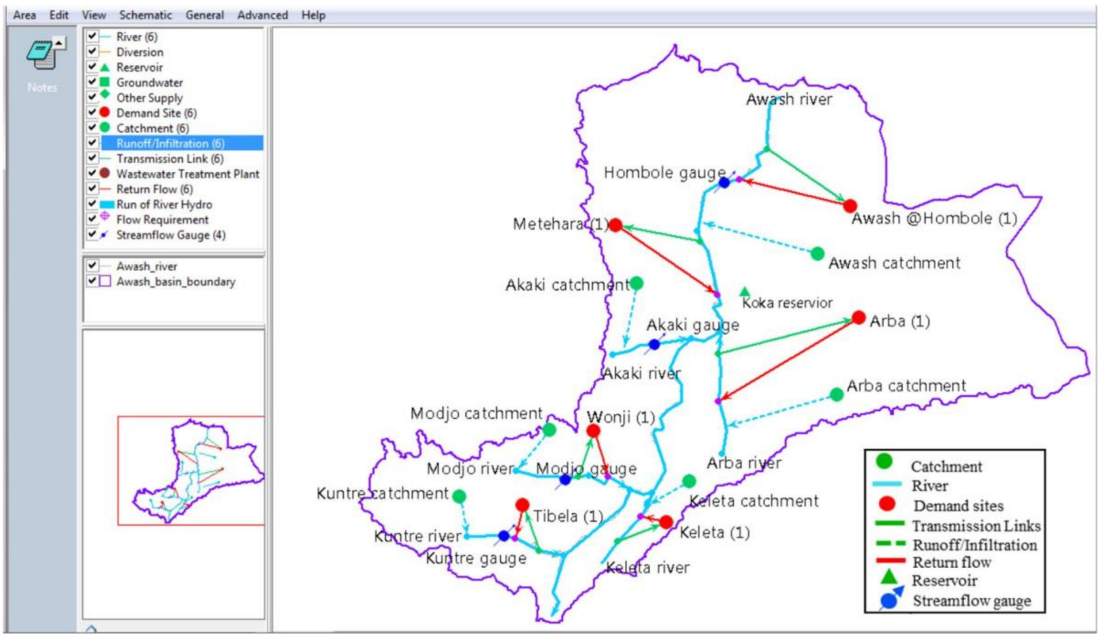

Figure 4. A snapshot of the WEAP model configuration showing the demand sites in the Awash River Basin.

3. Results

3.1. Analysis of Irrigation Water Demand under Irrigation Expansion Scenario

The simulation of the WEAP model provides the mean monthly and annual demands for downstream irrigation schemes. The scenario showed the full utilization of the irrigation potential from the Koka reservoir for 58,660 ha of land including the recent expansion coverage of 36,266 ha of irrigated land.

The total quantity of water needed to meet the irrigation demands of all the selected stations was 306.96 MCM from 1980 to 2016 under the current scenario. Seasonally, March, April, May, and June require the maximum irrigation water demand. However, July, August, and September require the minimum demand for water because of the Kiremt (wet) season. The extremely high unmet demand for water in May for the Tibela site was observed. This is probably due to a shortage of rainfall in Tibela since May is characterized as a dry month in the area. The average monthly supply of water delivered for each station are illustrated in Figure 5 without including the losses.

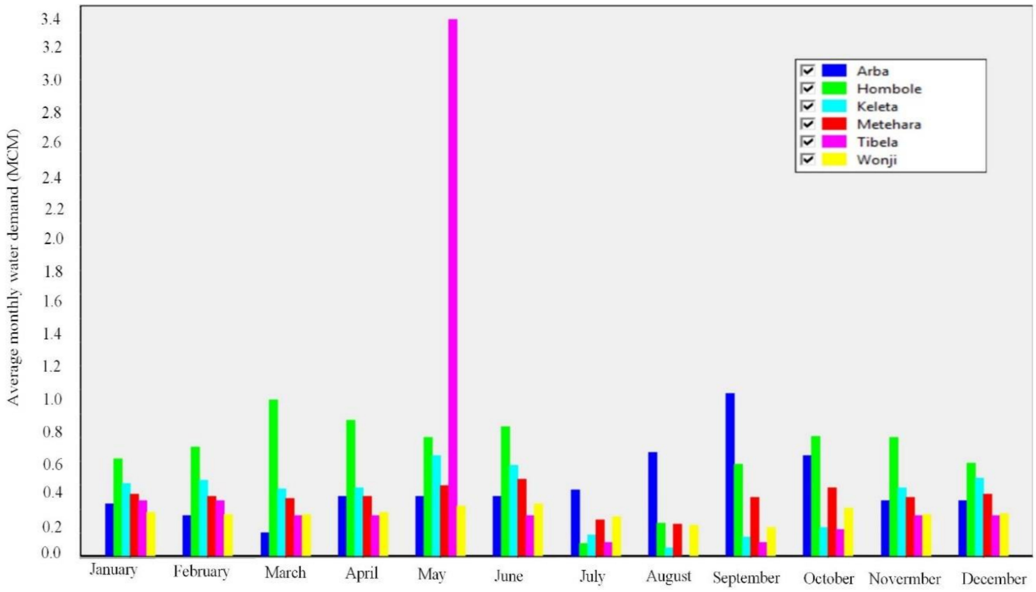

Figure 5. Mean monthly current demands without including losses.

3.2. *Spatiotemporal Occurrence of Unmet Demand under Each Irrigation Site*

The results of this study showed that the seasonal unmet demand was observed in all months of the year. This is ranged from 6×10^6 m^3 to 35.9×10^6 m^3 in August and May, respectively. The maximum water shortage occurred in May and declined relatively to an optimal level in July, September, and October. This indicates that, except during the rainy season (July to September), the water demand is not adequately met for each station (Table 2).

Table 2. Unmet demand across stations (MCM).

Irrigation Schemes	Arba	Hombole	Keleta	Metehara	Tibela	Wonji	Total
January	0.44	0.82	0.62	0.52	0.47	0.37	3.23
February	0.34	0.92	0.64	0.50	0.47	0.35	3.23
March	0.20	1.31	0.57	0.49	0.34	0.35	3.26
April	0.50	1.14	0.58	0.50	0.34	0.37	3.44
May	0.50	1.00	0.84	0.59	4.51	0.43	7.88
June	0.50	1.08	0.77	0.65	0.34	0.44	3.79
July	0.56	0.11	0.18	0.31	0.11	0.33	1.60
August	0.87	0.28	0.08	0.27	0.00	0.26	1.76
September	1.37	0.77	0.16	0.50	0.11	0.24	3.16
October	0.84	1.01	0.24	0.58	0.23	0.40	3.30
November	0.47	1.00	0.58	0.50	0.34	0.35	3.24
December	0.47	0.78	0.65	0.65	0.34	0.36	3.13
Total	7.06	10.23	5.90	5.90	7.62	4.27	41.0

3.3. Analysis of Unmet Demands under Each Scenario

All scenarios showed an increase of unmet demand throughout the simulation years. The gap between the current reference scenario and the long-term future development scenario was very high during simulation periods (Table 3). The demand was fully satisfied during wet/rainy seasons and high-water shortage happened in dry seasons. A significant increase of unmet demand was observed in the Wonji and Tibela demanding sites.

Table 3. Temporal occurrence of unmet demand across the basin (MCM).

Scenario	Reference (1980–2016)	Medium Term Development (2017–2030)	Long Term Development (2031–2050)
January	0.09	6.30	6.30
February	0.09	6.39	6.39
March	0.10	7.03	7.03
April	0.11	7.63	7.63
May	0.12	8.27	8.27
June	0.13	9.57	9.57
July	9.40	12.57	12.57
August	16.50	24.40	24.40
September	0.23	16.40	16.40
October	0.11	7.75	7.75
November	0.10	6.91	6.91
December	0.09	6.43	6.43
Summary	**27.07**	**119.65**	**119.65**

3.4. Analysis of Water Demand under Climate Scenario

The results showed that the average temperature was increased in the long-term climate scenario from the baseline scenario. It was increased from 22.08 °C (1980–2016) to 24.04 °C (2017–2030) and 26.49 °C for the long-term future development (2030–2050) scenario. The increased average temperature was mainly observed in the month of May.

The average temperature was increased by 1.96 °C and 4.41 °C in 2017–2030 and 2030–2050 from the reference scenario, respectively. Thus, the change in average temperature would cause a change in the reservoir surface temperature and significant evaporation loss.

The average precipitation in the basin also showed a fluctuation from the reference scenario. The average precipitation was 1733.33, 2433.33, and 2525.00 mm under the reference, medium-term development, and medium-term development future scenario, respectively. The precipitation would be increasing in the long-term development future scenario (2030–2050) as compared to the other two scenarios.

As far as the trends of evaporation in the reservoir are concerned, the modeled results showed decreasing and increasing trends in some months. The maximum and minimum evaporation was observed as 53.8 and 16.5 Mm^3 in October and August, respectively. The evaporation under each scenario was also 33.73, 35.21, and 35.71 Mm^3 in the 1980–2016, 2017–2030, and 2030–2050 scenarios, respectively. The simulation results of annual evaporation in each scenario was 404.80, 422.50, and 428.50 Mm^3, respectively. The increase of evaporation in the reservoir was due to the increase of temperature under the climate change scenario. The climate change scenario with respect to temperature, precipitation, and evaporation is shown in (Figure 6).

(a)
(b)
(c)

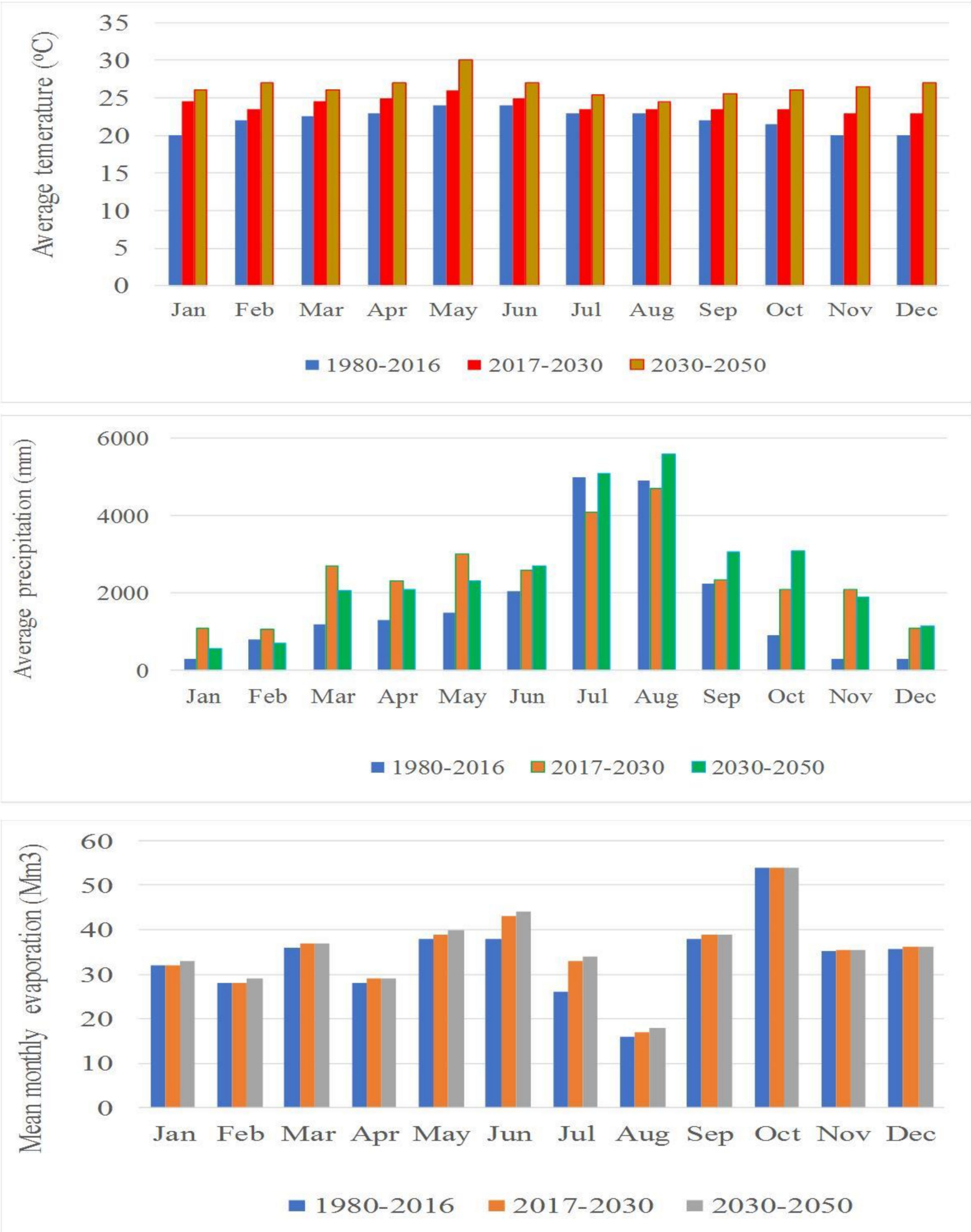

Figure 6. Average monthly temperature, precipitation, and evaporation under the three scenarios. (**a**) Average temperature, (**b**) average precipitation, and (**c**) mean monthly evaporation.

3.5. Model Calibration and Validation

The water balance of the basin was estimated based on climatic data analysis from 1980–2016. The base year is considered from January to December 2016, which is taken as a normal hydrological year. The results showed that the total water balance of the basin during the study period was found to be 427 MCM. The values of parameters for the calibration results in the WEAP model is shown (Table 4).

Table 4. The calibration parameters' possible ranges used in the WEAP model.

Parameters	Model Ranges	Optimal Range	Unit
Soil water capacity	0–higher	0–1200	mm
Root zone conductivity	Default = 20	10–50	Mm/month
Deep water conductivity	0.1–higher	20	Mm/month
Runoff resistance factor	0–1000 (default = 20)	0–100	
Preferred flow direction	0–1 (default = 0.15)	0.5–1	
Initial Z_1	0–100		%
Initial Z_2	0–100		%

The WEAP model was calibrated and validated with monthly observed streamflow from 1980–1999 and 2000–2014, respectively (Figure 7). In order to simulate the streamflow values in the model, the crop coefficient of (kc) of different land covers, soil water capacity, root zone conductivity, and preferred flow direction were manually calibrated using the default values of the WEAP model (Table 4). Hence, during the calibration period of this study, the values of the coefficient of determination (R^2) ranged from 0.73 to 0.91, with an average value of 0.82. On the other hand, the value of the Nash–Sutcliffe efficiency (NSE) was 0.65 and 0.83, the minimum and maximum values, respectively, with an average value of 0.74. However, during validation periods, 0.54 and 0.91 are the minimum and maximum values of the coefficient of determination (R^2), with an average value of 0.73. As far as the values of the Nash–Sutcliffe efficiency (NSE), 0.50 and 0.84 were the minimum and maximum values respectively, with an average value of 0.67. From these values, we have observed that in both calibration and validation periods, the values correspond to a perfect match between the observed and the modeled streamflow values. Thus, the performance of the model is acceptable between the trends of observed and simulated streamflow in both calibration and validation of the study basin. This also helps to accurately project the prediction of future discharges based on the future scenario set. The statistical values of Akaki (R^2 = 0.73; NSE = 0.65) were less than other gauging stations; Kuntre (R^2 = 0.85; NSE = 0.73), Hombole (R^2 = 0.89; NSE = 0.83), and Modjo (R^2 = 0.91; NSE = 0.85) (Table 5). This may be due to urbanization.

Table 5. Statistical values of stations for calibration and validation.

Gauging Stations	Calibration		Validation	
	R2	NSE	R^2	NSE
Hombole	0.89	0.83	0.91	0.84
Melka Kuntre	0.85	0.73	0.86	0.73
Akaki	0.73	0.65	0.63	0.5
Modjo	0.91	0.85	0.54	0.68

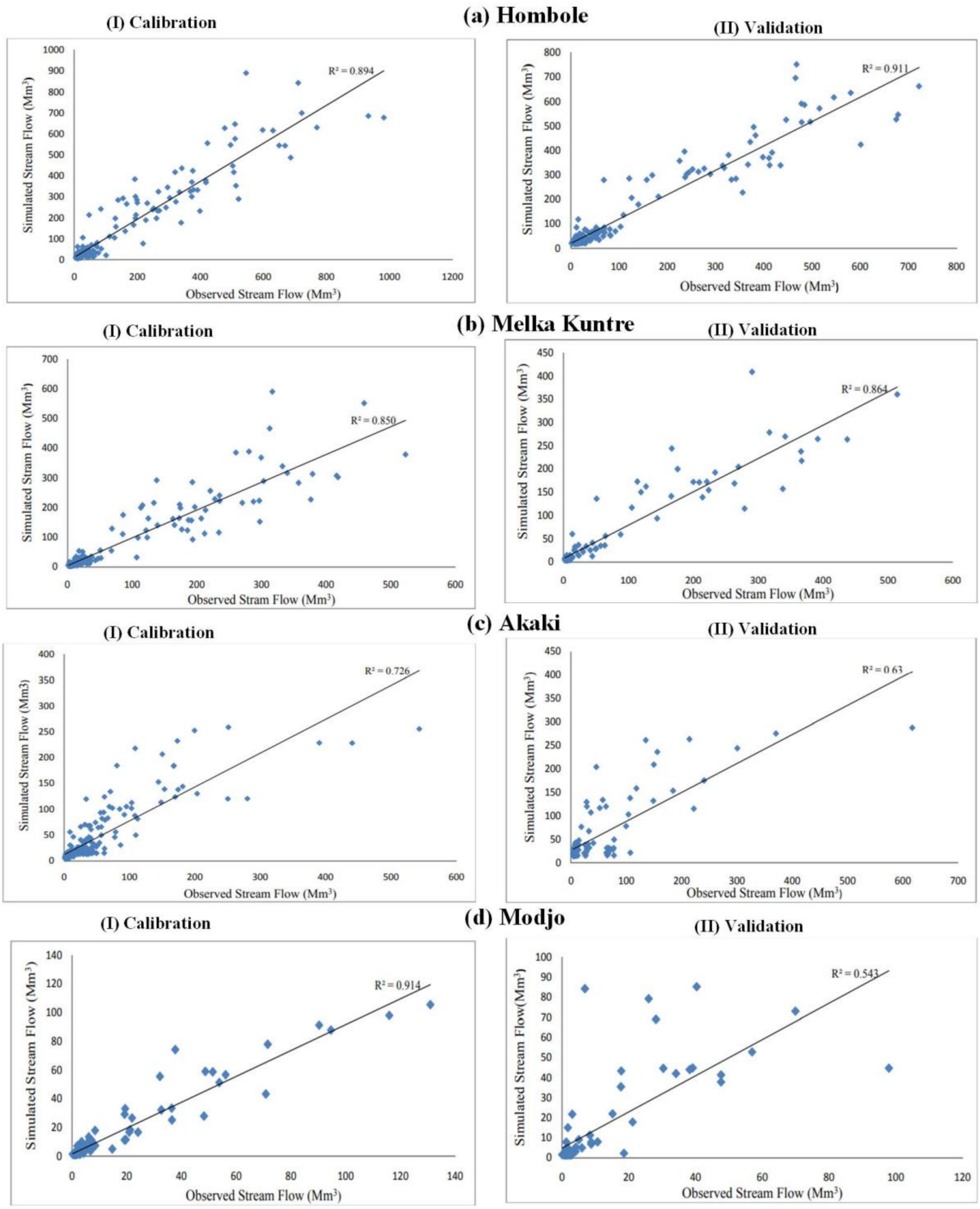

Figure 7. Calibration and validation of the four gauging stations and the entire Awash River Basin.

3.6. Shortage of Water in the Basin

There was a spatiotemporal variation of streamflow across the catchments during the study periods. Catchments which faced water shortage were identified in this analysis. The water shortage is very critical to meet the water demand of the sites in the Awash River Basin. All the demanding sites in the Awash River Basin were unmet at the end of the long-term development scenario (2030–2050). The annual water deficiency of Arba, Hombole, Keleta, Metehara, Tibela, and Wonji was 261.07, 378.43, 218.14, 219.74, 281.86, and 157.86 MCM, respectively. As far as temporal water deficiency is concerned, the biggest water shortage was observed in May.

4. Discussion

The findings of this study showed that the overall unmet demand under the long-term development future scenario by 2050 was from 6×10^6 m^3 to 35.9×10^6 m^3 in August and May, respectively. Water deficiency was observed in the dry season, especially in May. All scenarios showed an increase of unmet demand throughout the simulation years. The water demand was fully satisfied under each scenario because of the priority given for water allocation for each demanding site. Water shortage is aggravated by the expansion of irrigation lands and this, in turn, resulted in the failure of production. The spatiotemporal unmet demand of each demand site under the current scenario is shown (Figure 8). The population in the Awash River Basin is projected to increase and put more pressure on the limited water resources of the basin. With this trend of water consumption, the basin could face more water deficiency in the future. Sustainable and integrated water resources management approaches in the basin may overcome the observed problems that could affect the water resources. This may be done by developing reservoirs to store more water for the dry, low-flow season and create awareness among the public to use the water efficiently and sustainably. Strategic exploitation of additional water supplies and a paradigm reformation of policy of the basin management, which encourages sustainable use of water resources of the basin, should be done to improve the water shortage.

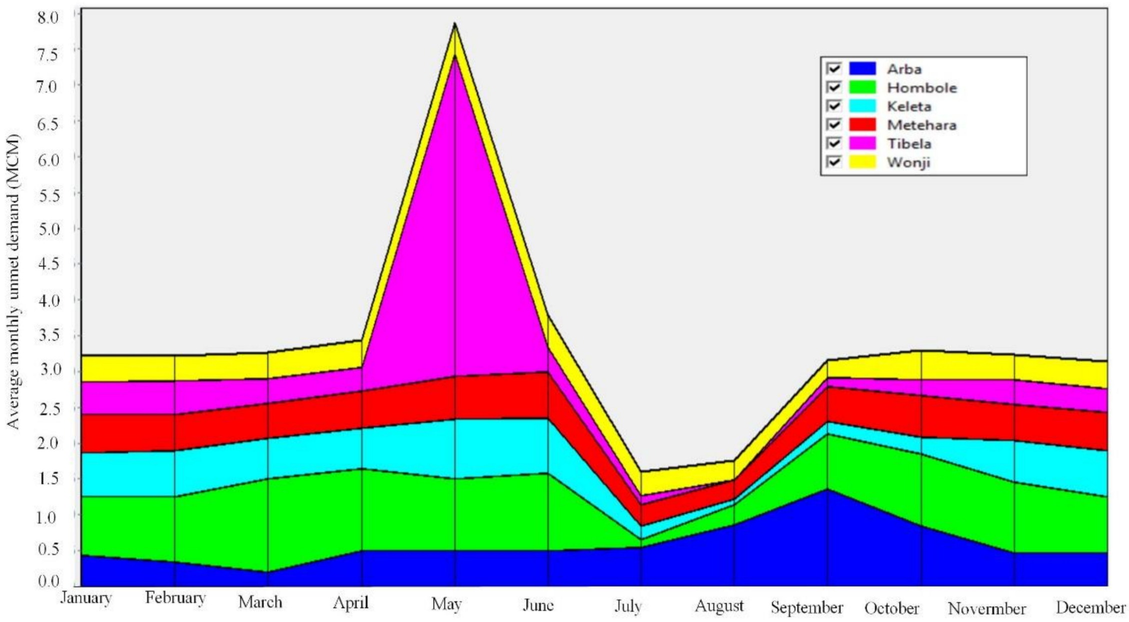

Figure 8. Mean monthly unmet demands of the current scenario for each irrigation sites.

Decrease of streamflow at the main outlet of the Awash River Basin could cause high pressure on available water resources. Thus, all the basin sections are impacted by the risks and cause conflicts between upstream and downstream dwellers [31]. No measurement is taken by the concerned entity of the basin to enhance the streamflow of the basin. The Awash River Basin has the most suitable space for future development of irrigation and will likely face huge population increases and industrial expansion. This will cause increased water consumption and large waterwork capacity deficits for the basin. As a result, prioritizing building and expansion of more water supply lines or reservoirs should be considered. Normally, warmer and wetter scenarios of the Awash River Basin are expected to increase the river discharge substantially and could serve to alleviate current local water shortages. The results of this study are consistent with other findings, such as [27,30,34,35]. The WEAP model in this study could not model reservoir water quality and cannot account for stream attenuation. Therefore, this can be a future research work for researchers to model the reservoir water quality by developing appropriate hydrological models in the study basin.

5. Conclusions

This study formulated the water allocation networks under an irrigation expansion and climate change scenario using the WEAP model for the Awash River Basin. The study also calibrated and validated the streamflow successfully with a reasonable range of R^2 and NSE. The annual water balance of the basin was also determined by considering the main parameters that could affect the water availability of the basin. Population growth, urbanization, industrialization, and agricultural intensification further magnify the conflicts of water among users. Equitable allocation of water among competing sites and finding alternatives to improve the water availability of the basin must be given attention. Water harvesting, soil, and water conservation to minimize the rate of runoff and digging boreholes are some options to enhance the water capacity of the basin.

The present study showed that the basin is faced with water shortage when meeting the requirements of the competing users. Previous studies also showed similar results, which was a water shortage of 1.27 BCM/year in 2011 and 2.82 BCM/year in 2012 [25]. The results of the present study also provide insights into the vulnerability of the available water resources of the Awash River Basin. Therefore, this study gives a direction for decision and policy makers to maintain the existing water resources and reduce further ecological threats that prevail in the Awash River Basin due to the scarcity of water resources.

Author Contributions: M.G. made substantial contributions to the design, idea generating, analysis, interpretation, and drafting of the original manuscript. D.Y. commented on the draft manuscript and supervised the whole work. H.W. was a resource person of the project. T.Q. and K.W. participated in the methodology and software, and A.G., D.B., and A.A. participated in designing this study. The final manuscript before submission was checked and approved by all the authors.

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Conflicts of Interest: All authors declare no conflict of interest.

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