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Rainfall-Runoff Modeling and Hydrological Responses to the Projected Climate Change for Upper Baro Basin, Ethiopia

Teressa Negassa Muleta*, **Knolmár Marcell**

Department of Sanitary and Environmental Engineering, Budapest University of Technology and Economics, Budapest, Hungary
Email: *teressa.muleta@emk.bme.hu

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Abstract

This paper presents the results of Rainfall-Runoff modeling and simulation of hydrological responses under changing climate using HEC-HMS model. The basin spatial data was processed by HEC-GeoHMS and imported to HEC-HMS. The calibration and validation of the HEC-HMS model was done using the observed hydrometeorological data (1989-2018) and HEC-GeoHMS output data. The goodness-of-fit of the model was measured using three performance indices: Nash and Sutcliffe coefficient (NSE) = 0.8, Coefficient of Determination (R^2) = 0.8, and Percent Difference (D) = 0.03, with values showing very good performance of the model. Finally, the optimized HEC-HMS model has been applied to simulate the hydrological responses of Upper Baro Basin to the projected climate change for mid-term (2040s) and long-term (2090s) A1B emission scenarios. The simulation results have shown a mean annual percent decrease of 3.6 and an increase of 8.1 for Baro River flow in the 2040s and 2090s scenarios, respectively, compared to the baseline period (2000s). A pronounced flow variation is rather observed on a seasonal basis, reaching a reduction of 50% in spring and an increase of 50% in autumn for both mid-term and long-term scenarios with respect to the base period. Generally, the rainfall-runoff model is developed to solve, in a complementary way, the two main problems in water resources management: the lack of gauged sites and future hydrological response to climate change data of the basin and the region in general. The study results imply that seasonal and time variation in the hydrologic cycle would most likely cause hydrologic extremes. And hence, the developed model and output data are of paramount importance for adaptive strategies and sustainable water resources development in the basin.

Keywords

Climate Change, Flow Simulation, HEC-HMS, Rainfall-Runoff Modeling, Upper Baro Basin

1. Introduction

According to the Series Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC) and many more studies, Earth's climate is changing mainly as a result of the increasing concentration of greenhouse gases in the atmosphere caused by anthropogenic activities (IPCC, 2014, 2021, 2007). Widespread and rapid changes in the atmosphere, ocean, cryosphere, and biosphere have occurred, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level. There are still strengthening indicators since the fifth IPCC Assessment Report (AR5) that the global water cycle will continue to intensify as global temperatures rise, with precipitation and surface water flow projected to become more variable over most land regions within seasons and from year to year (IPCC, 2014). In many regions, changing precipitation or melting snow and ice are altering hydrological systems, affecting water resources in terms of quantity and quality. Water resources planning based on the concept of a stationary climate is, therefore, increasingly considered inadequate for sustainable water resources management. So far, water resource issues have not been adequately addressed in climate change analyses and climate policy formulation in Upper Baro Basin. Projection of possible climate change over the basin is of paramount importance for the operation and planning of water resource projects in the basin for sustainable development (Jones, 1999).

In fact, according to the IPCC's (IPCC, 2021, 2022) latest findings, global average temperatures will probably raise a further 1.1˚C to 6.4˚C (2.0˚F to 11.5˚F) this century, depending on the extent of continued greenhouse gas emissions. In Ethiopia, studies by (Abegaz, 2020; Admassu & Seid, 2006; Elzopy et al., 2021) have shown that there has been a warming trend in the annual minimum temperature over the past 55 years (1951-2006) using 40 stations in the country. The recent study (Muleta, 2021) over the general Baro-Akobo River Basin has projected an annual temperature rise of 1˚C and 3.5˚C in the coming 2040s and 2090s, respectively. The same study has revealed a considerable seasonal and monthly precipitation fluctuation, reaching a reduction of up to 29% in the dry season and a rise of 47% in the wet season in Baro-Akobo River Basin. This seasonal variation in precipitation clearly warns the likely intensification of hydrologic extremes over the basin in the future. And hence, the projection of hydrological parameters for plausible future climate change scenarios is an inevitable step towards sustainability in water resources development.

Over the last few years, the literature on adaptation to climate change has expanded considerably worldwide. Studies such as (Schneider et al., 2000) have drawn lessons from adaptation to climatic variability or extreme events, whereas others have focused on how adaptation can reduce vulnerability to climate change. (Brekke et al., 2009; Quan & Kittiwet, 2020; Sheer et al., 2014) presented a flexible methodology for conducting climate change risk assessments involving reservoir operations. (Ahmadi et al., 2015; Mateus & Tullos, 2017; Raje & Mujumdar, 2010) have investigated the potential impacts of future climate change on stream flow and reservoir operation performance in a Northern American Prairie watershed. However, in Ethiopia, few studies including (Getachew et al., 2021; Ibrahim Mohammed, 2020; Rientjes et al., 2011), have addressed water management and adaptation measures in the face of changing water balance due to climate change with the implication that much more is still required to be done ahead.

Recently, hydrological changes associated with climatic change are becoming the main challenge for sustainable water resources development (Carvajal et al., 2019). Hydrological extremes are mainly the consequence of climate and land use changes affecting life and property (Dile & Srinivasan, 2014; Hyandye et al., 2018; Rodrigues et al., 2019; Woldesenbet et al., 2017). These extremes are highly endangering the sustainability of our development through damaging our infrastructure and environment (Kourtis & Tsihrintzis, 2021). There are different water resource projects in the Upper Baro Basin including Baro-1and Baro-2 hydropower projects, Genji irrigation project and many more proposed. The basin development has a transboundary environmental impact extending downstream to Sobat River of Sudan. The performances of these reservoirs under future climate conditions have not been assessed yet. For sustainable development and adaptive operation of any hydraulic structure in the basin, sufficient knowledge of hydrological phenomena, particularly variation in runoff with changes in climatic, geographic, or physical factors. Therefore, the current study is mainly aimed at developing rainfall-runoff model to predict the Baro River flow changes in the mid-term (2040's) and long-term (2090's) climate change scenarios.

2. Methodology

2.1. Description of the Study Area

The Upper Baro catchment is a subbasin of the Baro-Akobo River Basin which is located in the Eastern part of the basin between 7˚27'8"N to 8˚17'30"N Northing and 34˚57'31"E to 35˚52'41"E Easting (**Figure 1**). The catchment covers parts of the highlands of Illubabor and the lowlands of Gambella plain with altitudes ranging from 556 to 2690 m a.s.l. The total area commanded by the Baro River amounts to about 30,000 km^2 while the upper reaches of the Baro River (Upper Baro Basin) encompasses a total area of about 4828 km^2. Most areas of the sub-basin fall in the slope range of 0% - 44% with the higher elevation ranges at the south part of the catchment. The land use of the study area is categorized mainly as agricultural, natural forest, and wood land based on the information from Ministry of Water and Energy. Rainfall in the general eastern basin of the Nile, and hence in the Baro Basin, is controlled by the Intertropical Convergence Zone (ITCZ). As a consequence of the migration of the ITCZ north or south, different parts of the Upper Baro Basin experience different lengths of wet and dry seasons. According to the traditional classification based on altitude & temperature, three predominant climatic zones—Kola, Woina, Dega & Dega, prevail

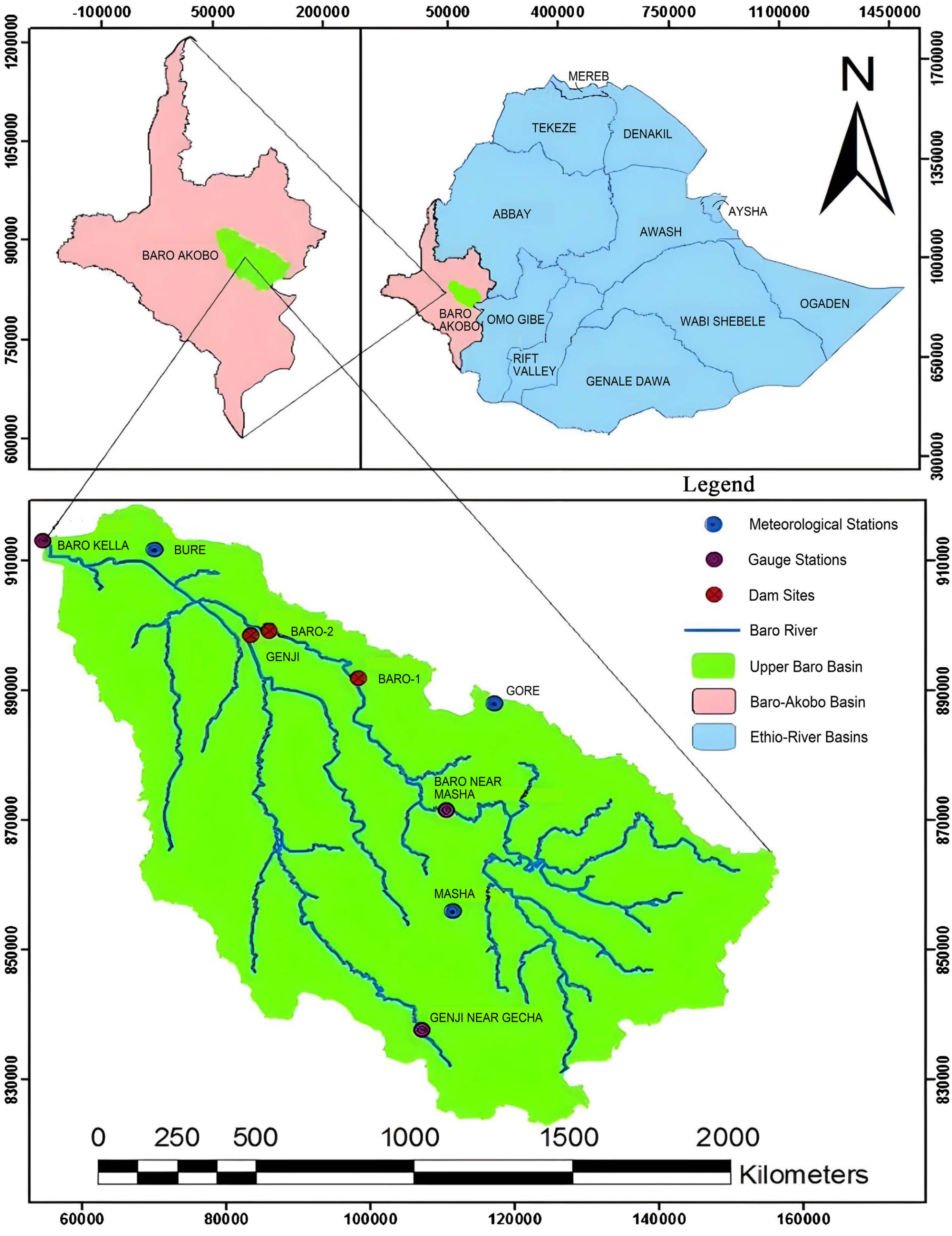

Figure 1. Location map of Upper Baro Basin relative to Baro-Akobo Basin.

in the Baro River Basin. Upper Baro Basin gets a mean annual rainfall of 1308 - 2358 mm between November and March, whereas generally dry conditions prevail throughout much of the country (**Figure 2**).

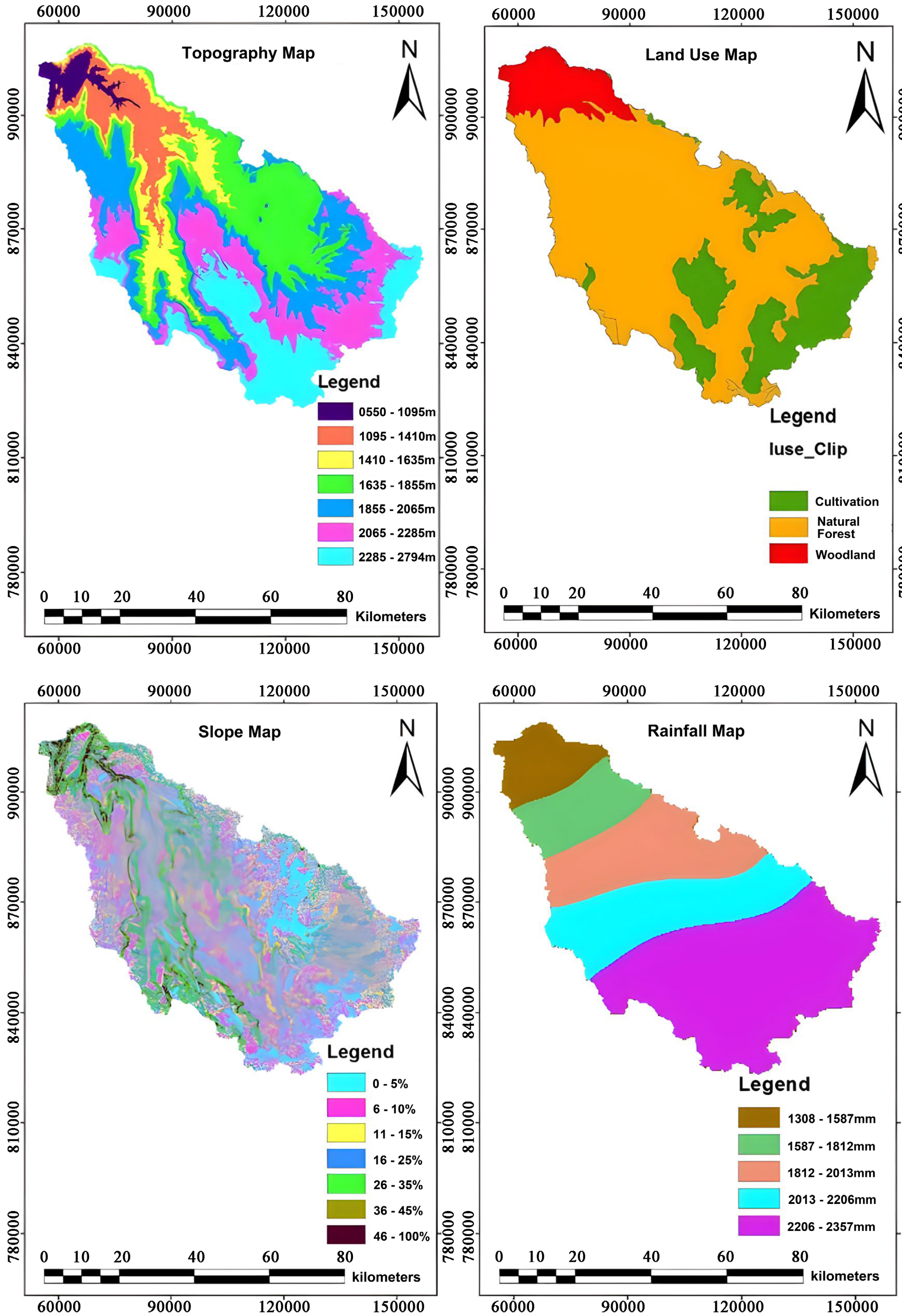

Figure 2. Upper Baro Basin graphical area description.

2.2. Data Collection

The 3-main parts of the methodology section 1) the different types of data used in this study—meteorological, hydrological, and spatial; 2) the subsequent step-by-step procedures followed from data collection through flow simulation; and 3) the various models applied in the data collection, processing and simulations are briefly summarized in the conceptual framework (Figure 3).

All available data and information regarding spatial, meteorological, hydrological, and water resource development projects' data relevant to the study were collected from the respective organizations/institutes and tested for quality. Spatial data such as Digital Elevation Model (DEM), Ethio-River basin shape files, land use/landcover, soil, and development data in the basin were collected from Ministry of Water and Energy (MoWE). Available meteorological data including precipitation, minimum and maximum temperature, relative humidity, sunshine duration, and wind speed were collected from National Meteorology Agency. These data were obtained for 11-meteorological stations at a daily time step in and around the Upper Baro Basin (Figure 4). The data covers a duration of about 30-years (1989 to 2018) for precipitation and temperature, whereas it is limited to 10-years' data for the remaining meteorologic variables.

Regional Climate Model (RCM) data that has been dynamically downscaled

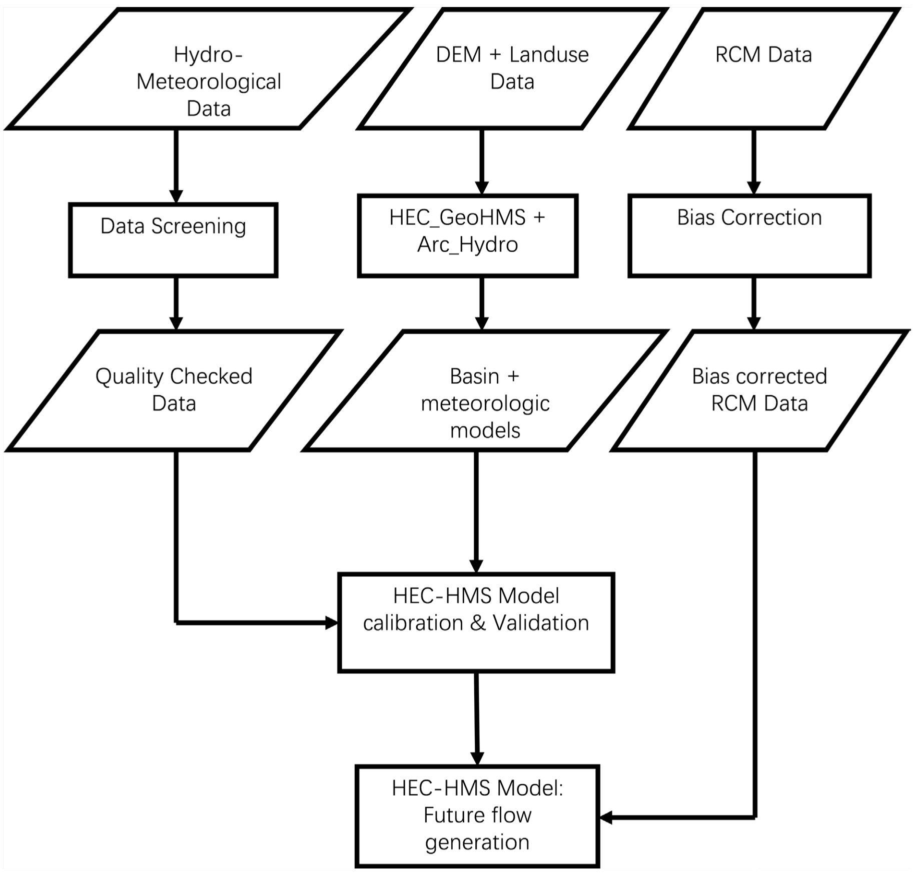

Figure 3. Conceptual framework for the study.

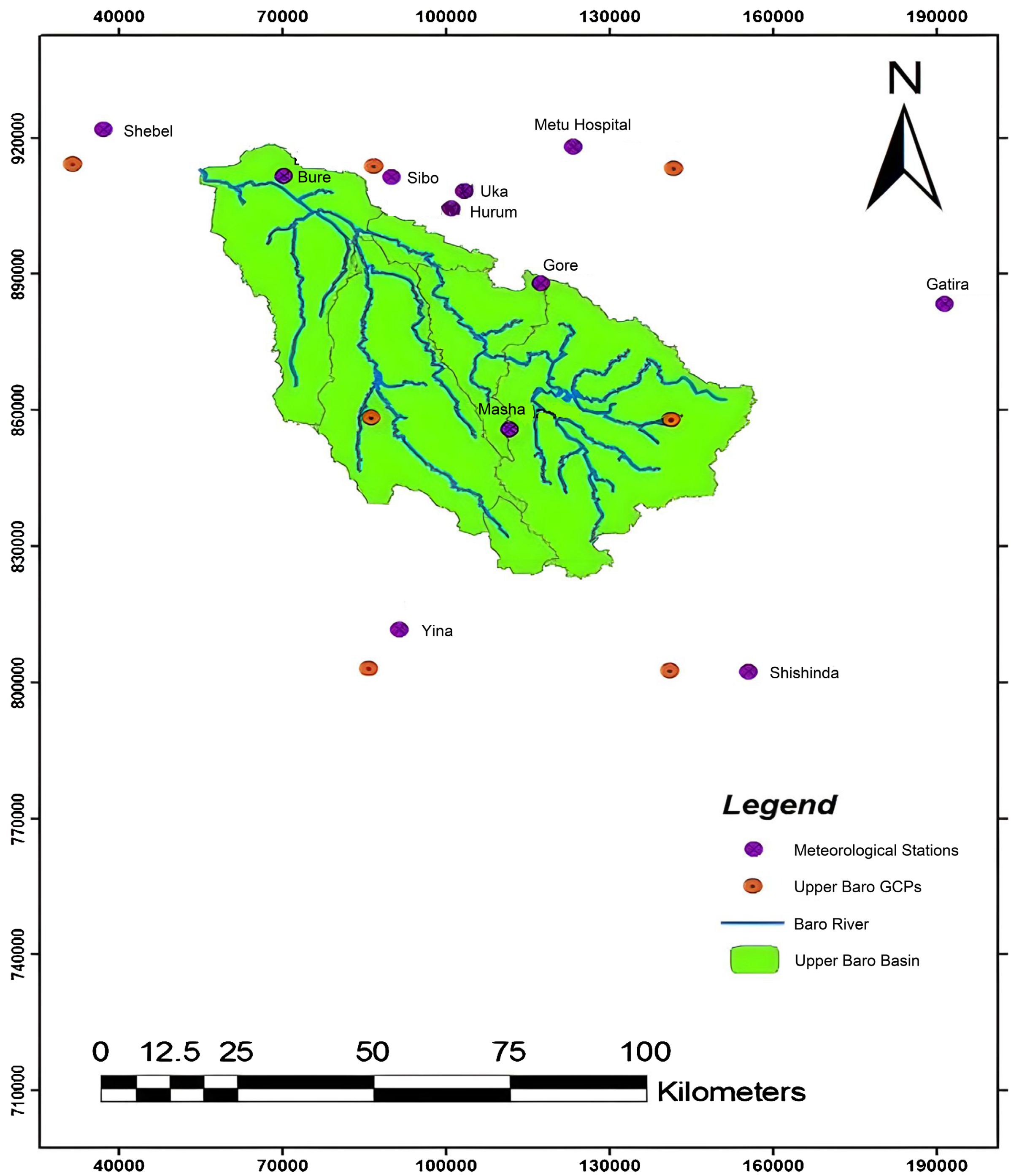

Figure 4. Meteorological Stations and RCM data Grid Center Points' relative location map.

by RegCM Version 3.1 from the General Circulation Model (GCM) for A1B emission scenario, bias corrected using the linear transformation method for temperature and power transformation method for precipitation are adopted from my previous study of "Climate Change Scenario Analysis for Baro-Akobo River Basin" (Muleta, 2021). The RCM data include baseline data (2000s) and projected data of mid-term (2040s) and long-term (2090s) scenarios. Especially, engineering studies of water resources development and management depend heavily on hydrological data. In the current study too, the observed hydrological data series was used mainly for model calibrations to generate flows at different spatial and temporal points of interest. The basin is drained mainly by Baro River and its tributaries: Genji, Guracha, and Fano rivers with the gauging stations located along few of them (**Figure 5**). Observed hydrological data series of three gaging stations, Baro gauge near Masha, Genji gauge near Gecha, and Baro Kella gaging stations available in the upper Baro basin (**Figure 5**) were used for the study. The other gaging stations on Baro River including Baro gauge at Gambella, Baro gauge near Bonga, and Baro gauge near Itang have been utilized for comparison and filling of the missing data. Instantaneous daily flow data obtained from these gauges covering a period of about 19 years (2000-2018) was used for the study.

2.3. Model Setup and Configuration

2.3.1. HEC-GeoHMS Setup and Configuration

HEC-GeoHMS is applied in this study to operate on the DEM to derive subbasin delineation and to prepare a number of hydrologic inputs. HEC-HMS accepts these hydrologic inputs as a starting point for hydrologic modeling. The major steps in HEC-GeoHMS processes include terrain preprocessing, hydrologic processing, basin processing, stream and watershed characterization, and development of hydrologic parameters and HEC-HMS model files. In the terrain preprocessing, the terrain model has been applied to derive different datasets representing flow direction, flow accumulation, stream definition, stream segmentation, and watershed delineation to describe the drainage pattern of the Upper Baro watershed (**Figure 6**). After the terrain preprocessing is completed and a new project is created, the basin processing menu in HEC-GeoHMS was used to revise the subbasin delineation in consideration with the existing project sites. In these customized subbasins and reach delineations, points where further information is needed are also incorporated. These include stream flow gauge (BaroNr.Masha & GenjiNr.Gecha) locations, Baro-1 & Baro-2 damsites, and Genji diversion site. To this end, the Upper Baro Basin is subdivided in to six subbasins to enhance HEC-HMS model calibration, information input, and generation of the hydrologic elements (**Figure 7**).

Hydrologic parameters such as initial constant and maximum soil loss rate, percent impervious time of concentration, etc. for loss and transform models were estimated as subbasin average and grid-based values using soil and land use datasets. This information populates the attribute tables for the basin and river layers and made available in HEC-HMS model files generated by HEC-GeoHMS, and thus provided initial values for parameter optimization during model calibration. HEC-GeoHMS is used to develop several hydrologic inputs for HEC-HMS including background map files, basin model file, grid-cell parameter file, and meteorologic model file. The background map layer captures the geographical information of the basin boundaries and stream reaches and the basin model captures the hydrologic elements, their connectivity, and related geographic

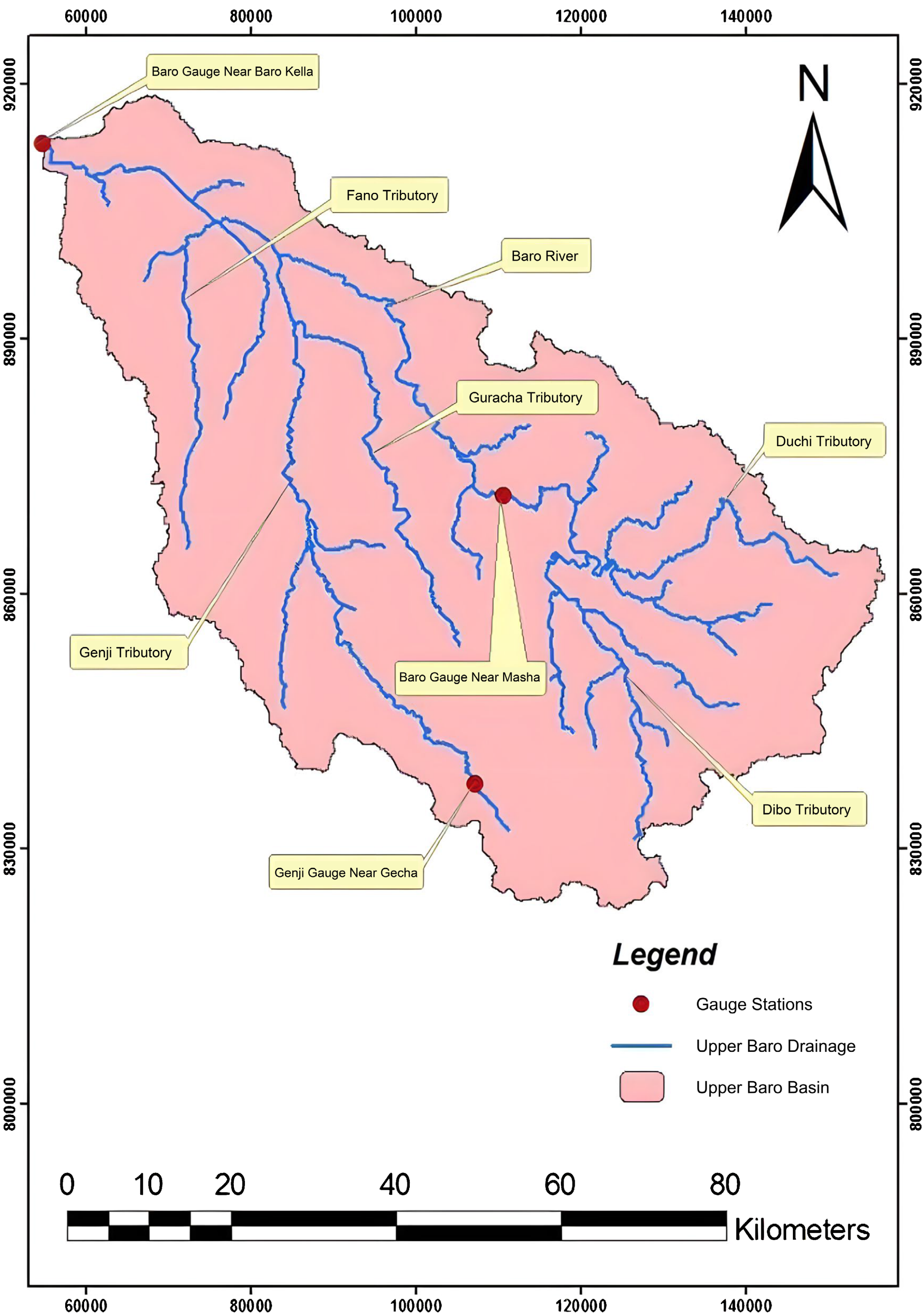

Figure 5. Upper Baro Basin drainage system and gauging stations' map.

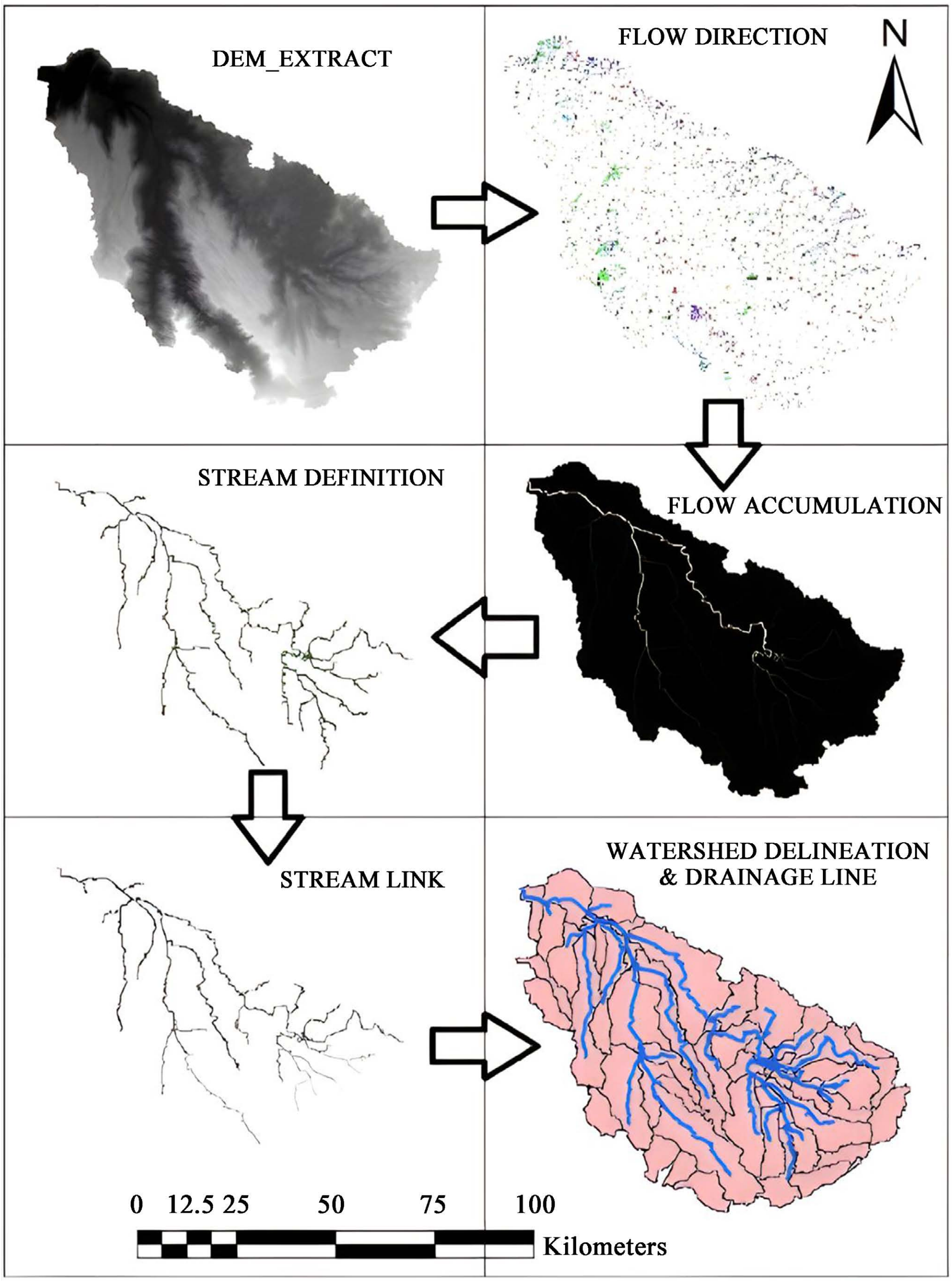

Figure 6. HEC-GeoHMS Terrain Preprocessing output raster/feature maps.

information that can be loaded into HEC-HMS project. The meteorologic model file contains a list of precipitation gauges (Masha, Gore, and Bure) used by the meteorologic model.

2.3.2. HEC-HMS Setup and Configuration

Hydrologic Model Simulation (HEC-HMS) is applied in this study based on model selection criteria (Cunderlik & Simonovic, 2007) and its widely application in the rainfall runoff modeling of rural watershed. The three major capabilities in HEC-HMS—watershed physical description, simulations, and parameter

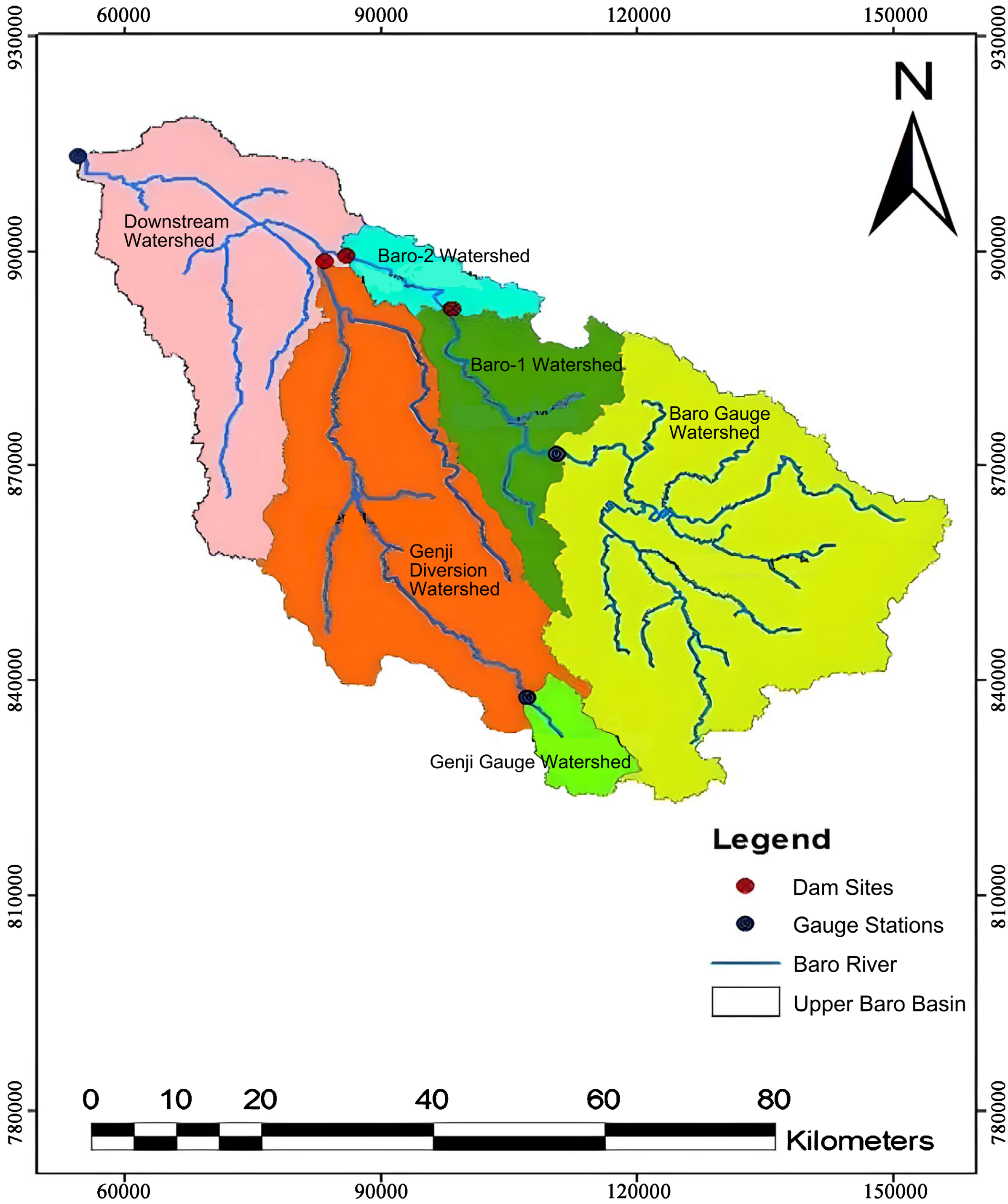

Figure 7. Upper Baro subbasins and considered hydrologic elements' map.

estimation—are used to simulate the hydrologic response in the basin. HMS model main components applied in this study include basin model, meteorologic model, control specifications, and input data. The simulation capability was applied to calculate the precipitation-runoff response in the basin model using input data from the meteorologic model. The control specification was used to define the period and time step of the simulation run. Input data was provided as parameters or boundary conditions in basin and meteorologic models. Basin model is applied for describing the physical properties of the basin and the topology of the stream network. It contains the modeling components that describes infiltration, surface runoff, base flow, and channel routing. Their principal purpose was to convert atmospheric conditions in to stream flow at a specific location in the basin of interest. Meteorologic model contains three components precipitation (where gauge type and weight can be specified), and evapotranspiration that allows the entry of evapotranspiration loss. Hence, meteorologic models, were created by HEC-GeoHMS and were imported to HEC-HMS to serve the purpose. Hydrologic elements (subbasin, junctions, source, sink, reservoirs, and diversions) are connected in a dendritic network to form a representation of the stream system in the study area. Hydrologic models often require time series of precipitation data for estimating basin average rainfall and flow data (observed discharge) for model calibration and parameter optimization. Observed discharges from two gauging stations (Baro Near Masha and Genji Near Gecha) in Upper Baro Basin were used for model calibration and parameter optimization.

In the present study, the gauge is imported from HEC-GeoHMS as a meteorologic model and was combined with watershed information to simulate the hydrologic response. Simulation run is the primary model for performing simulations and forms the basis for additional analysis using optimization trials or analysis. Each run is composed of one basin model, one meteorologic model, and one control specification. Simulation runs have been created here using a wizard that can be accessed from "compute menu" or "run manager command" of the HEC-HMS model. In our study, the univariate-Gradient Algorithm and the sum of squared residuals measures for goodness of fit were applied. As parameter estimation using optimization does not produce perfect results, it was aided by manual calibration. For the calibration of the model, the observed flow time-series data (2000 to 2013) from Baro gauge near Masha and Genji gauge near Gecha have been used. For validation purposes, a 5-years' data (2014 to 2018) was used. Finally, the rainfall-runoff model developed was applied to simulate the future flow of the basin for mid-term (2041-2050) and long-term (2091-2100) projected climate scenarios using bias-corrected RCM data adopted from the author's previous study (Muleta, 2021).

2.3.3. HEC-HMS Calibration

HEC-HMS consists of separate models of the major hydrological processes and transports. The main model components of HEC-HMS applied in this study are loss models, transform models, base flow model, and routing models. For the loss model, the deficit and constant-rate loss model is selected to compute the run-off volume. The corresponding model parameters—initial deficit, maximum deficit, and constant deficit—were fixed through calibration. And for the transform model Clark Unit Hydrograph model is selected for modeling direct runoff inconsideration of the availability of information for calibration and parameter estimation; the appropriateness of the assumptions inherent in the model; and their previous application in the HEC-HMS model. Furthermore, Interactive Statistics (Instat version 3.028) was used to compute the monthly mean of minimum flow for the analysis period from the areal observed flow for Upper Baro Basin. These monthly values are then fed into HEC-HMS base flow entry for flow simulation. Finally, Muskingum Routing Model is utilized for flow routing in reach elements, to compute a downstream hydrograph using the upstream hydrograph as a boundary condition.

In the calibration process, the observed hydrometeorological data was used in a systematic search for parameters (loss, transform, and routing parameters mentioned above) that yield the best fit of the computed results to the observed runoff. To this end, the sum of squared residuals goodness-of-fit indices was applied using a Univariate-Gradient Algorithm to judge how well the model "fits" the real hydrologic system. The performance of a model must be evaluated to the extent of its accuracy, consistency, and adaptability using a forecast efficiency criterion. In this study, the model performance in simulating the observed discharge was evaluated during calibration and validation using Nash and Sutcliffe efficiency criteria (NSE), coefficient of determination (R^2), percent difference/ Relative Volume Error (D), and through graphical inspection of simulated and observed hydrographs.

Nash-Sutcliffe Efficiency, NSE

The Nash and Sutcliffe coefficient (NSE) is a measure of efficiency that relates the goodness-of-fit of the model to the variance of the measured data. The NSE efficiency, proposed by Nash and Sutcliffe (Nash, 1970), is defined as

$$\text{NSE} = 1 - \frac{\sum_{i=1}^{n}\left[Q_o - Q_s\right]^2}{\sum_{i=1}^{n}\left[Q_o - \overline{Q_o}\right]^2} \tag{1}$$

where, Q_o = observed flow, Q_s = Simulated flow, and $\overline{Q_o}$ = Average of observed flow.

Coefficient of Determination, R^2

The coefficient of determination R^2 is defined as the squared value of the coefficient of correlation with values ranging between 1.0 (best) to 0.0. It is estimated as

$$R^2 = \frac{\left[\sum_{i=1}^{n}\left(Q_s - \overline{Q_s}\right)\left(Q_o - \overline{Q_o}\right)\right]^2}{\left[\sum_{i=1}^{n}\left(Q_s - \overline{Q_s}\right)\right]^2\left[\sum_{i=1}^{n}\left(Q_o - \overline{Q_o}\right)\right]^2} \tag{2}$$

where, Q_o = observed flow, Q_s = Simulated flow, $\overline{Q_o}$ = Average of observed flow, and $\overline{Q_s}$ = average of simulated flow.

Percent Difference, D

The percent difference for a quantity (D) over a specified period of total days was calculated from the measured and simulated values of the quantity in each model time step.

$$D = 100\% * \left[\frac{\sum_{i=1}^{n} Q_o - \sum_{i=1}^{n} Q_s}{\sum_{i=1}^{n} Q_o}\right] \tag{3}$$

where Q_o = Observed flow, Q_s = Simulated flow. The percent difference (D) can vary between ∞ and −∞ but it performs best when a value of 0 (zero) is generated. A percent difference between +5% or −5% indicates that the model performs well, while a percent difference between +5% and +10% and −5% and −10% indicates a model with reasonable performance (Worqlul et al., 2018).

3. Results and Discussion

3.1. HEC-HMS Model Calibration and Validation Results

In the present study, the Univariate-Gradient Algorithm and the sum of squared residuals measure for goodness of fit have been applied for calibrating the model. As mentioned in section 2.3.3, the loss parameters (initial deficit, maximum deficit, and constant deficit), transform parameters (storage coefficient & time of concentration), and routing parameters (Muskingum K & X) were estimated and optimized through calibration. Since parameter estimation using optimization does not produce perfect results, it was aided by manual calibration in this study case. For the calibration of the model, 14 years observed flow time-series data (2000 to 2013) from the Baro gauge near Masha and Genji gauge near Gecha have been used. And for the validation of the calibrated model, a 5-year' data (2014 to 2018) from the same stations were used. Below are given the observed and simulated flows comparison results as obtained from the calibration and validation of the model (**Figure 8** & **Figure 9**).

On the monthly basis, the simulation has shown a rather excellent correlation, which is an indication of the fact that the model can best predict the reservoir inflow on the monthly basis (**Figure 9**). This is of course expected as the extremes of daily data would relatively be dumped out when it is average over the monthly bases. Moreover, HEC-HMS has also been reported to perform better to anticipate both the total volume runoff and discharge peak rate across a wide range of literatures (Alsubeai & Burckhard, 2021; ben Khélifa & Mosbahi, 2021; Patil et al., 2019; Raj Kafle, 2019; Sahu et al., 2020; Shekar, 2021). This can infer the fact that the model output of monthly bases shall give a better information of seasonal variations which much is helpful to the water resource managers, particularly for reservoir operators to modify their reservoir release guide rules. From **Figure 8** & **Figure 9**, it can be visualized graphically that there exists a good match between the observed and simulated flows in all the important hydrograph properties (peak rate, time to peak, base time, and hydrograph area) for the Baro gauge in line with all three performance indices mentioned under section 2.3.3. Hence, the parameters estimated and optimized at Baro gauge near Masha were applied for the Upper Baro Basin in generating future flows. Therefore, the flow projection on the monthly basis can be utilized for water resources project planning and operation for a sustainable Upper Baro Basin development and for implementing an adaptive strategy for the existing projects.

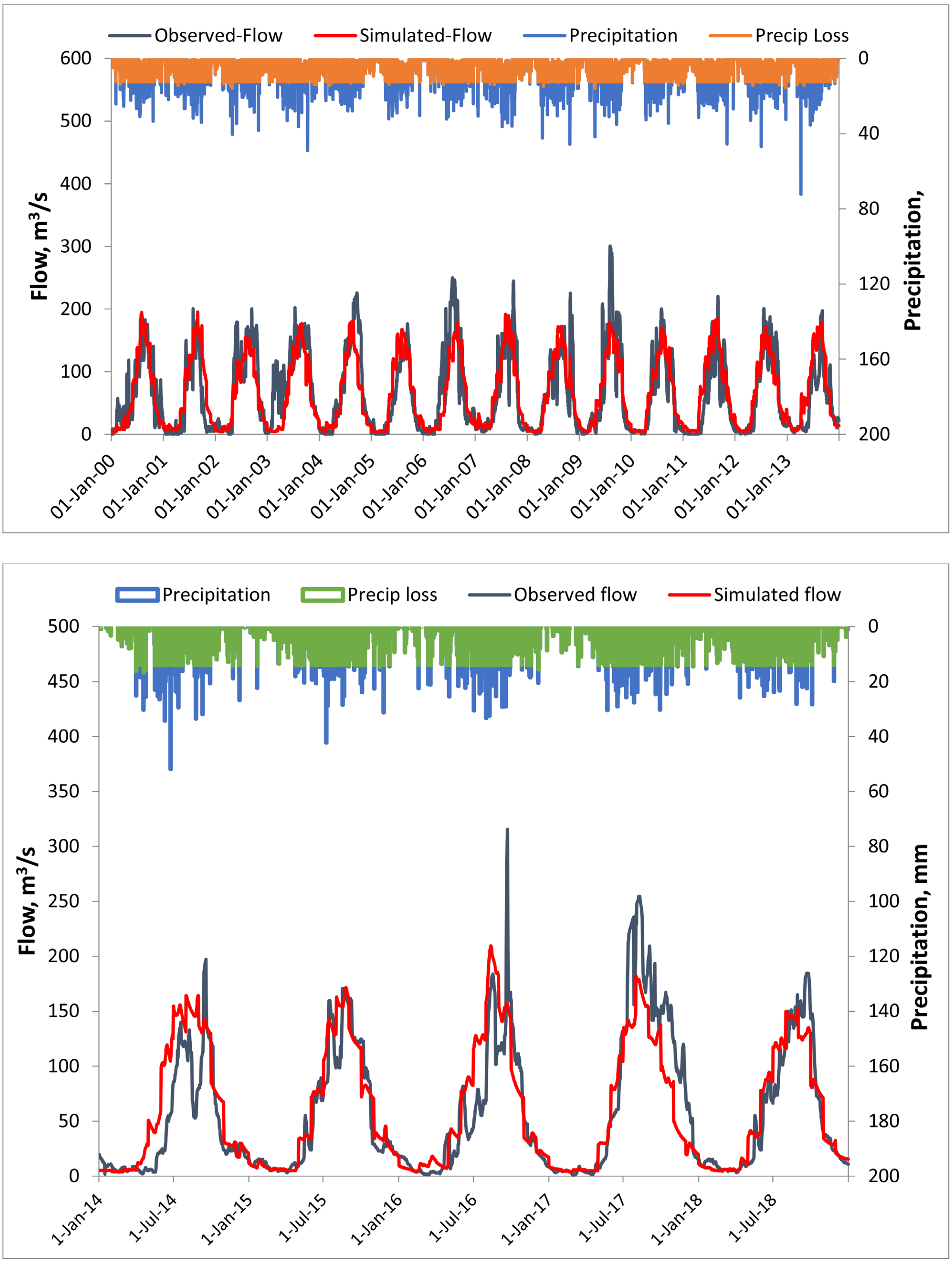

Figure 8. Comparison of observed and simulated daily flow hydrographs at Baro gauge.

3.2. HEC-HMS Model Performance Indices

In this study work, the model performance in simulating observed discharge has been evaluated during calibration and validation using Nash and Sutcliffe efficiency criteria (NSE), coefficient of determination (R^2), Percent difference /Relative Volume Error (D) and through graphical inspection of simulated and

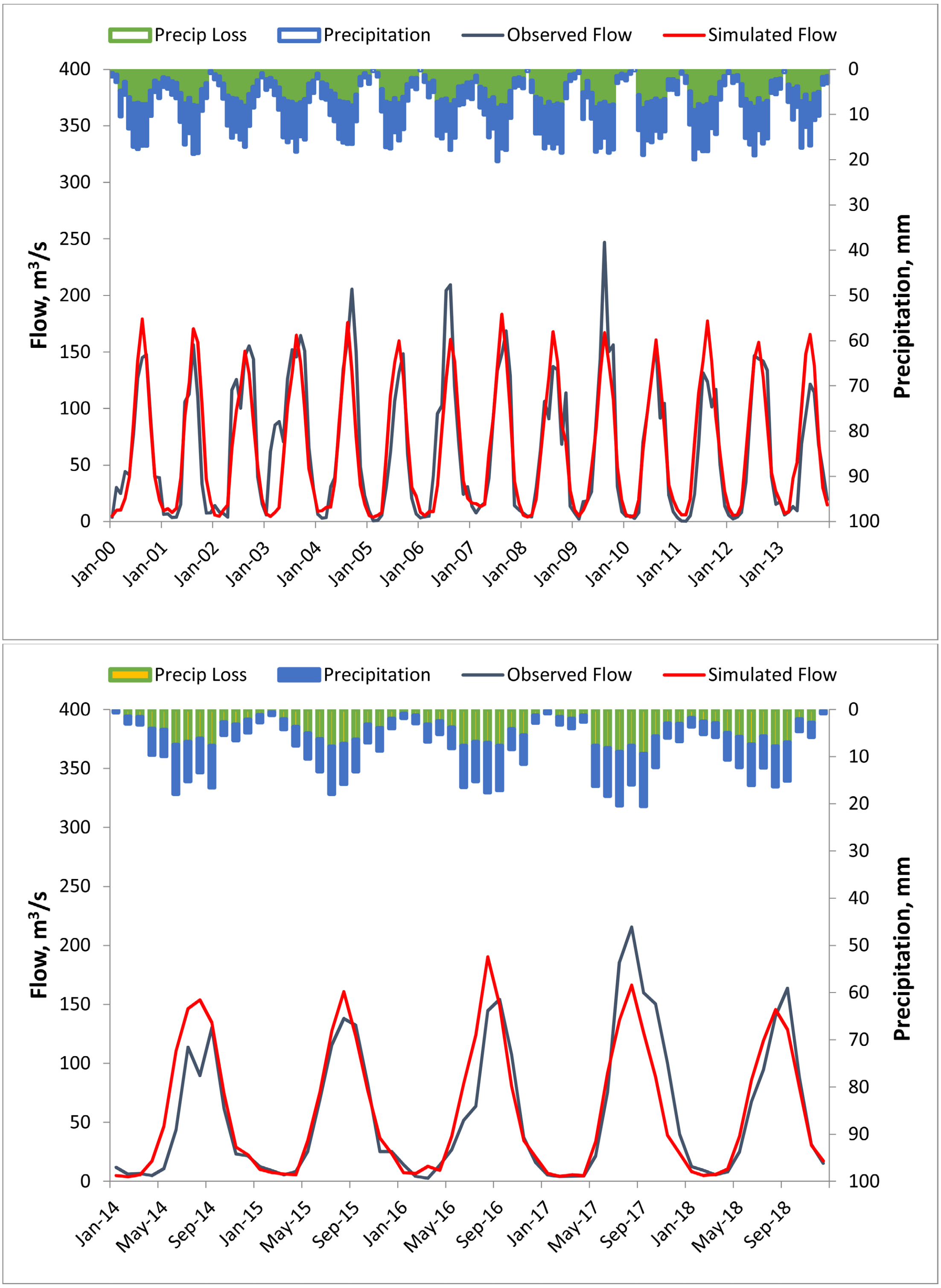

Figure 9. Comparison of observed and simulated monthly flow hydrographs at Baro gauge.

observed hydrographs. The results are summarized in tabular form as given below (Table 1). NSE values normally range from −∞ to 1 and an efficiency of 1 indicates a perfect match between the observed and simulated discharges. According to (Namara et al., 2020; Worqlul et al., 2018), NSE values between 0.9

Table 1. Tabular Summary of Performance indices for calibration and validation.

Indices	Daily basis				Monthly basis			
	Baro Gauge Near Masha		Genji Gauge Near Gecha		Baro Gauge Near Masha		Genji Gauge Near Gecha	
	Calibration	Validation	Calibration	Validation	Calibration	Validation	Calibration	Validation
NSE	0.72	0.76	0.28	0.59	0.80	0.82	0.67	0.72
R^2	0.72	0.75	0.28	0.58	0.80	0.81	0.67	0.71
D	0.0	−4.64	0.13	−2.76	0.03	−4.56	0.0	−2.33

and 1 indicate that the model performs very well, while values between 0.6 and 0.8 indicate the model performs well. Furthermore, (Moriasi et al., 2007), has recommended for monthly time steps that NSE values between 0.75 and 1 are very good and NSE-value between 0.65 and 0.75 can be considered good.

The model performance indices in the tabular results depict a Nash-Sutcliffe Efficiency (NSE) value between 0.6 and 0.8; a Coefficient of Determination (R^2) value near to 1 and a percent difference (D) value between −5% and +5% both for calibration and validation. According to the criterion recommended by (Worqlul et al., 2018) and (Moriasi et al., 2007) above, the results obtained shows that the model performs well in all the three indices at Baro gauge near Masha. This good model performance, to the authors' opinion, is mainly contributed by the bias correction made to the RCM data based on 30 years' time series data. Moreover, the performance indices imply that the developed model can certainly be applied to project the future flow scenarios for the basin under study. In the case of Genji gauge, the values obtained for all the three performance indices have resulted in poor performance and the gauge data was not applied for further simulation. To the authors' opinion, this is most likely attributed to the poor raw data as considerable missed data was filled from the neighboring gauges.

3.3. HEC-HMS Model Simulation Results

Clearly, river flow volumes are a function of both watershed (mainly land use and soil) and climate variables (typically precipitation and evapotranspiration rates). In this study case, flows in the future time span were generated as a function of changing climate variables while keeping the watershed physical characteristics similar to that of the base period. As the main objective of this paper, flows were calculated at different points of interest in terms of space and time. Accordingly, flows were generated at ungauged sites such as Baro-1 & Baro-2 reservoirs and Genji diversion sites using HEC-HMS model. Based on RCM projected climate variables of precipitation and temperature (evapotranspiration), river flows were predicted at all reservoir sites both for mid-term (2040s) and long-term (2090s) climate change scenarios. The estimated future Baro River flow hydrographs at Baro-1 reservoir for 2040's and 2090's scenarios compared with the base period (2000s) hydrograph is illustrated in (**Figure 10**).

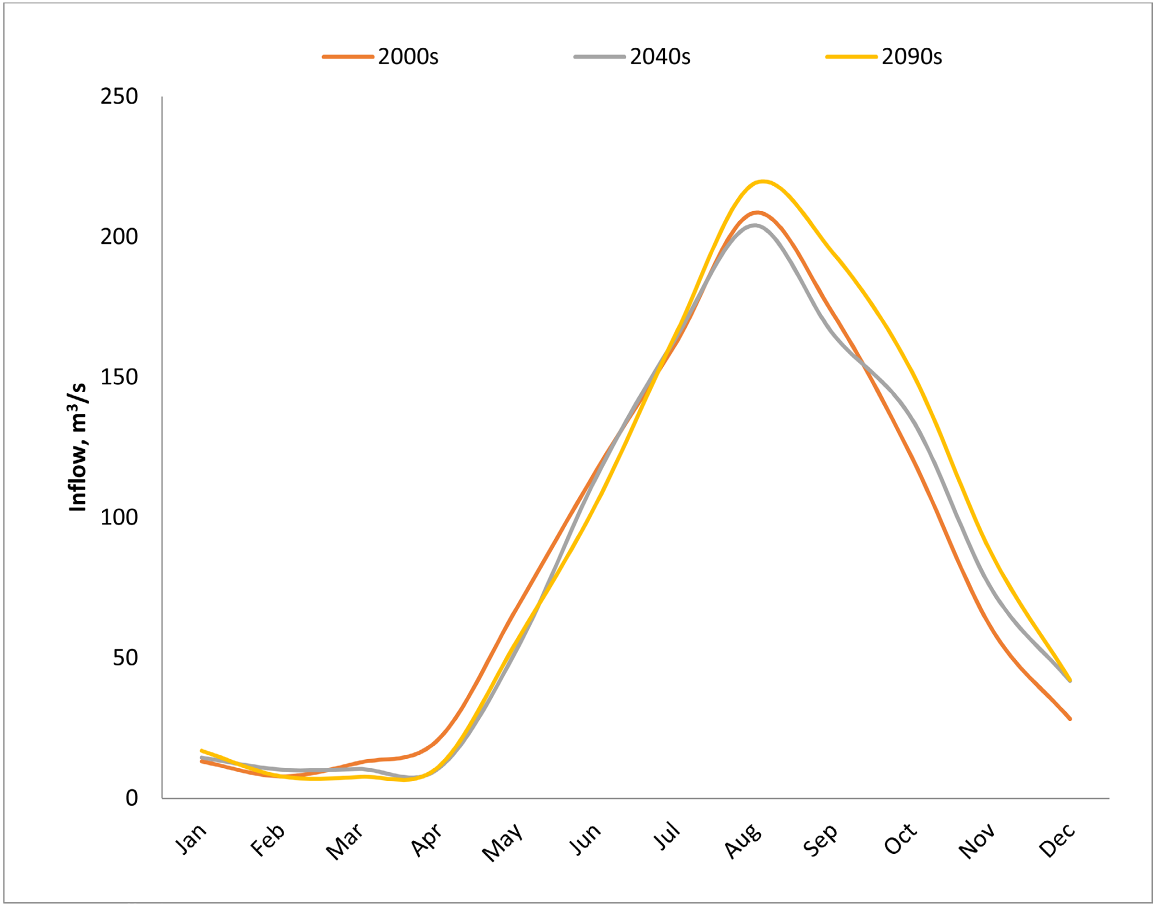

Figure 10. Future (2040s and 2090s) inflow hydrograph comparison with the base period at Baro-1 reservoir.

As can be observed from the **Figure 10**, the peak flow rates of the reservoir generally tend to decrease in the 2040s projection and exhibit an increase in the late century (2090s) compared to the base period (2000s). Across the different monthly time steps of the graph there exists inconsistent variation among the three hydrographs. In both future scenarios, fluctuations that sometimes increase and the other times decrease in the river flow relative to the base period can be recognized. In contrary to temperature, future precipitation change projections has shown inconsistency both temporally and spatially according to (Bhatti et al., 2021; Muleta, 2021; Musau et al., 2015) and many other studies. This inconsistency in future flow scenarios is, therefore, inline mainly owed to the irregularity in the future precipitation change scenarios. Additionally, a relatively more increase in evapotranspiration accompanied with future temperature increase could also attribute to the decreasing runoff even during a slight increase in precipitation (Sireesha Naidu et al., 2020).

3.4. Sensitivity of Baro River Flow to Climate Change

In general, the mean monthly reservoir inflow variation for the A1B scenario in the two future time periods follows the change in the precipitation, which tends to decrease in the mid-century, followed by an increase in the late century. From

(Figure 11), one can observe that the reservoir inflow at Baro-1 & Baro-2 reservoirs and Genji pool get decreased in a similar fashion by about a maximum of 50% in spring and similarly increases by about a maximum of 50% in the autumn season for both future periods compared to the baseline period. This is, of course, in agreement with different studies (Kure & Tebakari, 2012; Sireesha

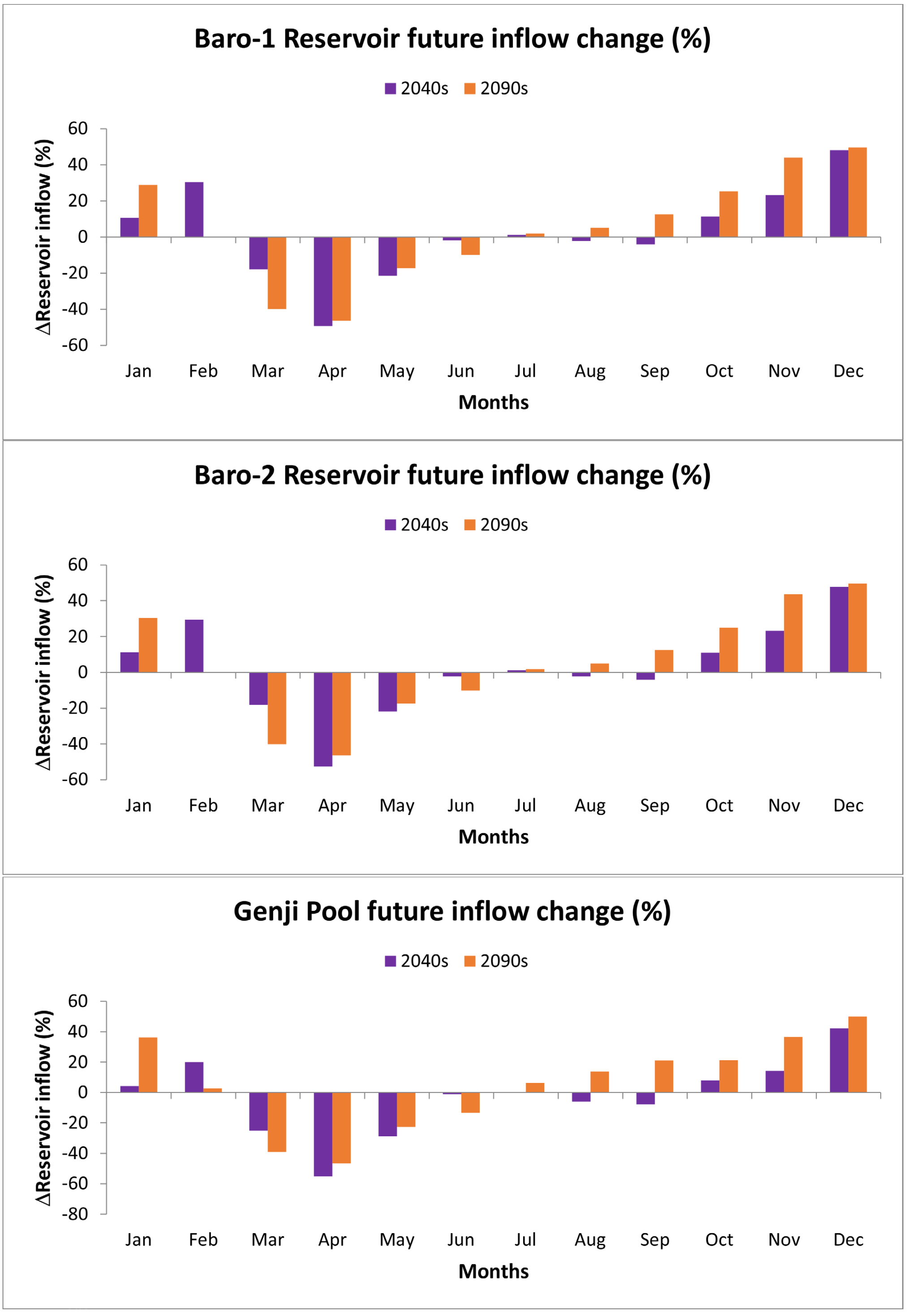

Figure 11. Percentage reservoir inflows change in the future periods relative to the base period.

Naidu et al., 2020) and the theory of the Clausius-Clapeyron (CC) which described the fact the warmer the atmosphere, the more moisture it can hold and hence increased rainfall intensities. However, there would not be a direct relationship between increase in temperature, rainfall intensity and runoff as is true in this study. This mainly happened during the dry periods when there exists high evaporation rates and low moisture which, in most cases, results in decrease of river flows in contrast to the increasing rainfall intensity (Patil et al., 2019).

The generated inflows to the reservoirs have shown a decreasing trend in the 2040s and an increasing trend in the 2090s at all three reservoirs following the reduction and increment of precipitation in the respective periods. A mean annual percent decrease of about 3.6, 3.5, and 2.1 was observed at Baro-1, Baro-2, and Genji reservoir inflows, respectively, in the 2040s forecast scenario. On the contrary, rises in reservoir inflow by 7.3%, 8.1%, and 7.5% for Baro-1, Baro-2, and Genji reservoirs' inflows, respectively, have been predicted in the 2090s. This clearly tells and warns us that future reservoir inflows will be influenced both in volume and timing in response to the changing climate. Generally, one can observe that there will be a considerable variation in river flows intensifying the extremes both in dry and rainy seasons following the changing climate. This clearly calls for any remedial action of mitigation and /or adaptation in our water resources planning and operation to better combat the impact of the changing climate.

On the seasonal basis, future flows show a decreasing trend for the dry season and tend to increase for the wet seasons for both future time horizons. This seasonal fluctuation both in flow volume and peak flow rate has a sound implication on water resources management as it highly intensifies the hydrological extremes (Ali et al., 2019). This is so because the flow variations are a consequence of variations in the precipitation and evaporation rates in response to the climate change. The reliability of these result lies in the fact that the warmer climate favors more evaporation and more moisture to be carried in the atmosphere which eventually turns into precipitation as far as sufficient moisture is there on the basin. On the other hand, during the dry season, though there is sufficient temperature to derive evapotranspiration, the saturation point shall not be satisfied to form precipitation owed to lack of moisture. As shown by the sensitivity results, the basin water resources are highly vulnerable to the impact of climate change. Therefore, the issue of developing climate change adaptive methods for the water resource management of the basin can only be achieved through the characterization of hydrological response to the changing climate conditions under different socio-economic futures and development prospects (Cradock-Henry et al., 2018). The current study, therefore, is thought to have laid a profound image of how the basin water resources would behave under changing climate.

On the other hand, the study has involved several models and model outputs in a cascaded mode where each possessed a certain level of uncertainty. Hence, it is unquestionable that the uncertainties presented in each of the models and model outputs keep on cumulating and attach a considerable uncertainty to the final output. Furthermore, even though land use and cover are expected to undergo a considerable change, it is assumed to remain unchanged for the sake of lacking data. It is, therefore, certain that some level of insecurity could be involved at this stage, and hence care and due consideration of these limitations is crucial while using results of the study. Regardless of these limitations, the study clearly showed considerable changes to the Baro River flow subjected to the changing climate in terms of peak flow rate, seasonal volume, and time variations. The sounding impact of climate change is the fact that the dry areas and seasons shall continue drier and drier, whereas the wet areas and seasons will get wetter and wetter in response to global warming. The current study has also projected the same trend in hydrological response (**Figure 11**) that would most likely impose a critical impact of climate change on the basin water balance with a high probability of hydrological extremes. In this regard, it is believed that the study shall give an increased awareness on the possible future risks of climate change and can be used as baseline data to develop adaptive strategies such as design modification, dynamic reservoir operation guide rules and support for decision makers to accommodate these changes.

In general, there are two major challenges in the planning and management of water resources in the Baro Basin. The first one, as already discussed in the preceding paragraphs, is lack of information related to future flow changes as a function of the changing climate. The second challenge is lack of gauging stations in different subbasins of the Baro Basin and insufficiency in distribution. Ultimately this study has put considerable effort in solving the challenges by 1) laying baseline flow change scenario data and 2) developing HEC-HMS model for the basin that could be applied to determine flow parameters at the ungauged subbasins.

4. Conclusion

The study has involved a cascade of models and model outputs to generate future climate change scenarios and to simulate the impacts of these changes on the water resources of the watershed. The HEC-HMS model, which is calibrated and validated in daily time step, has simulated the observed discharge in a reasonably good manner, particularly in simulating the runoff volume on the monthly basis. Ultimately, the developed HEC-HMS model can reasonably be applied for rainfall runoff simulation in the Upper Baro Basin and other similar basins at different point of time frames into the future based on meteorological or RCM output data. And hence, the projection of hydrological response parameters for plausible future climate change scenarios is an inevitable step towards adaptive water resources development. The modelled baseline information of Baro River flow in the near and far future can substantially be used for the planning and design of new projects as well as maintenance and operation of existing projects. Moreover, the data will also be used for supporting decision makers over the basin development agendas and shall have a paramount importance in minimizing the environmental effect of hydrological extremes. In general, the current study is of dual purposes in that the developed model can solve the problem of ungauged areas while also predicting future flow change scenarios for the study area, and hence, has paramount importance.

Lastly, it is worth to point out that, the different models involved in this study possess a certain level of uncertainty. Furthermore, the study couldn't account for land use changing owing to the lack of data, where, in reality, land use is possibly undergoing considerable change. Hence, the results of this study should be taken with care and be considered as indicative of the likely future rather than accurate predictions. Eventually, this study should be extended by considering changes in land use, seepage from reservoirs, soil, sedimentation, and other water resource development in the basin in addition to the climate variables.

Ethical Approval

This work has not been submitted elsewhere for publication, in whole or in part, and will not be considered for publication in other journals.

Credit Authorship Contribution Statement

Teressa Negassa Muleta: Conceptualization, Methodology, Software, Formal analysis, Writing—original draft. **Knolmár Marcell**: Formal analysis, Writing—review & editing, and Supervision.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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