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Integration of satellite and ground-based rainfall data for water resources assessment in Central Rift Valley Lakes Basin, Ethiopia

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CY CERGY PARIS UNIVERSITÉ

École Doctorale des Sciences et Ingénierie

Intégration des données de précipitations satellitaires et au sol pour l'évaluation des ressources en eau dans le bassin des lacs de la Vallée Centrale du Rift, en Éthiopie

Thèse présentée par:

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Summary

Significant changes have been observed in the water balance of Central Rift Valley (CRV) lakes basin in Ethiopia, which hinders their services for a wide variety of ecosystems. However, the contributions of river inflow, water withdrawal, and climate change have not been quantified yet due to lack of continuous data availability and sufficient rain gauge networks. Satellite rainfall estimates (SREs) may serve as an alternative input for water balance studies. In this study, we explore the use of Climate Hazards Group InfraRed Precipitation (CHIRP) satellite rainfall estimate using rainfall-runoff modelling where simulated runoff served as input to water level simulation. The study also evaluated actual water withdrawal from Lake Ziway and existing and future water demand for the entire CRV lakes basin using a combination of water abstraction survey (WAS) data, hydrological and Water Evaluation and Planning (WEAP) model.

The thesis consists of four subsequent steps, whereby the first two focus on the applicability of CHIRP satellite for streamflow and lake water level simulation, the third on the impact of abstraction and the fourth on existing and future water demand and the likely impacts of water resources development on the water balance of CRV lakes basin. The study area is bounded to the east and west by the escarpment of the rift valley and the highlands characterized by a chain of three interconnected lakes namely Lake Ziway, Langano and Abiyata. Lake Ziway receives most of its water from major Meki and Katar catchments and other minor tributaries. The lake has a surface area of 445 km^2, an average depth of 3 m and an average elevation of 1636 m.a.s.l. Lake Langano receives it water inflow from the Gedemso and other minor rivers with lake surface area of 233 km^2, an average depth of 12 m with an average surface elevation of 1584 m.a.s.l. Lake Abiyata receives water from Bulbula and the Horakelo Rivers with lake surface area of 148 km^2, average depth and surface elevation of 7 m and 1580 m.a.s.l, respectively.

1. Evaluation and Bias Correction of CHIRP Rainfall Estimate for Rainfall-Runoff Simulation over Lake Ziway Watershed: This study focuses on evaluation and bias correction of Climate Hazards Group InfraRed Precipitation (CHIRP) satellite estimate for rainfall-runoff simulation at major Meki and Katar catchments. The performance of CHIRP satellite product was evaluated using different numerical and categorical validation statistical measures at various spatiotemporal scales. We tested several cases in the calibration of the hydrological model by using gauged data, uncorrected and bias-corrected CHIRP rainfall data to evaluate the effect of

satellite rainfall bias correcton on streamflow simulation and calibrated model parameters. To correct the systematic errors of the CHIRP rainfall estimates a non-linear power bias correction method was applied using rain gauge data as a reference. The results show that CHIRP has biases at various spatial and temporal scales. The use of different rainfall inputs impacts both the calibrated parameters and their performance in simulating daily streamflow of the two catchments. We obtained a change of up to 63% on the parameters controlling the water balance when uncorrected CHIRP satellite rainfall served as model inputs. The results of this study indicate that bias correction of the satellite estimates effectively improved the performance of streamflow simulations.

2. Bias-corrected CHIRP Satellite Rainfall for Water Level Simulation, Lake Ziway: This study aims to explore the applicability of bias-corrected CHIRP satellite rainfall for Lake water level simulation from rainfall-runoff modelling as input to the lake water balance. A non- linear power transformation bias-corrected CHIRP satellite rainfall data was used as input to Hydrologiska Byråns Vattenbalansavdelning (HBV) model to simulate streamflow of Meki and Katar catchments. Results show that simulated runoff for Meki and Katar gauge catchments contributed 524 mm and 855 mm to the lake inflow, respectively. The runoff from ungauged catchments is around 182 mm that accounts for 8.5% of the total lake inflow. Simulation of lake water level shows good agreement from 1986 to 2000, but deteriorating agreement after 2000 which is mainly attributed to an error in any of the water balance terms and human-induced influences. The water balance closure error from 1986-2000 revealed 67.5 mm per year that accounts for 2.9% of the total lake inflow. Overall, this study indicates the applicability of CHIRP satellite estimate for lake water balance studies.

3. Impact of water abstraction on the water balance of Lake Ziway: The study aims to estimate actual water withdrawal from the lake through water abstraction survey. A water balance model was developed to evaluate the isolated impact of actual water withdrawal on the lake water volume and level. The likely impact of three development pathways on the lake storage and water level was assessed. The result shows that for existing development, the annual irrigation water withdrawal amount is 37 Mm^3. When the future development plans are fully implemented, the estimated annual water abstraction amount will increase by 2.5 folds, which will cause the lake water level to drop by 0.94 m and surface area reduction by 38 km^2. This consequently will yield 26% reduction of the actual storage volume from the baseline. Therefore, this study indicates that the current impacts of water resources development around the lake is substantially large and will exacerbate in the future. Hence, the study suggests integrated management of manage water abstraction from the lake.

4. Assessment of existing and future water demand on Central Rift Valley Lakes basin of Ethiopia: This study aimed to quantify existing and future water demand and availability for irrigation, domestic and industrial water use using the Water Evaluation and Planning (WEAP) model. Three water resources development (i.e current (2009-2018), short term (2019-2028) and long term (2029-2038) development) pathways were simulated and the likely impact of this development on the water level was assessed. The simulated streamflow using rainfall-runoff modelling through calibration and validation at major and minor tributaries were used for the supply sources. The results indicate during long term development to occur, an average 223.02 Mm^3 of water demand and 176.6 Mm^3 of water diverted from the lake and its tributaries. This will yield annual unmet demand of 46.5 Mm^3 in the central rift valley lakes basin. It also found that most of the water resources development schemes in all of the watersheds will have unmet demands in the long term pathways higher than in the current development. This consequently results in a reduction in the lake water level by 1.87, 0.97 and 2.1 m for Lake Ziway, Langano and Abiyata, respectively. The impacts of current and future water demand from the lake and its tributaries on the lake water level is substantial and hence we suggest the water resources management of the lake and its tributaries.

Conclusion: This research thesis contributes toward the attribution of lake water balance assessment in data-scarce and poorly gauged region. First, evaluation and bias correction of high-resolution satellite rainfall estimate was assessed to simulate total lake inflow from rainfall and river inflow. Second, a water balance model was developed for water level simulation from bias-corrected CHIRP satellite rainfall estimates. Third, the thesis evaluated the impact of water abstraction on the water balance of Lake Ziway. Finally, the study quantified existing and future water demand to evaluate the likely impact of water resources development on the water level of the lakes. Overall, this study shows the potential of bias-corrected CHIRP satellite rainfall for water resources assessment in the data-scarce region of Ethiopia.

Résumé

Des changements significatifs ont été observés dans le bilan hydrique du bassin des lacs de la Central Rift Valley (CRV) en Ethiopie, ce qui entrave leurs services pour une grande variété d'écosystèmes. Cependant, les contributions des apports fluviaux, des prélèvements d'eau et du changement climatique n'ont pas encore été quantifiées en raison du manque de disponibilité continue de données et de réseaux pluviométriques suffisants. Les estimations des précipitations par satellite (SREs) peuvent servir de contribution alternative pour les études du bilan hydrique. Dans cette étude, nous explorons l'utilisation de l'estimation des précipitations par satellite du Climate Hazards Group InfraRed Precipitation (CHIRP) en utilisant la modélisation des précipitations et du ruissellement où le ruissellement simulé a servi d'entrée à la simulation du niveau de l'eau. L'étude a également évalué les prélèvements d'eau réels du lac Ziway et la demande en eau actuelle et future pour l'ensemble du bassin des lacs CRV en utilisant une combinaison de données d'enquête sur les prélèvements d'eau (WAS), de modèles hydrologiques et d'évaluation et de planification de l'eau (WEAP).

La thèse se compose de quatre étapes subséquentes, les deux premières se concentrant sur l'applicabilité du satellite CHIRP pour le débit et la simulation du niveau de l'eau du lac, la troisième sur l'impact du captage et la quatrième sur la demande d'eau actuelle et future et les impacts probables des ressources en eau développement sur le bilan hydrique du bassin des lacs CRV. La zone d'étude est délimitée à l'est et à l'ouest par l'escarpement de la vallée du Rift et les hautes terres caractérisées par une chaîne de trois lacs interconnectés, à savoir le lac Ziway, Langano et Abiyata. Le lac Ziway reçoit la majeure partie de son eau des principaux bassins versants de Meki et Katar et d'autres affluents mineurs. Le lac a une superficie de 445 km^2, une profondeur moyenne de 3 m et une altitude moyenne de 1636 m.a.s.l. Le lac Langano reçoit son afflux d'eau du Gedemso et d'autres rivières mineures d'une superficie de 233 km^2, d'une profondeur moyenne de 12 m avec une élévation de surface moyenne de 1584 m d'altitude. Le lac Abiyata reçoit de l'eau de Bulbula et des rivières Horakelo avec une superficie de lac de 148 km^2, une profondeur moyenne et une élévation de surface de 7 m et 1580 m.a.s.l, respectivement.

1. Évaluation et correction du biais de l'estimation des précipitations du CHIRP pour la simulation des chutes de pluie et du ruissellement dans le bassin versant du lac Ziway: Cette étude se concentre sur l'évaluation et la correction des biais de l'estimation satellite Climate

Hazards Group InfraRed Precipitation (CHIRP) pour la simulation des précipitations et du ruissellement dans les principaux bassins versants de Meki et Katar. La performance du produit satellite CHIRP a été évaluée à l'aide de différentes mesures statistiques de validation numériques et catégorielles à différentes échelles spatio-temporelles. Nous avons testé plusieurs cas dans l'étalonnage du modèle hydrologique en utilisant des données jaugées, des données de pluie du CHIRP non corrigées et corrigées du biais pour évaluer l'effet de la correction du biais de la pluie par satellite sur la simulation du débit et les paramètres du modèle étalonné. Pour corriger les erreurs systématiques des estimations de précipitations du CHIRP, une méthode de correction du biais de puissance non linéaire a été appliquée en utilisant les données des pluviomètres comme référence. Les résultats montrent que CHIRP a des biais à différentes échelles spatiales et temporelles. L'utilisation de différents apports pluviométriques a un impact à la fois sur les paramètres calibrés et sur leurs performances dans la simulation du débit quotidien des deux bassins versants. Nous avons obtenu un changement allant jusqu'à 63% sur les paramètres contrôlant le bilan hydrique lorsque les précipitations non corrigées du satellite CHIRP ont servi de modèle d'entrée. Les résultats de cette étude indiquent que la correction du biais des estimations satellitaires a effectivement amélioré la performance des simulations de débit.

2.Précipitations satellites CHIRP corrigées des biais pour la simulation du niveau d'eau, lac Ziway: Cette étude vise à explorer l'applicabilité des précipitations satellites CHIRP corrigées des biais pour la simulation du niveau d'eau du lac à partir de la modélisation des précipitations et du ruissellement comme entrée dans le bilan hydrique du lac. Des données satellitaires CHIRP corrigées du biais de transformation de puissance non linéaire ont été utilisées comme données d'entrée dans le modèle Hydrologiska Byråns Vattenbalansavdelning (HBV) pour simuler l'écoulement des bassins versants de Meki et Katar. Les résultats montrent que le ruissellement simulé des bassins versants de Meki et Katar a contribué respectivement à 855 mm et 524 mm à l'afflux du lac. Le ruissellement des bassins versants non jaugés est d'environ 182 mm, ce qui représente 8,5% de l'apport total du lac. La simulation du niveau d'eau du lac montre une bonne concordance de 1986 à 2000, mais une détérioration de la concordance après 2000, qui est principalement attribuée à une erreur dans l'un des termes du bilan hydrique et aux influences anthropiques. L'erreur de fermeture du bilan hydrique de 1986 à 2000 a révélé 67,5 mm par an, ce qui représente 2,9% de l'apport total du lac. Dans l'ensemble, cette étude indique l'applicabilité de l'estimation satellite CHIRP pour les études de bilan hydrique des lacs.

3. **Impact du prélèvement d'eau sur le bilan hydrique du lac Ziway**: L'étude vise à estimer le prélèvement d'eau réel du lac par le biais d'un levé de prélèvement d'eau. Un modèle de bilan hydrique a été développé pour évaluer l'impact isolé du prélèvement d'eau réel sur le volume et le niveau d'eau du lac. L'impact probable de trois voies de développement sur le stockage du lac et le niveau de l'eau a été évalué. Le résultat montre que pour le développement existant, le montant annuel de prélèvement d'eau d'irrigation est de 37 Mm^3. Lorsque les futurs plans de développement seront pleinement mis en œuvre, la quantité annuelle estimée de prélèvement d'eau augmentera de 2,5 fois, ce qui entraînera une baisse du niveau d'eau du lac de 0,94 m et une réduction de la superficie de 38 km^2. Cela entraînera par conséquent une réduction de 26% du volume de stockage réel par rapport à la référence. Par conséquent, cette étude indique que les impacts actuels du développement des ressources en eau autour du lac sont substantiellement importants et vont s'accentuer à l'avenir. Par conséquent, l'étude suggère une gestion intégrée de la gestion des prélèvements d'eau du lac.

4. Évaluation de la demande en eau actuelle et future du bassin des lacs de la vallée du Rift central en Éthiopie: Cette étude visait à quantifier la demande actuelle et future en eau et la disponibilité pour l'irrigation, l'utilisation domestique et industrielle de l'eau en utilisant le modèle Water Evaluation and Planning (WEAP). Trois voies de développement des ressources en eau (c'est-à-dire le développement actuel (2009-2018), à court terme (2019-2028) et à long terme (2029-2038)) ont été simulées et l'impact probable de ce développement sur le niveau de l'eau a été évalué. Le débit simulé des cours d'eau à l'aide de la modélisation des précipitations et du ruissellement par étalonnage et validation aux affluents majeurs et mineurs a été utilisé pour les sources d'approvisionnement. Les résultats indiquent qu'au cours du développement à long terme, une moyenne de 223,02 Mm^3 de demande en eau et de 176,6 Mm^3 d'eau seront détournés du lac et de ses affluents. Il en résultera une demande annuelle non satisfaite de 46,5 Mm^3 dans le bassin central des lacs de la vallée du Rift.Il a également constaté que la plupart des plans de développement des ressources en eau dans tous les bassins versants auront des demandes non satisfaites dans les scénarios à long terme plus élevés que dans le développement actuel. Cela se traduit par conséquent par une réduction du niveau d'eau du lac de 1.87, 0,97 et 2,1 m pour le lac

Ziway, Langano et Abiyata, respectivement. Les impacts de la demande actuelle et future en eau du lac et de ses affluents sur le niveau d'eau du lac sont importants et nous suggérons donc la gestion des ressources en eau du lac et de ses affluents.

Conclusion: Cette thèse de recherche contribue à l'attribution de l'évaluation du bilan hydrique des lacs dans les régions où les données sont rares et mal jaugées. Premièrement, l'évaluation et la correction du biais de l'estimation des précipitations par satellite à haute résolution ont été évaluées pour simuler l'apport total des lacs par les précipitations et le débit des rivières. Deuxièmement, un modèle de bilan hydrique a été élaboré pour la simulation des niveaux d'eau à partir des estimations des précipitations par satellite du CHIRP corrigées du biais. Troisièmement, la thèse a évalué l'impact du prélèvement d'eau sur le bilan hydrique du lac Ziway. Enfin, l'étude a quantifié la demande en eau actuelle et future afin d'évaluer l'impact probable de l'exploitation des ressources en eau sur le niveau d'eau des lacs. Dans l'ensemble, cette étude montre le potentiel des précipitations du satellite CHIRP corrigées du biais pour l'évaluation des ressources en eau dans la région de l'Ethiopie où les données sont rares.

List of Abbreviations

ARC2	African Rainfall Climatology V2
ASTER	Advanced Space Thermal Emission & Reflection Radiometer
BS	Baseline
BIAS	Relative Bias
CSA	Centeral Statistical Authority
CSI	Critical Success Index
CC	Pearson correlation coefficient
CWR	Crop Water requirement
CCD	Cold Cloud Duration
CDF	Cumulative Distribution Function
CHG	Climate Hazards Group
CHIRP	Climate Hazards Infrared Precipitation
CHIRPS	Climate Hazards Infrared Precipitation with stations
CMORPH	Climate Prediction Centre morphing technique
CRV	Central Rift Valley
CPC	Climate Prediction Center
DEM	Digital Elevation Model
DMC	Double Mass Curve
ED	Existing Development
ETO	Reference Evapotransipration
FAO	Federal and Agriculture Organization
FAR	False Alarm Ratio
FPD	Full Planned Development
GDEM V2	Global Digital Elevation Model version 2
GPS	Global Positioning System
GIS	Geographic Information System
GPM	Global Precipitation Measurement

HBV	Hydrologiska Byråns Vattenbalansavdelning
IDW	Inverse Distance Weighting
IHMS	Integrated Hydrological Modelling System
LEO	Low Earth Orbiting
ITCZ	Inter-Tropical Convergence Zone
LFD	Likely Future Development
MAE	Mean Absolute Error
ME	Mean Error
MCM	Million Cubic Meter
MPEG	Multi-Sensor Precipitation Estimate Geostationary
MoWiE	Ministry of Water, Irrigation and Electricity
NMA	National Meteorological Agency
NOAA	National Oceanic and Atmospheric Administration
NSE	Nash-Sutcliffe efficiency
PET	Potential evapotranspiration
PMW	Passive Microwave
POD	Probability of Detection
PBIAS	Percentage Relative Bias
RMSE	Root Mean Squared Error
RVE	Relative volume error
SREs	Satellite rainfall estimates
TAMSAT	Tropical Application of Meteorology using SATellite
TIR	Thermal infrared
TMPA	Tropical Multi-satellite Precipitation Analysis
TRMM	Tropical Rainfall Measuring Mission
WEAP	Water Evaluation and Planning model
WAS	Water Abstraction Survey
WGS	World Geodetic System

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1 Introduction

1.1 Background

In Ethiopia, an uneven spatial and temporal occurrence of rainfall and distribution of water resources among others have been considered as the major factors affecting the development and management of water sectors of the country (MoWR, 1999). We note that 85% of the country's economy depends on rainfed agriculture. However, the Central Ethiopian Rift Valley (CRV) Lakes basin is one of rainfall deficit areas where the surrounding agro-climatic and geological factors are believed to have significant impact on the hydrological system of the basin (Ayenew, 1998).

According to Ministry of Water, Irrigation and Electricity of Ethiopia, different water resources development plans are ongoing to be implemented in all major river basins of the country. Inaddition, there are many water demanding projects upstream and downstream and investments as of irrigation, water supply and industrial demands, etc. (Awulachew et al., 2012). Furthermore, the policies of the Ethiopian government strongly support export-oriented irrigated horticulture and private large-scale floriculture as a means to increase foreign exchange earnings and employment opportunities. The CRV is a basin in Ethiopia where such policies have resulted in large scale investments in floriculture greenhouses and a number of irrigation schemes. However, recent expansion of intensive water abstraction activities from the lake and its feeding rivers are leading water level drops. Hence, this will consequently damage the hydrological and ecological integrity of the lake and its tributaries (Jansen et al., 2007), which create stress on available water resources in the sub-basin.

Worsening the problem, climate and human-induced impacts often contaminate the world's limited freshwater resources and make them unavailable for various uses. This might result for water claims/conflict between users to fulfill their demands. A rising demand for water resources will make its water system allocation struggle in the near future. The water system of CRV lakes basin is mainly used for irrigation, domestic, industrial, commercial fish farming, recreation, while it supports a wide variety of endemic wild animals such as birds (Ayenew, 2007).

The hydrology of many lakes and their basin has been relatively well documented. For instance, Lake Kenya (Van Oel et al., 2013), Lake Victoria (Nicholson and Yin, 2001), Lake Malawi (Kumambala, 2010), Lake Tana (Kebede et al., 2006; Wale et al., 2009;Rientjes et al., 2011; Dessie et al., 2015). However, the hydrology of Central Rift valley lakes basin is not well documented in scientific literature. Among the literature on the hydrology of Lake Ziway (Vallet-Coulomb et al., 2001; Legesse et al., 2003, 2004; Ayenew, 2007; Jansen et al., 2007) most of them focused on the water budget of the lake under historical condition for short periods. Furthermore, there is no detail study on downstream Lake Langano and Abiyata. However, a systematic study quantifying the water balance components, lake level simulation and water abstraction considering natural climate and human induced activities on the lakes and/or the basin is not available. This is mainly due to lack of continuous data and sufficient rain gauge network for long-term hydrological and water balance studies.

Furthermore, few monitoring stations are also available at sparse spatial coverage, a short length of records and substantial missing datasets. Hence, the spatial and temporal variation of the lake water balance and the attribution factors for variation of the water system have not been quantified yet. The absence of such knowledge in the study area hinders effective water management of the lake and its basin. Therefore, accurate determination of the water balance assessment is one of such instances of knowledge required for the better management of sub-basin and rational water allocation.

Significant change has been observed in the hydrology of the Rift Valley lakes in Ethiopia, as a result of natural processes and human activities over the past decades. For instance, Seyoum et al. (2015) showed a 70% reduction (~4.5 m) of water level of Lake Abiyata as a result of human activities. Jansen et al. (2007) reported that annual average water level of Lake Ziway approximately decreased by 0.5 m as a result of intensive expansion of irrigation activities around the lake and its tributaries. They also showed that this drop results in a tremendous decrease in the discharge of Bulbula River which in turn results in a reduction in size of Lake Abiyata by more than 40% of its size. Therefore, if the water level continues to drop, it may result in overexploitation of the lake water resources. This might creates shortage of water resources for irrigation and processing purposes. The increasing pressure on water resources and land intensifies conflicts between stakeholders which creates various socio-economic problems.

Above all, the contribution of long-term water balance components such as rainfall, river inflow, water withdrawal, open evaporation, land use and climate change has not been quantified yet over CRV lakes basin mainly due to scarce data for water resources modelling. However, satellite hydro-meteorological estimates may serve as important inputs for modeling in an area of scarce data and poorly gauged regions. Therefore, evaluation of satellite rainfall product over the study area is crucial to fill the data gap in water budget studies. In this study, **Climate Hazards Group InfraRed Precipitation (CHIRP)** satellite rainfall estimate at daily temporal and 0.05^0 X 0.05^0 spatial resolution was evaluated for rainfall-runoff and water balance simulation over Lake Ziway watershed, Ethiopia.

The study starts from evaluation and bias correction of satellite rainfall estimate (SREs) for streamflow simulation, water balance and lake level simulation. In this study we determine how water balance component of the sub-basin, water abstraction and existing and future water demand influence the hydrology of the CRV lakes and its sub-basin using an integrated approach (hydrological model, water balance model, water abstraction survey and water evaluation and planning model). The results of such study are relevant to the product users the applicability and potential of CHIRP satellite estimate for estimating catchment runoff and water budget studies in scarce data regions. In Lake Ziway area this study can contribute to filling the data gap in water budget studies which play a significant role for water resources development program in the study area.

1.2 Research Objectives

1.2.1 General Objective

The general objective of this study is to evaluate the applicability of merging data from multiple sources for water resources assessment of the Central Rift valley lakes basin of Ethiopia.

1.2.2 Specific Objective

The specific objectives of this study were:

- To evaluate the performance of CHIRP satellite rainfall estimate at various spatial and temporal scale for rainfall-runoff simulation.

- To assess the applicability of bias-corrected CHIRP SREs for water level simulation.
- To assess the impact of water abstraction on the water balance of Lake Ziway using water abstraction survey.
- To quantify existing and future water demands thereby to evaluate the likely impact of different water resources development pathways on the lake water balance using Water Evaluation and Planning (WEAP) model.

1.3 Research Questions

To meet the stated objectives, the following research questions are defined:-

- What is the performance of CHIRP satellite estimate at various spatiotemporal resolutions over Lake Ziway watershed for rainfall-runoff simulation and water budget studies?
- What is the actual water withdrawal from the lake due to water abstraction and its impact on lake level and volume?
- How much is the existing and future water demand of the basin? What is the implication of different water resources development plan of the basin on water balance of the lakes and its subbasin? Where and when the unmet water demands occur in the subbasin?

1.4 State of the art review

1.4.1 Satellite rainfall application for streamflow and water level simulation

Accurate and consistent hydro-metorological dataset at various spatio-temporal resolutions is crucial in providing required information for water resources of the sub-basin. Rainfall is an important component of the hydrologic cycle and plays a significant role for inputs in rainfall-runoff modelling. The accuracy of the rainfall input significantly influences the performances of the hydrological models (Yuan et al., 2017).

Rainfall is the only reliable source of fresh water in many developing countries, particularly in the central rift valley lakes basin of Ethiopia. We note that, rainfall dataset are obtained from rain gauge observations installed at various locations. However, existing rain gauge networks in Ethiopia in general over CRV basin in particular are limited both in space and time. Furthermore, most of the available rain gauge networks often have inadequate coverage and density. The available stations also mainly represent only point scales estimates and suffer from data quality and inconsistency (Haile et al., 2013). Besides, most of the available stations are located mainly in towns and therefore, do not adequately represent the spatial variability of rainfall across the regions. However, recently satellite remote sensing and processing algorithms are being extensively used to produce Satellite Rainfall Estimates (SREs). SREs may serve as an alternative data source for model inputs as they provide rainfall datasets at various temporal and spatial coverage (Dinku, 2014; Katsanos et al, 2016).

Several satellite rainfall products have been available as gauge-based and satellite-based products over the past decades. For instance, gauge-based products include Asian Precipitation Highly Resolved Observational Data Integration Towards Evaluation of water resources (APHRODITE; Yatagai et al., 2012), whereas satellite-based estimates such as Global Precipitation Climatology Centre (GPCC; Huffman et al., 1997), Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis (TMPA, Huffaman et al., 1997, 2007), Climate Prediction Centre Morphing Technique (CMORPH; Joyce et al., 2004), and Climate Hazards Group InfraRed Precipitation (CHIRP; Funk et al., 2015) are among others.

In this PhD study, CHIRP satellite rainfall product at daily temporal and 0.05^0 X 0.05^0 spatial resolutions was selected. The main reason why CHIRP satellite rainfall estimate was selected in this study is its relatively high spatiotemporal resolutions and availability at time series consistent for matching with the rain gauge data interval and the time step of the hydrological model.

SREs derive rainfall dataset using information ranging from visible to Thermal InfraRed (TIR) spectral bands of geostationary satellites and microwave (MW) spectral bands from Low Earth Orbiting (LEO) satellite estimate.The TIR uses cloud temperature threshold to discriminate between the rain and no rain clouds. Passive microwave (PMW) relies on a relationship between the radiance received in the microwave channel and precipitation (Tian et al., 2007).

Several studies have been reported that satellite rainfall products are subject to substantial systematic (baises) and random errors (Yong et al., 2010; Habib et al., 2014; Yuan et al., 2017). Authors reported that they might result in under or over prediction, missing seasonal variations of observed rainfall. These errors mainly arise due to uncertainties in spatial sampling (e.g. spatial interpolation errors) and retrieval algorithms and sampling frequency (Joyce et al., 2004; Huffman et al., 2007) among them to mention. Therefore, it is necessary either to minimize or remove the errors before the SREs can be used in hydrological and water resources applications.

A systematic error (bias) between satellite and rain gauge rainfall can be removed using gauged data as a reference by applying various bias correction algorithms. Bias correction may vary from simple linear to a more complex histogram matching that can correct multiple moments of the distribution of a variable at a time (Haerter et al., 2011). The selection of the bias correction method depends on the accuracy, data requirement and on the hydrologic application that the bias-corrected dataset can be used in (Habib et al., 2014).

Previous studies have reported that the performance of the hydrological model for streamflow simulation depends on the type of the satellite rainfall product, hydro-climatic condition, spatio-temporal resolutions, and topography of the study area (Yong et al., 2010; Bitew and Gebremichael, 2011; Zeweldi et al., 201; Yuan et al., 2017). We note that the approach used by different researchers is various among the studies. Some of the authors reported that applying the original satellite rainfall estimate revealed better performance. For instance, Bitew and Gebremichael (2011) reported that improved model performance when using a satellite-only product (TRMM 3B42RT) as compared to a satellite-gauge bias corrected product (TRMM 3B42). Such results could be partly attributed to the fairly poor quality or sparse rain gauge dataset that are used for the bias correction. However, other scholars indicated that bias-corrected satellite rainfall product as model input instead of an uncorrected product revealed improved performance on rainfall-runoff simulations (Yong et al., 2010; Yuan et al., 2017). Zeweldi et al. (2011) reported increased performance of a rainfall-runoff model when the model was calibrated using satellite data compared to when it was calibrated using rain gauge data.

Furthermore, Yong et al. (2010) showed the requirement of recalibrating sensitive parameters that control the hydrologic model using different rainfall inputs. Artan et al. (2007) reported two calibration approaches for simulating streamflow from satellite rainfall inputs. First, calibrating the model with rain gauge observations and validating the model with satellite rainfall inputs. Second, calibrating the model with the satellite rainfall estimates and validating with rain gauge observations. In this study, we tested calibration of the hydrological model by using gauged data, uncorrected and bias-corrected CHIRP datasets for rainfall-runoff simulation. Then, this study applies toward the use of better performed dataset for river inflow, water balance, actual withdrawal and overall water resources assessment of the basin. The satellite rainfall product used in this study was obtained on a Network Common Data Form (NetCDF) gridded format for each year from 1984-2018. Then, in order to extract the rainfall value over the study area and to export the data in to excel for each pixel, we used Panoply, Grads and MATLAB softwares.

1.4.2 Bias correction methods

Several bias corrections have been applied in different studies to correct the bias of satellite estimates (Haerter et al., 2011; Vernimmen et al., 2012). This includes spatio-temporal bias correction, linear scaling, non-linear power transformation, quantile mapping gamma distribution among others. The description of some of the above methods as follows.

1.4.2.1 Spatio-temporal bias correction

The daily rainfall estimates are multiplied by the bias-correction factor for the respective sequential time window for individual stations. We note that this method is advantages due to its straightforward and easy to implement which require less data inputs. However, this method doesn’t have the ability to fully correct the systematic error in rainfall frequency especially during wet day values (Teutschbein and Seibert, 2013).

1.4.2.2 Linear Correction Method

The monthly scaling factor is applied to each uncorrected daily observation of that month, generating the corrected daily time series. This method uses to match the monthly mean of the uncorrected satellite estimate and the corresponding mean of the rain gauge data. This method has the advantage of simplicity and modest data requirements. This linear bias-correction scheme has its origin in the correction of radar-based precipitation estimates (Tesfagiorgis et al., 2011) and downscaled precipitation products from climate models.

1.4.2.3 Non-linear Correction Method

The non-linear power transformation bias correction method has its origin in climate change studies (Lafon et al., 2013). However, other studies have shown the performance of this method in satellite rainfall estimate bias correction (Vernimmen et al., 2012). This method uses an exponential form to adjust the mean, coefficient of variation and standard deviation of the rainfall time series. The bias factors are determined iteratively by adjusting the mean of the statistical variables of the two datasets.

1.4.2.4 Quantile distribution Correction Method

The quantile gamma distribution correction method assumes that the probability distribution of rain gauge and satellite rainfall estimate datasets approximated by either empirical or gamma distribution function. The quantile based empirical statistical bias correction its origin in regional climate model bias correction (Themeßl et al., 2012). Note that this bias correction methods main benefit as it corrects quantiles and preserves the extreme rainfall values (Themeßl et al., 2012). However, it has drawbacks due to the assumption of both the rain gauge and satellite rainfall follow the same distribution which might bring new sources of uncertainty.

In general, there is no fixed bench mark to select best method of bias correction method in the scientific community. Lafon et al. (2013) concluded linear method showed the weakest correction as it is designed to alter only the mean, while the non-linear method corrects up to the second statistical moment of the frequency distribution revealed improved result as compare to linear method. The empirical quantile mapping method with 100 quantile divisions was highly accurate. However, the effectives of bias correction were found to be sensitive to the time period for which the bias correction procedures have been calibrated. Above all, the gamma distribution offers the best combination of accuracy and robustness. However, it is also reported that in certain circumstances where precipitation datasets cannot adequately be approximated using gamma distribution, the linear and non-linear correction methods were most effective at reducing bias across all moments. Therefore, from this study considering the dataset a non-linear power transformation bias correction method is employed to correct the uncorrected satellite dataset.

1.4.3 Rainfall-Runoff Modelling

In order to fill the data gap in streamflow over the study area, we applied a hydrological model to simulate streamflow over Lake Ziway watershed. In this study, the semi-distributed **Hydrologiska Byråns Vattenbalansavdelning** (**HBV**) hydrological model was applied to simulate streamflow over major Meki, Katar and minor tributaries. Although, selecting an appropriate hydrological model for a particular application is a complicated process, and various considerations need to be taken into account.

The HBV model was selected in this study due to its proven performance over different part of Ethiopian watersheds (Abdo et al., 2009; Wale et al., 2009; Reinjtes et al., 2011; Habib et al., 2014). Besides, operational and scientific applications of this model have been reported from more than 50 countries around the world (Johansson, 2013). The model will also allow us to divide the modeling domain into multiple sub-catchments, elevation and land use zones. Hence, our selection of HBV in this study arises from this fact and interest. Detailed description about the HBV hydrological model is given in the second chapter of this thesis.

1.4.4 Components of Lake Water Balance Model

The calibrated HBV model provides continues runoff and other water balance component from gauged and ungauged sub-basins of the Lake District. The rainfall-runoff model output data was used as input to the water balance model to evaluate the lake water level simulation.

Water Balance Model is a mathematical expression used to describe the flow of water in and out of a hydrological system such as drainage or lakes. Thus, the water balance of a lake is expressed by a continuous equation indicating that the rate of change of volume of the lake is equal to the rate of inflow from all sources, less the rate of water loss. A water balance model is given by:

$$\frac{\Delta V}{\Delta t} = [(R(t) - E(t))] \times A(h) + Q_{in}(t) - Q_{out}(t) + G_{in}(t) - G_{out}(t) + \varepsilon(t) \qquad (1.1)$$

where $\frac{\Delta V}{\Delta t}$ is the net inflow volume change over time ($m^3\ d^{-1}$); R and E are lake rainfall and evaporation, respectively ($m\ d^{-1}$); Q_{in} is surface water inflow to the lake ($m^3\ d^{-1}$); Q_{out} is surface water outflow ($m^3\ d^{-1}$); G_{in} and G_{out} are groundwater inflow and outflow, respectively ($m^3\ d^{-1}$); $A(h)$ is a lake surface area in m^2 as a function of water level and ε represent closure error in water balance arising from errors in the data or other terms.

1.4.4.1 Area Rainfall

The observed records from rainfall stations are used to derive time series of areal rainfall for the sub-basins. A rainfall measurement is a point observation and may not be used as representative value for some large drainage basin and/or catchment areas. Most of the stations in the study area have breaks in records. Hence, we checked outlier and homogeneity of the station for data quality. Then, we filled missing data using average and normal ratio methods based on the percentage of missing values. After filling the stations, the proportionality of the stations was verified using Double-mass curve analysis (DMC).

There are various methods available to determine areal rainfall over the catchment from the rain gauge measurement such as arithmetic mean; Thiessen polygon, Isohyet etc. For this particular study, Thiessen polygon approach was used to estimate area rainfall on the lake and its catchments from satellite rainfall estimate.

1.4.4.2 Lake Evaporation and Catchment Evapotranspiration

For estimating evaporation, maximum and minimum air temperature, wind speed, relative humidity and sunshine hour data are required on different methods of estimation. Beside, for accurate estimation of open lake evaporation pan evaporation data is required. However, pan evaporation data is not available in the study area. In addition, only few stations had temperature and other parameters required to apply empirical methods. For lake evaporation we applied Penman method (Penman, 1984). Due to absence of data in most of the stations we used a combination of Penman-Monteith (Allen et al., 1998) and Hargreaves method (Hargreaves and Allen, 1985) to estimate catchment potential evaporation transpiration.

1.4.4.3 Surface Inflow and Outflow

Runoff in the sub-basin was measured at gauging stations situated at the inlet and outlets of the lake. The calibrated HBV model was applied to simulate the streamflow from gauged area of the major and minor tributaries. The streamflow contribution from ungauged catchment was estimated using the area-ratio method. The outflow component was taken directly from the river outflow gauge stations or be calculated by a regression relationship between water level and outflow for missing outflow records.

After all water balance components were estimated accurately, a water balance model was developed to simulate the lake volume. Then, the lake volume was converted to lake level using the observed relationship between lake level and volume, which is obtained from the lake bathymetric relations.

1.4.5 Water Abstraction Survey (WAS)

In scientific literature several studies at global and local scales have indicated lack of accurate data as a major challenge in the estimation of actual water abstracted for irrigation (Döll, et al., 2012*)*. As such most of previous studies estimate irrigation water demand from a crop that requires the highest amount of water using national statistics, reports and climatic database (Alemayehu et al., 2010; Adgolign et al., 2015; Chinnasamy et al., 2015). However, recently remote sensing and field survey techniques are commonly applied by researchers to estimate actual irrigation water abstraction. The spatial and temporal coverage obtained from remote sensing data provides improvement in estimating water requirements as compared to other methods. Inaddition, water abstraction survey provides actual amount as it is based on actual measurement at field level.

A flow measuring device is not installed at places where water is abstracted in the study area. Hence, no record of water abstraction volume is available. Therefore, the water which is abstracted by individual users was estimated based on **Water Abstraction Survey (WAS)**. The survey includes smallholder farmers to large governmental and private companies. The amount of water abstracted was measured using a bucket with a known size at selected abstraction points. The time which is elapsed to fill the bucket was recorded and was used to estimate the capacity of the pump in volume per time unit. This value is then multiplied by the total operation time per day to estimate the amount of water abstracted. Hence, the contribution of water withdrawal from the lake and the impact on the lake water level variation was estimated using a water balance model coupling with simulated river inflow from rainfall-runoff model output.

1.4.6 Water Evaluation and Planning (WEAP) model

In CRV lakes basin, existing and future water demands are not quantified in the scientific literature. This is mainly due to the challenge of water resources development schemes demand sites and supply sources in the watershed. The major water demand of the study area includes domestic, industrial, irrigation and downstream environmental flow requirements. The water demand for various water sectors were estimated using field survey and appropriate methods based on available data. Then, we applied WEAP model to optimize the spatial and temporal water use in the study area using a linear programming algorithm as per the demand priorities, supply preferences, mass balance and other constraints. For more detail description about WEAP model see SEI (2015) or WEAP website (www.weap21.org).

1.4.7 Review of Previous studies

Previous studies on Central Rift valley lakes basin, mainly emphasized on the likely impact on rain-fed production and food security (Jansen et al. , 2007), soico-economic assessment on land and water resources (Legesse and Ayenew, 2006), agricultural development and water use (Scholten et al., 2007) at catchment level. Few studies exist on the body of the lake such as Lake Ziway evaporation estimation (Vallet-Coulomb et al., 2001), hydrological response of Lake Abiyata (Legesse et al., 2004), characterization of lake level variablity (Belete et al. , 2016) among others. However, there is no study being related to long-term water balance and impact of water abstraction using satellite rainfall estimate in CRV lakes basin. In this part of related literature review an attempt is carried out on available literature and case studies related to our study in Ethiopia.

A study on southern Ethiopia reviewed for this part of research, catchment response to climate and land use change in water resources of the basin, using Precipitation–Rainfall modelling system. The authors reported that a hypothetical climate change with a 10% decrease in rainfall results in 30% reduction in river discharge/streamflow, while a 1.5^{o}C increase in air temperature leads to a decrease in evaporation and consequently a decrease in simulated discharge about 15% over Lake Ziway. They also reported that when the grazing lands are replaced by woodland the flow decreases by 18% at the outlet of Katar inflow to Lake Ziway. In general, this study concludes that there is a significant change in the streamflow volume due to climate and land use change in the watershed (Legesse et al., 2003).

Seyoum et al. (2015) applied integrated approach (hydrologic model, remote sensing and statistical analysis) to evaluate the relative impact of natural processes and human activities on the hydrology of Lake Abiyata. In this study, lake volume is estimated from hydrologic model without human activity and compared with the satellite based (observed) storage volume to evaluate the impact. The results indicated that Lake Abiyata water level has decreased by 70% (~4.5 m) because of human-induced activities while the remianing 30% (~2.0 m) is related to climate variability. Modeling and prediction of lakes response with respect to future climate change scenarios due to global warming is suggested for further study.

The other research reviewed in our study area was the analysis of the hydrological response of tropical Lake Abiyata due to climate and human activities. The water balance of the lake Abiyata shows that good agreement between observed and simulated lake level for the simulation period, but after 1984 overestimation of the simulated occur due to human use activities. A comparison of the simulation with and without human consumption indicates that climate variability controls the inter-annual fluctuations and that the human water use affects the equilibrium of the system by reducing the lake level. The sensitivity analysis with respect to climate and land use changes indicated that lake Abiyata revelaed significant change in the water level and salinity of the lake (Legesse et al., 2004).

Outside the basin, Adogolign et al. (2016) applied WEAP to evaluate surface water resources allocation modelling in Didessa sub-basin. The study aims to evaluate surface water resources on instream and downstream availability and to identify the water shortage areas. In this study, three development scenarios were built based on integrated master plan of Abbay river basin. The Irrigation demand and downstream environmental flow requirement were computed using Cropwat and Indicator of Hydrologic Alterations, respectively. The results showed that almost all the development infrastructure in the basin meet the demand required for the basin under current and medium term future development. However, in the long term future development (2031-2050), there will be 1.101MCM, i.e 10.3% reduction in river flow in Didessa sub-basin. In addition, some of the sub-basin, Anger, Dabena and Upper Didessa will have unmet demand except environmental flow requirement that fully meets the demand required for the Didessa river outlet. Authors indicated that the potential climate and land use/cover scenarios and site specific crop water demand need to be estimated based on field survey (Adogolign et al., 2016).

Alemayehu et al. (2010) evaluated the water resources implications of planned infrastructure development in the Lake Tana Sub-basin of Ethiopia. Four development scenarios (i.e. baseline, ongoing development, likely future development and fully potential development) were built based on integrated master plan and feasibility study projects in the sub-basin using WEAP model. The result of the study revealed that, under future development scenario there is a likely change in water demand, consequently a reduction in water level of lake and surface area. The authors reported that under implementation of the full development plan, the mean annual water level of the lake would be lowered by 0.44 m with annual 30 km^2 reduction in the average surface area of the lake.

The other research reviewed for this studyis based on water allocation simulation of major existing and planned water resources project on Abbay basin using MIKE BASIN model (Wubet et al., 2007). The study assesses the impact of upstream water development on downstream water users. A reference scenario plus all identified project without storage reservoir and with storage reservoir scenarios was assessed and the likely impact of the water resources development on water demand and inflow to the downstream reservoir. From the simulations, total water extracted for irrigation requirement reached up to 1.624 BCM, which yield 3.04% reduction in annual flow volume of water at Border dam. The study concludes that few demands sites with unmet demand without reseravoir condition are fulfilled under storage reservoir scenarios.

Overall, one of the main challenges regarding to water resources assement in CRV lakes basin is availability of published literature in the region. This shows that very little work has been done to quantify or model in detail the contribution of each water balance components at different level especially due lack of long term database. Some of the available literatures applied localized approaches focusing only on lakes and limited to one of the water budget components. Although the ultimate effect is on the lakes, the impacts could be basin-wide affecting the rivers and the tributaries that feed the lakes. Hence, quantitative water balance assessment considering the natural processes and the human activities on the lakes or the CRV basin is not available. As a result this study will have a great input in filling of this missed gap in the area of water budget study in data-scarce region of CRV lakes basin.

1.4.8 Conceptual Framework of the study

The basic activities to be accomplished to meet the objectives of this research are basically based on field and secondary data collection from concerned offices. Model input data preparation, calibration and validation will be carried out. This study uses different software's such as HBV, Matlab, ArcGIS, CROPWAT, and WEAP model etc. The HBV model was mainly used to generate inflow/runoff from gauged and ungauged catchment of the basin. The WEAP model is used to assess existing and future water demand to evaluate the implication of water resources development of the basin. Figure 1.1 shows the conceptual framework followed in this study.

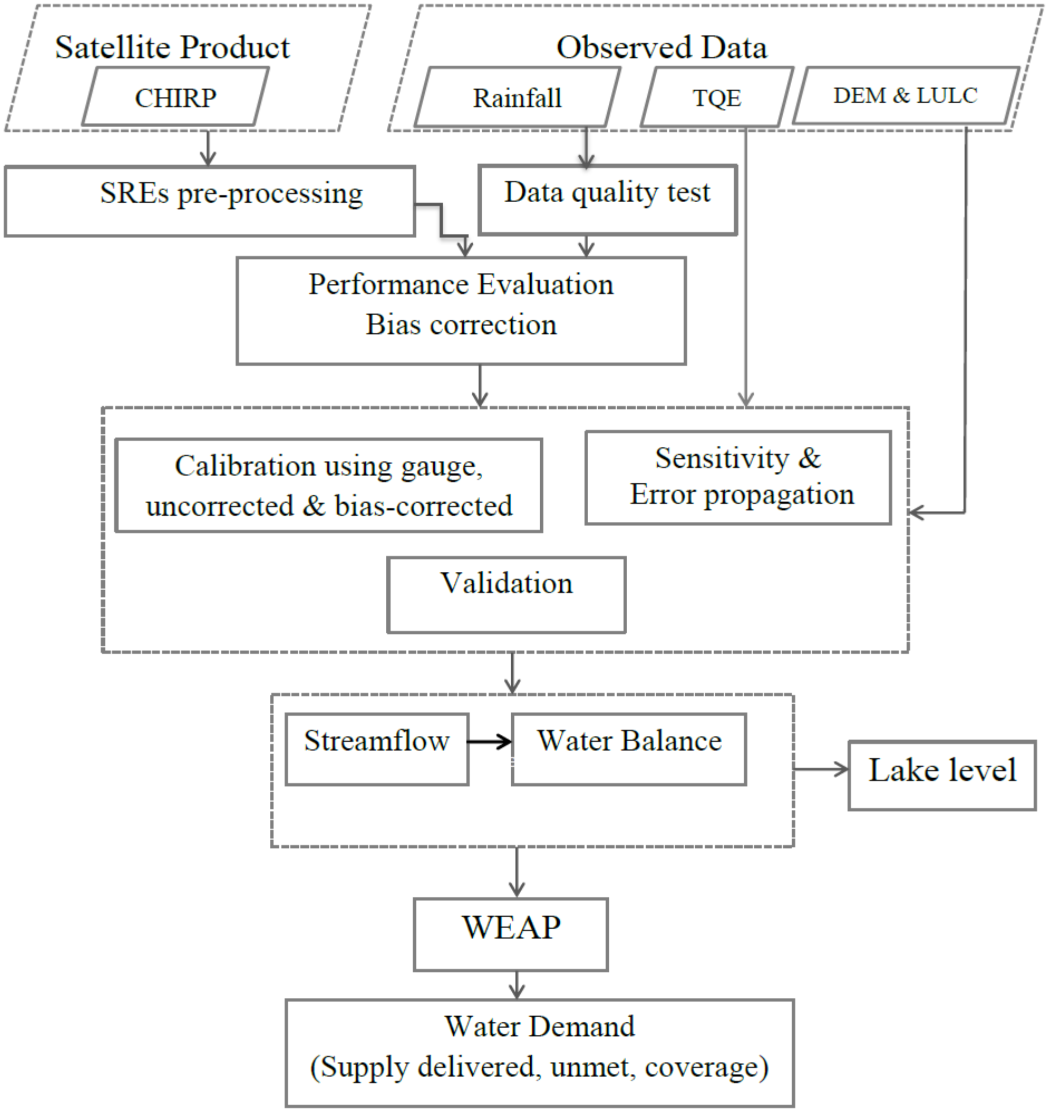

Figure 1.1. Methodological framework followed in this study

1.5 Description of study area

1.5.1 Location

The Central Rift Valley Lakes basin is located in the central section of the main Ethiopian Rift with a total drainage area of 10,685 km^2 situated between 7º10 - 8º30 N and 38º00'- 39º30' E. The basin is characterized by a chain of three interconnected lakes, namely Lake Ziway (445 km^2), Langano (233 km^2) and Abiyata (148 km^2). Lake Ziway receives most of its water from Meki and Katar rivers, which drain the western and eastern plateaus, respectively, with a total catchment area of 7020 km^2 about 67% of the basin.

Lake Langano receives it water inflow from Gedemso Rivers and Huluka, Lepis and Boku minor tributary rivers with a drainage area of 2006 km^2. Lake Abiyata receives water from the Bulbula River and the Horakelo River and from the intermittent of Gogessa River, with a drainage area of 1495 km^2. Lake Ziway and Langano are open lakes with overflow towards Lake Abiyata whereas Lake Abiyata is a closed lake without surface water outflow.

The basin is bounded to the east and west by the escarpment of the rift valley and the highlands. The elevation of the area is characterized by mountainous terrain with an altitude ranging from 1580 m above sea level at central rift valley floor to 4200 m above sea level at extreme western and eastern escarpments (Figure 1.2).

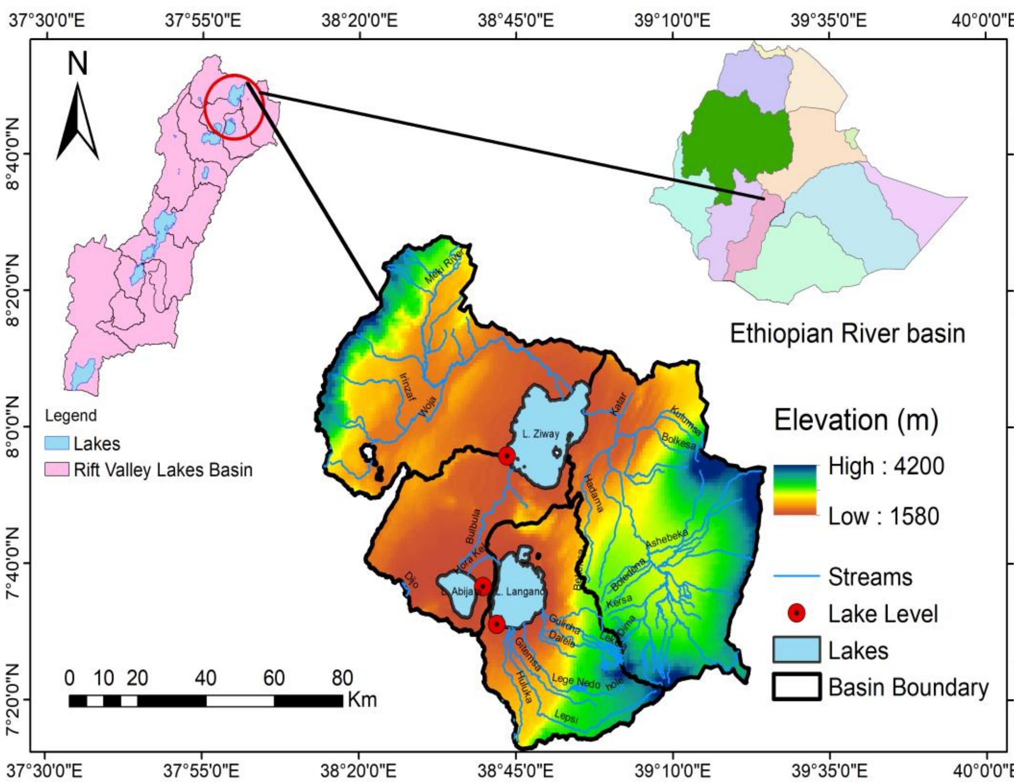

Figure 1.2. Location map of the study area showing digital elevation, lake level along with contributing stream networks

1.5.2 Climate

The climate of the study area is characterized by semi-arid to sub-humid climatic conditions. The lowland regions surrounding the lake area is nearly arid or semi-arid and the highland area varies from humid to sub-humid regions. For instance, Lake Ziway climate is semi-arid condition. The highest rainfalls occur during rainy season from June to September, with a highest peak in July. Whereas the rainfall amount is smaller during drier months from October to January, being December is the driest month with up to 5 mm rainfall. The average monthly temperature ranges between 19 ℃ to 21.8℃. Figure 1.3 shows the mean monthly climatic variation of Lake Ziway. The mean annual rainfall of Lake Ziway varies from 454 to 995 mm as estimated from 1986 to 2016 rain gauge datasets.

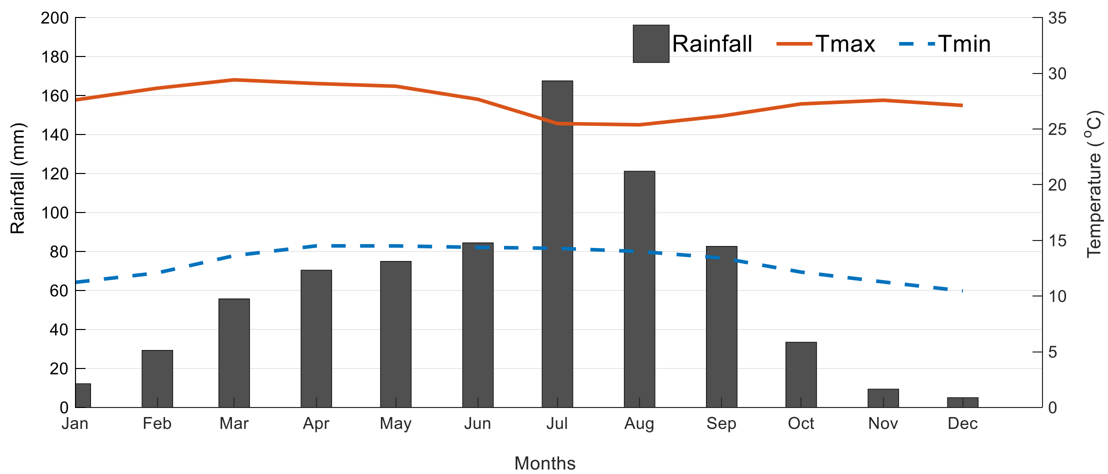

Figure 1.3. The mean monthly climatic conditions of rainfall and temperature of Lake Ziway (1984-2016)

Overall, the region is characterized by three main seasons. The long rainy season in the summer (June- September) locally known as "Kiremt" which is primarily controlled by the seasonal migration of the Inter-Tropical Convergence Zone (ITCZ) represents approximately about 50-70% of the total mean annual rainfall. The small rain season (March to May) locally known as 'Belg' representing 20-30% of the annual rainfall when the ITCZ moves from south to north over the country. The dry period lies between Octobers to February known as 'Baga', when the ITCZ lies in the south of Ethiopia. On average the mean annual rainfall of the catchment ranges from 740 to 1170 mm and from 750 to 1224 mm on the Meki and Katar catchments, respectively. The mean monthly average temperature of the catchments ranges from 15.6 to 22.5°C.

1.5.3 Land use and soils

The basin was previously a pastoral area covered by dense woodlands and there were no large cultivated lands before past five decades (Makin et al., 1976). However, in recent decades, much of the woodland has been converted to agricultural lands and settlement areas (Desta et al., 2017). The recent land use map of the study area (Figure1.4) shows that intensive and modern agricultural cultivation lands are the present major land use of the study area. The major crops that are grown in the region include onion, tomato, maize and vegetables such as cabbage, green beans, pepper, etc. With increasing altitude above 3000 m, the basin is mainly characterized by more cultivated lands with onion, tomato and maize crops are dominantin the area.

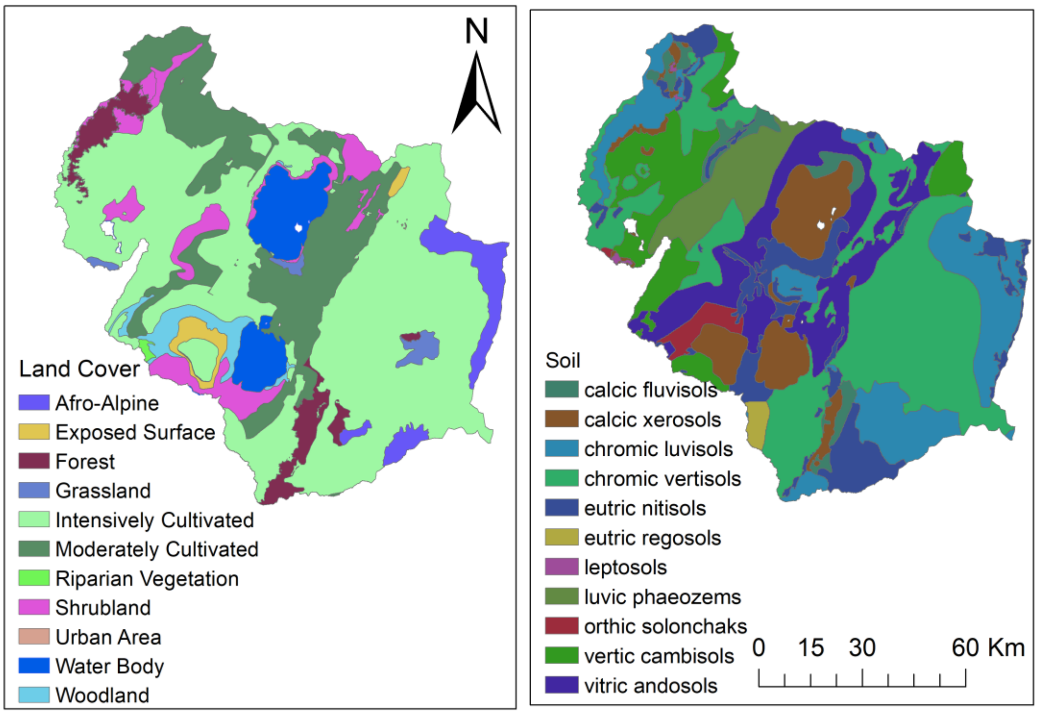

Figure 1.4. Land use (right) and soil (left) feature of CRV lakes basin

Soils in the region are predominantly sandy loam soils but their content in sand and gravel increases near Lake Abiyata. On highlands over 2000 m above sea level, the basaltic and ignimbrite geologic setting leads to have high silt clay contents (Makin et al., 1976) with variation in the eastern and western parts. On the lowland around the lake, the soils are developed on lacustrine sediments with sand texture. Overall, the Vertisols and Cambisols soil types are predominant in the CRV basin (Figure 1.4). The variation of these soils on the study area will have an impact on the type of crops and water requirement of the sub-basin.

1.5.4 Water Demand

The CRV basin and its lakes provide a wide variety of ecosystem services. They serve as a source of drinking and domestic water for Ziway towns, water for open and closed farm irrigation, and fish supply for the market in the country. The basic water demand from the lake and its tributaries are water used for irrigation, domestic, and industrial production.

In Lake Ziway and Bulbula river irrigation water abstraction is primarily used for production of horticulture flowers in addition to intensive smallholder irrigation farmers. Industrial water abstraction from Lake Abiyata is primarily used for soda ash production. Lake Langano and its contributing catchments use the water for irrigation and recreation activities. Besides, they also support the livelihoods for commercial fish farming, shipping and habitat for a wide variety of endemic birds and wild animals (Ayenew, 2007).

1.6 Significance of the study

The significance of satellite rainfall estimate evaluation and water balance assessment on water resources development has been highlighted by many researchers. The CRV lakes are important for export-oriented irrigated floriculture and holticulture, tourism and recreation activities. Therefore, it is important to quantify existing and future water resources developments of the basin.

The Ministry of Water, Irrigation and Electricity of Ethiopia, is a governmental organization which is responsible for the country's water sector development. The mission of the government is to play a role in the socio-economic development of the country through development and management of its water and energy resources in a sustainable manner. Therefore, the outcome of this study will help as a guide line for the Ministry of Water, Irrigation and electricity of Ethiopia and Rift valley lakes basin authority for decision making and water resources development plan of the basin. The results of such study are also relevant to the product users for the applicability and potential of CHIRP satellite product for estimating catchment runoff and water budget studies in scarce data regions. In Lake Ziway area this study can contribute to filling the data gap in water budget studies which play a significant role for water resources development program. Overall, the study will help to produce good understanding for planners, researchers, policy decision makers, stakeholders and any concerned to the interaction among climate, human activities, and hydrological processes at the basin scale.

1.7 Thesis outline

This thesis consists of six chapters. **Chapter one** provides the general introduction and objectives of the studies. This chapter also indicates the state of the art review in terms of satellite rainfall application, hydrological and lake water balance model, water abstraction survey and water resources planning and management including the conceptual framework of the study followed in this study. The chapter also provides the general description of the study area and the main significance of the study.

Chapter two evaluates the performance of Climate Hazards Group InfraRed Precipitation (CHIRP) product at various spatiotemporal scales and further investigates hydrological assessment of gauge, uncorrected and bias-corrected CHIRP satellite rainfall inputs to evaluate the effect of bias correction and calibrated model parameters.

Chapter three evaluated the applicability of bias-corrected CHIRP satellite product for water level simulation using rainfall-runoff modeling where simulated runoff served as input to the lake water balance.

Chapters four assesses the impact of water abstraction on the water balance of Lake Ziway under three development pathways using lake water balance model.

Chapter five quantifies existing and future water demands thereby evaluating the likely impact of three water resources development pathways on the lake and its basin using Water Evaluation and Planning (WEAP) model.

Chapter six finalizes by presenting general discussion, conclusion of the entire work and future outlooks for further studies.

References

Abdo, K. S., Fiseha, B. M., Rientjes, T. H. M., Gieske, A. S. M., Haile, A. T. (2009). Assessment of climate change impacts on the hydrology of Gilgel Abay catchment in Lake Tana basin, Ethiopia.*Hydrological Processes*, *23*(26), 3661-3669. doi.org/10.1002/hyp.7363.

Adgolign, T. B., Rao, G. V. R. S., Abbulu, Y. (2015). WEAP modeling of surface water resources allocation in Didessa sSub-basin, West Ethiopia. *Sustainable Water Resources Management*, *2*(1), 55–70. doi.org/10.1007/s40899-015-0041-4.

Alemayehu, T., McCartney, M., Kebede, S. (2009). Modelling to evaluate the water resource implications of planned infrastructure development in the Lake Tana sub-basin, Ethiopia. *Ecohydrology and Hydrobiology* 10: 211–221. doi.org/10.2478/v10104-011-0023-6.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M. (1998). Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements. *Irrigation and Drainage Paper*, United Nations Food and Agriculture Organization (FAO), Rome, Italy, P, 300.

Artan, G., Gadain, H., Smith, J. L., Asante, K., Bandaragoda, C. J.,Verdin, J. P. (2007). Adequacy of satellite derived rainfall data for stream flow modeling. *Natural Hazards*, *43*(2), 167–185.

Awulachew, S. B., Yilma, A. D., Loulseged, M., Loiskandl, W., Ayana, M., Alamirew, T. (2007). Water resources and irrigation development in Ethiopia (Vol. 123). International Water Management Institute.

Ayenew, T. (1998). The hydrogeological system of the Lake District Basin, Central Main Ethiopian Rift. PhD thesis, Free University of Amsterdam. The Netherlands.

Ayenew, T. (2007). Water management problems in the Ethiopian rift: Challenges for development. *Journal of African Earth Sciences*, *48*(2/3), 222–236.

Belete, M., Diekkrüger, B., Roehrig, J. (2016). Characterization of water level variability of the Main Ethiopian Rift Valley Lakes. *Hydrology*, *3*(1), 1. doi.org/10.3390/hydrology3010001.

Chinnasamy, P., Bharati, L., Bhattarai, U., Khadka, A.,Wahid, S. (2015). Impact of planned water resource development on current and future water demand in the Koshi River basin, Nepal. *Water International, 8060*. doi.org/10.1080/02508060.2015.1099192.

Dessie, M., Verhoest, N. E. C., Pauwels, V. R. N., Adgo, E., Deckers, J., Poesen, J., Nyssen, J. (2015). Water balance of a lake with floodplain buffering: Lake Tana, Blue Nile Basin, Ethiopia. *Journal of Hydrology*, *522*, 174-186. doi.org/10.1016/j.jhydrol.2014.12.049.

Desta, H., Lemma, B., Stellmacher, T. (2017). Farmers' awareness and perception of Lake Ziway (Ethiopia) and its watershed management. *Limnologica-ecology and management o f Inland Waters*, *65*, 61-75. doi.org/10.1016/j.limno.2017.07.005.

Dinku, T. (2014). Validation of the CHIRPS satellite rainfall estimate. Seasonal Prediction of hydro-climatic extremes in the Greater Horn of Africa (GHA). *Proceeding of the 7th International precipitation Working Group (IPWG) Workshop*, Tsukuba, Japan.

Funk, C., Verdin, A., Michaelsen, J., Peterson, P., Pedreros, D., Husak, G. (2015). A global satellite-assisted precipitation climatology. *Earth System Science Data*, *7*(2), 275–287. doi.org/10.5194/essd-7-275-2015.

Habib, E., Haile, A. T., Sazib, N., Zhang, Y., Rientjes, T. (2014). Effect of bias correction of satellite-rainfall estimates on runoff simulations at the source of the Upper Blue Nile. *Remote Sensing*, *6*(7), 6688–6708.

Haerter, J. O., Hagemann, S., Moseley, C., Piani, C. (2011). Climate model bias correction and the role of timescales. *Hydrology and Earth System Sciences*, *15*(3), 1065–1079. doi.org/10.5194/hess-15-1065-2011.

Haile, A. T., Habib, E., Rientjes, T. (2013). Evaluation of the climate prediction center (CPC) morphing technique (CMORPH) rainfall product on hourly time scales over the source of the Blue Nile River. *Hydrological Processes*,*27*(12),1829-1839.doi.org/10.1002/hyp.9330.

Hargreaves, G. H., Allen, R. G.(1985). History & evaluation of Hargreaves evapotranspiration equation. *Journal of Irrigation and Drainage Engineering*, *129*(1), 53-63. doi.org/10.1061 /(ASCE)0733-9437(2003)129:1(53).

Huffman, G. J., Adler, R. F., Arkin, P., Chang, A., Ferraro, R., Gruber, A., … Schneider, U. (1997). The global precipitation climatology project (GPCP) combined precipitation dataset. *Bulletin of the American Meteorological Society*, *78*(1), 5–20.

Huffman, G. J., Bolvin, D. T., Nelkin, E. J., Wolff, D. B., Adler, R. F., Gu, G., … Stocker, E. F. (2007). The TRMM multisatellite precipitation analysis (TMPA): Quasi-global, multiyear, combined-sensor precipitation estimates at fine scales. *Journal of Hydrometeorology*, *8*(1), 38–55.

Jansen, H., Hengsdijk, H., Dagnachew, L., Tenalem, A., Hellegers, P., Spliethoff, P. (2007). *Land and water resources assessment in the Ethiopian Central Rift Valley*. 81.

Johansson, B. (2013). *IHMS Integrated Hydrological Modelling System Manual*. 144.

Joyce, R. J., Janowiak, J. E., Arkin, P. A., Xie, P. (2004). CMORPH: A method that produces global precipitation estimates from passive microwave and infrared data at high spatial and temporal resolution. *Journal of Hydrometeorology*, *5*(3), 487–503.

Katsanos, D., Retalis, A., Michaelides, S. (2016). Validation of a high-resolution precipitation database (CHIRPS) over Cyprus for a 30-year period. *Atmospheric Research*, *169*, 459–464.

Kebede, S., Travi, Y., Alemayehu, T., Marc, V. (2006). Water balance of Lake Tana and its sensitivity to fluctuations in rainfall, Blue Nile basin, Ethiopia. *Journal of Hydrology*, *316*(1–4), 233–247. doi.org/10.1016/j.jhydrol.2005.05.011.

Kumambala, P. G. (2010). Water Balance Model of Lake Malawi and its Sensitivity to Climate Change. *The Open Hydrology Journal*, *4*(1), 152-162. doi.org/10.2174/187437810100401 0152.

Legesse, D., & Ayenew, T. (2006). Effect of improper water and land resource utilization on the central Main Ethiopian Rift lakes. *Quaternary International*, *148*(1), 8-18. doi.org/10.101 6/j.quaint.2005.11.003.

Legesse, D., Vallet-Coulomb, C., Gasse, F. (2003). Hydrological response of a catchment to climate and land use changes in Tropical Africa: Case study South Central Ethiopia. *Journal of Hydrology*, *275*(1–2), 67–85. doi.org/10.1016/S0022-1694(03)00019-2.

Legesse, D., Vallet-Coulomb, C., Gasse, F. (2004). Analysis of the hydrological response of a tropical terminal lake, Lake Abiyata (Main Ethiopian Rift Valley) to changes in climate and human activities. *Hydrological Processes*, *18*(3), 487-504.doi.org/10.1002/hyp.1334.

Makin MJ, Kingham TJ, Waddams AE, Birchall CJ, Eavis BW. (1976). Prospects for irrigation development around Lake Ziway, Ethiopia. Land resources study division, Ministry of Overseas Development: Tolworth, UK.

MoWR. (1999). The Federal Democratic Republic of Ethiopia, Ministry of water resources Ethiopian water resources management policy.

Nicholson, S. E., Yin, X. (2001). Rainfall conditions in equatorial East Africa during the nineteenth century as inferred from the record of Lake Victoria. *Climatic Change*, *48*(2–3), 387–398.

Penman, H. L. (1948). Natural Evaporation from Open Water, Bare Soil and Grass. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *193*(1032), 120–145. doi.org/10.1098/rspa.1948.0037.

Rientjes, T. H. M., Perera, B. U. J., Haile, A. T., Reggiani, P., Muthuwatta, L. P. (2011). Regionalisation for lake level simulation – the case of Lake Tana in the Upper Blue Nile, Ethiopia. *Hydrology and Earth System Sciences*, *15*(4), 1167-1183. doi.org/10.5194/hess-15-1167-2011.

Seyoum, W. M., Milewski, A. M., Durham, M. C. (2015). Understanding the relative impacts of natural processes and human activities on the hydrology of the Central Rift Valley lakes, East Africa. *Hydrological Processes*, *29*(19),4312-4324. doi.org/10.1002/hyp10490.

Tesfagiorgis, K., Mahani, S.E., Krakauer, N.Y., Khanbilvardi, R. (2011). Bias correction of satellite rainfall estimates using a radar-gauge product-a case study in Oklahoma (USA). *Hydrology and Earth System Sciences*, *15*, 2631–2647. doi.org/10.5194/hess-15-2631-2011.

Teutschbein, C., Seibert, J. (2013). Is bias correction of regional climate model (RCM) simulations possible for non-stationary conditions? *Hydrology and Earth System Sciences*, 17, 5061–5077. doi.org/10.5194/hess-17-5061-2013.

Themeßl, M. J., Gobiet, A., Heinrich, G.(2012). Empirical-statistical downscaling and error correction of regional climate models and its impact on the climate change signal. Climate Change, 112, 449-468.

Tian, X., Dai, A., Yang, D., Xie, Z. (2007). Effects of precipitation bias corrections on surface hydrology over northern latitudes. *Journal of Geophysical Research: Atmospheres*, *112* (D14).

Vallet-Coulomb, C., Legesse, D., Gasse, F., Travi, Y., Chernet, T. (2001). Lake evaporation estimates in tropical Africa (Lake Ziway, Ethiopia). *Journal of Hydrology*, *245*(1–4), 1–18.

van Oel, P. R., Mulatu, D. W., Odongo, V. O., Meins, F. M., Hogeboom, R. J., Becht, R., … van der Veen, A. (2013). The effects of groundwater and surface water use on total water availability and implications for water management: The case of Lake Naivasha, Kenya.*Water Resources Management*, *27*(9), 3477–3492. doi.org/10.1007/s11269-013-0359-3.

Vernimmen, R.R., Hooijer, A., Aldrian, E., Van Dijk, A.I. (2012). Evaluation and bias correction of satellite rainfall data for drought monitoring in Indonesia. *Hydrology and Earth System Sciences*, *16*, 133–146. doi/org/10.5194/hess-16-133-2012.

Wale, A., Rientjes, T. H. M., Gieske, A. S. M., & Getachew, H. A. (2009). Ungauged catchment contributions to Lake Tana's water balance. *Hydrological Processes: An International Journal*, *23*(26), 3682–3693.

Wubet, F. D.; Awulachew, S. B., Moges, A. (2009). Analysis of water use on a large river basin using MIKE BASIN Model: a case study of the Abbay River Basin, Ethiopia.

Yatagai, A., Kamiguchi, K., Arakawa, O., Hamada, A., Yasutomi, N., Kitoh, A. (2012). APHRODITE: Constructing a long-term daily gridded precipitation dataset for Asia based on a dense network of rain gauges. *Bulletin of the American Meteorological Society*, *93*(9), 1401–1415.

Yong, B., Ren, L. L., Hong, Y., Wang, J. H., Gourley, J. J., Jiang, S. H., … Wang, W. (2010). Hydrologic evaluation of Multisatellite Precipitation Analysis standard precipitation products in basins beyond its inclined latitude band: A case study in Laohahe basin, China. *Water Resources Research*, *46*(7), 1–20. doi.org/10.1029/2009WR008965.

Yuan, F., Zhang, L., Win, K. W. W., Ren, L., Zhao, C., Zhu, Y., … Liu, Y. (2017). Assessment of GPM and TRMM multi-satellite precipitation products in streamflow simulations in a data-sparse mountainous watershed in Myanmar. *Remote Sensing*, *9*(3), 302.

Zeweldi, D. A., Gebremichael, M., Downer, C. W. (2011). On CMORPH rainfall for streamflow simulation in a small, Hortonian watershed. *Journal of Hydrometeorology*, *12*(3), 456–466.

2 Evaluation and Bias Correction of CHIRP Rainfall Estimate for Rainfall-Runoff Simulation over Lake Ziway Watershed, Ethiopia

Abstract: In Lake Ziway watershed in Ethiopia, the contribution of river inflow to the water level has not been quantified due to scarce data for rainfall-runoff modeling. However, satellite rainfall estimates may serve as an alternative data source for model inputs. In this study, we evaluated the performance and bias correction of Climate Hazards Group InfraRed Precipitation (CHIRP) satellite estimate for rainfall-runoff simulation at Meki and Katar catchments using the Hydrologiska Byråns Vattenbalansavdelning (HBV) hydrological model. A non-linear power bias correction method was applied to correct CHIRP bias using rain gauge data as a reference. Results show that CHIRP has biases at various spatial and temporal scales over the study area. The CHIRP bias with percentage relative bias (PBIAS) ranging from −16 to 20% translated into streamflow simulation through the HBV model. However, bias-corrected CHIRP rainfall estimate effectively reduced the bias and resulted in improved streamflow simulations. Results indicated that the use of different rainfall inputs impacts both the calibrated parameters and its performance in simulating daily streamflow of the two catchments. The calibrated model parameter values obtained using gauge and bias-corrected CHIRP rainfall inputs were comparable for both catchments. We obtained a change of up to 63% on the parameters controlling the water balance when uncorrected CHIRP satellite rainfall served as model inputs. The results of this study indicate that the potential of bias-corrected CHIRP rainfall estimate for water balance studies.

Keywords: CHIRP; satellite rainfall; rainfall-runoff simulation; bias correction; Lake Ziway; Meki; Katar; Ethiopia

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2.1 Introduction

Rainfall-runoff modeling requires accurate rainfall input data. The accuracy of the rainfall input significantly influences the performance of hydrological models. However, accurate and consistent rainfall observations are limited in many regions, particularly in developing countries, due to limited rain gauge networks and density of deployment (Fuka et al., 2014; Gebremicheal. 2014). Satellite rainfall estimates (SREs) may serve as an alternative data source for model inputs, as they provide rainfall estimate at various temporal and spatial coverage, including ungauged basins (Duka et al., 2014; Katsanos et al., 2016). Nevertheless, the results of previous studies indicate that SREs can be subjected to substantial biases (Yong et al., 2010; Habib et al., 2014; Yuan et al., 2017). Hence, it is necessary to either minimize or remove the bias before the SREs can be used in any subsequent applications.

SREs derive rainfall datasets from either passive microwave (PMW) or thermal infrared (TIR), or a combination of both (Tapiador et al., 2004). PMW depends on the relationship between the radiance in the microwave channel and precipitation, such as Asian Precipitation Highly Resolved Observational Data Integration towards Evaluation of water resources (APHRODITE; Yatagai et al., 2012). TIR estimate relies on cloud top temperature threshold values and is relatively available at high temporal resolutions. Examples of TIR include Global Precipitation Climatology Centre (GPCC; Huffman et al., 1997), Climate Prediction Centre Morphing Technique (CMORPH; Joyce et al., 2004), and Climate Hazards Group Infra-Red Precipitation (CHIRP; Funk et al., 2015), among others. However, very few of these satellite products have been evaluated over eastern Africa (Haile et al., 2013; Habib et al., 2014; Dinku et al., 2018).

Previous studies on validation and inter-comparison of satellite products indicate that they are subjected to systematic (i.e., bias) and random errors (Vernimmen et al., 2012; Habib et al., 2014; Bhati et al., 2016). The sources of these errors may arise from an error in sampling, rain gauge data coverage, bias correction, and retrieval algorithms, among others. These studies have also shown that biases can be minimized or removed by applying a bias correction algorithm to compare with rain gauge data. A bias correction algorithm may vary from linear (Berg et al., 2012) to a multiple moment distribution matching (Haerter et al., 2015) of a variable at a time. The selection of the bias correction method depends on the accuracy, the data requirement, and the hydrologic application that the bias-corrected dataset can be used in (Habib et al., 2014).

Bias corrections have been applied in a number of previous satellite studies, such as (Xue et al., 2013; Habib et al., 2014; Yuan et al., 2017). Yuan et al. (2017) showed that linear bias correction applied to Global Precipitation Measurement (GPM) and Tropical Rainfall Measuring Mission (TRMM) effectively improved the streamflow simulations. Habib et al. (2014) showed that applying space and time fixed bias correction schemes in CMORPH revealed improved runoff simulation. Yong et al. (2014) indicated that a bias-corrected rainfall product as the model input instead of an uncorrected product revealed improved performance on rainfall-runoff simulation.

Several studies also reported that a hydrologic model parameter requires recalibration when satellite rainfall data replace rain gauge data as model inputs (Artan et al., 2007; Zeweldi et al., 2011; Vernimmen et al., 2012). They indicated an increase of hydrological model performance when the model was calibrated using SREs rather than rain gauge data. However, Worqlul et al. (2018) calibrated the hydrological model for gauge, uncorrected, and bias-corrected Multi-Sensor Precipitation Estimate-Geostationary (MPEG) rainfall inputs in the upper Blue Nile basin in Ethiopia. They found that calibration of the model using different rainfall inputs resulted in different parameter values. Yong et al. (2010) showed the requirement of recalibrating sensitive parameters that control the hydrologic model using different rainfall inputs during the validation period. Similar findings were also reported in other studies such as (Habib et al., 2014; Lakew et al., 2017). It is expected that different inputs might affect model performance and require different sets of parameters. However, studies that incorporate model parameters and rainfall input uncertainties are limited. Furthermore, the results of error tolerance and propagation into hydrologic model prediction are not consistent and need further assessment.

In the Central Rift valley lakes basin, rain gauge stations are sparse and unevenly distributed. Furthermore, some of the available rain gauge networks are inadequate to simulate reliable rainfall-runoff modeling, mainly due to sparse spatial coverage, a short length of records, and substantial missing data. Hence, satellite rainfall estimates at high spatiotemporal resolution may help to overcome these shortcomings. Therefore, the evaluation of satellite rainfall product over Lake Ziway watershed is crucial to fill the data gap in water budget studies. Most of the previous studies in Ethiopia over other parts of the basin have been conducted using coarse-resolution satellite rainfall products. In the present study, we focus on the use of relatively high space–time resolutions ($0.05° \times 0.05°$, daily) and Climate Hazards Group InfraRed Precipitation (CHIRP) satellite rainfall for rainfall-runoff simulation at Meki and Katar catchments.

The main objectives of this study are: (i) to evaluate the performance of CHIRP satellite product at different spatiotemporal scales, (ii) to assess the effect of gauge, uncorrected, and bias-corrected CHIRP satellite rainfall inputs on calibrated model parameters and the model performance on streamflow simulations. To achieve these objectives, we devised the following steps: first, CHIRP satellite estimate was compared with the rain gauge rainfall at various spatial and temporal scales using graphical comparison and different statistical measures. Next, a non-linear power bias correction method was applied to correct the CHIRP rainfall estimate using available rain gauge stations in the study area. Then, a semi-distributed Hydrologiska Byråns Vattenbalansavdelning (HBV) hydrological model was used to calibrate and simulate streamflow driven by gauge, uncorrected, and bias-corrected CHIRP satellite rainfall inputs at Meki and Katar catchments.

The CHIRP satellite was selected in this study due to its relatively high spatiotemporal resolutions and its availability at consistent time series matching the rain gauge data interval and the time step of the hydrological model used in this study. Although the performances of satellite products are highly variable in space and time, previous inter-comparison studies of satellite rainfall products over the eastern Africa region indicate that the CHIRP satellite rainfall product performance is slightly better than other products due to high spatiotemporal resolutions (Khandu et al., 2016; Ayehu et al., 2018; Dinku et al., 2018). Hence, in this study, CHIRP was selected. The results of this study provide information for the product users regarding the applicability of the CHIRP rainfall product for estimating catchment runoff in data scarce regions. In the Lake Ziway area, this study can contribute to filling the data gap in water budget studies, which play a significant role for water resources development programs in the study area.

2.2 Study Area and Data

2.2.1 Study Area

The study area is Meki and Katar catchments, which are the major tributaries of Lake Ziway, located in the Central Rift Valley (CRV) lakes basin of Ethiopia with a total land surface area of

7022 km^2. They are situated between 7.43°–8.58° N latitudes and 38.20°–39.25° E longitudes and drain the western and the eastern plateaus, respectively. The catchment area covers 6570 km^2, of which the gauged catchment covers 5783 km^2 (82% of the total Lake Ziway drainage area). The basin topography is characterized by mountainous terrain over east and west boundaries with an elevation ranging from 1600 to 4200 m above sea level (Figure 2.1).

Lake Ziway subbasin has tropical climate conditions with a mean monthly average temperature of the catchments ranging from 15.6 to 22.5 °C. The average annual rainfall of the catchment ranges from 740 to 1170 mm and from 750 to 1220 mm on the Meki and the Katar catchments, respectively. The rainfall in the rainy season (June to September) accounts for almost 60–70% of the total annual rainfall. Figure 2.1 shows the location of the study area with meteorological, river gauge and elevations indicated.

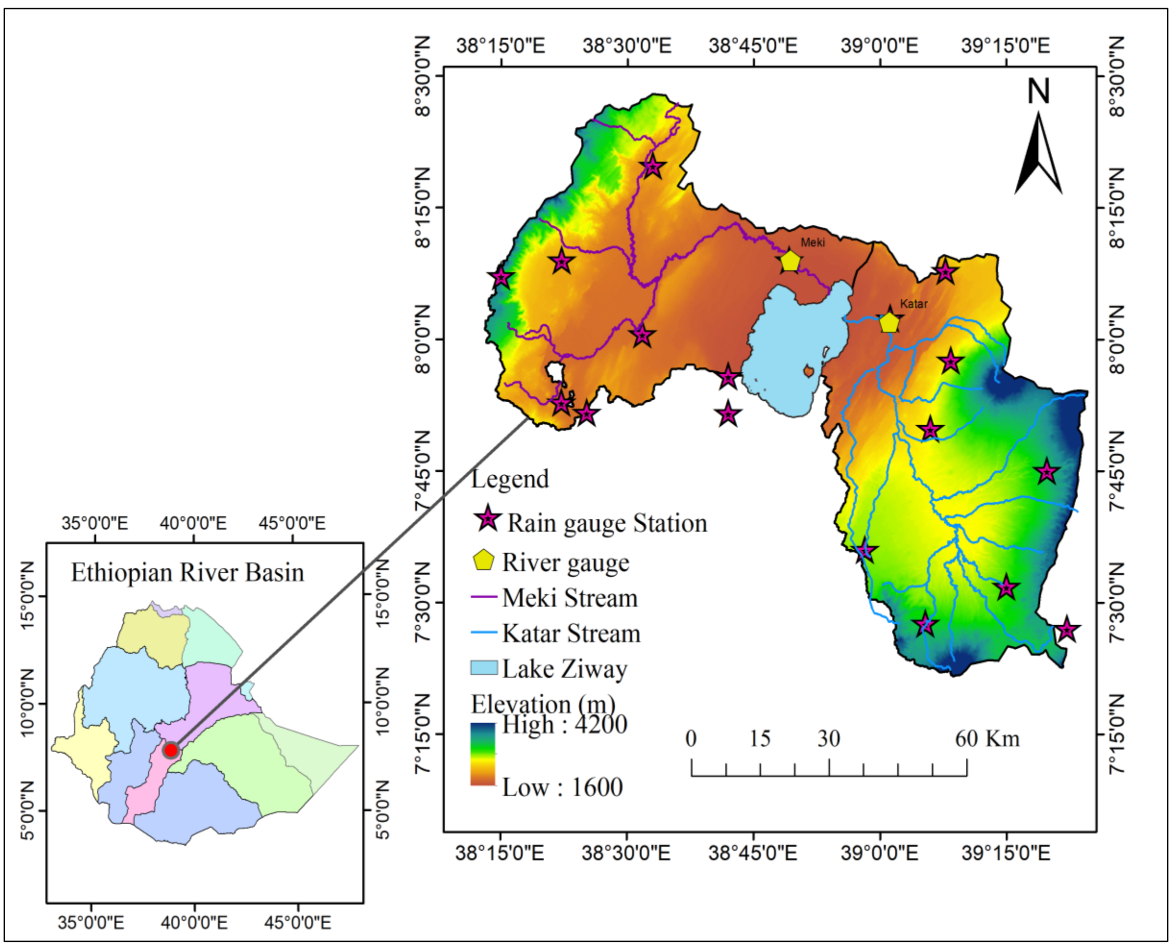

Figure 2.1. Location of the study area in relative to Ethiopian river basin with topography and location of rain gauge and stream gauge stations in Lake Ziway drainage area

2.2.2 Datasets

2.2.2.1 Rain gauge data

Daily rain gauge data for 20 meteorological stations from 1984 to 2014 were obtained from the National Meteorological Agency of Ethiopia. The dataset includes precipitation, maximum and minimum temperature, wind speed, humidity, and sunshine duration. Existing meteorological records in the study area are limited in both space and time. Data quality checks, homogeneity, and outlier tests were performed. After data screening, 14 rain gauge stations out of 20 stations were found to be reliable with relatively consistent records. In this study, these rain gauge datasets were used to simulate gauge-based streamflow and as a reference for comparison and bias correction of the satellite rainfall data.

Daily river discharge data are available for Meki and Katar Rivers, which are gauged at Meki and Abura town, respectively. Those data were obtained from the Ministry of Water, Irrigation and Electricity hydrology department database of Ethiopia. The data cover the period 1984–2000 at daily time steps. These observed data were used as a reference to compare and calibrate the hydrological model parameters as a result of different rainfall inputs.

2.2.2.2 Satellite Rainfall data

The Climate Hazards Group InfraRed Precipitation (CHIRP) satellite product was used in this study. The CHIRP satellite was recently developed by the US Geological Survey (USGS) in collaboration with the Climate Hazards Group at the University of California. CHIRP uses TIR satellite rainfall estimates combined with the globally gridded satellite from National Oceanic and Atmospheric Administration (NOAA) to produce the rainfall dataset.

The CHIRP product has the potential to produce a near-real time satellite estimate at relatively high spatiotemporal resolution covering regions between 50°S to 50°N latitudes and all longitudes. The CHIRP rainfall datasets are available for the period 1981 to near-present at http://chg.geo.uscb.edu/data. In this study, the CHIRP rainfall estimate at daily and at 0.05° × 0.05° spatial scales for the period 1984-2016 are used. For detailed descriptions about the CHIRP product, refer to (Funk et al., 2014, 2015).

2.3 Methods

2.3.1 Evaluation of CHIRP Satellite Rainfall

We applied a graphical comparison plot and statistical measures to evaluate the performance of CHIRP satellite data at various spatiotemporal scales. First, we evaluated the CHIRP satellite product through visual inspection of scatter plots at catchment average daily and monthly scales. Then, the CHIRP satellite rainfall was quantitatively evaluated against rain gauge observations using five performances of statistical measures at point and catchment scales on a daily and a monthly basis. The selected performance statistical measures included Pearson correlation coefficient (CC), percentage relative bias (PBIAS), mean error (ME), mean absolute error (MAE), and root mean square error (RMSE). The CC indicates the agreement in terms of dynamics between the satellite estimate and the rain gauge observation. The PBIAS represents the relative systematic bias of the satellite rainfall from the rain gauge observation. The ME and the MAE provide information on average and magnitude of error, respectively. The RMSE measures the average absolute errors of satellite rainfall, with smaller values indicating the closure between the two datasets.

In addition to the numerical statistical measures, three categorical validation statistics were used to assess the performance of the satellite in rain intensity detection capability. These verification statistics included probability of detection (POD), false alarm ratio (FAR), and citical success index (CSI), following biases (Yong et al., 2010; Xue et al., 2013;Ayehu et al., 2018).

POD was used to assess the observed rain events that were correctly detected by the satellite. FAR represents the observed rain events that were incorrectly detected by the satellite. The CSI measured the overall correspondence between the satellite and the rain gauge occurrence of rain events. These categorical verification statistics referred to the skill of a satellite estimate for detection of observed rainfall events, taking into account a threshold value for the presence of rain or no rain to separate events at any time scale (e.g. daily, monthly, etc.). The metrics were derived from a contingency term in which the letters H, F, and M represent, respectively, hits (event forecasted to occur and did occur), false alarms (event forecasted to occur but did not occur), and missing (event forecasted not to occur but did occur). A threshold value of 1 mm day^{-1} in each grid cell and rain gauge station was assumed in this study, following (Yong et al., 2010; Ayehu et al., 2018; Dinku et al., 2018). The values of POD and CSI varied from 0 to 1, with a perfect score when a value of 1 registered with a value of 0 for FAR. The statistical measures were evaluated at various spatial (point, catchment) and temporal (daily, monthly) scales from 1985 to 2000. The equations for all numerical and categorical metrics along with their descriptions are summarized in Table 2.1.

To further assess the season variation between the satellite and the rain gauge, the mean monthly rainfall amounts of the respective datasets for Meki and Katar catchments were compared. The rain gauge rainfall was from an ensemble of 14 rainfall stations (6 for Meki and 8 for Katar catchments), and the satellite data were from 215 grid cells aggregated to mean monthly for both catchments. Then, the mean monthly rainfall pattern and the season rainfall difference for the rainy season (June–September) and the dry season (October–February) were compared between the two datasets.

Table 2.1. Statistical measures used for performance evaluation of the satellite product

S. No	Statistical Measures	Equation	Unit	Best Fit
1	Pearson correlation coefficient (CC)	$\mathrm{CC} = \frac{\sum_{i=1}^{n}(G_i - \bar{G})(S_i - \bar{S})}{\sqrt{\sum_{i=1}^{n}(G_i - \bar{G})^2}\sqrt{\sum_{i=1}^{n}(S_i - \bar{S})^2}}$	-	1
2	Percentage relative bias (PBIAS)	$\mathrm{PBIAS} = \frac{\sum_{i=1}^{n}(S_i - G_i)}{\sum_{i=1}^{n} G_i} \times 100\%$	%	0
3	Mean error (ME)	$ME = \frac{1}{n}\sum_{i=1}^{n}(S_i - G_i)$	mm	0
4	Mean absolute error (MAE)	$MAE = \frac{1}{n}\sum_{i=1}^{n}\lvert S_i - G_i\rvert$	mm	0
5	Root mean squared error (RMSE)	$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(S_i - G_i)^2}{n}}$	mm	0
6	Probability of detection (POD)	$POD = \frac{H}{H+M}$	-	1
7	False alarm ratio (FAR)	$FAR = \frac{F}{H+F}$	-	0
8	Critical success index (CSI)	$CSI = \frac{H}{H+M+F}$	-	1

Note: G_i, gauged rainfall; S_i, satellite rainfall; n, number of samples of rainfall data pair time series; $\bar{G}$ and $\bar{S}$ are the mean of gauge and satellite rainfall dataset, respectively; H (Hit) represents the number of rain events correctly detected by the satellite; M (missed) refers to the number rain events not detected by the satellite, F (False) represents the number of rain events detected by the satellite but not observed by the rain gauge.

2.3.2 CHIRP Satellite Bias Correction

We note that satellite rainfall estimates are subject to substantial systematic errors (Yong et al., 2010; Habib et al., 2014; Yuan et al., 2017). These errors may produce uncertainty in the hydrological model, which could result in under or overestimation of the simulated streamflow. Furthermore, model parameter values obtained using uncorrected SREs inputs into the model might not respond with reliable estimates of the watershed characteristics (Bitew et al., 2012). Therefore, biases in rainfall estimate must be corrected before it can be used as input into a hydrological model for streamflow simulation. In this study, the bias of the uncorrected CHIRP satellite estimate was corrected using the non-linear power transformation bias correction method (Vernimmen et al., 2012; Lafon et al., 2013). The approach is based on matching the probability distribution function (such as mean, standard deviation, coefficient of variation) of the CHIRP with that of the rain gauge data. The equation reads:

$$P_c = aP_o{}^b \qquad (2.1)$$

where P_c is bias-corrected CHIRP rainfall, P_o is original satellite-only (uncorrected) rainfall, and a and b are bias factors.

The values of bias factors were determined iteratively until the observed value matched with the CHIRP satellite by jointly arranging the whole daily data of both data sources for each month over the period 1985–2000. First, the bias factor (b) was estimated with a coefficient of variance of the satellite that matched with that of the rain gauge. Then, the bias factor (a) was determined by adjusting the mean of the satellite and the rain gauge datasets (Wörner et al., 2019). The bias factor at the selected 14 grid pixels was estimated at a minimum zero error objective function using the Excel Solver function available in the Microsoft Excel program. Then, the bias factors were applied on a monthly basis for the entire dataset. For other grid cells that did not contain rain gauge stations, the bias factors were interpolated using inverse distance weighted (IDW) methods. The bias-corrected areal CHIRP rainfall for the respective catchments was estimated using the Thiessen polygon from representative grid pixels and was then used as input in the hydrological model.

To verify the bias correction algorithm and to show the improvement obtained after bias correction, we applied a comparison of all statistical measures between daily bias-corrected satellite and rain gauge datasets. In addition, plots of cumulative distribution function (CDF) between gauge, uncorrected, and bias-corrected satellite rainfall at areal catchment average basis were compared for both Meki and Katar catchments.

2.3.3 HBV Hydrological Model

In this study, we applied the Integrated Hydrological Modeling System (IHMS) version 6.3 HBV rainfall-runoff model for streamflow simulation. The HBV model was selected in this study due to its proven performance over Ethiopian catchments (Abdo et al.,2009; Wale et al.,2009; Rientjes et al.,2011; Habib et al.,2014; Worqlul et al.,2015). The model also allowed us to divide the modeling domain into multiple sub-catchments, elevation, and land use zones. The climate and the hydrological input data for the simulation included daily rainfall, temperature, potential evapotranspiration, and river discharge. The catchment potential evapotranspiration was estimated by the Penman-Monteith (Allen et al., 1998) method from eleven meteorological stations. The areal potential evapotranspiration over the catchment was computed using the Thiessen polygon method from representative stations and then used as input of the hydrological model.

The HBV model consists of subroutines for precipitation, soil moisture accounting, runoff generation, and routing routine. Precipitation routines ensure that precipitation is either simulated as snow or rain. In the Lake Ziway catchment area, precipitation was simulated only in the form of rainfall. The soil moisture routine controls the formation of runoff based on FC, BETA, and LP parameters. FC is the field capacity at maximum soil moisture storage. BETA accounts for non-linearity of indirect runoff from the soil layer. LP is the limit of potential evaporation, which indicates the soil moisture value above which actual evapotranspiration reaches its potential value. The runoff generation routine transforms excess water from the soil moisture zone to runoff. The relation of runoff routine is expressed by:

$$Q_u = K_u \times UZ^{(1+Alfa)} \quad (2.2)$$

$$Q_L = K_4 \times LZ \quad (2.3)$$

where Q_u and Q_L are the runoff components from upper and lower reservoir zones, respectively; K_u is the recession coefficient in the upper zone, and K_4 is the recession coefficient in the lower zone; UZ and LZ are the actual storages in the upper and the lower zones, respectively; *Alfa* is a measure of the non-linearity of the flow in the upper reservoir zone. The total sum of the upper and lower runoff routine yields the amount of the streamflow generated at the catchment outlet.

In this study, the parameters used for model calibration were selected from previous studies (Wale et al., 2009; Rientjes et al., 2011; Worqlul et al., 2018). Accordingly, eight model parameters (FC, BETA, LP, K4, Khq, Alfa, CFLUX, and PREC) were selected for model calibration. The ranges and the initial values of these parameters were defined as recommended by (Johansson, 2013). A detailed description of the HBV model is available in (Lindström et al., 1997; Johansson, 2013). Table 2.2 presents the summary of the descriptions, the value ranges (minimum–maximum), and the initial values of the selected calibrated parameters.

Table 2.2. Hydrologiska Byråns Vattenbalansavdelning (HBV) model calibrated parameters and their descriptions

Parameter	Description	Unit	Value Range	Initial Value
FC	Field capacity at maximum soil moisture storage	mm	100–1500	200
BETA	The exponent in drainage from the soil layer	-	1–4	2.0
LP	The limit for the potential evapotranspiration	-	0.1–1	0.9
K4	The recession coefficient for the lower zone	d^{-1}	0.001–0.1	0.01
Khq	The recession coefficient for the upper zone	d^{-1}	0.005–0.5	0.1
Alfa	The coefficient for non-linearity of flow	-	0–1.5	0.6
CFLUX	The maximum capillary flow from the upper zone	mm	0–2	1.0
PERC	Percolation capacity from upper to the lower zone	mmd^{-1}	0.01–6	0.5

2.3.3.1 Model Calibration and Evaluation

In this study, the HBV model was calibrated and verified for an independent validation period using three rainfall datasets. These were gauge, uncorrected, and bias-corrected CHIRP satellite rainfall data. For each dataset, the HBV model parameters were calibrated by comparing the simulated streamflow against the observed discharge data at Meki and Katar river gauge stations. To aid model calibration, sensitive model parameters were identified based on the model performance objective function values. For comparison of sensitive calibrated model parameter values over a common scale, we normalized between the minimum and the maximum value range. A manual model calibration by changing one parameter value at a time within the allowable range was applied to obtain the optimal parameter values. Then, the most sensitive parameters that control runoff volume were calibrated first, followed by the routing parameters. The model calibrations run from 1986–1991 periods for Meki and Katar catchments. Then, the model was validated for an independent period from 1996–2000 for both catchments. The 1984–1985 periods was used as the warm-up period for initializing the levels of the model reservoirs. Note that substantial data records from 1992–1995 are missing, hence this period was not considered either for calibration or validation.

The simulated streamflows from the three datasets were compared to the observed streamflow to assess the model performance for rainfall-runoff simulations. The model performance was evaluated using Nash–Sutcliffe efficiency (NSE) and relative volume error (RVE) in addition to visual inspection of the simulated hydrograph. NSE measures the agreement between the simulated and the observed hydrographs. RVE measures the average volume difference between the simulated and the observed streamflow. The equations for both objective functions are:

$$NSE = 1 - \frac{\sum_{i=1}^{n}\left(Q_{sim,i} - Q_{obs,i}\right)^2}{\sum_{i=1}^{n}\left(Q_{obs,i} - \overline{Qobs}\right)^2} \tag{2.4}$$

$$RVE = \left[\frac{\sum_{i=1}^{n}\left(Q_{sim,i} - Q_{obs,i}\right)}{\sum_{i=1}^{n} Q_{obs,i}}\right] \times 100\% \tag{2.5}$$

where Q_{sim} and Q_{obs} represent simulated and observed streamflow, respectively (m^3s^{-1}), and the over-bar symbol denotes the mean of the statistical values; *i* is the time step; *n* is the number of a sample size of a paired data time series. NSE has a dimensionless value ranging from $-\infty$ to 1.0, 1.0 corresponding to a perfect fit. RVE ranges between $-\infty$ and ∞, but the model performs best when a value of 0 is obtained. A value between +5% and -5% indicates that a model performs very well while a value between ±5 and ±10% indicates that a model has reasonably good performance.

2.4 Results and Discussion

2.4.1 Comparsion of CHIRPat multiple spatiotemporal scales

The scatter plots in Figure 2.2 compare the satellite products (uncorrected) and the gauge rainfall at daily and monthly time scales for Meki and Katar catchments. The data plots are shown for areal average at the catchment level covering the period from 1985 to 2000. There was wide scatter for both catchments, indicating strong disagreement between the uncorrected and the rain gauge observation at daily time scales. Few data points were spread along the 45° degree line, indicating a poor correlation between the two datasets with correlations of 0.37 and 0.40 for Meki and Katar catchments, respectively. On average, rainfall amounts up to 45 mm per day were missed by CHIRP for both catchments. However, for monthly time scale comparison, more data points were close to the 45° degree line, indicating a better agreement of the satellite estimate with the rain gauge observation. This phenomenon might be related to the performance of the CHIRP satellite estimate at seasonal time scales.

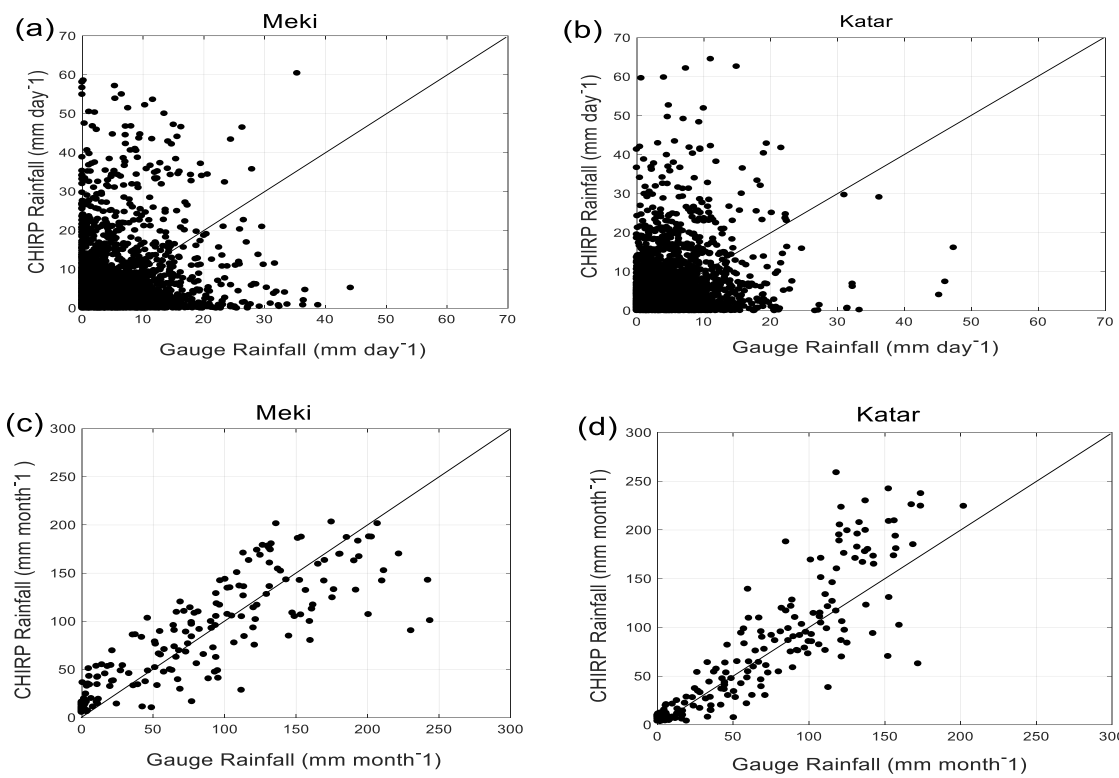

Figure 2.2. Scatter plots of Climate Hazards Group InfraRed Precipitation (CHIRP) satellite rainfall products against rain gauge rainfall for a time series from 1985–2000, for (a) and (b) daily at Meki and Katar catchment, (c) and (d) monthly at Meki and Katar catchments, respectively

2.4.1.1 Point-scale daily rainfall comparison

The performance of the CHIRP satellite estimate was evaluated by comparing it with 14 rain gauge stations based on statistical measures at daily scales from 1985 to 2000. We selected six stations (i.e., Bui, Butajira, Koshe, Meki, Tora, and Ziway) that are located at Meki catchment and eight stations (i.e., Arata, Assela, Bekoji, Dagaga, Ketera Genet, Kulumsa, Merero, and Ogolcho) from Katar catchment to evaluate the performance of the CHIRP satellite estimate

Table 2.3 shows the result of both numerical and verification statistical measures obtained by comparing each grid with rain gauge stations at daily time scales. We note that CHIRP showed poor performance in the majority of the stations at a daily time step. The CC values ranged from 0.17 to 0.4 (less than 0.5), which indicated a poor correlation of the CHIRP satellite with gauge rainfall. The results show that the correlation varied from one station to another—lower at Arata, Tora, and Ogolcho stations and relatively higher at Merero, Bekoji, and Dagaga stations. This phenomenon is related to the performance of the CHIRP satellite at lower and higher rainfall regions, respectively.

The PBIAS result showed that CHIRP overestimated in most of the stations except for underestimations in Tora (−15%) and Assela (−16%), where they revealed a negative PBIAS (Table 2.3). The possible reason for this could be that both stations are located in relatively higher elevation regions as compared to the other stations. Dinku (2014) and Khandu et al. (2016) reported similar results over Eastern Africa and Bhutan, respectively. The mean error revealed to be relatively smaller compared to other performance measures. Butajira and Kulumsa stations showed a smaller error with relatively similar altitude locations. In terms of MAE and RMSE, most of the stations contained similar error magnitude.

The categorical measures also showed POD values ranging from 0.51 to 0.69, indicating that the CHIRP satellite correctly detected the observed rain events by a maximum of 69% over the study area (Table 2.3). According to Table 2.3, the FAR values for most of the rain gauge stations were greater than 0.5, implying that over 50% of observed rain events were incorrectly detected by the satellite. Furthermore, the values of CSI registered smaller values less than 0.5 in all the rain gauge stations and the corresponding grid cells, indicating the error of the CHIRP satellite with the rain gauge dataset. It is in this aspect that the application of bias correction is necessary to remove the bias before it can be used for streamflow simulation.

Table 2.3. Daily comparison of 14 rain gauges and the CHIRP satellite at point scale from 1985–2000

Catchment	Stations	Statistical Measures							
		CC (-)	PBIAS (%)	ME (mm d^{-1})	MAE (mm d^{-1})	RMSE (mm d^{-1})	POD (-)	FAR (-)	CSI (-)
Meki	Bui	0.29	8.99	0.25	3.50	6.88	0.69	0.56	0.36
	Butajira	0.23	2.05	0.06	3.98	7.97	0.57	0.55	0.39
	Koshe	0.22	6.87	0.16	3.38	7.32	0.56	0.67	0.30
	Meki	0.22	5.76	0.12	3.04	6.71	0.66	0.66	0.29
	Tora	0.17	−15.99	−0.41	3.46	7.52	0.62	0.65	0.29
	Ziway	0.20	18.46	0.36	3.09	6.49	0.69	0.68	0.28
Katar	Arata	0.17	10.29	0.23	3.27	7.19	0.56	0.60	0.31
	Assela	0.26	−14.96	−0.43	3.34	6.70	0.69	0.46	0.43
	Bekoji	0.32	14.64	0.43	3.47	6.76	0.51	0.34	0.49
	Dagaga	0.28	11.23	0.32	3.48	6.81	0.67	0.36	0.49
	K.Genet	0.23	19.64	0.44	3.08	6.35	0.68	0.51	0.40
	Kulumsa	0.21	3.67	0.08	3.20	6.81	0.56	0.52	0.35
	Merero	0.40	18.96	0.53	2.90	5.43	0.59	0.26	0.48
	Ogolcho	0.18	6.51	0.14	3.14	6.97	0.67	0.63	0.32

2.4.1.2 Point-Scale Monthly Rainfall Comparison

Figure 2.3 shows the selected statistical measures for 14 rain gauge stations compared against the grid cells at a monthly period from 1985 to 2000. The figures illustrate that the agreement between the CHIRP satellite and the rain gauge stations significantly improved when the daily data were aggregated to a monthly scale. We note that the correlations for all stations were increased above 0.5. The probable reason for this improvement was because the CHIRP satellite might have captured the temporal pattern of seasonal rainfall over the study area.

The PBIAS for monthly basis remained the same as the daily scale. However, higher values of MAE and RMSE error magnitude revealed up to 44 and 62 mm, respectively, indicating the error between the satellite and the rain gauge stations. In general, at a monthly time scale, the CHIRP satellite performed relatively poorly at Ogolcho, Butajira, Arata, and Tora stations as compared to other stations, which showed relatively lower CC and higher values of PBIAS, ME, MAE, and RMSE (Figure 2.3).

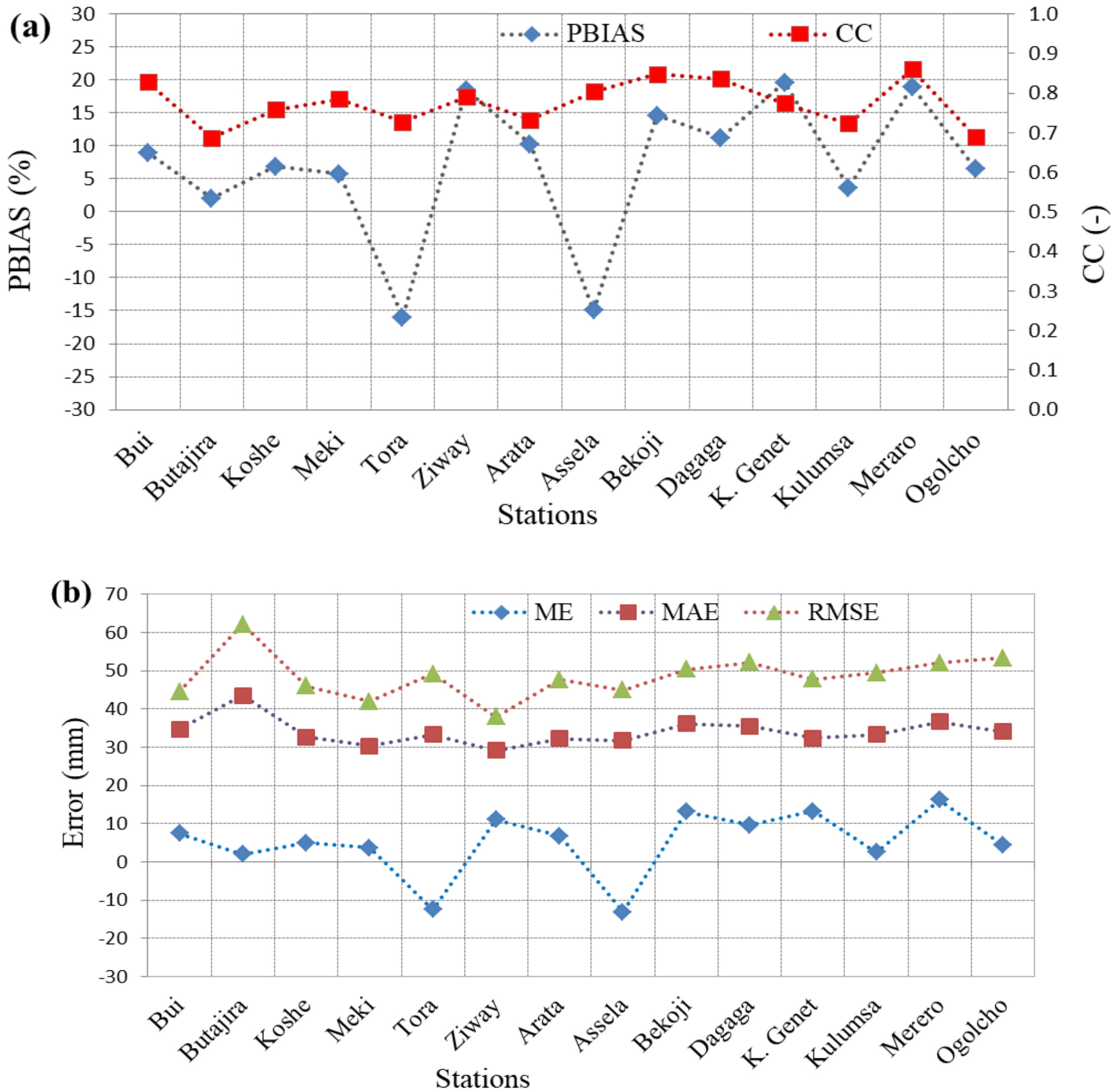

Figure 2.3. Monthly comparison of CHIRP rainfall estimate against 14 rain gauge stations time series from 1985–2000 (a) PBIAS and CC; (b) error (ME, MAE, and RMSE)

2.4.1.3 Catchment-Scale Rainfall Comparison

To evaluate the performance of the CHIRP satellite at the catchment scale, the comparison was performed between daily areal average rainfall from the rain gauge and the satellite. Figure 2-4 shows the daily rainfall time series comparison of the rain gauge and the satellite at Meki and Katar catchments. The figure indicates that the CHIRP satellite rainfall better captured the temporal variations of the daily gauge rainfall at both catchments. However, the agreement for Katar catchment was better than for Meki catchment, as there were some observed extreme peaks not effectively captured by the satellite. This phenomenon was partly attributed to the sparse rain gauge network in Meki catchment compared to Katar.

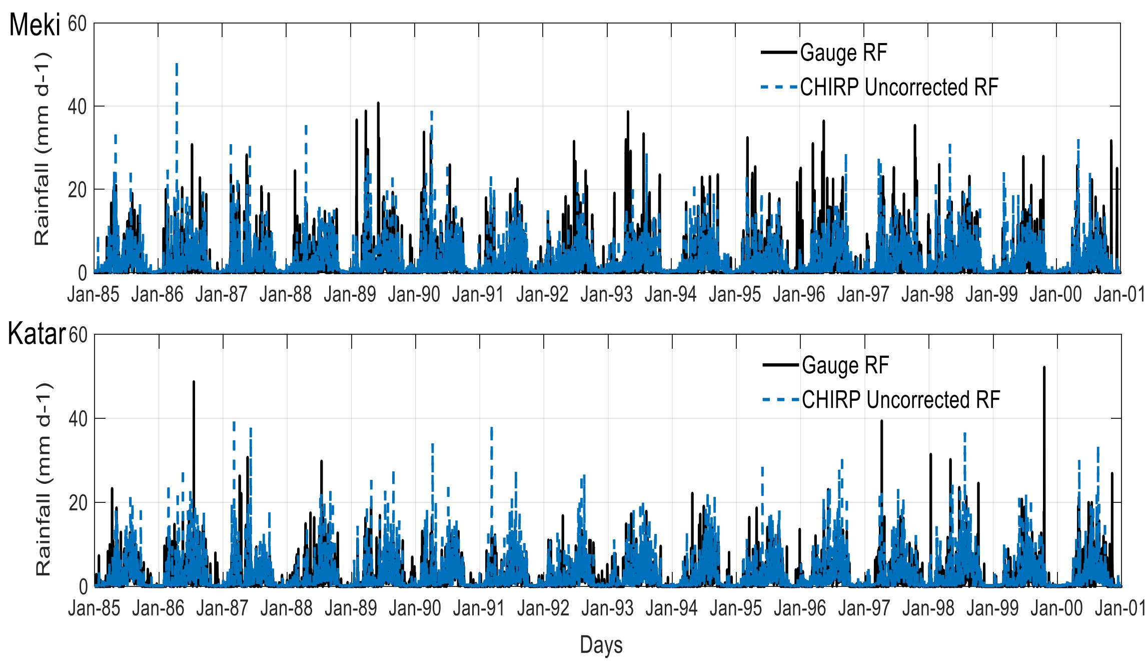

Figure 2.4. Comparison of daily CHIRP rainfall estimate against the gauge rainfall at Meki and Katar catchments for a time series from 1985 to 2000

Table 2.4 shows the comparison of the CHIRP satellite with the gauge counterparts at a daily catchment level. At a daily time scale, the CHIRP satellite showed poor correlation with the rainfall from the rain gauges for both catchments, with CC values of 0.37 and 0.40 for Meki and Katar catchments, respectively. PBIAS results showed that CHIRP overestimated at Meki with a positive bias of 3.8% and underestimated over Katar catchment with a negative bias value of −2.0%. The ME revealed a smaller value of 0.1 mm for Meki and 0.3 mm for Katar catchment. The magnitude of the error in terms of RMSE and MAE revealed almost similar error values for both catchments.

The POD results showed that 62% and 70% of the rain gauge rainfall events were correctly detected by the CHIRP for Meki and Katar catchments, respectively. The observed rainfalls that were not detected by the satellite reached up to 39% for Meki and 25% for Katar catchments (Table 2-3). The CSI resulted in 0.45 and 0.50 for Meki and Katar catchments, respectively, which measured the overall correspondence of the satellite and the rain gauge occurrence of rain events. Overall, the results showed relatively better performance for Katar than Meki catchment in terms of all statistical measures. Possible reasons for the better performance of Katar catchment were due to a relatively higher rainfall in the region and a larger number of rain gauge networks compared to Meki catchment. Khandu et al.’s study (2016) also indicated that the CHIRP satellite performed slightly better in the higher rainfall region over Bhutan.

Table 2.4. Catchment scale daily average rainfall comparison from the rain gauge and the CHIRP satellite from 1985–2000

	Statistical Measures							
Catchment	CC (-)	PBIAS (%)	ME (mm d^{-1})	MAE (mm d^{-1})	RMSE (mm d^{-1})	POD (-)	FAR (-)	CSI (-)
Meki	0.37	3.8	0.1	1.0	4.9	0.62	0.39	0.45
Katar	0.40	−2.0	0.3	1.1	4.1	0.70	0.25	0.50

To further evaluate the seasonal difference between the two datasets, the mean monthly rainfall patterns of the CHIRP satellite and the rain gauge stations for Katar and Meki catchments from 1985–2000 are shown in Figure 2.5. The results revealed that the mean monthly rainfall better captured the pattern of rainfall for the rain gauge. However, it did not satisfactorily capture the gauged rainfall amount, especially for the rainy season (June–September). The highest difference between the two datasets was in the month of July, with values of 17 and 41 mm for Meki and Katar catchments, respectively. During the dry season (October–February), the highest difference of the satellite from the rain gauge was −16 mm for Meki and −19 mm for Katar catchments. This clearly showed that an overestimation of the CHIRP satellite estimate during wet seasons and an underestimation during dry seasons. These results showed the magnitude of the CHIRP satellite bias varied at seasonal scales over the study area.

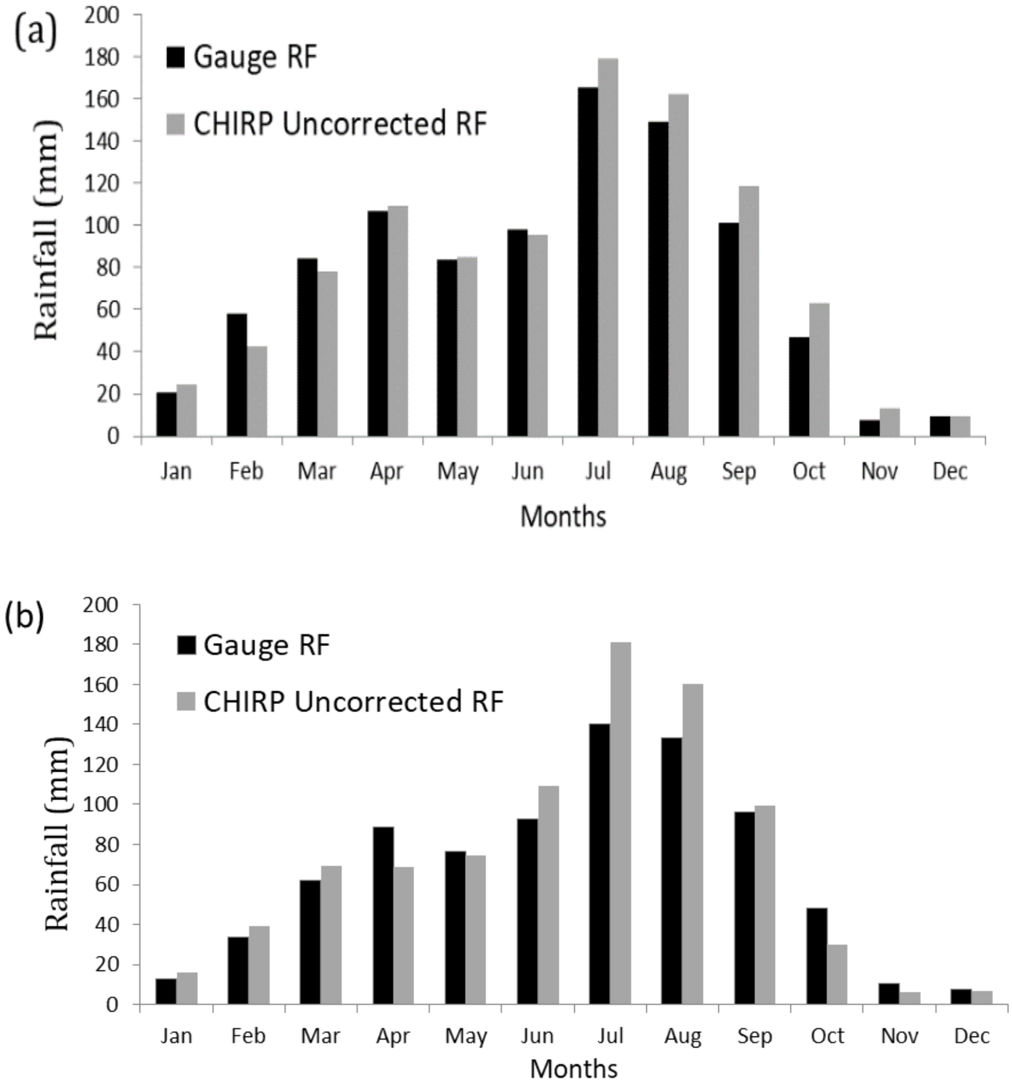

Figure 2.5. Comparison of mean monthly rainfall (1985–2000) for the CHIRP satellite and the rain gauge time series from an ensemble of 14 rain gauges and grid cells; (a) Meki catchment (b) Katar catchment

2.4.2 CHIRP Satellite Bias Correction

We note that the CHIRP satellite has biases at various spatial and temporal scales. Furthermore, several studies have also indicated that SREs must be corrected for use in various applications (Habib et al., 2014; Saber & Yilmaz, 2016; Yuan et al., 2017; Gumindoga et al., 2019). In this study, we applied a non-linear power bias correction approach (described in section 3.2) using Equation (2.1) to estimate bias-corrected CHIRP satellite rainfall datasets. The bias factors were determined by comparing satellite and rain gauge data with established constraints and objective functions. The results from an ensemble of 14 rain gauge stations indicated that bias factors varied at spatial and temporal scales for both catchments. The results showed that, on average, the bias factor *a* varied from 0.01 to 1.72 and *b* from 1 to 4 over the two catchments. The spatial variability of the bias factors (a and b) are shown in annex Figure 6-A.

Table 2.5 shows the statistical measures between the daily bias-corrected CHIRP estimate and the rain gauge after applying bias correction. Improvements were found in all numerical statistical measures (CC, PBIAS, ME, MAE, and RMSE) and categorical statistics (POD, FAR, and CSI). This indicated better performance and improvement after bias correction of the CHIRP rainfall estimate as compared to the uncorrected CHIRP estimate. Hence, the bias-corrected CHIRP satellite effectively reduced the bias of the original uncorrected CHIRP rainfall. The POD result showed that more than 76 and 82% of the observed rainfall events from the rain gauge were correctly detected by the bias-corrected CHIRP satellite in Meki and Katar catchments, respectively. Moreover, smaller values of FAR and larger CSI values were registered after bias correction of the CHIRP satellite rainfall for both catchments, indicating better agreement of the bias-corrected satellite estimate and the rain gauge observation over the study area.

Table 2.5. Daily catchment average rainfall comparison between the bias-corrected CHIRP satellite and the rain gauge dataset after bias correction from 1985–2000

	Statistical Measures							
Catchment	CC (-)	PBIAS (%)	ME (mm d^{-1})	MAE (mm d^{-1})	RMSE (mm d^{-1})	POD (-)	FAR (-)	CSI (-)
Meki	0.56	−0.7	0.1	0.8	4.0	0.76	0.28	0.57
Katar	0.64	0.3	0.1	0.8	3.5	0.82	0.19	0.64

Figure 2.6 presents the cumulative distribution function (CDF) plot between gauge, uncorrected, and bias-corrected CHIRP rainfall at a monthly average catchment scale from 1985 to 2000. The figure indicates that the bias-corrected CHIRP rainfall estimate was very close to the rain gauge at all rainfall measurement values except for low rainfall (less than 50 mm $month^{-1}$) for Meki catchment. This phenomenon was mainly related to the sparse rain gauge network in Meki catchment and the uncertainty of the bias-correction method for the satellite rainfall estimate. A similar result was reported by previous studies of Ayehu et al. (2018) over the upper Blue Nile basin in Ethiopia. Overall, the bias-corrected satellite rainfall very well predicted the cumulative gauge rainfall distribution. It showed significant improvement and a

better correlation between the satellite and the rain gauge data when the CHIRP data were corrected. However, the uncorrected CHIRP satellite data were below the rain gauge data at most of the data points as compared to the bias-corrected data for both catchments. Therefore, the results indicated that bias-correction significantly lowered the error of the CHIRP satellite rainfall estimate.

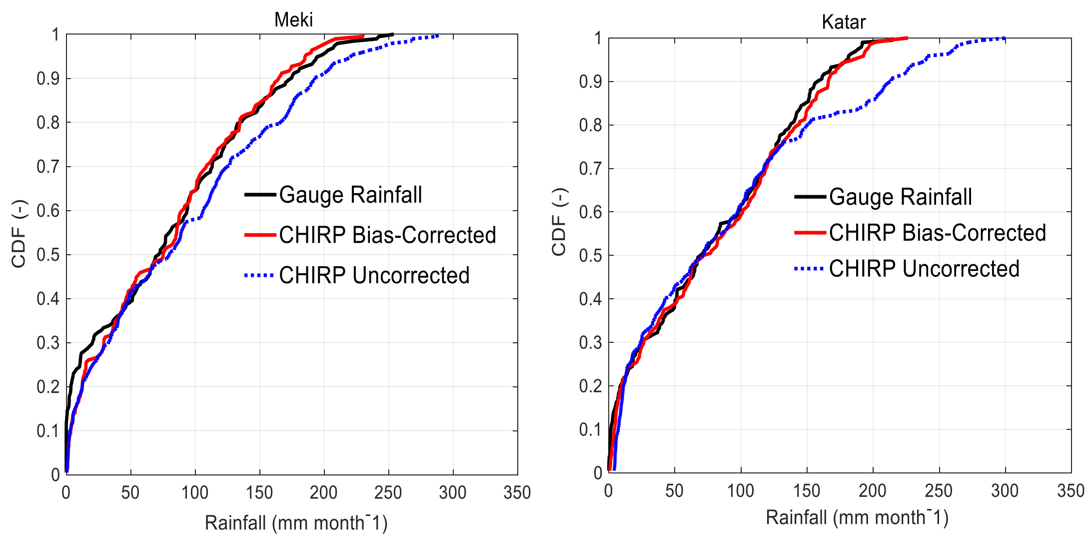

Figure 2.6. Cumulative distribution function (CDF) of monthly rainfall time series of gauge, CHIRP uncorrected, and bias-corrected estimate for Meki and Katar catchments

2.4.3 Model Calibration and Evaluation

For each calibration run, the HBV model parameter was independently calibrated for different rainfall inputs by comparing each simulated streamflow time series with the observed streamflow. First, the sensitive model parameter was evaluated. The result indicated that the parameters controlling the water balance (BETA, FC, and LP) were found to be the most sensitive parameters, while routing parameters (K4 and Khq) were relatively less sensitive. Parameters Alfa, PERC, and CFLUX were the least sensitive model parameters. Worqlul et al. (2018) reported similar results at Gilgel Abbay and Gumara watersheds in Ethiopia. Next, we assessed how the calibrated model parameters and the performance of the hydrological model were affected as a result of gauge, uncorrected, and bias-corrected CHIRP satellite rainfall inputs at Meki and Katar catchments from 1986–1991. We chose to use the observed streamflow as a reference to compare the simulated streamflow for the three rainfall inputs.

Figure 2.7 shows the simulated and the observed daily hydrograph at Meki gauge stations for calibration periods (1986–1991) as input from the gauge, the uncorrected, and the bias-corrected CHIRP satellite rainfall datasets. For all rainfall inputs, the simulated streamflow captured the pattern of the observed hydrograph. However, it was reasonably captured over the simulation period when the model was forced by bias-corrected CHIRP satellite rainfall. We note that the simulated peaks for the three rainfall datasets were lower than the observed peaks. This phenomenon was partly attributed to poor quality and sparsely distributed rain gauge networks over Meki catchment.

The uncertainties of bias-correction of the satellite estimate were also possible reasons for poor capture of the peak discharge during the model driven by bias-corrected satellite rainfall. Figure 2.5 shows that CHIRP overestimated during most of the rainy season for the two catchments. However, this did not cause higher streamflow to be simulated. This indicated that some of the excess rainfall might have been stored in the soil moisture zone and behaved as a low-pass filter instead of generating runoff. A similar finding was also reported by Habib et al. (2014) for Gilgel Abbay catchment.

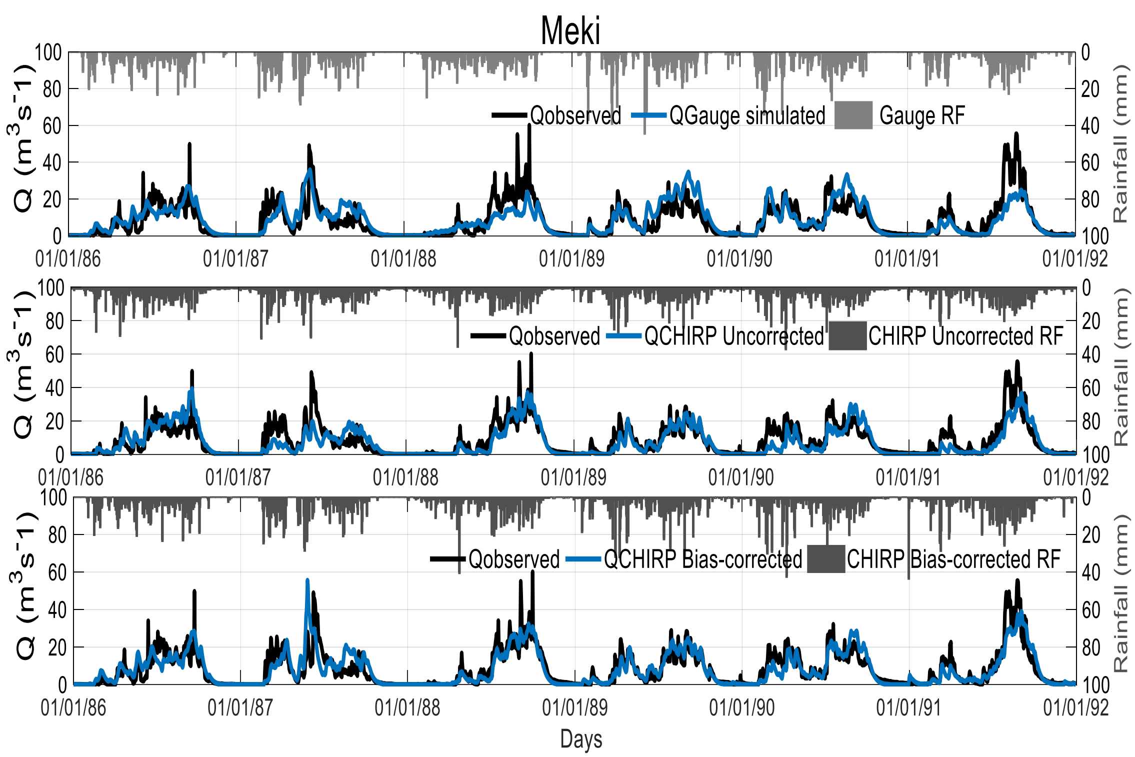

Figure 2.7. Model calibration result of Meki catchment (1986–1991) from gauge, uncorrected, and bias-corrected CHIRP satellite rainfall input

Table 2.6 presents the calibrated model parameter values and the model performance of Meki catchment using gauge, uncorrected, and bias-corrected CHIRP satellite rainfall inputs. The results showed that the bias-corrected CHIRP satellite significantly improved the performance of streamflow flow simulations. In terms of objective functions, the simulations for the gauge and the bias-corrected CHIRP satellite resulted in comparable values. In Meki catchment, the gauge and the bias-corrected CHIRP satellite indicated NSE of 0.67 and 0.71, respectively, and an RVE of less than 5%. This indicated good performance of the HBV model in the study area for the two datasets. Furthermore, the calibrated model parameter values for gauge and bias-corrected were also very close, except for a few routing parameters such as K4, Khq, and Alfa.

The calibrated model parameter values were within the allowable range for all rainfall inputs. However, parameter values were significantly changed when the uncorrected CHIRP served as model input. The model performance simulated using the uncorrected CHIRP satellite revealed lower performance than the gauge and the bias-corrected models in terms of both NSE and RVE. In Meki catchment, the CHIRP satellite rainfall overestimated gauge rainfall by 3.8% at a catchment average scale (Table 2-4) and underestimated by 16% at Tora station (Table 2.3). The simulated streamflow when the uncorrected CHIRP satellite rainfall served as model input revealed underestimation of runoff volume by 13.5% (Table 2.6). The results indicated that overestimation bias in rainfall translated into underestimation in streamflow. This was related to a proportion of the rainfall inputs in the model being stored as excess rainfall in the reservoir instead of contributing to streamflow simulations.

This study also indicated that rainfall input errors were compensated using independent model calibration by changing the best-fitted parameter values. The best-fitted parameter values were significantly varied when the uncorrected CHIRP rainfall served as model input as compared to the gauge rainfall. We note that parameters that control baseflow, water balance, and routing noticeably varied. For instance, in the HBV model, parameter FC (field capacity) corresponded to the maximum soil moisture storage, which affected the runoff volume. A higher value of FC tends to generate higher total runoff. Table 2.6 shows that the calibrated parameter FC increased from 850 mm for the gauged-based simulation to 960 mm for the uncorrected CHIRP satellite rainfall. This indicated that soil moisture storage should have been increased at least by 110 mm to minimize the reduction in runoff as a result of rainfall difference.

Parameters Khq and Alfa also related to peak flows, and a higher value of these parameters resulted in higher peaks and more dynamic response in the hydrograph. A value of Khq increased from 0.02 in the gauge-based model simulation to 0.2 in the uncorrected CHIRP rainfall estimate to cope with few extreme flows. The parameters related to baseflow and recession parameters (PERC, K4, and CFLUX) were increased to respond to the catchment characteristics for the uncorrected CHIRP rainfall inputs. Hence, this study indicates that different rainfall inputs result in different calibrated model parameters.

Table 2.6. Calibrated model parameter values and their performance for gauged, uncorrected, and bias-corrected CHIRP rainfall estimate for Meki catchment

Parameters		Gauge Rainfall	CHIRP Uncorrected Rainfall	CHIRP Bias-Corrected Rainfall
FC		850	960	860
BETA		1.94	1.95	1.96
LP		0.5	0.5	0.5
K4		0.07	0.1	0.1
Khq		0.02	0.2	0.1
Alfa		1.05	1.2	0.8
CFLUX		0.01	0.2	0.01
PERC		1.5	4.5	1.15
Calibration	NSE (-)	0.67	0.65	0.71
	RVE (%)	−1.63	−13.5	−1.47
Validation	NSE (-)	0.70	0.64	0.64
	RVE (%)	1.27	−4.96	3.84

Note: NSE, Nash–Sutcliffe efficiency; RVE, relative volume error.

Figure 2.8 presents the monthly time series scatter plots between the observed and the simulated streamflows for gauge, uncorrected, and bias-corrected CHIRP satellite rainfall datasets at Meki catchment. When the model was driven by the gauge and the uncorrected CHIRP rainfall estimate, few streamflow data points were scattered and revealed a lower correlation than the bias-corrected CHIRP estimate. This scatter may have been attributed to the uncertainty of the rain gauge data and bias of the uncorrected CHIRP satellite estimates. However, the bias-corrected CHIRP estimate had less scatter and higher correlation as compared to the gauge and the uncorrected CHIRP estimates. These results indicated improvement of streamflow simulation after bias correction at the monthly time scale.

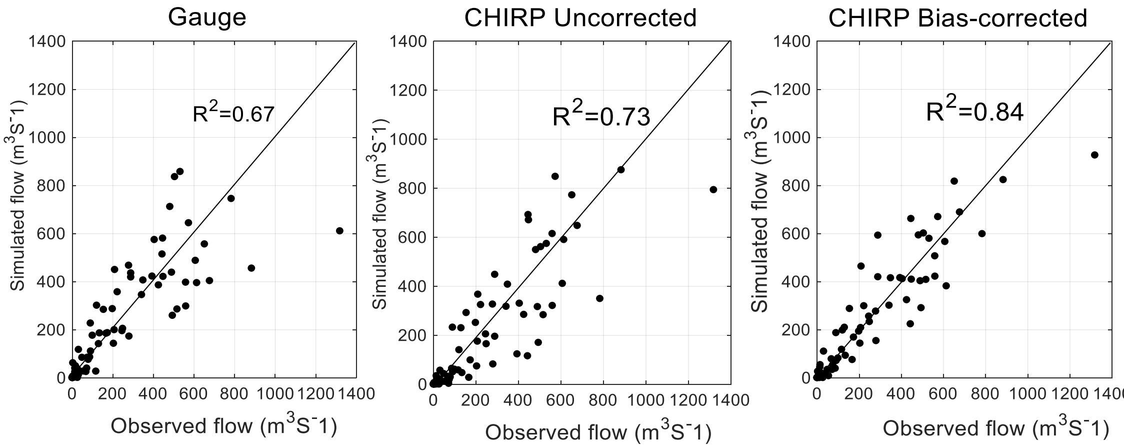

Figure 2.8. Monthly scatter plots of the observed flow against the simulated flow using gauge-based, uncorrected, and bias-corrected CHIRP rainfall data at Meki catchment from 1986–1991

Figure 2.9 shows a comparison of the simulated and the observed streamflows for the calibration period (1986–1991) using gauge, uncorrected, and bias-corrected CHIRP rainfall inputs at Katar gauge stations. The figure demonstrates that observed peaks were better captured in most of the simulation period by the simulated streamflow when the model was forced by gauge and bias-corrected CHIRP satellite rainfall estimates. However, the pattern and some observed peaks were not satisfactorily captured by the simulated hydrograph when the uncorrected CHIRP served as model input. This was mainly because excess rainfall might have been stored in different reservoirs zones instead of generating runoff in addition to the underestimation of higher rainfall values of the rain gauge by the CHIRP rainfall (Figure 2.4). As compared to Meki, in Katar, the simulated peaks in the gauge-based simulation better captured the observed peaks, similar to the bias-corrected satellite rainfall inputs. This was mainly related to the relatively larger number of rain gauge stations used to simulate the gauge-based streamflow and evaluate bias correction at Katar catchment.

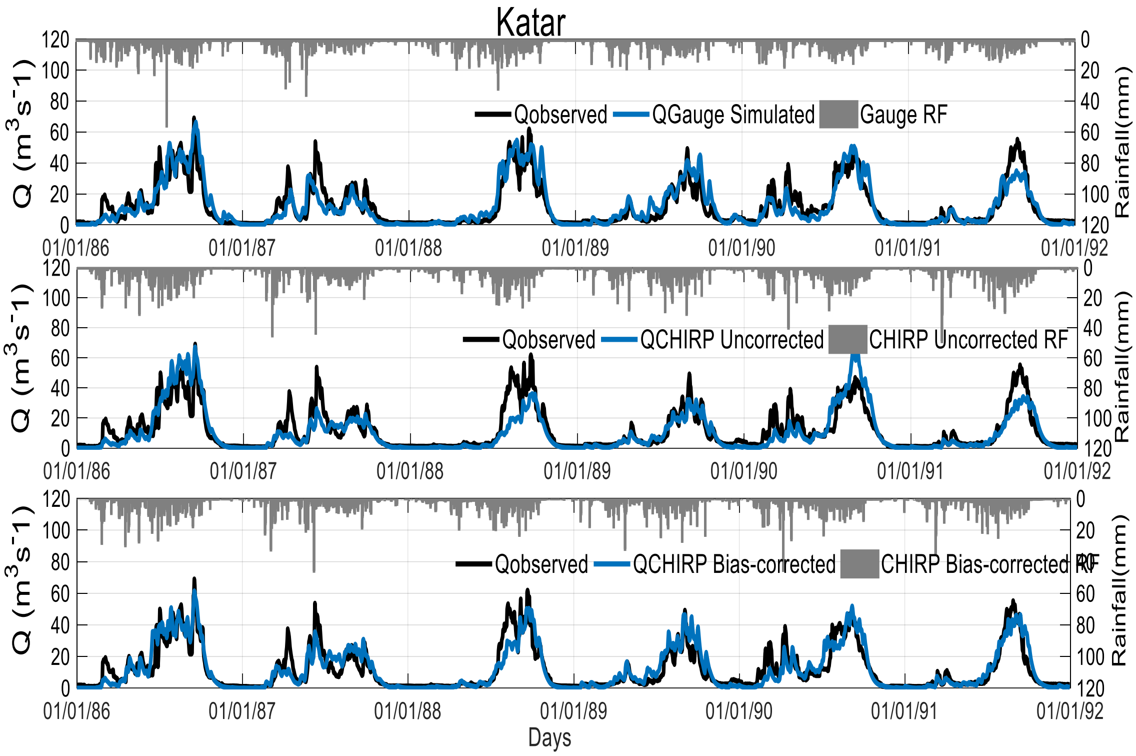

Figure 2.9. Model calibration results of Katar catchment (1986–1991) from gauge, uncorrected, and bias- corrected CHIRP satellite rainfall inputs

Table 2.7 presents the calibrated model parameter values and the model performance of Katar catchment using gauge, uncorrected, and bias-corrected CHIRP rainfall inputs. In Katar catchment, the gauge and the bias-corrected rainfall resulted in comparable model performances with NSE of 0.78 and 0.80, respectively, and an RVE of less than 5%. Similarly, the calibrated model parameter values for gauged and bias-corrected CHIRP were closer, except FC, Khq, and BETA parameters. However, when the uncorrected CHIRP satellite was used to derive the simulation run, most sensitive parameters were significantly varied. The model performance deteriorated with NSE of 0.70 and −13.4% RVE as compared to the gauge and the bias-corrected CHIRP rainfall inputs. This result was mainly related to underestimation of the CHIRP satellite estimate at a catchment average level (PBIAS −2%, Table 2.4) and point scales (PBIAS −20%, Table 2.3).

In Katar catchment, the best-fitted model parameters also remained within the allowable parameter range for all rainfall inputs. However, there were significant differences in the calibrated model parameter values when the uncorrected CHIRP rainfall served as model input. Parameters that control the water balance (FC, BETA, and LP), the routing parameters (Khq and

K4), and the baseflow parameter (PERC) showed significant change during uncorrected CHIRP inputs. For instance, FC increased from 860 mm in the gauge rainfall input to 930 mm in the uncorrected CHIRP input. The recession (Khq and K4) and the percolation (PERC) parameters were also changed during the uncorrected CHIRP rainfall input.

Table 2.7. Calibrated model parameter values and their performance for gauged, uncorrected, and bias-corrected CHIRP rainfall data for Katar catchment

Parameters		Gauge Rainfall	CHIRP Uncorrected	CHIRP Bias-Corrected Rainfall
FC		860	930	820
BETA		2.98	2.95	3.05
LP		0.7	0.6	0.7
K4		0.1	0.08	0.1
Khq		0.08	0.2	0.12
Alfa		1.15	1.2	1.1
CFLUX		0.002	0.015	0.005
PERC		2.15	3.5	2.75
Calibration	NSE (-)	0.78	0.70	0.80
	RVE (%)	−0.80	−13.4	−1.28
Validation	NSE (-)	0.70	0.67	0.74
	RVE (%)	1.96	−16.8	3.04

Overall, when the uncorrected CHIRP rainfall input replaced the calibration process, changes up to 63% and 55% were obtained in water balance and routing parameters, respectively, as compared to the rain gauge rainfall. Hence, this study shows that common optimized parameter values could not be achieved for different rainfall inputs over the study area. Therefore, the biases of streamflow simulation are not only derived from rainfall estimates but also the uncertainty in the hydrological model parameters as a result of different rainfall inputs..

Figure 2.10 shows the monthly time series scatter plots between the observed and the simulated streamflows for gauge, uncorrected, and bias-corrected CHIRP satellite rainfall datasets at Katar catchment. The scatters for streamflow simulated using the gauge and the uncorrected CHIRP rainfall estimates were higher than the bias-corrected CHIRP rainfall, implying the bias correction of the CHIRP rainfall estimate effectively improved the streamflow simulation.

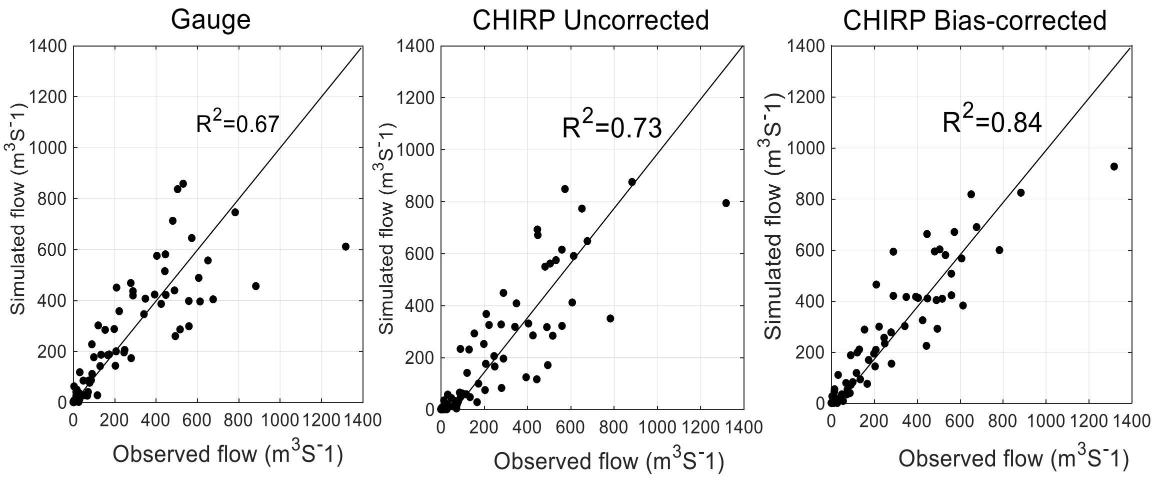

Figure 2.10. Monthly scatter plots of the observed flow against the simulated flow using the gauge-based, the uncorrected, and the bias-corrected CHIRP rainfall data at Katar catchment from 1986–1991

The calibrated process was verified through validation for an independent period from 1986–2000 for the three rainfall inputs at Meki and Katar gauge stations. Note that we did not recalibrate the model for different rainfall inputs during validation. We used calibrated model parameters of the respective rainfall inputs in all model simulations. Figure 2.11 compares the daily observed and the simulated streamflows for Meki and Katar catchments simulated by gauge, uncorrected, and bias-corrected CHIRP satellite rainfall. The figure illustrates that, for both catchments, the simulated streamflows better captured the patterns of the observed hydrographs for all rainfall inputs, except for a slight underestimation of observed peaks.

The model performance deteriorated slightly in the validation period as compared to the calibration period for all rainfall inputs. The model performance for both stations indicated acceptable results, with NSE greater than 0.70 and RVE less than 5% when the model was forced by gauge and bias-corrected CHIRP satellite rainfall. However, when the uncorrected CHIRP satellite served as model input, the model performance significantly deteriorated, with NSE of 0.64 and −4.96 RVE for Meki (Table 2.6) and NSE of 0.70 and −16.8% RVE for Katar catchment (Table 2.7). This indicated that systematic error (biases) of the CHIRP satellite propagated through the HBV model in the streamflow simulations.

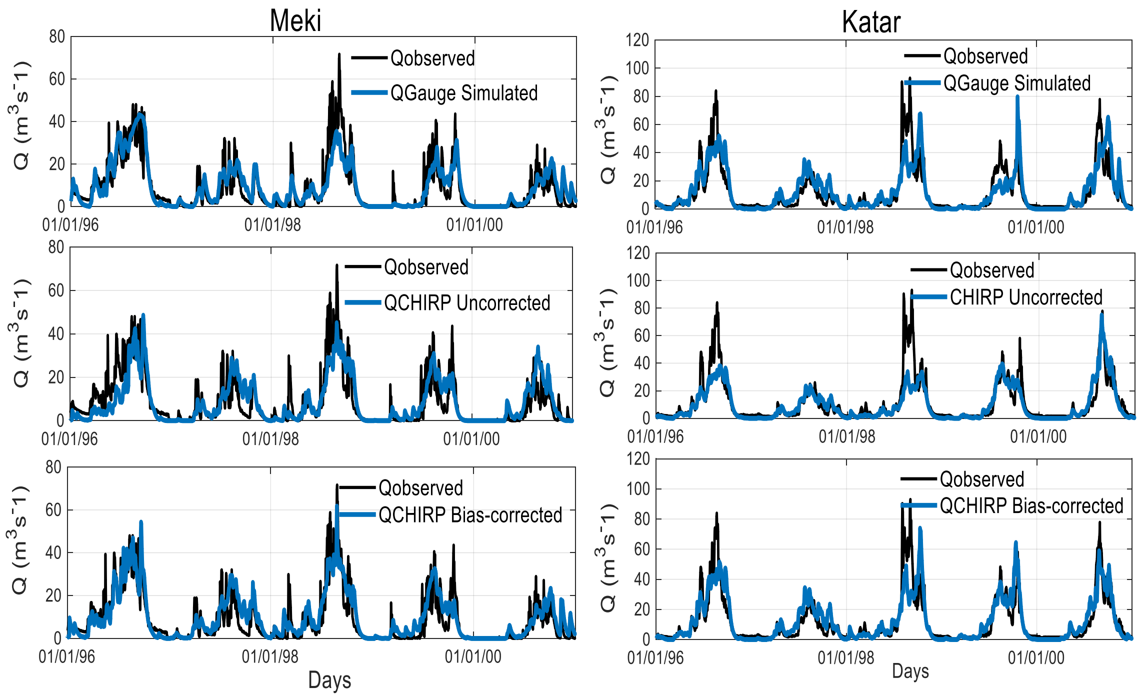

Figure 2.11. Model validation result (1996–2000) between daily observed and simulated flow of Meki and Katar catchments using gauge, uncorrected, and bias-corrected CHIRP rainfall inputs

This study indicated that, for both catchments, the bias-corrected CHIRP satellite simulation performed slightly better than the gauge-based simulation. Such results could be partly attributed to sparsely distributed rain gauge networks over the study area and the availability of CHIRP satellite data at relatively high spatiotemporal scales. Similar results have been reported in other satellite studies by (Artan et al., 2007; Zeweldi et al., 2011; Yuan et al., 2017; Saber & Yilmaz, 2018) which they found an increased performance of the hydrological model when the model was calibrated using SREs rather than gauge rainfall. Therefore, this study suggests that bias-corrected CHIRP satellite rainfall can be used as a potential alternative data source for water budget studies in Lake Ziway watershed.

2.4.4 Evaluating the Value of Bias Correction on Streamflow

To evaluate the contribution of bias correction on streamflow and error propagation, we used the calibrated model parameter with gauge rainfall to simulate streamflow using the uncorrected and the bias-corrected CHIRP rainfall estimates. This helped to minimize the uncertainty related to model parameters. To offset the effect of rainfall input errors, gauge-based simulated streamflow was used as a reference for comparison and to quantify the model performance objective functions. In this study, we followed Habib et al.'s (2014) approach that assessed the effect of CMORPH bias correction on streamflow of Gilgel Abbay catchment. To quantify the magnitude of error propagation in streamflow simulation, rainfall bias (BIAS) and relative volumetric error (RVE) performance measures were used. The rainfall bias (BIAS) was calculated as a ratio of the total sum of the satellite and gauge rainfall, and the RVE was calculated using Equation (2.5).

Table 2.8 shows the rainfall bias and the RVE for the uncorrected and the bias-corrected CHIRP satellites compared with the gauge-based estimation. For Meki catchment, the uncorrected CHIRP satellite rainfall amount was smaller by 18% (BIAS = 82%, Table 8) than the gauge rainfalls, which resulted in a 17% reduction in streamflow volume. In Katar catchment, the rainfall difference was −16% (BIAS = 84%, Table 8), which contributed 11% in streamflow volume difference. However, after bias correction, the error propagation significantly reduced. The bias obtained between the bias-corrected CHIRP and the gauge-based was smaller than the uncorrected CHIRP satellite. After applying the bias-corrected CHIRP rainfall estimate, the rainfall bias was reduced to 4% (BIAS = 96%, Table 8) and translated to only 5% in streamflow bias in Meki catchment, whereas 10% rainfall bias (BIAS = 90%, Table 8) translated to 3% in streamflow volume difference in Katar catchment. The results indicated that the bias in the CHIRP satellite rainfall was translated through the HBV model in streamflow simulations. Table 2.8 clearly shows that the bias correction added value to the satellite estimate by effectively reducing the error magnitude in rainfall and streamflow simulations. Habib et al. (2014) and Yuan et al. (2017) reported similar results over Ethiopian and China basins, respectively.

Table 2.8. Comparison of rainfall and streamflow differences between uncorrected and bias-corrected CHIRP satellites against gauge-based datasets from 1996–2000

Catchment	Performance Measure	CHIRP Uncorrected	CHIRP Bias-Corrected
Meki	BIAS	0.82	0.96
	RVE	17	5.0
Katar	BIAS	0.84	0.90
	RVE	11	3.0

2.5 Conclusions

Satellite rainfall estimates are subject to substantial systematic biases. However, only a few studies have been conducted over eastern Africa that incorporate uncertainties of the satellite estimate in streamflow simulations. In this study, we evaluated the performance and the bias correction of the Climate Hazards Group InfraRed Precipitation (CHIRP) satellite rainfall for rainfall-runoff simulation at Meki and Katar catchments. The study is unique, as it considers the performance of the CHIRP satellite at various spatiotemporal scales and contains a hydrological assessment of this product for rainfall-runoff modeling. We also evaluated the effect of gauge, uncorrected and bias-corrected CHIRP satellite rainfall inputs on calibrated model parameters and model performance on streamflow simulations using the HBV hydrological model. The results of this study contribute to guiding satellite product users in the applicability of the CHIRP satellite product for rainfall-runoff simulations. The main conclusions drawn from the result of this study are as follows:

i. The results showed that the CHIRP satellite rainfall had biases at various spatial and temporal scales over Lake Ziway watershed. CHIRP had PBIAS ranging from −16 to 20% and lower correlation at a daily time step with the rain gauge data. Overall, CHIRP performance better improved at monthly and areal catchment scales.

ii. We found comparable calibrated model parameters and model performances for the gauge and the bias-corrected CHIRP satellite rainfalls in simulating daily streamflow of the two catchments. However, calibrated model parameters significantly changed when the uncorrected CHIRP rainfall input served as model input. Changes up to 55% and 63% were obtained for water balance and routing controlling parameters, respectively, as compared to the gauge-based simulations. Hence, this study shows that common optimized parameter values could not be achieved for different rainfall inputs over the study area.

iii. The simulated streamflow better captured the observed hydrographs when using the bias-corrected CHIRP satellite rainfall input compared to the uncorrected CHIRP satellite. We note that biases in satellite rainfall inputs were translated to simulated streamflow through the HBV hydrological model. The application of non-linear bias correction effectively reduced the rainfall bias and revealed improved streamflow simulation compared to the uncorrected product.

In general, this study shows that the bias-corrected CHIRP rainfall estimate can serve as an alternative data source in rainfall-runoff simulations for water budget studies. The study also suggests that bias correction is necessary to improve the performance of the satellite rainfall for accurate estimation of the hydrological response of the watershed. Future studies should incorporate a comparison of various bias correction algorithms to further explore the reported changes.

References

Abdo, K.S., Fiseha, B.M., Rientjes, T.H., Gieske, A.S., Haile, A.T. (2009). Assessment of climate change impacts on the hydrology of Gilgel Abay catchment in Lake Tana basin, Ethiopia. *Hydrologic Processes*, *23*, 3661–3669. doi.org/10.1002/hyp.7363.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M. (1998). Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements. *Irrigation and Drainage Paper*,FAO, Rome, Italy.

Artan, G., Gadain, H., Smith, J.L., Asante, K., Bandaragoda, C.J., Verdin, J.P. (2007). Adequacy of satellite derived rainfall data for stream flow modeling. *Natural Hazards, 43*, 167–185.

Ayehu, G.T., Tadesse, T., Gessesse, B., Dinku, T. (2018). Validation of new satellite rainfall products over the Upper Blue Nile Basin, Ethiopia. *Atmospheric Measurement Techniques*, *11,* 1921–1936.

Berg, P., Feldmann, H., Panitz, H. J. (2012). Bias correction of high resolution regional climate model data. *Journal of Hydrology, 448*, 80–92.

Bhatti, H., Rientjes, T., Haile, A., Habib, E., Verhoef, W. (2016). Evaluation of bias correction method for satellite-based rainfall data. *Sensors*, *16*, 884.

Bitew, M.M., Gebremichael, M, Ghebremichael, L.T., Bayissa, Y.A. (2012). Evaluation of high-resolution satellite rainfall products through streamflow simulation in a hydrological modeling of a small mountainous watershed in Ethiopia. *Journal of Hydrometeorology.*, *13*, 338–350.

Dinku, T. (2014). Validation of the CHIRPS Satellite Rainfall Estimate. In Seasonal Prediction of Hydro-Climatic Extremes in the Greater Horn of Africa. *Proceedings of the 7th International Precipitation Working Group Workshop, Tsukuba, Japan*, 17–21 2014**.**

Dinku, T., Funk, C., Peterson, P., Maidment, R., Tadesse, T., Gadain, H., Ceccato, P. *(2018).* Validation of the CHIRPS satellite rainfall estimates over eastern of Africa. *Quarterly Journal of the Royal Meteorological Society*, *144*, 393–312.

Fuka, D.R., Walter, M.T., MacAlister, C., Degaetano, A.T., Steenhuis, T.S., Easton, Z.M. (2014). Using the climate forecast system reanalysis as weather input data for watershed models. *Hydrological Processes*, *28*, 5613–5623.

Funk, C.C., Peterson, P.J., Landsfeld, M.F., Pederos, D.H., Verdin, J.P., Rowland, J.D., Romero, B.E., Husak, G.J., Michaelsen, J.C., Verdin, A.P. (2014). A quasi-global precipitation time series for drought monitoring; *U.S. Geological Survey Data Series* 832; U.S. department of the interior, Reston, Virginia, pp. 1–12.

Funk, C.; Verdin, A., Michaelsen, J., Peterson, P., Pedreros, D., Husak, G. (2015). A global satellite-assisted precipitation climatology. *Earth System Science Data*, *7*, 275–287.

Gebremichael, M., Bitew, M.M., Hirpa, F.A. Tesfay, G.N. (2014). Accuracy of satellite rainfall estimates in the Blue Nile Basin: Lowland plain versus Highland Mountain. *Water Resources Research*, *50*, 8775–8790.

Gumindoga, W., Rientjes, T.H., Haile, A.T., Makurira, H., Reggiani, P. (2019). Performance of bias correction schemes for CMORPH rainfall estimates in the Zambezi river basin. *Hydrology and Earth System Sciences Discussions*, *23*, 2915–2938.

Habib, E., Haile, A.T., Sazib, N., Zhang, Y., Rientjes, T. (2014). Effect of bias correction of satellite-rainfall estimates on runoff simulations at the source of the Upper Blue Nile. *Remote Sensing*, *6*, 6688–6708.

Haerter, J.O., Eggert, B., Moseley, C., Piani, C., Berg, P. (2015). Statistical precipitation bias correction of gridded model data using point measurements. *Geophysical Research Letters*, *42*, 1919–1929.

Haile, A.T., Habib, E., Rientjes, T. (2013). Evaluation of the Climate Prediction Center (CPC) morphing technique (CMORPH) rainfall product on hourly time scales over the source of the Blue Nile River. *Hydrological Processes*, *27*, 1829–1839.

Huffman, G.J., Adler, R.F., Arkin, P., Chang, A., Ferraro, R., Gruber, A., Janowiak, J., McNab, A., Rudolf, B., Schneider, U. (1997). The global precipitation climatology project (GPCP) combined precipitation dataset. *Bulletin of the American Meteorological Society*, *78*, 5–20.

Johansson, B.(2013). *IHMS Integrated Hydrological Modeling System Manual version 6.3*; *Swedish Meteorological and Hydrological Institute*, Norrkoping, Stockholm, p. 144.

Joyce, R.J., Janowiak, J.E., Arkin, P.A., Xie, P. (2004). CMORPH: A method that produces global precipitation estimates from passive microwave and infrared data at high spatial and temporal resolution. *Journal of Hydrometeorology*, *5*, 487–503.

Katsanos, D., Retalis, A., Michaelides, S. (2016). Validation of a high-resolution precipitation database (CHIRPS) over Cyprus for a 30-year period. *Atmospheric Research*, *169*, 459–464.

Khandu., Awange, J.L., Forootan, E. (2016). An evaluation of high-resolution gridded precipitation products over Bhutan (1998–2012). *International Journal of Climatology*, *36*, 1067–1087.

Lafon, T., Dadson, S., Buys, G., Prudhomme, C. (2013). Bias correction of daily precipitation simulated by a regional climate model: A comparison of methods. *International Journal of Climatology*, *33*, 1367–1381.

Lakew, H.B., Moges, S.A., Asfaw, D.H. (2017). Hydrological Evaluation of Satellite and Reanalysis Precipitation Products in the Upper Blue Nile Basin: A Case Study of Gilgel Abbay. *Hydrology*, *4*, 39.

Lindström, G., Johansson, B., Persson, M., Gardelin, M., Bergström, S. (1997). Development and test of the distributed HBV-96 hydrological model. *Journal of Hydrology*, *201*, 272–288.

Rientjes, T.H.M., Perera, B.U.J., Haile, A.T., Reggiani, P., Muthuwatta, L.P. (2011). Regionalisa -tion for lake level simulation-the case of Lake Tana in the Upper Blue Nile, Ethiopia. *Hydrology and Earth System Sciences*, *15*, 1167–1183.

Saber, M., Yilmaz, K. (2016). Bias correction of satellite-based rainfall estimates for modeling flash floods in semi-arid regions: Application to Karpuz River, Turkey. *Natural Hazards Earth System Sciences Discussions*, 1–35. doi: 10.5194/nhess-2016-339.

Saber, M., Yilmaz, K. (2018). Evaluation and bias correction of satellite-based rainfall estimates for modeling flash floods over the mediterranean region: Application to Karpuz river basin, Turkey. *Water*, *10*, 657

Tapiador, F.J., Kidd, C., Levizzani, V., Marzano, F.S. (2004).A maximum entropy approach to satellite quantitative precipitation estimation (QPE). *International Journal of Remote Sensing*, *25*, 4629–4639.

Vernimmen, R.R., Hooijer, A., Aldrian, E., Van Dijk, A.I. (2012). Evaluation and bias correction of satellite rainfall data for drought monitoring in Indonesia. *Hydrology and Earth System Sciences*, *16*, 133–146.

Wale, A., Rientjes, T.H.M., Gieske, A.S.M., Getachew, H.A. (2009). Ungauged catchment contributions to Lake Tana's water balance. *Hydrological Processes*, *23*, 3682–3693.

Wörner, V., Kreye, P., Meon, G. (2019). Effects of bias-correcting climate model data on the projection of future changes in high flows. *Hydrology*, *6*, 46.

Worqlul, A.W., Collick, A.S., Tilahun, S.A., Langan, S., Rientjes, T.H., Steenhuis, T.S.(2015) Comparing TRMM 3B42, CFSR and ground-based rainfall estimates as input for hydrological models, in data scarce regions: The Upper Blue Nile Basin, Ethiopia. *Hydrology and Earth System Sciences Discussions*, *12*, 2081–2112.

Worqlul, A.W., Ayana, E.K., Maathuis, B.H.P., MacAlister, C., Philpot, W.D., Leyton, J.M.O. Steenhuis, T.S. (2018). Performance of bias corrected MPEG rainfall estimate for rainfall-runoff simulation in the upper Blue Nile Basin, Ethiopia. *Journal of Hydrology*, *556*, 1182–1191.

Xue, X. Hong, Y. Limaye, A. S. Gourley, J. J. Huffman, G. J. Khan, S. I., Dorji, C., Chen, S. (2013). Statistical and hydrological evaluation of TRMM-based Multi-satellite precipitation analysis over the Wangchu Basin of Bhutan: Are the latest satellite precipitation products 3B42V7 ready for use in ungauged basins? *Journal of Hydrology*, *499*, 91–99.

Yatagai, A., Kamiguchi, K., Arakawa, O., Hamada, A., Yasutomi, N., Kitoh, A. (2012). APHRODITE: Constructing a long-term daily gridded precipitation dataset for Asia based on a dense network of rain gauges. *Bulletin of the American Meteorological Society*, *93*, 1401–1415.

Yong, B.; Chen, B., Gourley, J.J., Ren, L., Hong, Y., Chen, X., Wang, W., Chen, S., Gong, L. (2014). Intercomparison of the Version-6 and Version-7 TMPA precipitation products over high and low latitudes basins with independent gauge networks: Is the newer version better in both real-time and post-real-time analysis for water resources and hydrologic extremes? *Journal of Hydrology*, *508*, 77–87.

Yong, B. Ren, L.-L. Hong, Y. Wang, J.-H. Gourley, J.J. Jiang, S.-H., Chen, X., Wang, W. (2010). Hydrologic evaluation of multisatellite precipitation analysis standard precipitation products in basins beyond its inclined latitude band: A case study in Laohahe basin, China. *Water Resources Research*, *46*, W07542.

Yuan, F., Zhang, L., WahWin, K.W., Ren, L., Zhao, C., Zhu, Y., Jiang, S., Liu, Y. (2017). Assessment of GPM and TRMM multi-satellite precipitation products in streamflow simulations in a data-sparse mountainous watershed in Myanmar. *Remote Sensing*, *9*, 302.

Zeweldi, D.A., Gebremichael, M., Downer, C.W. (2011). On CMORPH rainfall for streamflow simulation in a small, Hortonian watershed. *Journal of Hydrometeorology*, *12*, 456–466.

3 Bias-corrected CHIRP Satellite Rainfall for Water Level Simulation, Lake Ziway, Ethiopia

Abstract: Applicability of satellite rainfall products must be explored since rain gauge networks have limitations to provide adequate spatial coverage. In this study, Climate Hazards InfraRed Precipitation (CHIRP) satellite-only product was evaluated for rainfall-runoff modelling whereas the simulated runoff served as input to simulate water level from 1986 to 2014 of Lake Ziway. CHIRP dataset was bias-corrected using power transformation and used as input to Hydrologiska Byråns Vattenbalansavdelning (HBV) model to simulate streamflow of Katar and Meki catchments. Results show that gauged catchments of Meki and Katar contributed 524 mm and 855 mm to the annual lake inflow, respectively. The estimated runoff from ungauged catchments is 182 mm that amounts to approximately 8.5% of the total lake inflow over the period 1986-2000.The results of lake level simulation show good agreement from 1986 to 2000, but deteriorating agreement after 2000 which is mainly attributed to errors in water balance terms and human-induced impacts. For the period 1986-2000, the water balance closure error for the lake was 67.5 mm per year that accounts for 2.9% of the total lake inflow from rainfall and river inflow. This study shows bias correction increases the applicability of CHIRP satellite product for lake water balance studies.

Keywords: CHIRP; Lake Ziway; satellite rainfall; bias correction; water balance, HBV; Lake Level

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3.1 Introduction

Accurate rainfall data at high spatial and temporal resolution is highly desirable for rainfall-runoff modelling. However, consistent rainfall measurements are not available or readily accessible in many less developed countries like Ethiopia (Ashenfi and Hailu, 2014). Satellite rainfall products may complement rain gauge data. Therefore, satellite rainfall estimation algorithms are extensively being explored to produce reliable and accurate satellite rainfall estimates (SREs) that are meaningful for hydrological assessments. Evaluation studies on the accuracy of SREs show that estimates are subject to systematic and random errors (Haile et al., 2013; Fuka et al., 2014; Habib et al., 2014; Bhatti et al., 2016). Hence, the systematic error (bias) should be removed before the products can be used for hydrological and water resources applications.

Satellite rainfall products have become available over the past decades at global coverage. Examples are the Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis (TMPA; Huffman et al., 2007), Climate Prediction Centre (CPC) morphing technique (CMORPH; Joyce et al., 2004), Precipitation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN; Sorooshian et al., 2000), and Climate Hazards Group InfraRed Precipitation (CHIRP; Funk et al., 2015). Comparison studies have shown that the performance of these products varies considerably across geographic locations and over time periods.

Bias correction of satellite rainfall is advantageous as reported in recent studies. Krakauer et al. (2013) indicated that bias-correction increases the match between rainfall amounts from satellite products and rain gauge records. Yuan et al. (2017) reported that the application of bias-corrected satellite rainfall product in runoff modelling resulted in substantial improvements in capturing both runoff volume and hydrograph pattern. Yong et al. (2014) found the use of bias-corrected rainfall product as model input instead of uncorrected products revealed better performance on rainfall-runoff simulation. Similar results were also reported by others (Ebert et al., 2007; Habib et al., 2014; Dembélé and Zwart, 2016; Worqlul et al., 2018).

Subject to availability of products, studies have used products mostly at an application period of 10 years or shorter. Some satellite rainfall products are available for time periods longer than 10 years. Among these products, the Climate Hazards Group (CHG) InfraRed Precipitation

(CHIRP) satellite-only product and CHIRP combined with stations observations (CHIRPS) are available at relatively high space-time resolutions (5.5km,daily) (Funk et al., 2014 , 2015).

Several recent studies have investigated the accuracy of CHIRP and CHIRPS products across the world. For instance, Le and Pricope (2017) demonstrated the applicability of CHIRPS product for streamflow simulation over Nzoia basin, Western Kenya. The authors reported that the use of CHIRPS data as input into the hydrological model significantly improved streamflow simulation as compared to rainfall from gauge observations. However, such results might be attributed to poor quality and inadequate rain gauge data coverage over the study area.

Duen et al. (2016) showed that CHIRPS performed better as compared to eight high-resolution satellite rainfall products over Adiga Basin (Italy). Hessels (2015) compared 10 satellite rainfall products over the Nile basin. Their findings suggest that CHIRPS is suited for water resources assessment studies. Dinku et al. (2018) evaluated CHIRP and CHIRPS satellite products and compared them against other two satellite products (i.e ARC2 (African Rainfall Climatology V2) and TAMSAT (Tropical Application of Meteorology using SATellite). Authors reported that both CHIRP and CHIRPS products better performed than ARC2 and TAMSAT at decadal and monthly time scales.

Khandu et al. (2015) reported CHIRP performed relatively better in flat regions with elevation ranges from 150 to 1500 m.a.s.l. Similarly, Shrestha et al. (2017) showed that CHIRP satellite-only product was found to better perform at lower elevation regions of Koshi Basin in Nepal than CHIRPS product. Furthermore, studies indicated that products are also subjected to substantial biases. For instance, CHIRP underestimated the observed rainfall magnitude by 200-240 mm per month over Bhutan (Khandu et al., 2015). Their results also showed the bias correction of the CHIRP satellite significantly improved the accuracy of the products.

In Ethiopia, previous evaluation of satellite products for runoff simulation mostly focuses on the upper Blue Nile and Awash Basin (Haile et al., 2013; Habib et al., 2014; Gebere et al., 2015). Similar studies are lacking over Central Rift Valley (CRV) Lakes basin of Ethiopia for application in hydrological and water resources management. Dinku et al. (2014) reported that CHIRP satellite-only product better performed than CHIRPS over Ethiopia. Similar findings are reported in studies for the upper Blue Nile Basin of Ethiopia (Ayehu et al., 2018). Hence, in this study we selected to use CHIRP satellite-only rainfall estimate. Furthermore there is no study that demonstrated the applicability of CHIRP in data scarce regions like Lake Ziway in Ethiopia with the objective to simulate lake water levels by lake water balance assessment. Therefore, the main objective of this study is to simulate river inflow and lake level using bias-corrected CHIRP satellite-only rainfall product. CHIRP will be used at daily temporal and 0.05º × 0.05º spatial resolutions for the period 1984-2014.

To address the main objectives of this study i.e. to simulate lake level and the lake water balance, long term rainfall data series is needed. By lack of sufficient rain gauge data we selected CHIRP satellite rainfall products to complement and complete rainfall time series data. CHIRP data has the longest time series that goes back to 1981 and still is made available till near present time. An advantage of using CHIRP in this study is its fine spatial resolution (0.05º × 0.05º) than other products (Dinku et al., 2014; Khandu et al., 2015; Shreshta et al., 2017). In addition, previous inter-comparison and performance assessment of satellite products have shown that CHIRP product better performed in different regions as compared to other satellite products. Furthermore, CHIRP uses thermal infrared (TIR) data, which provide consistent time series data. The study area is Lake Ziway in the Central Rift Valley Lake basin of Ethiopia. As such, this study will contribute to the applicability of CHIRP satellite product for estimating lake balance and lake level simulation in data scarce regions.

3.2 Study Area

Lake Ziway subbasin is located in the Central Rift Valley (CRV) Lakes basin of Ethiopia. The subbasin has a total surface area of 7022 km^2, of which the land surface covers 6572.5 km^2. Lake Ziway is the highest of a chain of four lakes in the CRV basin with a surface area covering 445 km^2 and an island area of 4.5 km^2. The Lake subbasin is situated between latitudes of 7º25'30''-8º34'30''N and longitudes of 38º12'00''-39º15'00''E (Figure 3.1).

The topography of the subbasin is characterized by mountainous terrain over eastern and western margins, with an elevation variation from 4200 to 1600 m.a.s.l (Figure 3.1). According to a bathymetric map of 2013, the maximum and average depth of the lake was 8 and 3 m, respectively, with an average volume of 1148 Million Cubic Meter (MCM) at an average elevation of 1636 m.a.s.l. The lake level rises during the rainy season (July to September) with highest levels in October, at the end of rainy season. Lowest water levels occur in December through March.

Meki and Katar catchments, which drain the western and eastern plateaus respectively, provide a major inflow to Lake Ziway. The two catchments cover a total gauged area of 5783 km^2, with an ungauged catchment area of 785 km^2. The lake outflow drains towards Lake Abiyata via Bulbula River and is monitored at Kekersitu gauge station. Figure 3.1 indicates the location of the study area including elevation variation, meteorological and river gauge stations.

The mean annual temperature of the lake ranges from 18.2 ℃ to 21.6 ℃, with tropical climate. The average annual rainfall of Lake Ziway varies between 454 to 995 mm as estimated for the period 1984-2014, while annual lake evaporation during the same period ranges from 1775 to 1969 mm. The average annual rainfall and evaporation from the lake is 746 and 1870 mm, respectively for the specified period. The major land uses in the subbasin includes intensive agriculture cultivation land (both rain-fed and irrigated), wetland and water bodies.

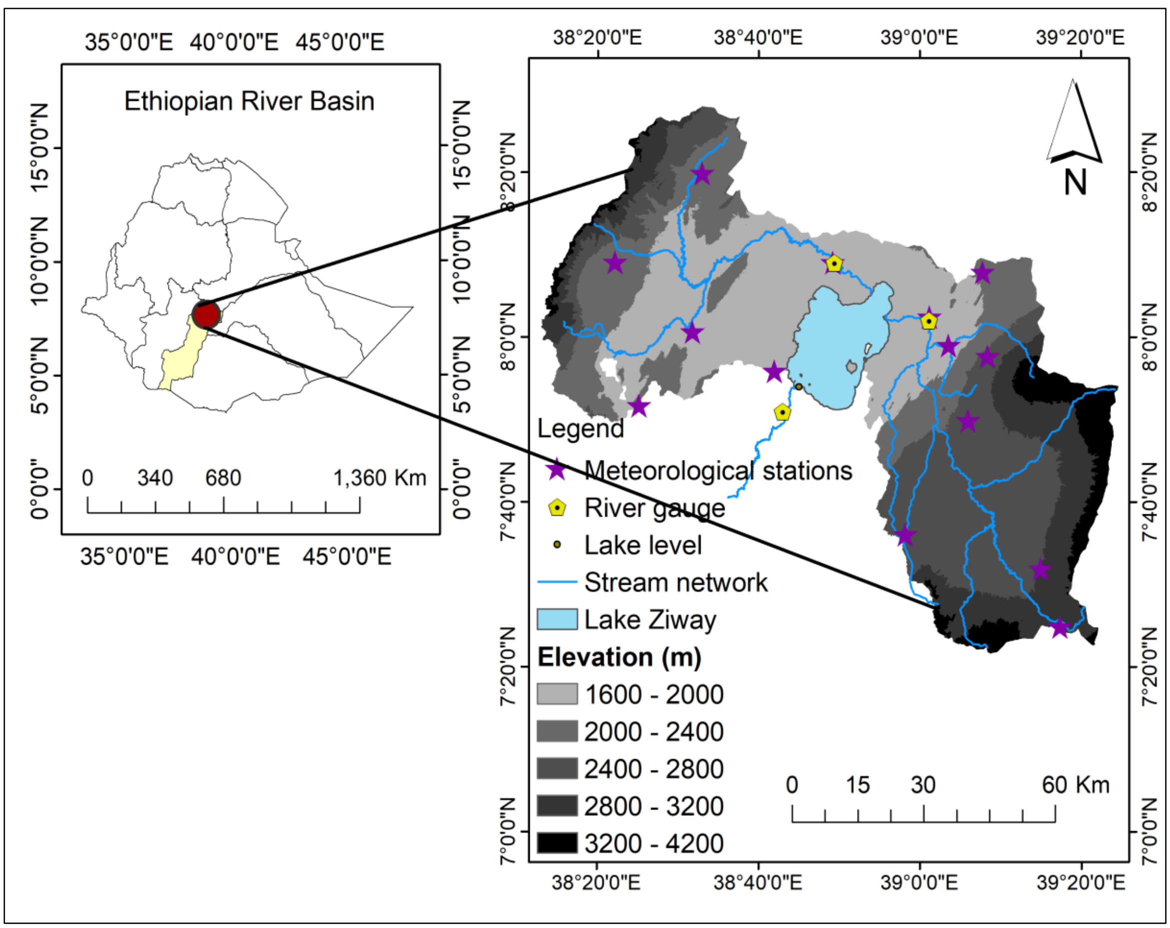


Figure 3.1. Location map of Lake Ziway sub basin, including elevation, meteorological, lake level and river gauge stations

3.3 Datasets

3.3.1 Observed data

Daily meteorological data from 20 rain gauge stations were obtained from the National Meteorological Agency (NMA) of Ethiopia. The data covers the period from 1984 to 2014. The dataset includes rainfall, maximum and minimum temperature, wind speed, relative humidity and sunshine duration. Only eleven stations with maximum and minimum temperature and four stations with complete datasets were collected for this study.

In this study, the quality of the observed rainfall was assessed using outlier, homogeneity, stationary and consistency tests. The analysis showed that rainfall data of only 14 ground stations (6 for Meki and 8 for Katar catchments) were found complete and consistent for use in this study. After screening about 26% of missing records were identified. Missed data were filled using arithmetic and normal ratio methods mainly for potential evaporation estimation. For bias correction of the satellite product, only the available rainfall data of the selected stations were used while days with missing records were ignored.

The Ministry of Water, Irrigation and Electricity (MoWiE) of Ethiopia provided the Lake water level (at Ziway station), streamflow data at five stations (Meki at Meki town, Katar at Abura and Sagure, Chiufa at Arata and Timala near Sagure) and lake outflow discharge (Kekersitu station at Bulbula River) (Figure 3.1). Daily observations were of water level and streamflow were made available to us for the period 1984-2014. Stations of small tributaries (such as Sagure, Chiufa and Timala) had short records, and hence data from those stations were not considered.

Digital Elevation Model (DEM) of ASTER GDEM V2 was downloaded from a freely available data source (https://lpdaac.usg.gov.data access). The DEM has a spatial resolution of 30m × 30m and was used to delineate the watershed. Land use/ land cover data was obtained from MoWiE for the year 1992 and 1996. MoWiE also provided the lake bathymetric data of 1984 and 2013 and are used in this study.

3.3.2 Satellite Rainfall Product

CHIRP data is a near real-time product which is available since 1981 up to the present time. The data covers the region that is situated between 50ºS-50ºN latitude and all longitudes (Funk et al., 2014, 2015).

CHIRP estimates precipitation data in two stages based on two global geosynchronous thermal infrared (TIR) archives i.e. the 1981-2008 globally gridded satellite from National Oceanic and Atmospheric Administration (NOAA) and the 2000-present NOAA Climate Prediction Center (CPC) dataset. First, optimal temperature threshold for Cold Cloud Duration (CCD) of a given region was defined as a percentage of pentads (or 5day averages at 0.05º × 0.05º) with respect to their long-term (1981-2012) climatology. Then, a regression relationship is developed to translate CCD values into estimates of precipitation depth. This produces CHIRP satellite-only gridded precipitation dataset. In our study area, the precipitation is only in the form of rainfall. Thus, this study will use the term rainfall instead of precipitation. The CHIRP rainfall satellite data can be obtained freely from http:chg.geog.uscb.edu/data. Readers are advised to refer to Funk et al. (2015) for more details about CHIRP satellite rainfall estimate.

3.4 Methods

3.4.1 Bias Correction of CHIRP Satellite Estimate

The accuracy of CHIRP rainfall product was evaluated using gauge rainfall as a reference. First, a comparison of satellite and gauge rainfall amounts through visual inspection of scatter plots was performed. Then, performance indicators of relative bias (BIAS) and mean error (ME) were estimated to evaluate bias of CHIRP satellite estimates at monthly average time scale. For a more detailed performance assessment of CHIRP satellite product at various spatiotemporal scales refer Goshime et al. (2019).

The ME describes the average difference between satellite estimate and rain gauge observations. BIAS represents the systematic error of the satellite-based rainfall estimate as a percentage of the observed rainfall. A positive ME and BIAS indicates an overestimation, whereas a negative value indicates underestimation by the satellite. The ME and BIAS are expressed by:

$$\mathrm{ME} = \frac{1}{\mathrm{n}}\sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{S_i} - \mathrm{G_i}) \qquad (3.1)$$

$$\mathrm{BIAS} = \frac{\sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{S_i} - \mathrm{G_i})}{\sum_{\mathrm{i}=1}^{\mathrm{n}}\mathrm{G_i}} \times 100\% \qquad (3.2)$$

where G_i and S_i are rainfall values from gauged-based and satellite product, respectively; and n represents the number of rainfall pair time series in the sample.

In this study, a non-linear power transformation bias correction method was applied to remove the systematic error in CHIRP satellite estimates. For For bias correction 14 rain gauge stations were available after screening. The non-linear power equation reads:

$$P_c = aP_o{}^b \qquad (3.3)$$

where P_c is bias-corrected CHIRP rainfall amount; P_o is uncorrected CHIRP rainfall amount; a and b are bias factors.

The approach was selected as it accounts for the first and second statistical moment (mean and standard deviation) of rainfall time series and following (Lafon et al., 2013; Pratama et al., 2018). However, it is noted that there is no sufficient evidence in the scientific literature that guide best selection of a bias correction method. A power transformation bias correction has been applied for satellite rainfall bias correction at various previous studies. For instance, Leander and Buishand (2007) and Terink et al. (2010) applied power law for European river basins. The authors reported that a non-linear bias correction revealed better performance than commonly used linear bias correction method. Gumindoga et al. (2019) applied power law in comparison with other methods for bias correction of CMORPH rainfall estimates in the Zambezi River basin. We also refer to recent studies (Wagesho et al., 2013; Goshime et al., 2019) who applied a non-linear power bias correction method for Rift Valley Lakes basin of Ethiopia. Therefore, we have chosen to apply a power transformation bias correction method to remove the systematic errors of the CHIRP satellite estimate.

The bias factors are determined iteratively until the statistics (mean and coefficient of variation) of the satellite-estimates match with the observed rainfall amount at a monthly time step. First, daily data of both data sources were arranged for each month over the period from

1984-2000. Then, the values of a and b were estimated using excel solver function at selected 14 grid pixels that overlay the locations of the rain gauge stations.

The bias correction algorithm was verified for an independent period from 2001-2007. The verification was conducted to evaluate the applicability of the bias factors outside the bias correction data periods. The bias-corrected rainfall estimate was compared against observed rainfall amount using a plot of average monthly aggregate values for Meki and Katar catchments. The bias factors were spatially interpolated to other CHIRP grid pixels, which did not contain rain gauges, using Inverse Distance Weighting (IDW) method across the watershed. A similar approach was also adopted by Yong et al. (2010). Finally, the interpolated bias factors (a and b) were used in Equation (3.3) to estimate bias-corrected satellite rainfall data.

3.4.2 Potential Evapotranspiration

The potential evapotranspiration (PET) was estimated using Penman-Monteith (Allen et al., 1998) and Hargreaves method (Hargreaves and Allen, 1985) at 4 principal stations (Ziway, Kulumsa, Bui and Merero). To correct for overestimation of Hargreaves estimate, we established a linear regression relationship (i.e.$y = mx + c$) between Penman-Monteith and Hargreaves values at the four mentioned stations.

The slope of the regression line (c) and its intercepts (m) at the four stations were transferred to the location of the 7 ordinary stations (recording only temperature and rainfall) using the IDW method. Next, the error of the PET estimates from the Hargreaves method was corrected at the seven stations using the estimates of Penman-Monteith method. The catchment average areal PET was then computed from 11 stations in the watershed from an estimate of Penman-Monteith using Theissen polygon, which was then used as input to the hydrological model. The potential evapotranspiration estimation approach applied in this study is based on the study of Ayalew (2010) who applied a simplified regional potential evapotranspiration estimation method for Abbay river basin in Ethiopia. The author evaluated at 23 selected meteorological stations based on available maximum and minimum temperature. The authors reported that the method revealed satisfactory results and recommended as alternative approach to estimate PET in ungauged areas. Similar work has been done in South Africa by Pike (1988) and in Tanzania by Moges et al. (2003).

3.4.3 HBV Rainfall-Runoff Modeling

The Hydrologiska Byråns Vattenbalansavdelning (HBV) model has been widely applied in various countries for runoff simulation, climate change, and water accounting studies (Bergström, 1992). The HBV model was selected due to its performance in simulating streamflow in different Ethiopian river basin (Rientjes et al., 2011; Worqlul et al., 2015). Furthermore, operational and scientific applications of this model have been reported from more than 50 countries around the world (Johansson, 2013). The HBV model reads rainfall, temperature, PET and land cover (forest, field and water) as main inputs. Observed streamflow data is used as reference data for model calibration.

The model consists of four subroutines for precipitation, soil moisture, runoff routine and routing routine. Precipitation routine controls precipitation either to be simulated as snow or rain depending on a specified temperature threshold value. Precipitation is only in the form of rainfall in the Lake Ziway subbasin.

The soil moisture controls the formation of runoff (both direct and indirect). Direct runoff occurs when the simulated soil moisture (SM) in the soil moisture reservoir exceeds the maximum field capacity (FC). The indirect runoff in the system is expressed using power relationship as follows:

$$R = IN \times \left(\frac{SM}{FC}\right)^{BETA} \tag{3.4}$$

where R denotes indirect runoff (mm); IN is water infiltrating amount (mm); SM is soil moisture storage (mm); FC is the field capacity at maximum soil moisture (mm). $BETA$ is a parameter that accounts for a non-linearity of indirect runoff from the soil layer.

In soil moisture routine, the actual evapotranspiration (E_a) equals the PET when the actual soil moisture exceeds a certain threshold which is defined by LP. LP is a dimensionless parameter that represents the limit for potential evaporation. When water is available in the upper zone, percolation (PERC) will occur to the lower zone at approximately constant rate. Percolation (PERC) represents a constant percolation rate that occurs when water is available in the upper storage zone.

At runoff routine three parameters such as capillary transport (C_f) to the soil moisture reservoir, percolation to the baseflow reservoir and runoff relationships are governed in the model. Capillary transport is determined as a function of maximum soil moisture storage (SM), Field capacity (FC) and maximum capillary flow (CFLUX) which is a calibrated model parameter. The relationship reads:

$$C_f = CFLUX \times \left(\frac{FC - SM}{FC}\right) \tag{3.5}$$

Excess water is transformed from the soil moisture zone to runoff. The summation of runoff from the upper and lower storage zones yields the total runoff. The runoff from the upper and lower storages reads:

$$Q_{u=} K_u \times UZ^{(1+Alfa)} \tag{3.6}$$

$$Q_l = K_4 \times LZ \tag{3.7}$$

where Q_u and Q_l are the runoff components from the upper and lower storage zones, respective ly; *UZ* is the actual storage in the upper zone and *LZ* is the actual storage in the lower zone; K_u and K_4 are storage (recession) coefficients in the upper and lower zone, respectively. *Alfa* is a measure of the non-linearity of the flow in the upper storage zone.

We selected 8 parameters (Alfa, BETA, CFLUX, FC, LP, K4, Khq and PERC) for calibration based on recommendations in the literature (Wale et al., 2009; Rientjes et al., 2011) and HBV model documentation. Initial values of these model parameters were specified based on HBV model documentation (Johansson, 2013). In this study, calibrated model parameters and their ranges are adopted from Goshime et al. (2019) which was given in Table 2.1 (Chapter 2). For more detail descriptions of the HBV model reference is made to Lindström et al. (1997) and Johansson (2013).

3.4.3.1 Model Calibration and Evaluation

Sensitivity analysis was conducted to find the parameters for which model response is sensitive to aid model calibration. The default model values of the parameters were used in the model as reference to decide the sensitive model parameter. Parameter values were then varied within their allowable range by changing the value of one parameter at a time by a constant increment. The parameter for which the model is sensitive was determined based on Nash-Sutcliffe efficiency (NSE) and relative volume error (RVE) objective functions following Dessie et al. (2014).

In this study, the HBV model was initialized for the study area with a 2-year warm-up period (1984-1985). The model was then calibrated for the period 1986 to 1991 using bias-corrected CHIRP rainfall input. This calibration period was selected since water abstraction for this period is limited. The calibration period covered for normal, flood and dry weather periods so the calibrated model is considered as representative to simulate lake streamflow inflows.

The model performance was evaluated in terms of visual inspection of the hydrographs and quantitatively through objective functions. Two objective functions were used to assess the model performances which are NSE and RVE. NSE is a measure of a degree of match between the pattern of simulated and observed hydrographs. The equation reads:

$$NSE = 1 - \frac{\sum_{i=1}^{n}\left(Q_{sim,i} - Q_{obs,i}\right)^2}{\sum_{i=1}^{n}\left(Q_{obs,i} - \overline{Qobs}\right)^2} \qquad (3.8)$$

where Q_{sim} and Q_{obs} represent simulated and observed daily streamflow, respectively (m^3s^{-1}); and the over-bar symbol denotes the mean of the statistical values; *i* is the time step; n represents the number of days in the sample. NSE is a dimensionless value, ranges from -∞ to 1, a value of 1 indicates a perfect fit.

RVE measures the average tendency of the simulated runoff to be larger (overestimation) or smaller (underestimation) than the observed values. The equation reads:

$$RVE = \left[\frac{\sum_{i=1}^{n}\left(Q_{sim,i} - Q_{obs,i}\right)}{\sum_{i=1}^{n} Q_{obs,i}}\right] \times 100\% \qquad (3.9)$$

RVE ranges between -∞ to ∞, but the model performs best when a value of 0 is generated. A value between -5% and +5% indicates that a model performs very well while a value between ±5 and ±10% indicates that a model has reasonably good performance.

The performance of the calibrated model was validated using the rainfall input for the period 1996 to 2000. Again, NSE and RVE were used to evaluate performance for the validation period. The streamflow data which was recorded from 1992-1995 was not considered either for calibration or validation, due to incomplete data records.

Next, three (3) rainfall dataset was constructed, namely gauge, uncorrected CHIRP and bias-corrected CHIRP rainfall to evaluate the effect of bias correction on streamflow simulation. The calibrated model parameters from bias-corrected CHIRP satellite rainfall inputs were used in all model simulation. Note that parameter recalibration was not performed for a model with different rainfall inputs. The simulated streamflows from 1996-2000 which is outside the calibration period for the three datasets were compared to observed streamflow as a reference to assess the effect of bias correction of CHIRP satellite estimates.

3.4.4 Lake Water Balance and Lake level simulation

This study followed (Wale et al., 2009; Rientjes et al., 2011) who assessed water balance closure of Lake Tana, Ethiopia. The inflow and outflow from all sources were estimated at daily time step and estimated net inflow at daily time step (t) as follows:

$$\frac{\Delta V}{\Delta t} = [(R(t) - E(t))] \times A(h) + Q_{in}(t) - Q_{out}(t) + G_{in}(t) - G_{out}(t) + \varepsilon(t) \qquad (3.10)$$

where $\frac{\Delta V}{\Delta t}$ represents net inflow volume over time ($m^3 d^{-1}$); R and E are lake rainfall and evaporation, respectively ($m\ d^{-1}$); Q_{in} is lake streamflow inflow ($m^3 d^{-1}$); Q_{out} is lake streamflow outflow ($m^3 d^{-1}$); G_{in} and G_{out} are groundwater inflow and outflow, respectively ($m^3 d^{-1}$); $A(h)$ is a lake surface area in m^2 as a function of water level and ε represent closure error in water balance arising from errors in the data or other terms. The water balance closure term is an error term that cannot be accounted for directly, and hence is estimated as water balance flux that closes the lake water balance.

Due to lack of piezometric groundwater data underneath and around the lake, the groundwater component was ignored in the water balance as shown in other studies as well (Vallet-Coulomb et al., 2001; Ayenew, 2007; Seyoum et al., 2015; Desta et al., 2017). These studies argued that significant interaction is unlikely to occur due to the very shallow nature of the lake with flat topography and substantial sediment loads of inflowing rivers. As such, we neglected the groundwater contribution in the lake water balance of this study. Therefore, Equation (3.10) is simplified as follows:

$$\frac{\Delta V}{\Delta t} = [\{R(t) - E(t)\} \times A(h) + Q_{in}(t) - Q_{out}(t)] \qquad (3.11)$$

where all water balance terms have been defined above in Equation (3.10).

The daily areal rainfall over the lake was estimated from bias-corrected CHIRP satellite data. The bias correction was applied according to power transformation between satellite and gauge rainfall data series as described in earlier section. The water evaporation from the lake was estimated using the Penman method (Penman, 1984). This method was selected as it combines the energy balance and water vapour transfer. Its input data includes surface air temperature, relative humidity, wind speed, and sunshine hours. First, open water evaporation was estimated at three stations Ziway, Ogolcho and Arata, which are situated close to the lake. Then, average lake evaporation was estimated using Thiessen polygon. The surface albedo in this study is assumed 0.06 following Vallet-Coulomb et al. (2001) for Lake Ziway and Dessie et al. (2015) for Lake Tana in Ethiopia.

The calibrated HBV model was applied to simulate the streamflow over the simulation period 1986-2014 from the gauged area of the two major tributaries. The ungauged part of the subbasin accounts for 18% of the total subbasin area. The streamflow contribution from ungauged catchment was estimated using the area-ratio method. This method was selected due to its simplicity. Furthermore, only about 38% of Lake Tana is gauged whereas a large parts of (almost 82%) the Lake Ziway catchment is gauged at major Meki and Katar Rivers. Applying other methods for estimating lake inflow from ungauged areas is intricate by the lack of river gauging stations that constrain the application of advanced regionalization applied in (Wale et al., 2009; Rientjes et al., 2011) for the Lake Tana basin area.

The outflow of Lake Ziway is measured at Kekersitu station which is situated at the head of Bulbula River. Incomplete records in lake outflow during the analysis period were filled by using a regression relationship between Lake water level and outflow discharge. A similar approach was applied in other studies for Lake Ziway (Vallet-Coulomb et al., 2001), Lake Tana (Kebede et al., 2006), Lake Victoria (Nicholson & Yin, 2001), and Lake Malawi (Kumambala and Ervine, 2010). The regression relationship between water level and outflow discharge reads:

$$Q_{out} = \alpha \, (H - H_o)^{\beta} \tag{3.12}$$

where Q_{out} is the simulated lake outflow; H is the lake water level; H_o is the water level at zero reference datum; α and β are constants. The parameters α and β were estimated from the regression relationship between the lake level and outflow.

The relationship between lake level and outflow were established for a period in which complete data was available for the period 1987 to 2007. From the relationship, values of 1.73 and 3 were adopted for α and β, respectively. In this study, a reference datum level of 1635 m.a.s.l, was used for lake level simulation.

For lake level simulation a spreadsheet water balance model was developed to simulate the lake volume as follows:

$$V_{lake}(t) = V_{lake}(t-1) + \Delta V \tag{3.13}$$

where V_{lake} *(t)* is the lake volume at day t; V_{lake} *(t-l)* is lake volume at previous day (t-1); and ΔV represents net inflow volume as estimated using Equation (3.10).

The updated lake volume was then converted to lake level using the bathymetric relation between lake level and volume. Finally, comparison of the match of the simulated lake level was evaluated by comparing against observed counterparts. Note that in the present study, human-induced impacts such as water abstraction are not considered in the rainfall-runoff and water balance model. Hence, any major deviation of the simulated lake level from observed lake level was assumed to indicate the magnitude of human-induced impacts. A number of studies have shown that temporal variation between the model simulated and observed lake level can vary as a result of climate change, human activities or both (Wang et al., 2010; Peng et al., 2013; Seyoum et al., 2015; Zhou et al., 2018). We also refere previous studies that evaluated the extent of land use and land cover changes between 1973 and 2014 (Desta et al., 2017).

Furthermore, the study applied statistical methods such as linear regression; Mann-Kendall test and using Standard precipitation index (SPI) and streamflow drought index (SDI) were applied to understand the effect of climate variability over the study area.

The linear regression method is parametric t-test methods, which is basically through fitting a linear regression equation with time and the hydrological variable (i.e. rainfall, streamflow, water level etc.) and then assess the statistical significance of the slope of the regression relationship.

The Mann-Kendall test was used to detect the presence of trend (existence of decreasing or increasing trends in the hydro-meteorological time series) for a specified period (Mann, 1945; Kendall, 1975). In this study, we used all water balance component dataset over Lake Ziway and its catchments for the period 1984–2016. A 5% significance level (α=0.05) was used to assess the extent of significance of the trend. We note that, at α=0.05, there is no trend in the data, whereas for p-value ≤ 0.05, then the existing trend is considered to be statistically significant. More detail about Mk trend test reference was made Zhang et al. (2006) and Pingale et al. (2014). This test was performed using the evaluation version of XLSTAT 2019 software.

The SPI and SDI indices were used to assess the existence of long-term climate variability in relation to the fluctuation of Lake water level and storage. The drought index calculator (DrinC) (Tigkas et al., 2015) was used to compute the above mentioned indices at annual time scales. SPI and SDI provide a normalized measure of length and intensity of dry or wet periods at a given location, which is based on historical precipitation observations and cumulative probability distributions. For more detail about SPI & SDI refer (McKee et al., 1993; Hayes et al., 1999; Blain, 2014).

Both indices calculated from a continuous monthly precipitation data using defined time scales (1, 3, 6, 12, and 24 months). In this study, we used a 29 years dataset from bias-corrected CHIRP satellite dataset and the streamflow simulated from the major contributing catchments i.e. western and eastern side of the lake. We selected annual (12 month) time scale to assess the effect of rainfall and streamflow variation over the lakes. A value of SPI ranging between -3 and +3 indicates dry and wet conditions, respectively. A value ± 1 indicates normal conditions whereas values greater than 1 and less than -1 indicate moderate to extreme wet and dry conditions, respectively (Guttman, 1999).

3.5 Results

3.5.1 Evaluation of CHIRP Satellite product

The scatter plot between the daily gauge observation and CHIRP satellite-only estimates are shown in Figure 3.2. The data plots are shown for selected stations covering the period from 1984 to 2007. The scatter plot demonstrates that there is strong disagreement between the two data sets. Only a few data points are spread along the 45º slope line, indicating a poor correlation between the CHIRP satellite-only product and the rain gauge data. The data points are mostly below the diagonal line, indicating an underestimation of observed rainfall.

Several data points are spread along the x-axis, indicating that CHIRP missed observed rainfall. Rainfall amounts up to 80 mm per day were missed by CHIRP. Similarly, there are several data points which are spread along the y-axis, indicating the satellite product reported false rains.

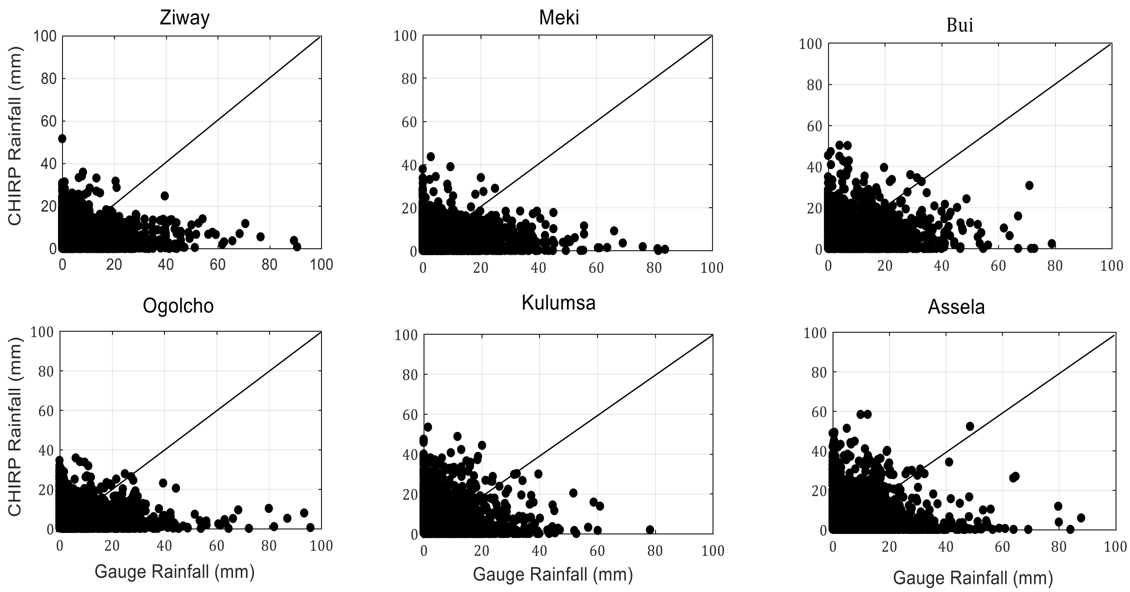


Figure 3.2. Scatter plots of daily CHIRP satellite rainfall estimates against gauge rainfall at six selected main weather stations from 1984-2007

Table 3.1 shows the percentage of relative bias (BIAS) of CHIRP monthly rainfall at six (6) selected rain gauge stations. The satellite product has a significant bias, which is time and location specific. We note that overestimation dominates at Ziway and Ogolcho whereas underestimation dominates at Kulumsa and Assela stations. This phenomenon is presumably related to the location of the stations at relatively low and high altitude regions, respectively. Khandu et al. (2015) reported similar results over Bhutan where CHIRP underestimated over higher elevation regions. Overall, CHIRP has a large bias that reaches up to 73% at rainy seasons. In terms of mean error (ME), the monthly difference between CHIRP satellite-only and observed rainfall reaches up to 13 mm. Thus, overall bias is large which indicates that the uncorrected CHIRP product cannot serve as input to a rainfall-runoff model. Therefore, bias correction was applied to improve the accuracy of the product. The bias correction was first performed using the satellite and gauge data from 1984 to 2000 at 14 selected stations.

Table 3.1. Monthly percentage bias between CHIRP satellite only product versus gauged rainfall for a period from 1984-2007

Stations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Ziway	33.0	17.3	30.2	16.4	-0.4	0.8	-2.9	22.2	22.9	26.2	63.7
Meki	10.0	-8.4	2.5	31.9	0.0	0.4	-13.7	2.0	28.0	29.5	35.8
Bui	-3.5	-43.2	-2.2	16.7	9.8	-11.9	-11.3	3.5	24.8	60.7	42.4
Ogolcho	30.7	3.5	-12.5	-8.9	6.3	1.3	9.1	68.3	-6.3	-21.2	8.0
Kulumsa	-25.3	-30.3	-20.7	-29.2	-31.8	-13.3	73.1	61.3	-7.2	-39.3	-25.9
Assela	0.4	-4.4	-23.2	-41.1	-25.1	-17.1	3.0	0.6	-31.0	-48.0	-47.1

Figure 3.3 (a and b) summarize the monthly aggregate rainfall from the gauge, CHIRP bias-corrected and uncorrected satellite-only product for Meki and Katar catchments, respectively. The comparisons were performed for the verification period 2001 to 2007. The bias-corrected CHIRP estimates captured the pattern of the annual cycle of the observed rainfall. Overall, this study indicates that bias correction has significantly minimized the systematic error in CHIRP rainfall estimates as the bias-corrected and observed rainfall amounts are equal for bias correction period from 1984-2000.

The bias correction successfully reduced the bias of the satellite data even when validated outside the bias correction period 2001-2007 (Figure 3.3). However, there is still some disagreement between the bias-corrected and gauge data for the validation period. The disagreement was during the rainy reason, which is most likely related to the bias of CHIRP satellite rainfall at seasonal scale. Such disagreement can be caused by the ineffectiveness of the bias correction algorithm to capture the difference in rainfall characteristics in the bias calibration and validation period. Note that the period 2001-2007 was relatively wetter than the period 1984-2000. We should therefore be very cautious in using the bias correction method outside the bias calibration period. As a result, we have re-calibrated the parameters of the power law equation for the entire period 1984-2014.

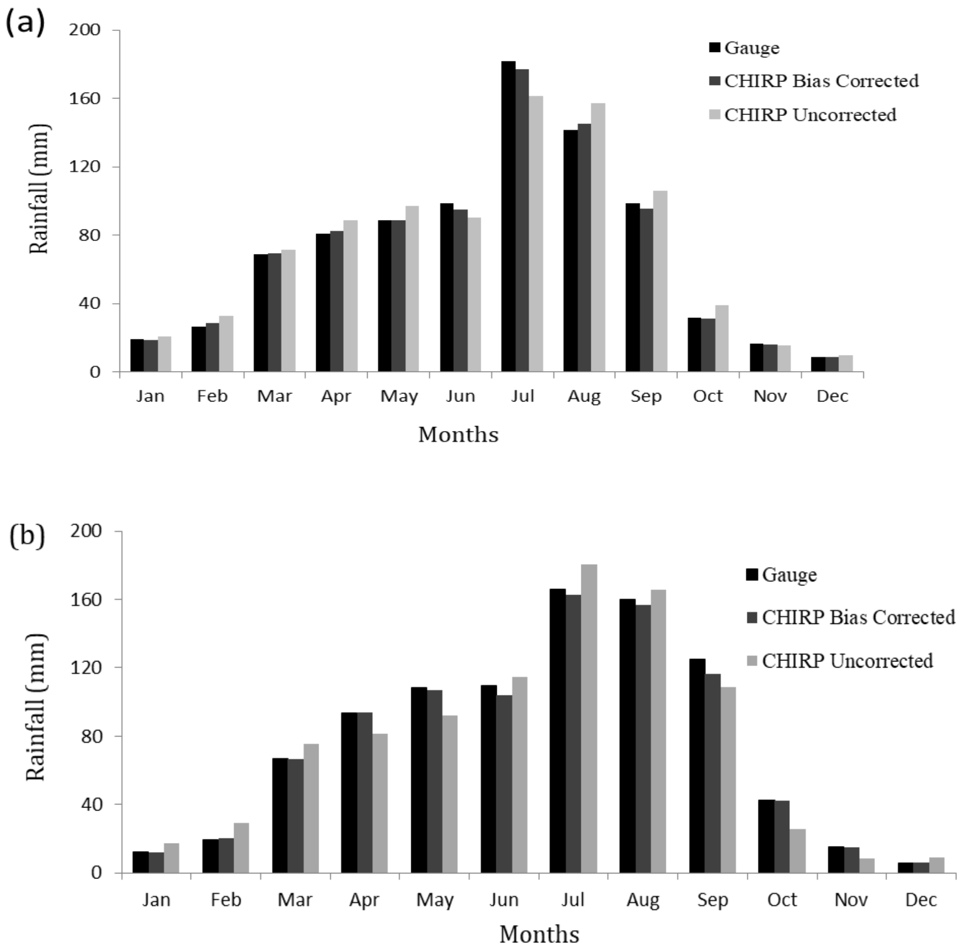


Figure 3.3. Comparison of monthly average rainfall amount from CHIRP Bias corrected, uncorrected (satellite only) and gauge time series from 2000 to 2007 (a) Meki catchment; (b) Katar catchment

3.5.2 Model Calibration and Sensitivity

The result of sensitivity analysis indicated that the HBV model of the study area is most sensitive to volume controlling parameters (FC, BETA and LP). The shape controlling parameters (K4 and Khq) were found to have less effect on streamflow simulation. Parameters Alfa, CFLUX and PERC showed to have least effect. Similar findings were reported in Dessie et al. (2014) and Worqlul et al. (2018) over upper Blue Nile basin in Ethiopia.

In Table 3.2 the calibrated parameter values of the HBV model for Meki and Katar catchments are tabulated. Note that the values of all parameters are within their allowable ranges as specified in the HBV manual. Values of K4, Khq and Alfa are almost equal for the two catchments. However, most sensitive parameters (FC, BETA and LP) values show a noticeable difference between the two catchments. The possible reason for this might be the differences in a rainfall-runoff relationship as affected by variation in rainfall, topographic and physiographic properties among catchments.

Table 3.2.Calibrated values of HBV model parameters using bias corrected CHIRP satellite data

Parameter	Alfa	BETA	CFLUX	FC	K4	Khq	LP	PERC	hq
Unit	-	-	mm	mm	d^{-1}	d^{-1}	-	mmd^{-1}	-
Meki	0.8	1.98	0.01	860	0.1	0.1	0.5	1.15	0.83
Katar	1.1	3.05	0.005	820	0.1	0.12	0.7	2.75	1.13

Figure 3.4 shows a comparison of simulated and observed streamflow hydrograph for the calibration period (1986-1991) for Meki and Katar catchments. The model reasonably captured the pattern of the observed hydrograph of both catchments. The peak and baseflow were reasonably captured with the exception of a few high magnitude peak discharges.

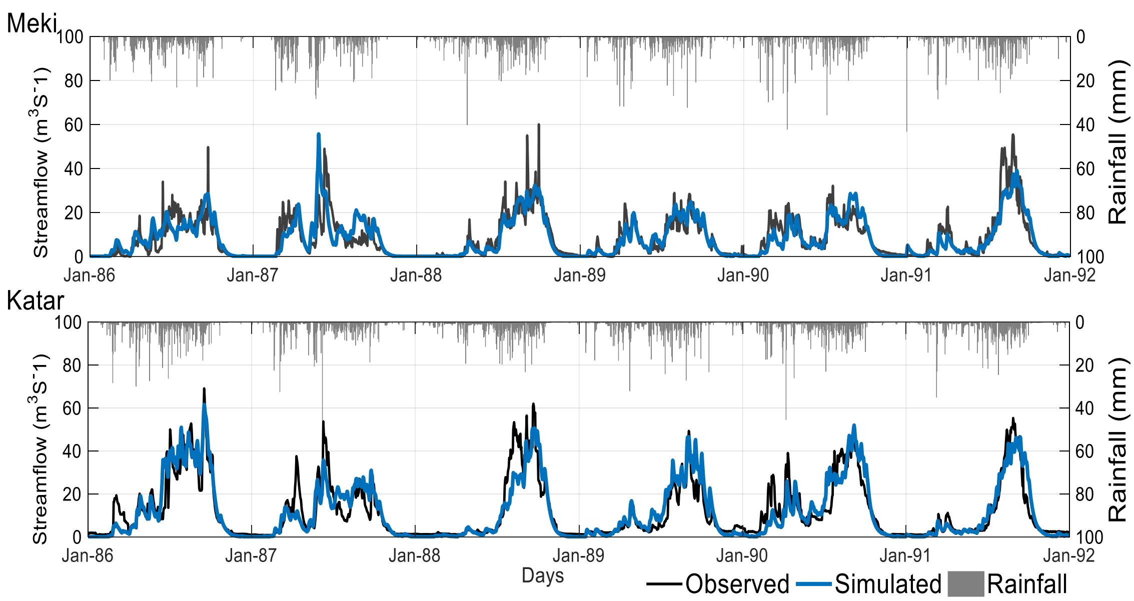


Figure 3.4. Model calibration result of Meki and Katar catchments (1986-1991) using bias corrected CHIRP rainfall as model input

Figure 3.5 shows a comparison of the simulated and observed hydrograph for the validation period (1996-2000) for Meki and Katar catchments. There is good agreement between the simulated and observed hydrographs in terms of pattern, volume, and baseflow.

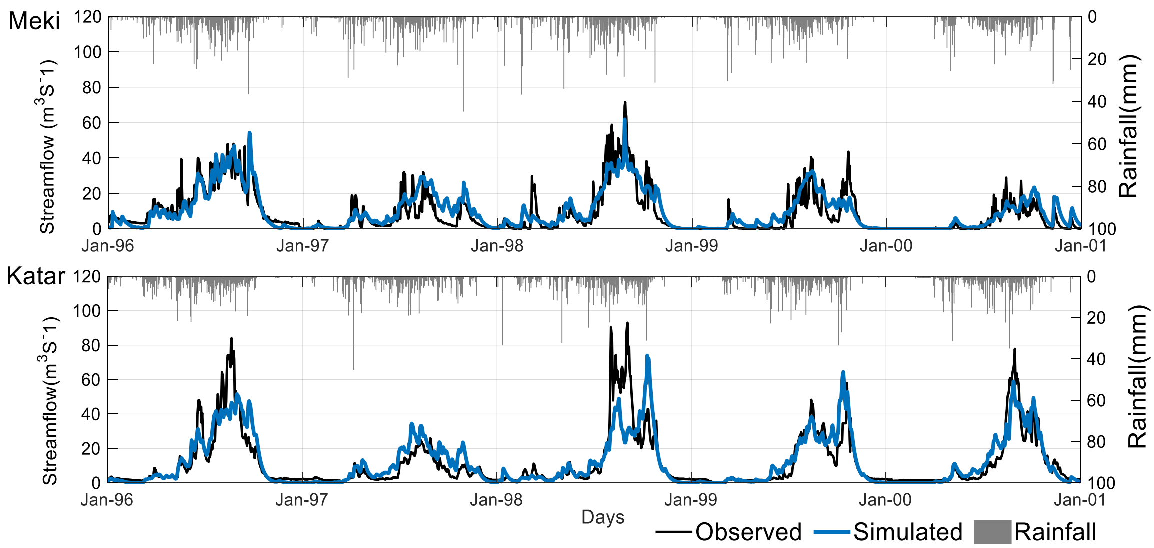


Figure 3.5. Model validation results of Meki and Katar catchments (1996-2000) using bias corrected CHIRP rainfall as model input

The HBV model performance is satisfactory when evaluated quantitatively using NSE and RVE (Table 3.3). The model performance is comparable for Meki and Katar catchments during both the calibration and validation periods. The NSE values are 0.71 and 0.80 whereas RVE values are -1.47 and -1.28% for Meki and Katar, respectively for the calibration period. Note that the model performance efficiency slightly deteriorated in the validation period as compared to the calibration period. However, its performance is still very good for the validation period, indicating that the model can be applied to study rainfall-runoff relations in both catchments.

Table 3.3. The performance of HBV model using objective function for the calibration (1986-1991) and validation (1996-2000) periods

Catchment	Objective Functions	Calibration	Validation
Meki	NSE (-)	0.70	0.67
	RVE (%)	-1.47	2.91
Katar	NSE (-)	0.81	0.76
	RVE (%)	-1.28	2.84

3.5.3 Effects of Bias Correction on Streamflow Simulation

The simulated streamflow hydrographs are compared using gauged, uncorrected and bias-corrected CHIRP rainfall as model inputs for Meki catchment (Figure 3.6). The outputs of the streamflow from the three datasets were compared with observed streamflow as a reference. The model missed some observed peak flows when rain gauge data were used as model input. There is also a noticeable difference between the observed and simulated hydrographs when uncorrected CHIRP satellite-only rainfall is specified as model input. The hydrographs indicated that the model performance showed improvement when using bias-corrected CHIRP satellite rainfall as model input. The pattern and volume of simulated hydrograph were better matched with the observed counterparts.

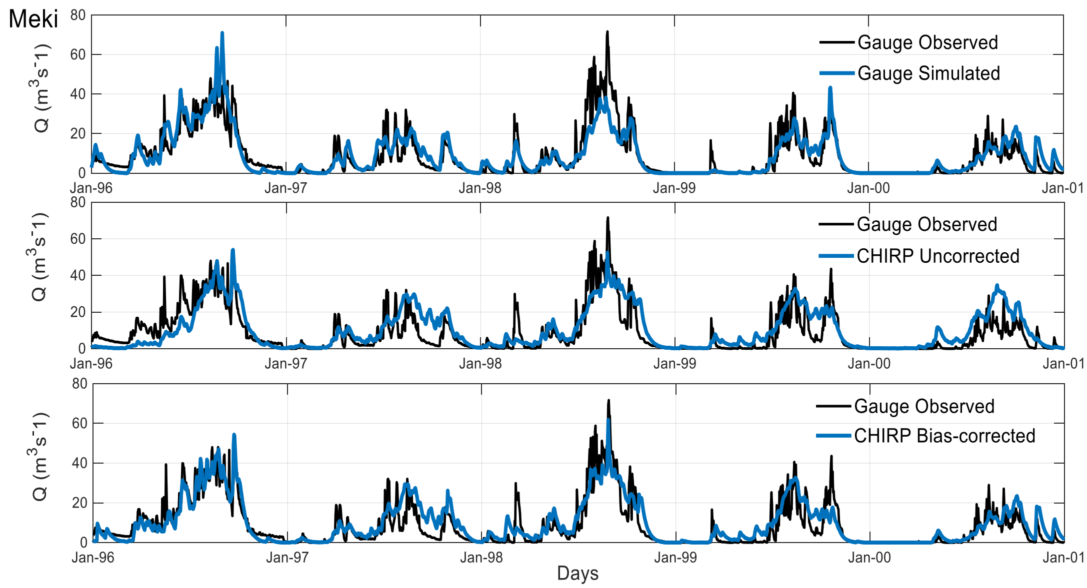


Figure 3.6. Comparison of observed and simulated streamflow hydrograph for Meki catchment from 1996-2000 based on Gauge, CHIRP uncorrected and CHIRP bias corrected rainfall inputs

Figure 3.7 presents the simulated streamflow for Katar catchment when using gauged, uncorrected and bias-corrected CHIRP rainfall data. The figure demonstrates that the bias-corrected CHIRP product improved the performance of streamflow simulation. The values of bias correction are shown for Meki than Katar as the model performance significantly deteriorated in terms of pattern and magnitudes (peak and low flows) when uncorrected satellite-only rainfall served as model input instead of the bias-corrected rainfall estimates. Overall, the study results indicate that CHIRP bias propagates to streamflow simulation via the HBV model. From both plots (Figure 3.6 & 3.7), this study indicated that bias-corrected CHIRP satellite better captured the volume and pattern of observed hydrograph than the satellite-only dataset.

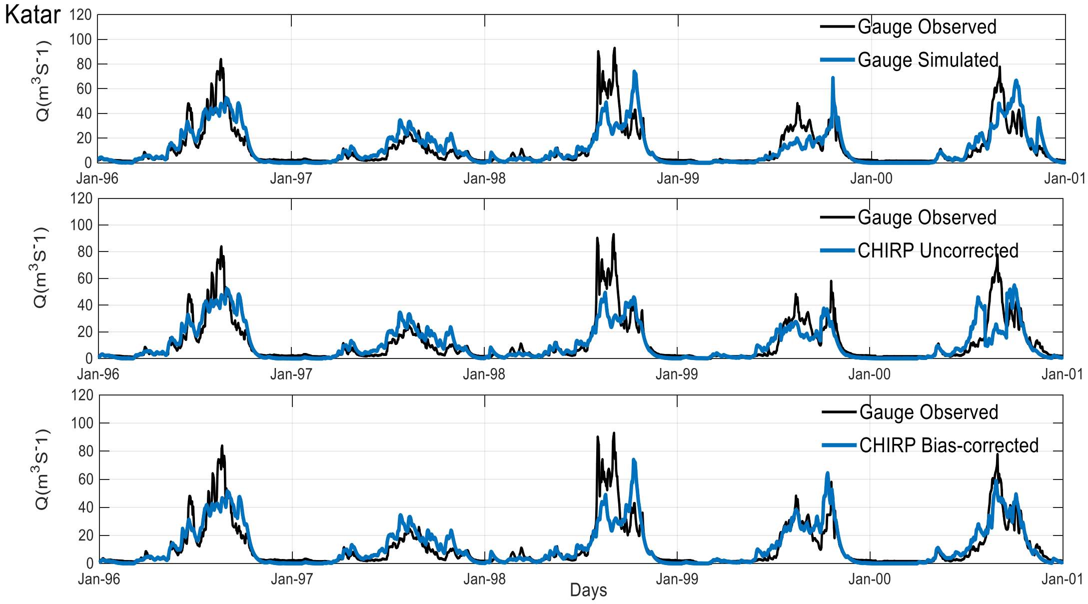


Figure 3.7. Comparison of observed and simulated streamflow hydrograph for Katar catchment from 1996-2000 based on Gauge rainfall, CHIRP uncorrected and CHIRP bias corrected rainfall inputs

The simulated hydrograph was also evaluated using values of the objective function from gauged, uncorrected and bias-corrected CHIRP satellite as model inputs (Table 3.4). The results revealed better performance in terms of NSE and RVE when bias-corrected CHIRP rainfall data serves as model input. Note that, the error of the uncorrected CHIRP satellite rainfall propagated into the HBV simulation as this input resulted in 10% more volumetric error in streamflow as compared to the bias-corrected CHIRP satellite for the validation period.

Table 3.4. Comparison of model objective function between gauge-only, uncorrected, and bias corrected CHIRP dataset to the corresponding observed streamflow

Catchment	Objective function	Gauge	CHIRP Uncorrected	CHIRP Bias-corrected
Meki	NSE (-)	0.60	0.55	0.67
	RVE (%)	6.52	12.6	2.91
Katar	NSE (-)	0.70	0.64	0.76
	RVE (%)	7.56	14.2	2.84

3.5.4 Lake Level Simulation

Figure 3.8 presents daily estimate of Lake Ziway water balance components for a period from 1986 to 2014. The figure indicated that variation of climatic seasonality over each water balance component. The fluctuation/variability of the observed lake level is more distinct than the long term gradual change. The level reduced for the period from 2000 to 2005 and recovered afterwards. We note that the year 1995, 2002, 2005 and 2011 was relatively a drier year both in terms of rainfall and discharge. It is plausible that the lower lake levels in 2000 to 2005 are the result of relatively lower river inflows being drier years. The decrease of the water levels in Lake Ziway would also imply that less water is being discharged into the Bulbula River. As it expected there is a direct relation between the water level and the outflow into the Bulbula River. In years with relative low lake levels (2002 to 2005 and 2009) the outflow has also been low and decreased dramatically.

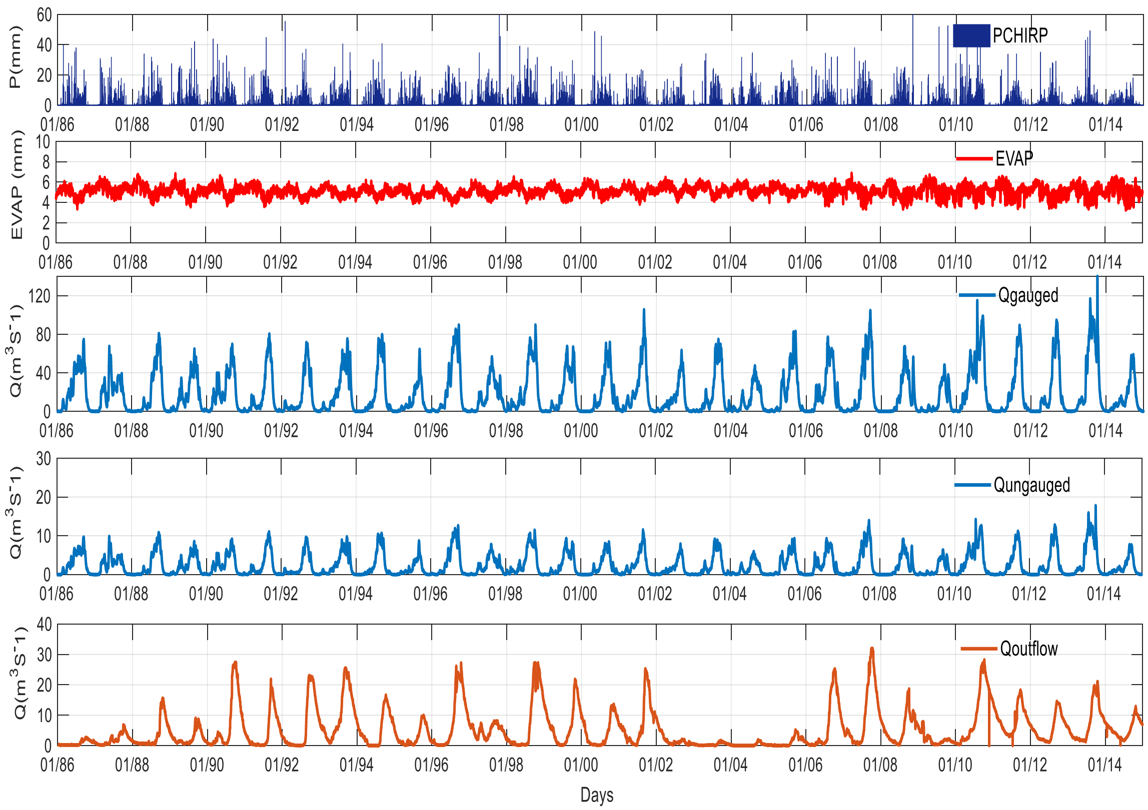


Figure 3.8. Daily estimates of water balance terms of Lake Ziway from 1986-2014

After determining the daily water balance terms, Equation (3.13) was used to simulate changes in lake volume by the net inflow volume. The updated lake volume was transformed into a new lake level using area-elevation-storage relationships. The simulated lake levels were compared with observed lake levels. Figure 3.9 shows a time series of simulated and observed lake level on a daily time scale from 1986-2014.

The simulated lake water level shows a better agreement with the observed water level from 1986-2000. However, the deviation between the two water levels continuously increased from 2000 onwards. The observed lake level declined while the simulated level increases for the period 2001-2014. This could be most likely attributed to an error in any of the water balance terms and human-induced activities that cannot be represented in model simulation. According to (Seyoum et al., 2015) human-induced activities mostly apply for the period 2001-2014. Furthermore, the uncertainities related to bias correction of the satellite, lake inputs obtained by the HBV model, Lake Outflow obtained by water level-flow relationships and overall the cumulative impact might contribute the disagreement between the simulated and observed lake level.

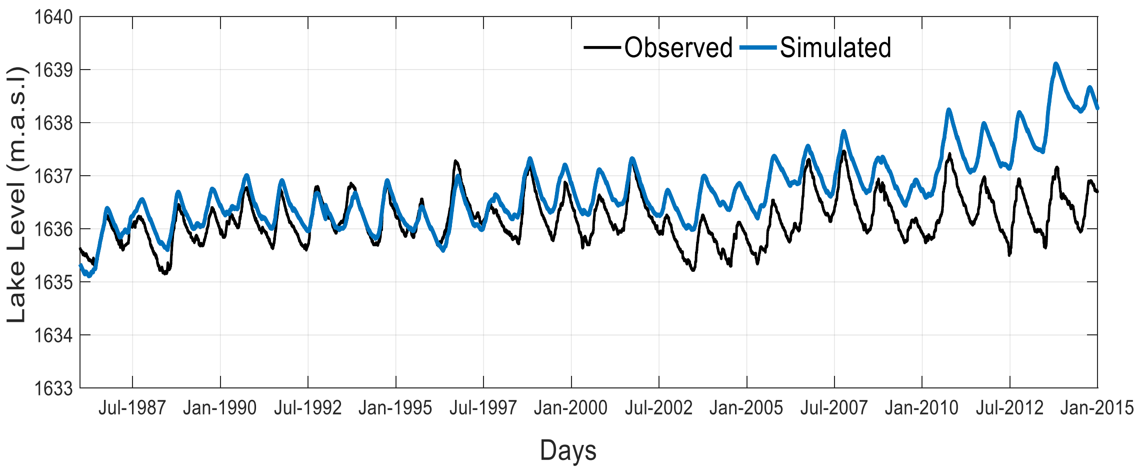


Figure 3.9. Comparison of Observed and Simulated Lake levels from 1986-2014

We also refer to Desta et al. (2017) who evaluated the extent of land cover changes (conversion of woodlands into agricultural lands and settlement areas) for the period 1973-2014 in Lake Ziway catchment areas. Authors reported that agricultural lands and settlement areas together increased from 57% in 1973 to 75% in 2014 of the total area. As such impact could contribute to a mismatch between observed and simulated lake level. Overall, on average 0.90 m annual decline of simulated water level was revealed in the simulation period 2001-2014. The daily maximum simulated water level deviated from the observed level by up to 2.28 m for both 2013 and 2014 period.

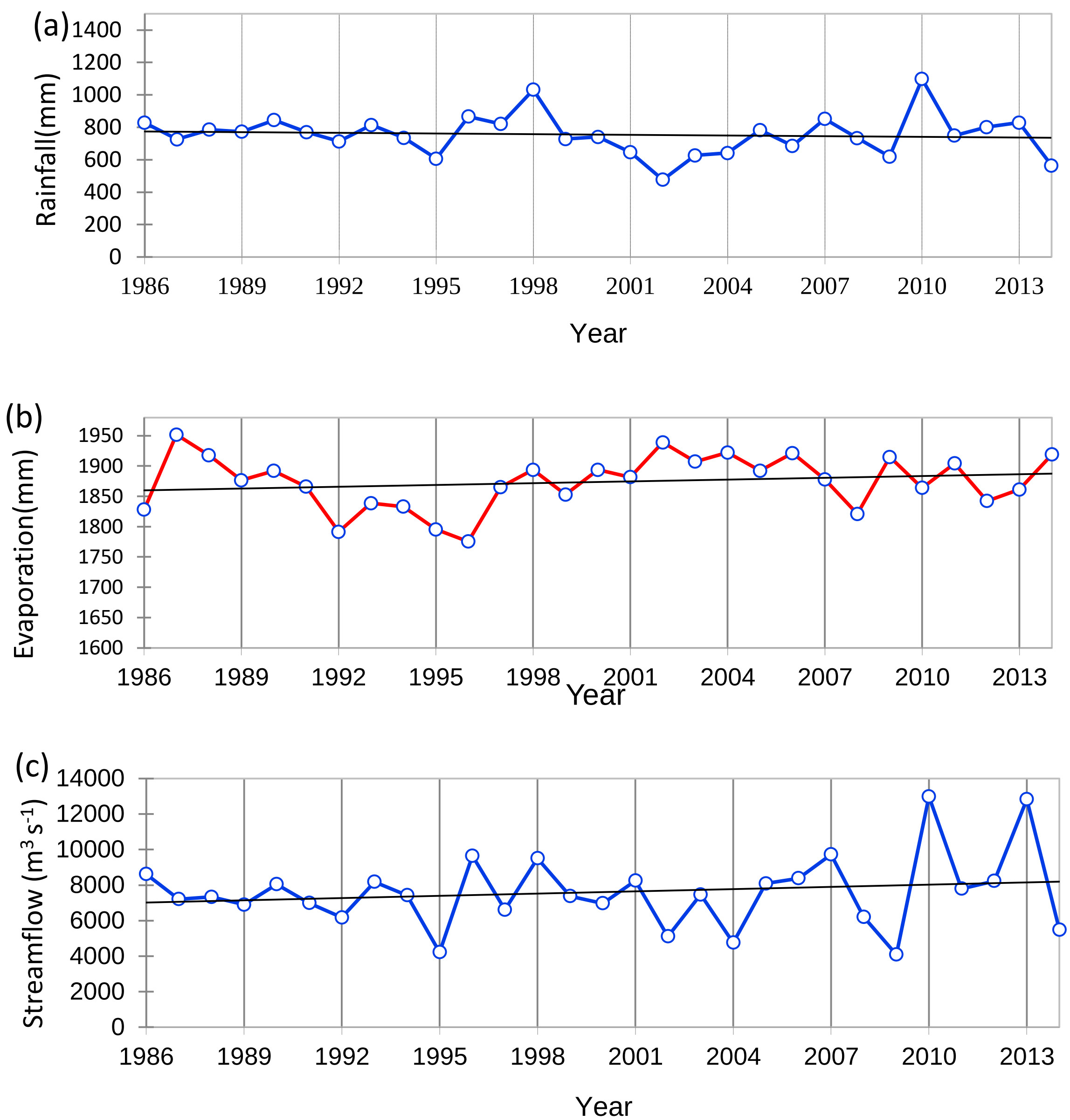
The bias-corrected CHIRP satellite estimates account for an average annual lake rainfall of 755 mm y^{-1} for the period 1986-2014. The average annual evaporation of the lake is estimated at 1875 mm y^{-1} for the same period. In Table 3.5 the summary of Lake Ziway water balance components for the period 1986-2014 are shown. Evaporation from the lake is considerably larger as it is 2.5 times the rainfall amount over the lake. The gauged catchment contributes 1404 mm y^{-1} to the lake inflow whereas the ungauged catchment contribution is 184 mm y^{-1} which constitutes 8.6% of the total lake inflow from rainfall and river inflow. Lake Ziway outflow is 386 mm y^{-1} which constitutes 16.5% of the total lake inflow. Overall, the closure term in this study over the simulation period 1986-2014 indicates a water balance error of 82 mm y^{-1} that accounts for 3.5% of the total lake inflow from rainfall and river inflow.

Table 3.5. Lake Ziway Water Balance Components simulated for a period from 1986-2014

Water Balance Components	mm yr^{-1}	MCM yr^{-1}
Lake Areal Rainfall	755.1	336.0
Lake Evaporation	1875.1	834.4
Gauged River Inflow	1404.0	624.8
Ungauged River Inflow	184.8	82.2
Outflow Discharge	386.9	172.2
Closure term	81.9	36.4

3.5.5 Trend analysis and climate variability

The result of linear regression analysis (with water balance components as a dependent variable and the time as the independent variable) are shown in Figure 3.10. The results indicate that a variation in the trend of the climate variables. Overall, the trend shows an upward trend after 2001 for most of the water balance components except the outflow components. The result of linear regression also indicates variation on the trend of water level, slightly decreasing during the period from 1986 to 2000, then after upward increasing trend in most of the time. The trends of water level present a somewhat similar pattern as compared with the streamflow and rainfall being the major water balance contributor to the lake. We also note that the trend of water level become significant over time. In some cases, the trend of rainfall and streamflow variation is not coinciding with the water level. This phenomenon indicate that the water level change are not influenced by only the variation of water balance components rather by multiple factors such as human activities.



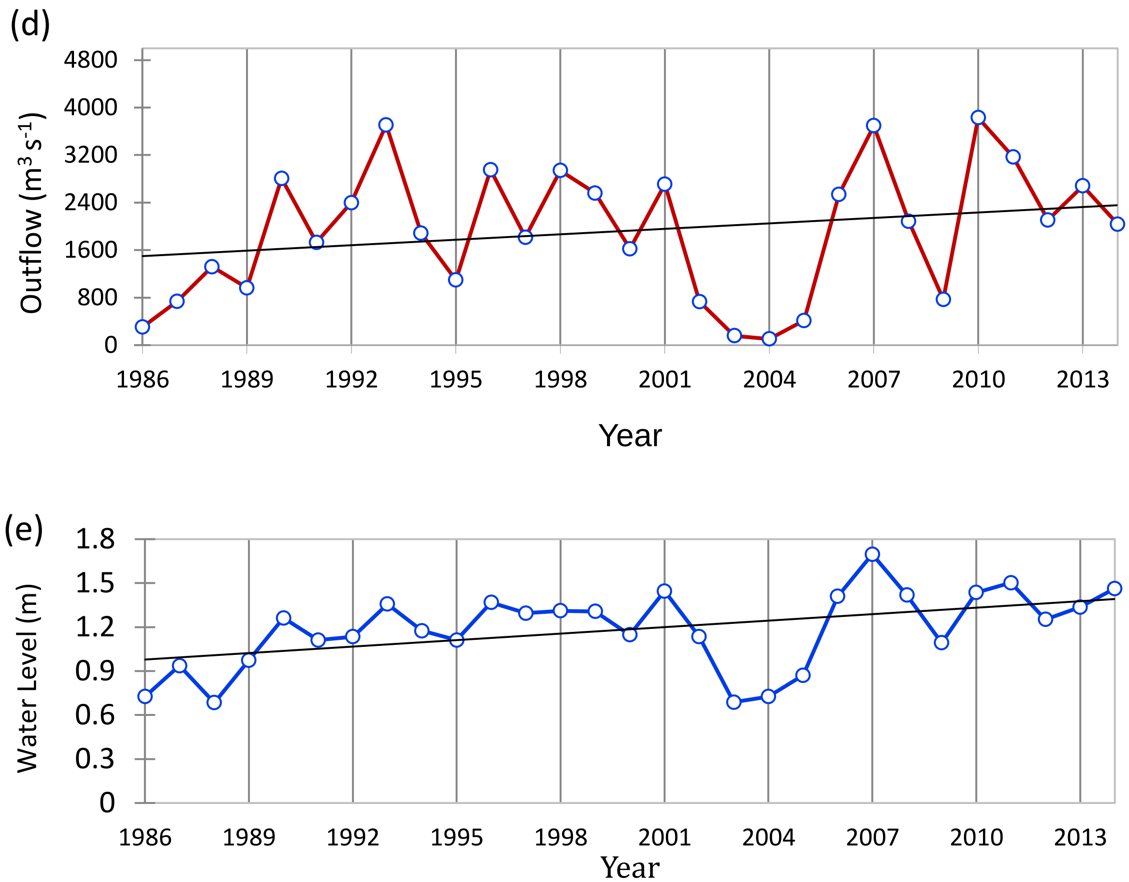


Figure 3.10. Water balance component trend for Lake Ziway for the time period (1986 to 2014) (a) Rainfall, (b) Evaporation, (c) Streamflow, (d) Outflow and (e) lake water level

Table 3.6 shows the results of a Mann-Kendall trend test on each water balance components for the period 1986-2014. The result indicates that increase in streamflow, evaporation, and outflow variables and slightly decreasing in rainfall at the central part near to the lake of the basin. However, in all of the water balance components the change was not statistically significant except the water level. As the computed P-value is lower than alpha=0.05, then the test decision will be to reject the null hypothesis (Ho) and to accept the other alternative hypothesis which show indicates the existence of significant trend. Overall, streamflow and outflow water balance components indicated increasing trend with positive trend nature and slight decreasing trend for rainfall which finally lead to significant increasing trend for water level.

Table 3.6. Mann-Kendell trend test for Lake Ziway water balance components from 1986-2014

Water Balance term	Kendall's tau	S	p-value	Sen's Slope	Test Decision	Trend Nature
Rainfall (mm)	-0.099	-40	0.464	-0.0011	Accepted the Ho	Negative
Evaporation (mm)	0.113	46	0.399	0.0006	Accepted the Ho	Positive
Streamflow (m^3s^{-1})	0.079	32	0.561	0.0102	Accepted the Ho	Positive
Outflow ($m^3 s^{-1}$)	0.153	62	0.253	0.0156	Accepted the Ho	Positive
Water level (m)	0.389	158	0.003	0.00001	Rejected the Ho	Positive

Note: Ho indicates null hypothesis, S represent standard deviation and we assumed 0.05 significance level.

To further evaluate the existence of long-term climate variability in relation to the fluctuation of water level and storage the estimated SPI and SDI indices are shown in Figure 3.11. SPI results showed an anomalous variation in magnitude and duration of wet and dry conditions in the study area (Figure 3.11a). Relatively several dry period magnitudes (SPI value <-1) are observed in the basin after 2001. However, in some cases the dry magnitude values in rainfall are not observed in the simulated streamflow from the major tributaries (SDI) (Figure 3.11 b). This could be due to the some of the small rain amount were directly translated to generate higher streamflow volume. A similar finding was also reported by Seyoum et al. (2015) for the same study area. Besides, rainfall and streamflow indices are relatively higher between 2010 and 2013. Similarly, the SPI depicted extremely wet periods during the same periods. This is consistent with the water level and storage variation of Lake Ziway, which shows a considerable decreasing trend during this period. Alternatively, wet-dry conditions are observed at the beginning of the simulation between 1986 to 2000. However, the impact on water level variation is no significant. This indicates that temporal climate variability also the other contributing factors for variation in water levels.

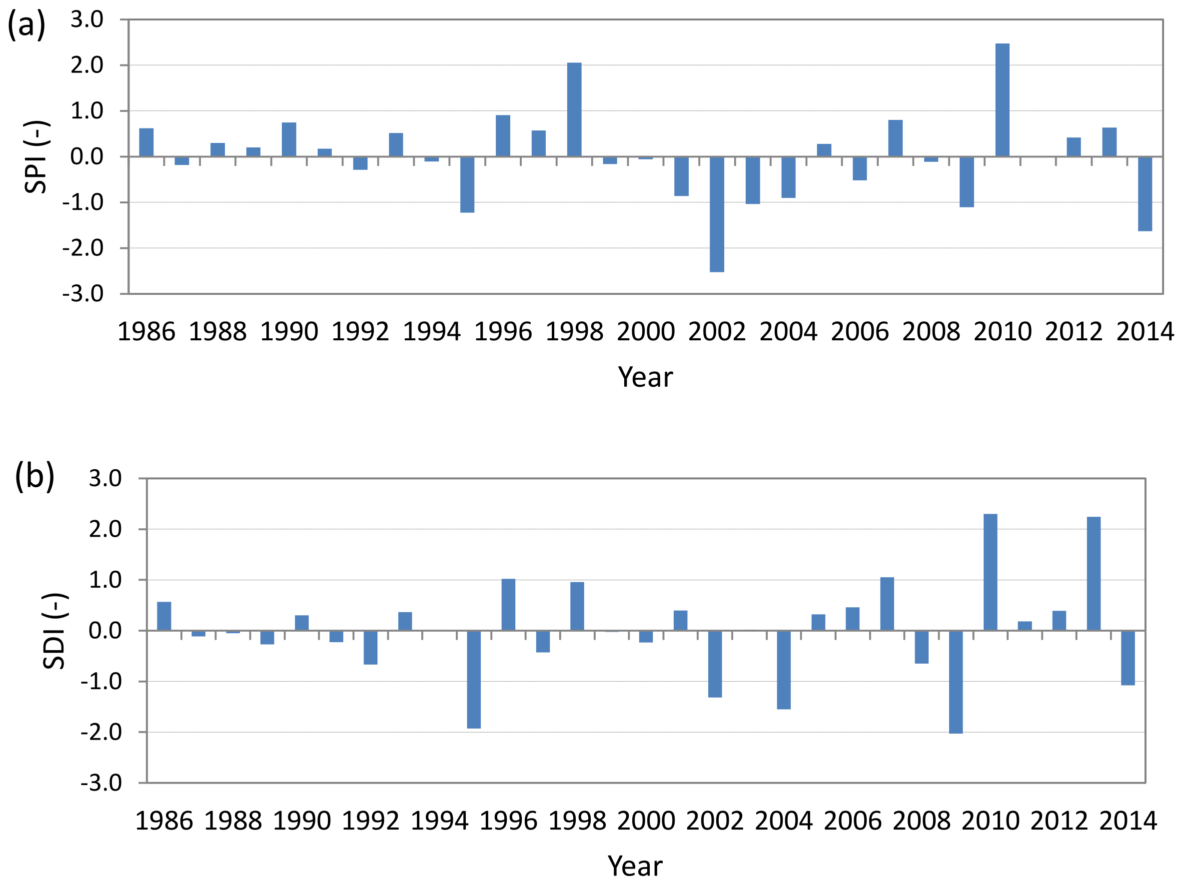


Figure 3.11. Standard precipitation and streamflow index results from 1986-2014 on Lake Ziway (a) Standard precipitation Index (SPI), (b) Steramflow drought Index (SDI)

3.5.6 Variation of temporal water balance components

Figure 3.12 presents the monthly average simulated water balance components of Lake Ziway from 1986 to 2000 (baseline condition). The plot indicates that lake inflows (rainfall and river inflow) mostly occur during the wet season (i.e. June-October), with the highest inflow in August. Lowest contribution to the inflow occurs for four months (November-February). The lake outflow due to evaporation was greater than the river outflow. The larger outflow through Bulbula River occurs from September to January while lower river outflow occurs from February to July.

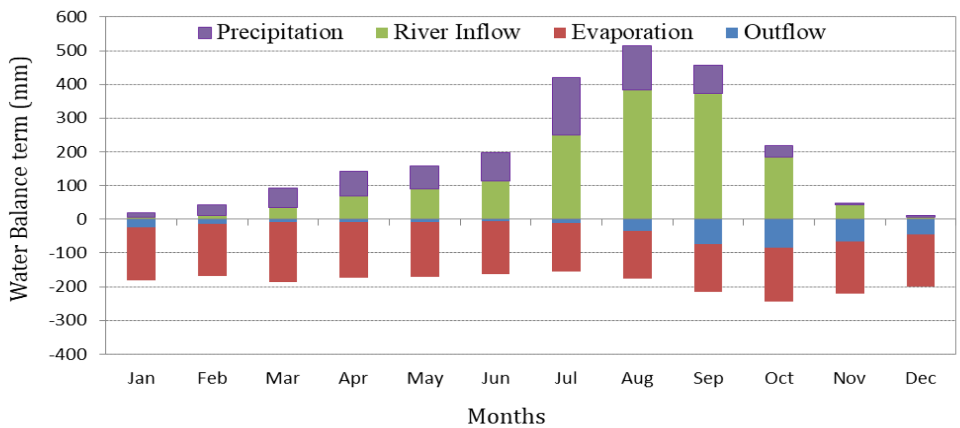


Figure 3.12. Monthly average water balance components of Lake Ziway for a period from 1986-2000

Table 3.7 shows the mean monthly and annual water level fluctuation for 2013 and 2014. The result indicates a maximum mean monthly variation of 2.04 m in 2013 (August) and 2.24 m in 2014 (July) during the rainy season. The deviation is small between September and December. The average annual water level variation is 1.78 m and 1.97 m in 2013 and 2014, respectively.

Table 3.7. Mean monthly and annual deviations of the observed water level from simulated levels in 2013 and 2014

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
2013	1.56	1.58	1.62	1.60	1.59	1.75	2.04	2.10	2.02	2.08	2.05	2.27	1.86
2014	2.16	2.10	2.06	2.03	2.20	2.30	2.31	2.12	1.92	1.82	1.75	1.69	2.04

Figure 3.13 shows the deviation of the simulated lake volume from observed volume for the period 2001-2014. The difference in lake volume increased with time except for 2007, which was a drought year in the study area. The rate of increase was highest in 2012 and 2013. The highest average annual lake volume difference is 346 MCM in 2013 and 381 MCM in 2014, which is nearly 25% and 27.5% of the average lake volume from 1986-2000, respectively. The average annual volume difference from 2001-2014 is ~173 MCM, which accounts for 12.5% of the average volume of the lake from 1986-2000 (~1388.3 MCM). This large volume difference reveals the presence of increased human intervention by water abstraction from Lake Ziway and its tributaries. Similar findings are shown (Legesse et al., 2004; Seyoum et al., 2015) for Lake Abiyata situated within the same climatic zone and fed by the runoff from Lake Ziway outflow.

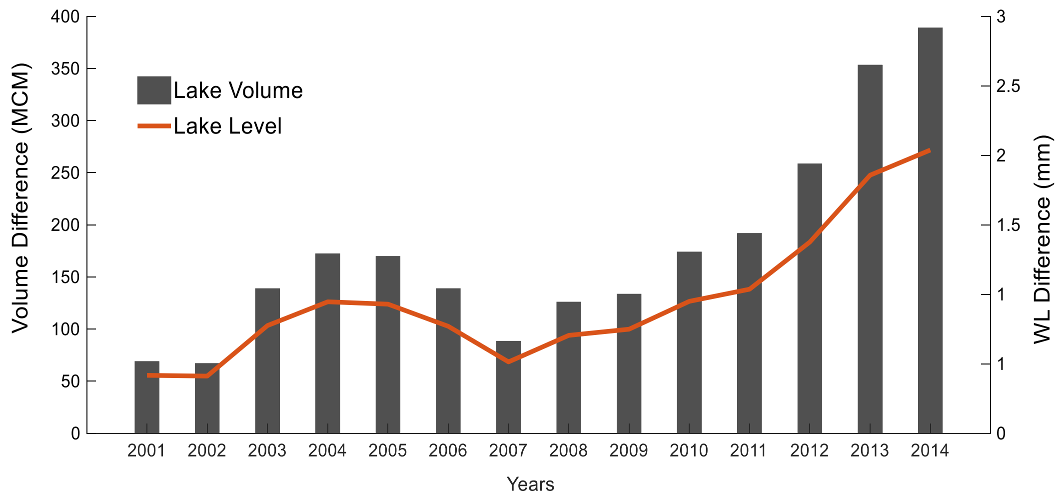


Figure 3.13. Annual difference of simulated and observed volume and mean annual water level between 2001 to 2014

In this study, the lake water balance estimation was mainly from historic climatic conditions. However, it is reported that future climate change will affect the temporal distribution of rainfall and runoff in the Central Rift Valley lakes basin (Wagesho et al., 2013; Abraham et al., 2018). This further will affect the water balance components of the hydrological cycles such as rainfall, evaporation, and runoff of the lake area. Hence, for future water resources planning and management of the lake, the projected impacts of climate change and water abstraction needs to be considered.

3.6 Discussions

3.6.1 Comparison to the previous water balance studies

To compare water balance components of findings in this study to findings in previous studies in the study area, two hydrological regimes were constructed for periods 1986-2000 (baseline natural period) and 2001-2014 (human-induced period). These classification period was based on the finding of this study and reference was made from previous studies on Lake Ziway (Seyoum et al., 2015; Desta and Lemma, 2017; Desta et al., 2017). To avoid the variation in water balance components among the studies with respect to the study period comparison was for baseline natural condition (1986-2000). This period was selected as previous studies of water balance estimation were up to 2000.

The water balance analysis for the baseline natural period (1986-2000) resulted in an average annual lake rainfall of 760 mm y^{-1}, open water evaporation of 1870 mm y^{-1}, river inflow from gauge and ungauged catchments constitutes of 1561 mm y^{-1} and outflow discharge from the lake of 384 mm y^{-1} (Table 3.8). Results of this study show that the Lake Ziway water balance error of 67.5 mm per year for the baseline natural condition, that accounts for 2.9% of the total lake inflow from rainfall and river inflow. We note that the water balance components and water balance closure error for the human-induced period (2001-2014) is slightly attributed as compared to the baseline condition. The variation in some water balance components reported in these more recent period points out more water abstraction from the lake and its tributaries. The water balance closure error for the human-induced period increased by 26 mm as compared to the baseline condition, which results in a water balance closure error of 3.9% of the total lake inflow from rainfall and river inflow.

Under the baseline period (1986-2000) the average annual lake rainfall resulted in 760 mm y^{-1}. The lake average annual rainfall estimated in this study is higher than estimated in (Ayenew, 2004; Legesse and Ayenew, 2006; Jansen et al., 2007) (734 mm y^{-1}) but lower than estimated in Desta et al. (2017) (768 mm y^{-1}). However, the estimate better matches with an estimate in Vallet-Coulomb et al. (2001) which used three stations (Ziway, Meki and Abura) situated near to the lake. In most of the previous studies, lake rainfall estimation is only from Ziway town meteorological station which is situated close to the lake. In this study, lake areal rainfall estimation has benefited from the use of bias-corrected satellite rainfall on the lake surface.

Table 3.8. Water Balance Component of Lake Ziway by different studies (the unit of all terms is mm)

Water Balance Terms	This Paper (2019) Natural condition	This Paper (2019) Human-induced	Vallet-Coulomb et al (2001)	Ayenew (2004)	Jensen et al (2007)
Study period	1986-2000	2001-2014	1969-1995	1970-1996	1990-2000
Lake Areal Rainfall	760.5	765.8	752.8	734.1	733.9
Lake Evaporation	1869.8	1881.4	1875	2023.0	1791.0
Gauged River Inflow	1379.3	1428.6	1474.1	1492.0	1476.4
Ungauged River Inflow	181.6	186.2	112.4	109.1	85.4
Lake outflow	384.1	386.3	352.8	386.4	397.8
Closure term	67.4	92.9	111.5	-73.9	107.0

The average annual lake evaporation is estimated at 1870 mm y^{-1} for the period 1986-2000. This estimate is significantly lower than as estimated in Ayenew (2004) (2023 mm y^{-1}) and Desta et al. (2017) (1920 mm y^{-1}) but higher than Melesse et al. (2009) (1662 mm y^{-1}) and Jansen et al. (2007) (1791 mm y^{-1}). Evaporation estimate in this study is similar to the result obtained in Vallet-Coulomb et al. (2001) (1870 mm y^{-1}) who also used the Penman method. In most of the previous studies, evaporation was estimated at monthly time step for meteorological time series from Ziway station only. In this study, the analysis is at daily time step with two additional stations (Ogolcho and Arata) at the lake shore. Hence, lake evaporation computations benefited from the additional air temperature data of stations near the lake. The differences in the estimated lake evaporation among the studies arise from this fact and other aspects concern the difference in estimation methods.

Simulated river inflow from major tributaries for the baseline period indicates 1379 mm runoff inflow to Lake Ziway (38% of Meki and 62% of Katar) whereas the contribution of the ungauged catchment is 182 mm (8.5% of the total lake inflow from rainfall and river inflow) (Table 7). The river inflow to the lake estimated in this study is lower than reported in (Ayenew, 2004; Jansen et al., 2007). In this study, the runoff from the gauged catchments is simulated by the use of a rainfall-runoff model using bias-corrected satellite rainfall estimates as input. However, most of the previous studies used river gauges streamflow for a shorter period. The relative difference among the studies originates from the selected method for estimation of runoff and the dataset used. The Lake outflow obtained in this study was closer to Ayenew (2004) but higher than estimated in Vallet-Coulomb et al. (2001). The result revealed higher lake outflow which is related to lake water levels. Hence, more water abstraction would lead to lower lake outflow.

Unlike other previous studies, this study applied improved rainfall data quality by correcting the bias of CHIRP satellite-only product with rain gauge dataset as a reference. Hence, we advocate the use of bias-corrected satellite product to overcome the data gap in water budget studies and to improve accuracy of the research findings. However, note that there are many sources of uncertainty in the estimation of each lake water balance component. This study assumed that lake-groundwater interaction is negligible. Another source of uncertainty is in the estimation of lake evaporation using the Penman method from observed data and lake rainfall from satellite rainfall and bias correction method. There is also error due to runoff simulation from gauged and ungauged catchments. Hence, we suggest that future studies consider uncertainties in the water balance by using improved approaches to represent each component.

Also uncertainties by advanced model calibration approaches and use of more advanced bias correction algorithms should be considered.

3.7 Conclusions

In this study, the Climate Hazards Group InfraRed Precipitation (CHIRP) satellite-only rainfall product was used to simulate lake level fluctuation using a combination of HBV rainfall-runoff modelling and a simple lake water balance model. The study area is the Lake Ziway subbasin, in the Central Rift Valley Lakes basin of Ethiopia. In this study, the estimated lake rainfall and evaporation are expected to have better accuracy than previous studies (Ayenew, 2004; Jansen et al., 2007; Melesse et al., 2009; Desta et al., 2017). That is, since (i) rainfall is estimated from bias- corrected satellite data using rain gauge data as a reference, and (ii) three stations (Ziway, Ogolcho and Arata) were considered for evaporation estimation whereas previous studies only used Ziway station. The following conclusions were drawn based on the findings of this study:

i. The bias of CHIRP satellite rainfall product is very large and accounts for 73% over estimation at rainy season. Bias is considered too high to allow for the direct use of CHIRP product in HBV rainfall-runoff modelling that serves lake inflow simulation of Lake Ziway. However, the study has shown that the bias can be significantly reduced using a non-linear power bias correction using rain gauge data as a reference. The bias-corrected CHIRP satellite product better captured the temporal pattern and magnitude of the observed rainfall than uncorrected product.
ii. The bias-corrected CHIRP rainfall estimate was used as the HBV model input. The HBV model performed adequately when evaluated in terms of NSE and RVE objective functions for both the calibration and validation periods. Thus, the streamflow pattern, peak flows and baseflow of the simulated hydrograph agreed with those of the observed hydrograph. A disagreement between the simulated and observed hydrographs noticeably increased when the uncorrected CHIRP rainfall served as model input. Small errors in CHIRP data were found to propagate to relatively larger errors in streamflow simulation by means of the HBV model.
iii. Under baseline natural conditions (1986-2000), the inflow to the lake consists of 33% from rainfall over the lake, 59% from gauged catchments and 8% from ungauged catchments. This indicates that the gauged catchments are the major contributors to Lake Ziway inflow.

Whereas the outflow consists of 83% evaporation and 17% outflow through Bulbula River. As such, evaporation over the lake surface is the major lake water loss term. Results of this study show a water balance closure error of Lake Ziway is 67.5 mm per year for the assessment period 1986-2000, which accounts for 2.9% of the total annual lake inflow by rainfall and river inflow. Since the estimation of each water balance term must be associated with aspects of uncertainty, further assessment on the accuracy of the lake water balance component is required.

iv. The lake level simulation indicates good agreement between the simulated and observed lake levels for the period 1986-2000. However, there was an increasing disagreement from the year 2000 onwards which most likely can be attributed to human-induced influences such as water abstraction. The maximum difference between simulated and observed lake levels occasionally reached up to 2.28 m in 2013. This suggests that the actual lake level in 2013 should have been at least 2.28 m higher than the observed level if there were no human-induced influences.

v. The observed lake volume is less than the simulated counterpart by up to 381 MCM in 2014, which accounts for 27.5% of the average lake volume under the baseline condition. This difference mainly results from human-induced influences. Overall, the water balance closure error for the period 2001-2014 is higher than the baseline natural condition, which could be by increased water abstraction from the lake itself and from its tributaries. The observed lake volume is less than the simulated counterpart by up to 381 MCM in 2014, which accounts for 27.5% of the average lake volume under the baseline condition. This difference mainly results from human-induced influences.

In general, this study shows that applying bias-corrected CHIRP rainfall products is effective to fill the data void in Lake Ziway water budget studies. Hence, in data scarce regions use of bias-corrected CHIRP data is feasible for Lake water level simulation. The findings of this study indicate a significant human impact on lake level and volume. Therefore, the study suggests future studies to explore impacts by projected climate change and anticipated increasing lake water abstractions.

References

Abrahama, T., Woldemicheala, A., Muluneha, A., Abateb B. (2018). Hydrological Responses of Climate Change on Lake Ziway Catchment, Central Rift Valley of Ethiopia. Journal of Earth Science and Climate Change 9, 474.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M. (1998). Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements. *Irrigation and Drainage Paper*, United Nations Food and Agriculture Organization (FAO), Rome, Italy, P. 300.

Ashenafi, Y., Hailu, D. (2014). Assessment of the use of remotely sensed rainfall products for runoff simulation in the Upper Blue Nile basin of Ethiopia. *Zede Journal*, 31, 1–9.

Ayalew, S. (2010). Developing simplified regional potential evapotranspiration estimation method for Abbay river basin. *Journal of European Economic Association, 27*.

Ayehu, G.T., Tadesse, T., Gessesse, B., Dinku, T. (2018).Validation of new satellite rainfall products over the Upper Blue Nile Basin, Ethiopia. *Atmospheric Measurement Techniques,* 11(4), 1921–1936.

Ayenew, T. (2004). Environmental implication of changes in the levels of lakes in the Ethiopian Rift since 1970. *Regional Environmental Change*, *4(4)*, 192-204.

Ayenew, T. (2007). Water management problems in the Ethiopian rift: Challenges for development. *Journal of African Earth Scinecs*, *48*(2–3), 222–236.

Bergström, S. (1992). The HBV model: Its structure and applications. *Swedish Meteorological and Hydrological Institute (SMHI),* Norrköping, Sweden.

Bhatti, H. A., Rientjes, T., Haile, A. T., Habib, E., Verhoef, W. (2016). Evaluation of bias correction method for satellite-based rainfall data. *Sensors*, *16*(6), 884.

Blain, G.C. (2014). Extreme value theory applied to the standardized precipitation index. Acta Science Technology 36, 147–155.

Dembélé, M., Zwart, S. J. (2016). Evaluation and comparison of satellite-based rainfall products in Burkina Faso, West Africa. *International Journal of Remote Sensing*, *37*(17), 3995–4014.

Dessie, M., Verhoest, N. E., Pauwels, V. R., Adgo, E., Deckers, J., Poesen, J., Nyssen, J. (2015). Water balance of a lake with floodplain buffering: Lake Tana, Blue Nile Basin, Ethiopia. *Journal of Hydrology*, *522*, 174–186.

Dessie, M., Verhoest, N. E., Pauwels, V. R., Admasu, T., Adgo, E., Deckers, J., Poesen, J., Nyssen, J. (2014). Analyzing runoff processes through conceptual hydrological modeling in the Upper Blue Nile Basin, Ethiopia. *Hydrology and Earth System Science, 18, 5149–5167*.

Desta, H., Lemma, B. (2017). SWAT based hydrological assessment and characterization of Lake Ziway sub-watersheds, Ethiopia. *Journal of Hydrology: Regional studies*, *13*, 122–137.

Desta, H., Lemma, B., Gebremariam, E. (2017). Identifying sustainability challenges on land and water uses. Case of Lake Ziway watershed, Ethiopia. *Applied Geography*, *88*, 130–143.

Dinku, T. (2014). Validation of the CHIRPS satellite rainfall estimate. *Proceeding of 7th International precipitation Working Group (IPWG) Workshop,* Tsukuba, Japan.

Dinku, T., Funk, C., Peterson, P., Maidment, R., Tadesse, T., Gadain, H., and Ceccato, P. (2018). Validation of the CHIRPS satellite rainfall estimates over eastern of Africa. *Quarterly Journal of the Royal Meteorological Society, 1-21*.

Duan, Z., Liu, J., Tuo, Y., Chiogna, G., Disse, M. (2016). Evaluation of eight high spatial resolution gridded rainfall products in Adige Basin (Italy) at multiple temporal and spatial scales. *Science of the Total Environment*, 573, 1536–1553.

Ebert, E. E., Janowiak, J. E., Kidd, C. (2007). Comparison of near-real-time rainfall estimates from satellite observations and numerical models. *Bulletin American Meteoroligical Society*, *88*(1), 47–64.

Fuka, D. R., Walter, M. T., MacAlister, C., Degaetano, A. T., Steenhuis, T. S., Easton, Z. M. (2014). Using the climate forecast system reanalysis as weather input data for watershed models. *Hydrological Processes*, *28*(22), 5613–5623.

Funk, C. C., Peterson, P. J., Landsfeld, M. F., Pedreros, D. H., Verdin, J. P., Rowland, J. D., … Verdin, A. P. (2014). A quasi-global rainfall time series for drought monitoring. *U.S. Geological Survey Data Series*.

Funk, C., Verdin, A., Michaelsen, J., Peterson, P., Pedreros, D., and Husak, G. (2015). A global satellite-assisted rainfall climatology. *Earth System Science Data*, *7*(2), 275–287.

Gebere, S. B., Alamirew, T., Merkel, B. J., and Melesse, A. M. (2015). Performance of high resolution satellite rainfall products over data scarce parts of Eastern Ethiopia. *Remote Sensing*, *7*(9), 11639–11663.

Goshime, D.W., Absi, R., and Ledésert, B. (2019). Evaluation and bias correction of CHIRP rainfall estimate for rainfall-runoff simulation over Lake Ziway watershed, Ethiopia. *Hydrology, 6 (3), 68*.

Gumindoga, W., Rientjes, T. H. M., Haile, A. T., Makurira, H., Reggiani, P. (2019). Performance of bias-correction schemes for CMORPH rainfall estimates in the Zambezi River basin. *Hydrology and Earth System Sciences*, *23*, *2915–2938*.

Guttman, N. B. (1999). Accepting the standardized precipitation index: a calculation algorithm. Journal of the American Water Resources Association, 35,311–322.

Habib, E., Haile, A. T., Sazib, N., Zhang, Y., and Rientjes, T. (2014). Effect of bias correction of satellite-rainfall estimates on runoff simulations at the source of the Upper Blue Nile. *Remote Sens*ing, 5, 6688–6708.

Haile, A. T., Habib, E., and Rientjes, T. (2013). Evaluation of the climate prediction center (CPC) morphing technique (CMORPH) rainfall product on hourly time scales over the source of the Blue Nile River. *Hydrology Processes*, *27*(12), 1829–1839.

Hargreaves, G. H., and Allen, R. G. (1985). History and evaluation of Hargreaves evapotranspiration equation. *Journal of Irrigation and Drainage Engineering*, *10.1061/ (ASCE) 0733-9437, 53-63.*

Hayes, M.J., Svoboda, M. D., Wilhite, D. A., Vanyarkho, O.V. (1999). Monitoring the 1996 drought using the standardized precipitation index. Bulletin of the American Meteorological Society 80, 429–438.

Hessels, T. M. (2015). Comparison and validation of several open access remotely sensed rainfall products for the Nile Basin. *Delft University of Technology*.

Huffman, G. J., Bolvin, D. T., Nelkin, E. J., Wolff, D. B., Adler, R. F., Gu, G., … Stocker, E. F. (2007). The TRMM multi-satellite precipitation analysis (TMPA): Quasi-global, multiyear, combined sensor rainfall estimates at fine scale. *Journal of Hydrometeorology*, *8*(1), 38–55.

Jansen, H. C., Hengsdijk, H., Legesse, D., Ayenew, T., Hellegers, P., Spliethoff, P. C. (2007). Land and water resources assessment in the Ethiopian Central Rift Valley : project: ecosystems for water, food and economic development. *Alterra report 1587*. Wageningen, The Netherlands.

Johansson, B. (2013). Integrated Hydrological Modelling System (IHMS) manual version 6.3. *Swedish Meteorological and Hydrological Institute (SMHI)*, Norrköping, Sweden.

Joyce, R. J., Janowiak, J. E., Arkin, P. A., Xie, P. P. (2004). A method that produces global rainfall estimates from passive microwave and infrared data at high spatial and temporal resolution. *Journal of Hydrometeorology,* 5, 487–503.

Kebede, S., Travi, Y., Alemayehu, T., Marc, V. (2006). Water balance of Lake Tana and its sensitivity to fluctuations in rainfall, Blue Nile basin, Ethiopia. *Journal of Hydrology, 316 (1–4), 233–247*.

Kendall, M. (1975). Rank correlation measures. Charles Griffin: London, 202.

Khandu, X., Awange, J. L., Forootan, E. (2015). An evaluation of high-resolution gridded rainfall products over Bhutan (1998-2012). *International Journl of Climatology, 36 (3), 1067–1087*.

Krakauer, N. Y., Pradhanang, S. M., Lakhankar, T., Jha, A. K. (2013). Evaluating satellite products for rainfall estimation in mountain regions: A case study for Nepal. *Remote Sensing, 5(8), 4107–4123*.

Kumambala, P.G., and Ervine, A. (2010). Water balance model of Lake Malawi and its sensitivity to climate change. *The open hydrology Journal*, 4(1), 152–162.

Lafon, T., Dadson, S., Buys, G., Prudhomme, C. (2013). Bias correction of daily rainfall simulated by a regional climate model: A comparison of methods. *Interntional Journal of Climatology, 33(6), 1367-1381*.

Le, A. M., Pricope, N. G. (2017). Increasing the accuracy of runoff and streamflow simulation in the Nzoia Basin, Western Kenya, through the Incorporation of satellite-derived CHIRPS data. *Water, 9*(2), 114.

Leander, R., Buishand, T. (2007). Resampling of regional climate model output for the simulation of extreme river flows. *Journal of Hydrology, 332, 487–496*.

Legesse, D., Ayenew, T. (2006). Effect of improper water and land resource utilization on the central main Ethiopian rift lakes. *Quaternary International*, *148(1), 8-18*.

Legesse, D., Vallet-Coulomb, C., Gasse, F. (2004). Analysis of the hydrological response of a tropical terminal lake, Lake Abiyata (main Ethiopian rift valley) to changes in climate and human activities. *Hydrology Processes, 18(3), 487-504*.

Lindström, G., Johansson, B., Persson, M., Gardelin, M., Bergström, S. (1997). Development and test of the distributed HBV-96 hydrological model. *Journal of Hydrology, 201(1–4), 272–288*.

Mann, H.B. (1945). Non-parametric test against trend. Econometrica 13, 245–259.

McKee, T.B, Doesken, N.J, Kleist, J. (1993). The relationship of drought frequency and duration to time scales. Eighth Conference on Applied Climatology, Anaheim, California.

Melesse, A. M., Abtew, W., Dessalegn, T. (2009). Evaporation estimation of rift valley lakes: comparison of models. *Sensors*, *9*(12), 9603–9615.

Moges, S. A., Katambara, Z., Bashar, Z. (2003). Decision support system for estimation of potential evapotranspiration in Pangani Basin. *Physical and Chemistry of the Earth, 28 (20-27), 927-934.*

Nicholson, S. E., and Yin, X. (2001). Rainfall conditions in equatorial East Africa during the nineteenth century as inferred from the record of Lake Victoria. *Climate Change*, *48*(2–3), 387–398.

Pingale, S.M., Khare, D., Jat, M.K., Adamowski, J. (2014). Spatial and temporal trends of mean and extreme rainfall and temperature for the 33 urban centers of the arid and semi-arid state of Rajasthan. India. Atmospheric Research, 138, 73–90.

Peng, S., Liu, W., Wang, W., Shao, Q., Jiao, X., Yu, Z., … Luo, Y. (2013). *E*stimating the effects of climatic variability and human activities on streamflow in the Hutuo river basin, China. *Journal of Hydrologic Engineering, 422-430.*

Penman, H. L. (1948). Natural evaporation from open water, bare soil and grass. *Proceedings of the Royal society. A Mathematical Physics Engineering Science, 193(1032), 120-145*.

Pike, A. (1988). The Use of Temperature based Evaporation Equations in Southern Africa. *B.Sc. Seminar. Pietermaritzburg: Department of Agricultural Engineering, University of Natal.*

Pratama, A. W., Buono, A., Hidayat, R., Harsa, H. (2018). Bias correction of daily satellite rainfall data using genetic algorithm. *IOP Conference series: Earth Enviromental Science*, Vol. 149.

Rientjes, T. H. M., Perera, B. U. J., Haile, A. T., Reggiani, P., Muthuwatta, L. P. (2011). Regionalisation for lake level simulation – the case of Lake Tana in the Upper Blue Nile, Ethiopia. *Hydrology and Earth System Science, 15(4), 1167-1183*.

Seyoum, W. M., Milewski, A. M., Durham, M. C. (2015). Understanding the relative impacts of natural processes and human activities on the hydrology of the Central Rift Valley Lakes, East Africa. *Hydrology Processes, 29(19), 4312-4324*.

Shrestha, N. K., Qamer, F. M., Pedreros, D., Murthy, M. S. R., Wahid, S. M., Shrestha, M. (2017). Evaluating the accuracy of Climate Hazard Group (CHG) satellite rainfall estimates for rainfall based drought monitoring in Koshi basin, Nepal. *Journal of Hydrology: Regional studies*, *13*, 138–151.

Sorooshian, S., Hsu, K.-L., Gao, X., Gupta, H. V., Imam, B., and Braithwaite, D. (2000). Evaluation of PERSIANN system satellite–based estimates of tropical rainfall. *Bulletin American Meteorological Society, 81(9), 2035–2046.*

Terink, W., Hurkmans, R.T.W.L., Torfs, P.J.J.F., Uijlenhoet, R. (2010). Evaluation of a bias correction method applied to downscaled precipitation and temperature reanalysis data for the Rhine basin. *Hydrology and Earth System Science, 14, 687-703*.

Tigkas, D., Harris, V., George, T. (2015). DrinC: A software for drought analysis based on drought indices. *Earth Science Informatics* 8(3), 697–709.

Wagesho, N., Jain, M. K., and Goel, N. K. (2013). Effect of climate change on runoff generation : application to Rift Valley Lakes Basin of Ethiopia. *Journal of Hydrologic Engineering*,1048-1063.

Vallet-Coulomb, C., Legesse, D., Gasse, F., Travi, Y., Chernet, T. (2001). Lake evaporation estimates in tropical Africa (Lake Ziway, Ethiopia). *Journal of Hydrology, 245, 1–18*.

Wale, A., Rientjes, T. H. M., Gieske, A. S. M., Getachew, H. A. (2009). Ungauged catchment contributions to Lake Tana's water balance. *International Journal of Hydrologic Processes, 23(26), 3682–3693.*

Wang, J., Hong, Y., Gourley, J., Adhikari, P., Li, L., Su, F. (2010). Quantitative assessment of climate change and human impacts on long-term hydrologic response: a case study in a sub-basin of the Yellow River, China. *International Journal of climatology*, *30*(14), 2130–2137.

Worqlul, A. W., Ayana, E. K., Maathuis, B. H. P., MacAlister, C., Philpot, W. D., Osorio Leyton, J. M., Steenhuis, T. S. (2018). Performance of bias corrected MPEG rainfall estimate for rainfall-runoff simulation in the upper Blue Nile Basin, Ethiopia. *Journal of Hydrology, 556, 1182–1191*.

Worqlul, A. W., Collick, A.S., Tilahun, S. A., Langan, S., Rientjest, T. H., Steenhuis, T. S. (2015). Comparing TRMM 3B42, CFSR and ground-based rainfall estimates as input for hydrological models, in data scarce regions: the Upper Blue Nile Basin, Ethiopia. *Hydrology and Earth System Science Discussions, 12, 2081-2112*.

Yong, B., Chen, B., Gourley, J. J., Ren, L., Hong, Y., Chen, X., … Gong, L. (2014). Intercomparison of the Version-6 and Version-7 TMPA rainfall products over high and low latitudes basins with independent gauge network. *Journal of Hydrology, 508, 77–87*.

Yong, B., Ren, L. L., Hong, Y., Wang, J. H., Gourley, J. J., Jiang, S. H., … Wang, W. (2010). Hydrologic evaluation of multisatellite precipitation analysis standard rainfall products in basins beyond its inclined latitude band: A case study in Laohahe basin, China. *Water Resourecs Research, 46(7), 1-20. W07542*.

Yuan, F., Zhang, L., Win, K. W. W., Ren, L., Zhao, C., Zhu, Y., … Liu, Y. (2017). Assessment of GPM and TRMM multi-satellite rainfall products in streamflow simulations in a data-sparse mountainous watershed in Myanmar. *Remote Sensing, 9(3), 302*.

Zhang, Q., Liu, C., Xu, C., Xu, Y., Jiang, T. (2006). Observed trends of annual maximum water level and streamflow during past 130 years in the Yangtze River basin, China. Journal of Hydrology 324: 255–265.

Zhou, Z., Jia, Y., Qiu, Y., Liu, J., Wang, H., Xu, C-Yu, … Liu, L. (2018). Simulation of dualistic hydrological processes affected by intensive human activities. *Journal of Water Resources Planning and Management, 144 (12).*

4 Impact of water abstraction on water balance of Lake Ziway, Ethiopia

Abstract: The storage of Lake Ziway in Ethiopia is declining at an alarming rate which hinders the lake services for a wide variety of sectors. However, there is a lack of systematic study to evaluate the contribution of water withdrawal by various sectors to the decline in the lake actual storage. In the present study, we conducted a Water Abstraction Survey (WAS) to estimate actual water withdrawal from the lake and a water balance model to evaluate the isolated impact of water withdrawal on the lake water volume and level. The likely impact of three development pathways on the lake storage and water level was assessed. Our findings indicate that the existing water withdrawal for irrigation has significantly contributed to the change in the actual storage of Lake Ziway. When the future development plans (2029-2038) are fully implemented, the annual amount of irrigation water withdrawal from the lake will be 94 Mm^3. This will cause the lake water level to drop by 0.94 m, which translates to 38 km^2 reduction in the lake surface area. Consequently, the lake will lose 26% of its actual storage volume. Hence, the current impact of water resources development around the lake is substantially large and will exacerbate if the future development plans are fully implemented. The storage can significantly decline resulting in large unmet demands by fishery, irrigation, domestic water supply and other ecosystem services. It may also threaten the sustainability of the lake water resources. This calls serious actions to monitor and manage water abstraction from the lake.

Keywords: Lake Ziway, Water balance; Irrigation water abstraction; Impact; Ethiopia

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4.1 Introduction

Lake Ziway is a vital source of water for irrigation, domestic use, livestock, and fish to the community. Furthermore, the lake and its basin are the focus of the Ethiopian government to develop large scale export-oriented irrigated floriculture and several irrigation schemes. However, intensive water abstraction mainly for irrigation activities from the lake and its feeding rivers has led heavy pressure on the lake water (Ayenew, 2004; Jansen et al., 2007). As a result, the Lake Ziway volume and water level is significantly declining (Jansen et al., 2007). Such pressures will ultimately damage the hydrological and ecological integrity of the lake and its surroundings unless appropriate measures are taken.

Significant change has been reported in the hydrology of some Ethiopian lakes because of both natural processes and human activities over the past decades. For instance, Lake Alemaya faced strong water budget deficit due to multiple anthropogenic pressures and natural factors. The lake completely dried up in the year 2000 as a result of uncontrolled water abstraction for water supply and irrigation (Lemma, 2003). Similarly, human activities caused a significant reduction in the water level of Lake Abiyata. Seyoum et al. (2015) reported that about 70% (~4.5 m) reduction in the water level of the lake has been attributed to human-induced impacts while 30% (~2 m) reduction was related to natural climate variability.

Alemayehu et al. (2010) showed that the water system of Lake Tana in Ethiopia is also under heavy pressure because of a number of water resources infrastructure development. The authors reported that under implementation of the full development plan, the mean annual water level of the lake would be lowered by 0.44 m with 30 km^2 reduction in the average surface area of the lake. It can be expected that the water level of many Ethiopian lakes will further decline due to lack of appropriate regulation and monitoring mechanism to manage water abstraction from the lakes.

Several studies at global and local scale highlighted that lack of data as a major challenge on the actual amount of water abstracted for irrigation (Döll et al., 2012). Therefore, most studies base their water abstraction estimates on national statistics, reports and climatic database of a crop that requires an optimal amount of water (Alemayehu et al., 2010; Adgolign et al., 2015; Chinnasamy et al., 2015). Alternatively, Desta et al. (2017) estimated the water abstraction from Lake Ziway by multiplying the available number of pumps with constant pumping rate and working hours. In reality, pumping rate can vary with the type of pump and mode of operation.

Besides, farmers change the working hours with the growing season of the crops. Therefore, accurate estimation of actual water abstraction requires site specific survey.

Deribessa (2006) indicated that in recent time there is an increase in water abstractions for horticulture and floriculture around Lake Ziway. Therefore, such intensive water abstraction activities are likely to decrease the water level and volume, which in turn may decrease the water discharged into Bulbula River which leads to decline of Lake Abiyata inflow. However, most of the literature on the hydrology of Lake Ziway (Vallet-Coulomb et al., 2001; Legesse et al., 2003, 2004; Ayenew,2007; Jansen et al., 2007) focused on the water budget of the lake under natural condition without explicitly considering the actual water abstraction. Therefore, there is a knowledge gap on the impact of water abstraction for irrigation on the lake storage volume and level.

In this study, we aim to estimate actual water withdrawal from the lake and evaluate its impact on lake level and volume using a simple water balance modelling approach based on water abstraction survey. The findings of this study will provide information for decision-makers, planners and water users for better management of water abstraction from the lake. Results of such study are also relevance for to the scientific community to incorporate human effect on assessment of lake water balance by using data from water abstraction survey.

4.2 Study Area

Lake Ziway is located within the upstream section of the Central Rift Valley (CRV) lakes basin of Ethiopia. The CRV encompasses a chain of three main lakes (i.e. Ziway, Abiyata and Langano) and streams that are spatially strongly interlinked. Lake Ziway is the highest of a chain of three lakes in the CRV basin with a surface area covering 445 km^2. It is located on the rift floor between 7º25'30" and 8º34'30"N and 38º12'00" and 39º15'00"E.

The Meki and Katar Rivers are the main tributaries of Lake Ziway with catchment area of 2824 and 3744 km^2, respectively. These two rivers have an average annual runoff approximately 695 Mm^3, about 62% belongs to the Katar River and 38% to the Meki River (Goshime et al., 2019). Then, the outflow from Lake Ziway water is discharged into the Bulbula River, which flows to Lake Abiyata, being the terminal lake.

Topographically, Lake Ziway subbasin is characterized by mountainous terrain over its eastern and western parts, with an elevation ranging from about 1600 m.a.s.l to over 4200 m.a.s.l

(Figure 4-1). Its climate is sub-humid to humid climatic condition, with a mean annual temperature from 13℃ to 27.5℃. The mean annual rainfall over the lake surface varies from 454 to 995 mm. Its main rainy season is from June to September, with the highest rainfall amount occurring in July. The rainfall amount is smaller during drier months from October to February, with near zero rainfall amount in December.

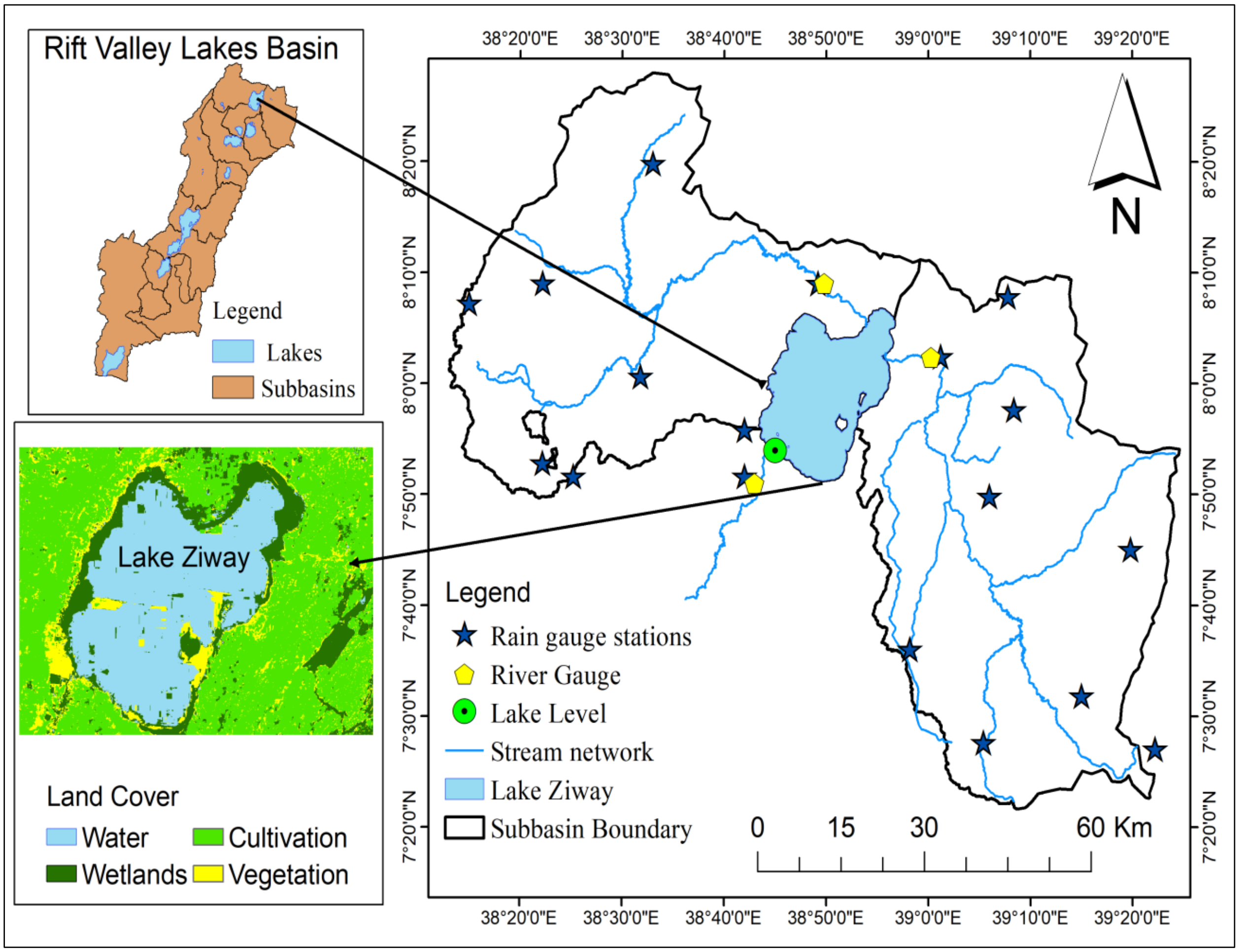

Figure 4.1 Lake Ziway, sub basin and its main tributaries, meteorological stations, elevation and land cover classification around the lake. The Lake Ziway land cover map is derived from google earth image

Lake Ziway supports the livelihoods of the fishing community and serves as a habitat for biological diversity. Recent irrigation development around the lake starting from smallholder to large investment floriculture and horticulture depend on the lake water system to meet their irrigation requirement. The lake has been a vital source of water for irrigation for smallholder farmers and drinking water for Ziway town. This water system is preferred by various water sectors, mainly because of its fresh water and low salinity level as compare to other lakes in the basin. The main land cover around the lake includes intensive agriculture cultivation land (such as onion, tomato, maize, pepper, beans and cabbage), wetland, water bodies and vegetation (Figure 4.1).

4.3 Datasets

In this study, we mainly used observed and satellite climate, hydrological and water abstraction datasets. The climate dataset covers the period from 1986 to 2014 at daily time scales. These datasets includes precipitation, maximum and minimum temperature, wind speed, relative humidity, and sunshine duration. These data were obtained from the National Meteorological Agency (NMA) of Ethiopia.

The rainfall data is obtained from Climate Hazards Group Infra-Red Precipitation (CHIRP) satellite-only product, at (daily temporal and 5.5km spatial resolution) for the period 1984 to 2014. The CHIRP rainfall dataset is freely extracted from http://chg.geog.ucsb.edu/data/. CHIRP covers regions that are situated between 50^{o}S-50^{o}N latitude and all longitudes (Funk et al., 2014, 2015). The CHIRP rainfall estimate was bias-corrected using rainfall data from stations that are situated in the study area, see (Goshime et al., 2019) and the bias-corrected data served as model input.

Lake water level (at Ziway), outflow (at Kerekesitu) and streamflow (for Meki and Katar rivers) data are available for the period 1986-2005. These data were obtained from Ministry of Water, Irrigation and Electricity (MoWIE) of Ethiopia. The storage-area-elevation relationship was established for the lake through a bathymetric survey by MoWIE in 1984 and 2013, and this relationship was used in this study.

Water abstraction data around Lake Ziway were collected from field survey and from relevant administrative organizations such as Rift Valley lakes basin authority, Oromia water works design and supervision enterprise, and regional agriculture, municipal water supply, water, mine and energy offices of the three districts. A field investigation was undertaken for 15 days from 20th of October 2018 to 5th of November 2018. The survey covered pumping points of individual farmers, irrigation schemes, flower farm lands, and domestic water supply. A data collection format was prepared beforehand for both field measurement and conducting key informant interview. The format includes abstraction point and location, pump type, size, operation hour per day, irrigation interval per week, crop type and area.

We measured the amount of water abstraction for selected abstraction points and managers were interviewed based on our data collection format. A GPS device, bucket, tape meter, current meter, and stopwatch were used to conduct flow measurements. To estimate abstraction throughout the year, seasonal information on the pump and/or scheme operation, crop types, command area and irrigation scheduling were collected. The GPS coordinate were directly taken at the pumping stations (abstraction points) with latitude and longitude were taken in UTM (m) using WGS1984 reference datum.

4.4 Methods

This study is based on the analysis of existing meteorological and satellite datasets, water abstraction survey, and review of published articles in the study area. The methodologies followed in this study are: first, we estimated water abstraction for all abstraction points based on data from the Water Abstraction Survey (WAS). Next, we evaluated the monthly water balance of the lake under natural hydrologic condition (1986-2000) which served as a baseline. Then, the implication of three development pathways was evaluated using water balance modelling approach. Finally, we quantified the impact of water abstraction on lake level, volume and surface area for the three development pathways.

The impact of each development pathway was compared with the baseline simulated water level of the lake under natural condition. The baseline period was set from 1986 to 2000 as water abstraction was insignificant and the lake storage was at its near natural condition. We also referred to previous studies that indicated increased irrigation water abstraction during recent periods in the central Rift Valley lakes basin (Seyoum et al., 2015; Desta et al., 2017). Hence, simulated lake level from 1986 to 2000 was considered as the baseline period to evaluate the impact of water abstraction for three development pathways. During this period, the lake water level estimates are assumed to represent natural flow condition that occur with minimum human interference on the lake and its tributaries (Desta and Lemma, 2017; Seyoum et al., 2015; Goshime et al., 2019).

4.4.1 Estimation of Water Abstraction

A flow measurement device is not installed at abstraction points. Hence, a record of water abstraction volume is not available. Therefore, the water which is abstracted by individual users was estimated based on WAS. The survey covered smallholder farmers to large governmental and private companies. It was performed at three districts around Lake Ziway (i.e Ziway (Adami Tulu), Dugda (Meki) and Ziway Dugda).

The amount of abstracted water was measured using a bucket with a known size. The time which is elapsed to fill the bucket was recorded and was used to estimate the pumping rate in volume per unit time. Then, we multiplied the pumping rate by the total operation time per day to estimate the actual amount of water abstracted for each irrigation event. The equation reads:

$$Q_{abs} = Qd \times n \times T \tag{4.1}$$

where Q_{abs} is the amount of water abstracted (l); n is number of pumps used by the farmer, Qd is the pumping rate ($l\ s^{-1}$) and T is duration of the pumping abstraction (s).

We applied Equation (4.1) to estimate the water abstracted by individuals in each district. We measured the water abstraction amount for the pumps which were under operation during field survey. However, the characteristics of all pumps was recorded and used to extrapolate from surveyed pump type, size and sampled abstraction rates. The abstraction rate was assumed to vary with pump type, size and operational time of the same district. In this study, a total of 856 pumps of individual farmers, 4 irrigation schemes, 7 flower farms and 1 water supply facilities were surveyed. The water abstraction rate was measured for 164 schemes and interpolated for 692 points based on some characteristics of the same district and office data. For flower farms, Meki-pump irrigation, and water supply facilities estimate of water abstraction amount was from their daily water use report (personal field visit and communication).

The rate of water abstraction was assumed to be constant throughout the year. However, the total abstraction volume by individual farmers is assumed to vary seasonally with cropping pattern and schemes operation. Hence, crop type, irrigated area per crop and irrigation schedule were collected during the WAS. For the rainy season (June-September), most of the private companies reduce their pump operation capacity and duration by half. Such information and irrigation scheduling data were used to estimate the water abstraction at monthly time step outside the survey period. Then, this estimated monthly water abstraction rate was assumed to apply each year over the simulation period.

4.4.2 Lake Water Balance estimation

The monthly water balance of the lake is determined as follows:

$$\frac{\Delta V}{\Delta t} = R(t) - E(t) + Q_{in}(t) - Q_{out}(t) - G_{net}(t) - Q_{abs}(t) \qquad (4.2)$$

where $\frac{\Delta V}{\Delta t}$ is the change in lake water volume over time; R is rainfall over the lake surface and E is evaporation from the lake surface; Q_{in} *is* surface water inflow to the lake; Q_{out} is surface water outflow from the lake; G_{net} is the net groundwater seepage and Q_{abs} is water abstraction from the lake. All terms are in m^3 $month^{-1}$ unit.

We note that piezometric data are too scarce in the study area to estimate groundwater contributions to the water balance. Furthermore, the topography of the lake area is flat with very shallow lake depth. Hence, it is unlikely to have significant groundwater in the lake. Therefore, this study also shares similar view with other previous study that assumed negligible groundwater component around the lake (Vallet-Coloumb et al., 2001; Desta et al., 2017).

In this study, lake areal rainfall is estimated from bias-corrected CHIRP satellite rainfall. A non-linear bias correction method was applied to correct the bias of original CHIRP using rain gauge as a reference, see (Goshime et al., 2019). Lake open water evaporation was estimated from three representative stations (i.e. Ziway, Ogolcho and Arata) which are located close to the lake using Penman (Penman, 1948) method.

The Hydrologiska Byråns Vattenbalansavdelning (HBV) rainfall-runoff model (Lindström et al., 1997) was used to simulate the runoff generated from gauged catchment (Meki and Katar). The model consists of four routines (i) a precipitation accounting routine, (ii) a soil moisture routine, (iii) a runoff routine and (iv) a baseflow routine. HBV simulates mass exchange across three stores which are the soil moisture reservoir, the upper zone store and the lower zone store. We chose not to describe the equation for various routines of the model as it has been described in several articles in the past (Wale et al., 2009; Dessie et al., 2015; Reintjes et al., 2015).

The main inputs to the model include daily rainfall, potential evapotranspiration, and Digital Elevation model (DEM), and land use land cover of the catchment areas. Observed streamflow at major river inflow of Meki and Katar were used for model calibration. The model was initialized for two years (1984 to 1985) in order to reasonably reproduce antecedent conditions in the various model stores. The calibration period covers seven years (1986 to 1991). During calibration, eight parameters are slected based on previous studies: *FC, BETA, LP, Alfa, Khq, K4, PERC and CFLUX*. First, we calibrated the parameters that control the streamflow volume and baseflow. Next parameters that control the wet season streamflow dynamics, mainly streamflow peaks, are calibrated. The model is validated for independent data sets over a period of five years (1996 to 2000).

The ungauged part of the watershed which accounts for 18% of the total catchment area was estimated using the area-ratio method. The sum of the discharges derived from gauged and ungauged catchments has been used to estimate the river inflow into the lake. In the present study, we used the rainfall-runoff simulation result from bias-corrected CHIRP rainfall input of our previous study (Goshime et al., 2019). Lake outflow discharge at the Kerkersitu station was directly used to simulate the natural condition.

After all water balance components were estimated, a water balance model was developed using Equation (4.3) as follows to simulate lake volume for the entire simulation over the period 1986 to 2014 and natural condition on a monthly time step. Similar approach was also followed in Lake Tana water balance studies by (Kebede et al., 2006; Wale et al. 2009; Rientjes et al., 2011; Dessie et al., 2015).

$$V_{lake}(t) = V_{lake}(t-1) + \Delta V \tag{4.3}$$

where V_{lake} (t) is the lake volume at month t; V_{lake} (t-l) is lake volume at previous month (t-1) and ΔV represents net inflow volume as estimated using (Equation 4.2).

The lake volume was then converted to lake level using the observed relationship between lake level and volume, which is obtained from the lake bathymetric surveys. In this study, the temporal variation of the lake surface area was derived from available bathymetric survey conducted in 1984 and 2013, with a reference datum level of 1635 meter above sea level. Using available bathymetry data, we established a regression relationship between lake surface area, elevation and volume for lake level simulation. Figure 4.2 depicts the plot of elevation-volume-area relationship of the lake Ziway for 2013 year of bathymetric survey data.

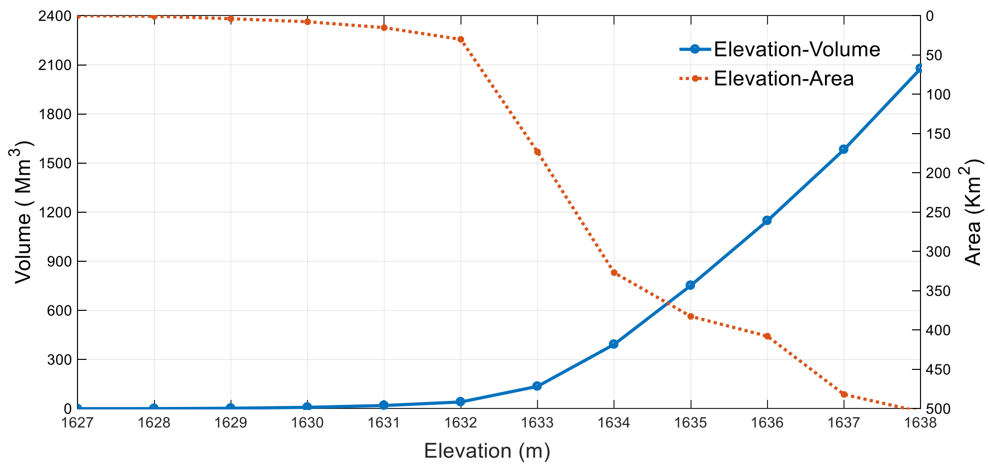

Figure 4.2. Lake Ziway elevation-volume-area relationships from 2013 year bathymetric survey (Source: Ministry of Water, Irrigation and Electricity of Ethiopia)

After isolating the natural condition, first we simulated the lake water balance without water abstraction component incorporated in Equation (4.2). This simulated lake volume (and corresponding lake level) using Equation (4.3) was then used as a baseline to evaluate the impact of water abstraction on the lake volume and water level. The performance of the water balance model for water level simulation was assessed in terms of Nash-Sutcliffe Efficiency (NSE), Relative volume error (RVE) and coefficient of determination (R^2) in addition to visual inspection of the simulated and observed water level.

4.4.3 Development Pathways

In this study, three development pathways were built based on consultation of key informants and literature review about development plans in the study area. The main data used for these pathways were obtained from consultation of main water users of the lake, Central Rift Valley (CRV) Lakes basin master plan, feasibility studies and administrative regional water office. These pathways include existing, likely future and full planned development (Table 4-1).

The amount of water abstraction was estimated for all development pathways. First, the amount of water abstraction for existing development (ED) based on our own water abstraction survey was estimated for 2000 ha of irrigated areas and 1 domestic water use. Then, the amount of water abstraction for likely future and full planned development was estimated using rate of water withdrawal for ED and the planned irrigated area of the scheme under the corresponding pathways. Then, the lake water balance was estimated using Equation (4.2) for water abstraction component incorporated here in for lake level simulation. The impact of water withdrawal from the lake on the lake volume and water level will be estimated from the net difference between the simulated volumes for natural condition and simulated volumes for the three development pathways. In Table 4.1 the summary and descriptions of each development pathways are given.

Table 4.1. Summary of the development pathways for water used from Lake Ziway

Pathways	Time frame	Main users	Descriptions
Baseline (BS)	1986-2000	None	Simulated natural condition without significant water abstraction
Existing Development (ED)	Current (2018)	• Smallholders:1108 ha • Flower farms : 639 ha • Irrigation schemes :253 ha	Existing water abstraction: total irrigated area withdrawing water from the lake: 2000 ha
Likely Future Development (LFD)	Short term (2019-2028)	• Smallholders:1686 ha • Flower farms :944 ha • Irrigation schemes: 470 ha	Existing development plus realistic expansion based on consultation of stakeholders: total irrigated area:310 0 ha
Full Planned Development (FPD)	Long term (2029-2038)	• Smallholders: 2830 ha • Flower farms:1292 ha • Irrigation schemes: 878 ha	Likely future development plus further full potential expansion= total irrigated area:5000 ha

4.4.4 Impact of water abstraction

To evaluate the impact of water abstraction on available water, we established three critical thresholds for lake water levels following Alemayehu et al. (2010) and Van Oel et al. (2013) who applied critical thresholds for Lake Tana in Ethiopia and Lake Naivsha in Kenya, respectively. The critical threshold levels are defined according to the Ministry of Water, Irrigation and Electricity master plan report and feasibility studies. These levels include steady state level (1636 m.asl), water stress level (1635.56 m.a.s.l) and water scarcity level (1635 m.a.s.l).

The steady state water level refers to the level at which the impact of water abstraction is minimal and it is expected that at this level all water sectors including fishing and shipping water requirement is satisfied. This level was estimated from the long-term mean of observed lake level over the period 1986-2000 data. The water stress level refers to a minimum level required for outflow discharge to Bulbula River. Hence, a lake level drop below this level will bring water stress situation and irrigation water abstraction from the lake should be reduced for downstream environmental flow requirement. Therefore, in this study a minimum level required for outflow to Bulbula River (i.e.1635.56 m.a.s.l) was taken as water stress critical threshold level from master plan. The water scarcity level represents a minimum threshold level required for fish habitat and their food chain as per master plan document. Below this level, irrigation water abstraction should be ceased for shipping, fishing and other activities. We assessed the impact of three development pathways using each critical threshold levels.

4.5 Results and Discussion

4.5.1 Water Abstraction

Figure 4.3 shows the spatial location of abstraction points surveyed at three districts (Ziway, Dugda and Ziway Dugda). In terms of irrigated area, the survey showed that the lake is currently supplying water to a total irrigated area of 1120 ha at Ziway, 614 ha at Dugda and 266 ha at Ziway Dugda district. A larger irrigated area in Ziway district at Adami Tulu Jido Kombolcha woreda is due to presence of both flower farm and smallholder farmers. At Dugda and Ziway Dugda district relatively smallholder farm lands are dominant except for presence of the Meki-Ziway pump irrigation in Dugda woreda. Overall, a total of 856 pumping stations are currently supply water from the lake to smallholder farms. Also, 4 irrigation schemes, 7 flower farm lands, and 1 water supply facilities are currently using the lake.

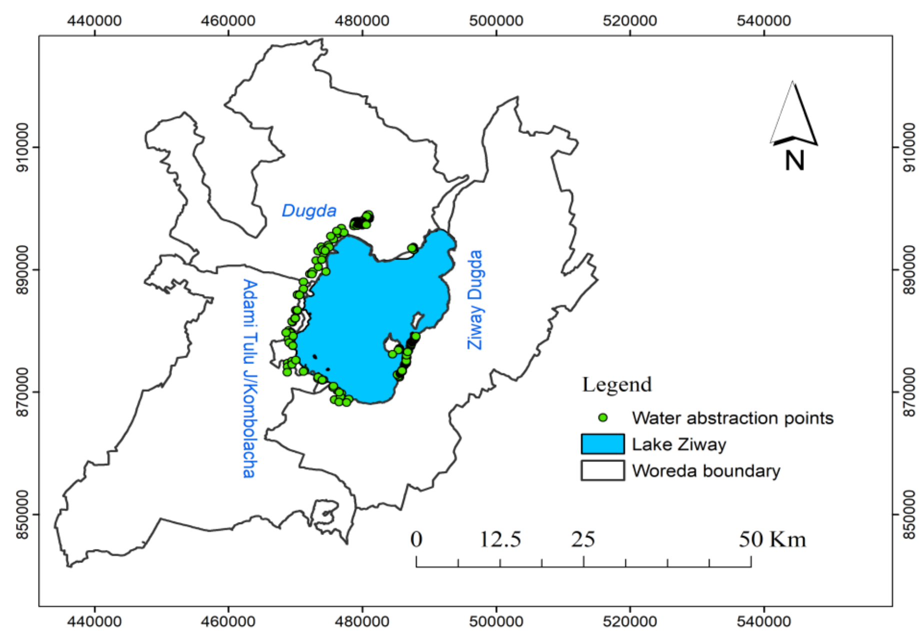

Figure 4.3. Location map of three administrative district woreda (Ziway, Dugda and Ziway Dugda) and Lake Ziway including the spatial distribution of the surveyed water abstraction points, and the elevation map

The percentage shares of the estimated water abstraction amount are shown in Figure 4.3 for existing situation in 2018. We note that about 53% of the lake water abstraction is by individual farmers for irrigation. Abstraction by flower farm accounts for 27%. The water abstraction for irrigation schemes around the lake accounts for 17%. A very small amount of 3% belongs to domestic water supply for Ziway town. Overall, the analysis indicates that water abstraction for irrigation accounts for 97% of the major abstraction from the lake.

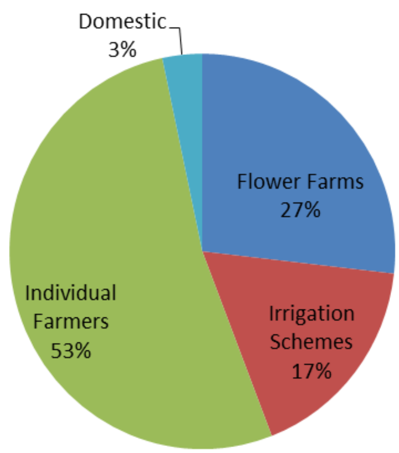

Figure 4.4. Water abstraction amount by different users from Lake Ziway for existing condition

The results of water abstraction which were estimated following the procedure described in section (4.1) are shown in Figure 4.5 for three development pathways. The figure shows that smallholder farmers at three district, Sher Ethiopia flower farm and Meki-Ziway pump irrigation are the highest water users from the lake. The other water sectors are significantly smaller. The municipal water supply in Ziway town was estimated to be 96 $l\,s^{-1}$ according to regional municipal water supply office report (personal communication). Currently, spring water at Telo area 37 km far from Ziway town is ongoing to supply for the town. Hence, the current domestic demands of the town from the lake are kept constant for all development pathways. Hence, a value of 1.26 Mm^3 per annual has been assumed to apply for the entire water balance simulation.

Figure 4.5 (b) shows the aggregate of all water user into flower farm, smallholder, domestic and irrigation schemes water use. We note that flower farms and smallholder water users will increase their consumption by the largest amount in the future with the highest in smallholder farmers.

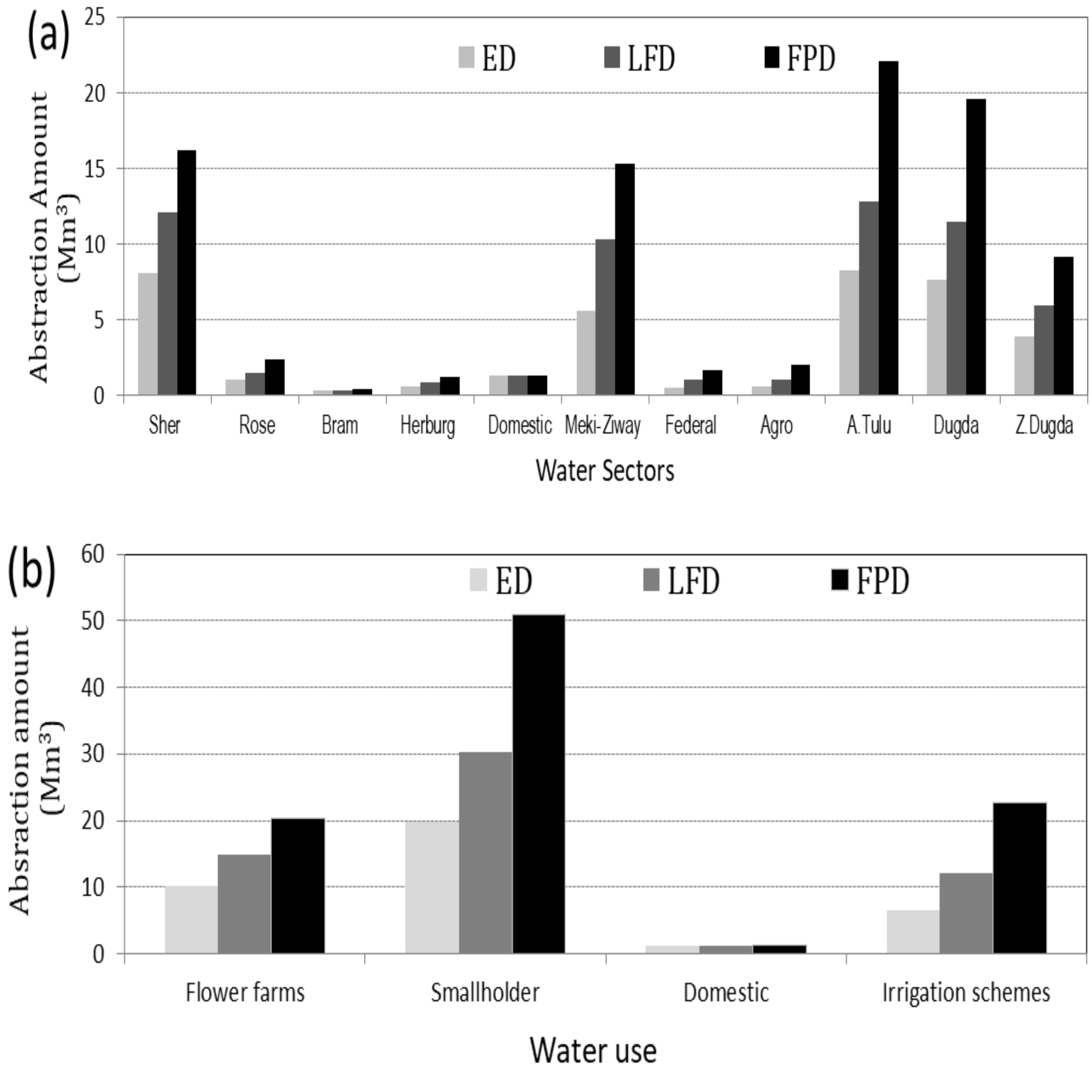

Figure 4.5. Annual water abstraction amount for a) all water sectors b) aggregate of all water sectors into four water uses for ED, LFD and FPD pathways

Table 4.2 shows the summary of monthly and annual estimated water abstraction amount for all development pathways. For existing development, the annual estimated water abstraction amount is 38 Mm^3 including domestic water use. This value is greater than that estimated in Ayenew (2004) (28 Mm^3) and slightly lower than the estimate by Desta et al. (2017) (41 Mm^3). The total irrigated area for existing development pathway is 2000 ha. If all the planned irrigated areas are fully implemented, the estimated annual water abstraction amount will increase by 2.5 folds (i.e. 95 Mm^3).

Table 4.2. Monthly and annual water abstraction from Lake Ziway for three development pathways (unit in Mm^3)

Pathways	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
ED	3.59	3.14	3.59	3.38	3.59	2.07	2.22	2.22	3.38	3.59	3.38	3.59	37.8
LFD	5.59	4.88	5.59	5.27	5.59	3.15	3.39	3.39	5.27	5.59	5.27	5.59	58.6
FPD	9.17	7.98	9.17	8.63	9.17	4.95	5.33	5.33	8.63	9.17	8.63	9.17	95.3

Note: ED=existing development; LFD=likely future development, and FPD =full planned development pathway

4.5.2 Lake water balance

The results of the monthly and annual lake water balance for natural condition (1986-2000) for Lake Ziway are presented in Table 3. The result revealed that river inflow, rainfall, evaporation, and outflow constitute 34, 17, 41 and 8 % of the annual water balance of the lake, respectively. Overall, this will result a water balance closure error of 67.5 mm over the simulation period that accounts for 2.9% of the total lake inflow from rainfall and river inflow. The source of this error can be attributed to uncertainty in the estimation of each water balance component in addition to our assumption of negligible groundwater component (Vallet-Coloumb et al., 2001; Ayenew, 2004).

Table 4.3. Monthly and annual Lake Ziway water balance in Mm^3 from 1986 to 2000

Water Budget	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Rainfall	6.1	14.6	26.2	32.0	30.5	37.1	76.1	57.8	37.2	16.1	2.71	1.99	338.4
Evaporation	69.5	68.5	78.7	73.4	73.3	70.1	63.9	63.3	63.6	70.9	68.3	68.5	832.1
Gauged Inflow	2.2	3.6	13.2	27.0	34.9	44.8	98.4	151.4	147.7	71.3	16.3	2.9	614.0
Ungauged Inflow	0.3	0.8	2.1	3.8	4.6	6.1	12.6	19.4	18.4	10.3	2.1	0.3	80.8
River Outflow	11.0	6.1	4.0	3.5	3.2	3.0	4.7	15.5	32.4	37.8	29.8	19.9	170.9

The results obtained by this study were compared with other previous studies such as (Vallet-Coloumb et al., 2001; Ayenew, 2004; Jansen et al., 2007; Desta et al., 2017). Table 4.4 shows the summary of the water balance components of Lake Ziway as estimated by this and other studies. The results of our estimate of the annual water balance components are comparable with other previous studies. The lake rainfall, river inflow and evaporation estimate of this study exactly match with Vallet-Coulomb et al. (2001). The lake areal rainfall estimates by other studies are also closer to the result of this paper. The relatively slight variation of the river inflow estimate of this study is possibly arising from the method of estimation. In this study, river inflow was simulated using rainfall-runoff modelling approach from gauge catchment and area-ratio for ungauged catchment. Our comparison indicates that, slight difference in the values of outflow components (evaporation, outflow and water abstraction) were observed among the studies. This is mainly related to lack of monitoring and regulation of the lake.

Open water evaporation estimated in the present paper (832 Mm^3) is lower than estimated in Ayenew (2004) (890 Mm^3) but higher than that by Jansen et al. (2007) (774 Mm^3). The major difference arises from the number of the meteorological station used to estimate the lake evaporation. The estimate of lake evaporation in this study is from three stations located near the eastern and western shore of the lake whereas previous studies only used Ziway station. The outflow discharge obtained by this study is lower than Ayenew (2004) and Jansen et al. (2007) but higher than Vallet-Coulomb et al. (2001). The amount of water abstraction estimated by Ayenew (2004) and Jansen et al. (2007) was lower than this study. This is due to the difference in time for which the abstraction was estimated. However, water abstraction estimated by Desta et al. (2017) was closer with this study which they used relatively recent survey of water abstraction.

Table 4.4. Comparison of annual water balance components of Lake Ziway estimated by this study and other different studies (all terms in Mm^3)

Water Balance terms	This study (2019)	Vallet-Coulomb et al. (2019)	Ayenew (2004)	Jansen et al. (2007)	Desta et al. (2017)
Study Period	1986-2000	1969-1995	1970-1996	1991-2005	1988-2000
Lake Areal Rainfall	338	335	323	327	356
River Inflow	695	691	704	685	656
Evaporation	832	832	890	774	854
Outflow	171	157	184	185	165

Figure 4.6 shows the lake inflow and outflow components of the water balance in the period 1986–2000. The figure shows that the major contributor to the lake is the river inflow from Meki and Katar catchments. We note that there is an increasing outflow during recent

periods than other water balance components. The outflow component also indicated a higher inter-annual variability in the study area.

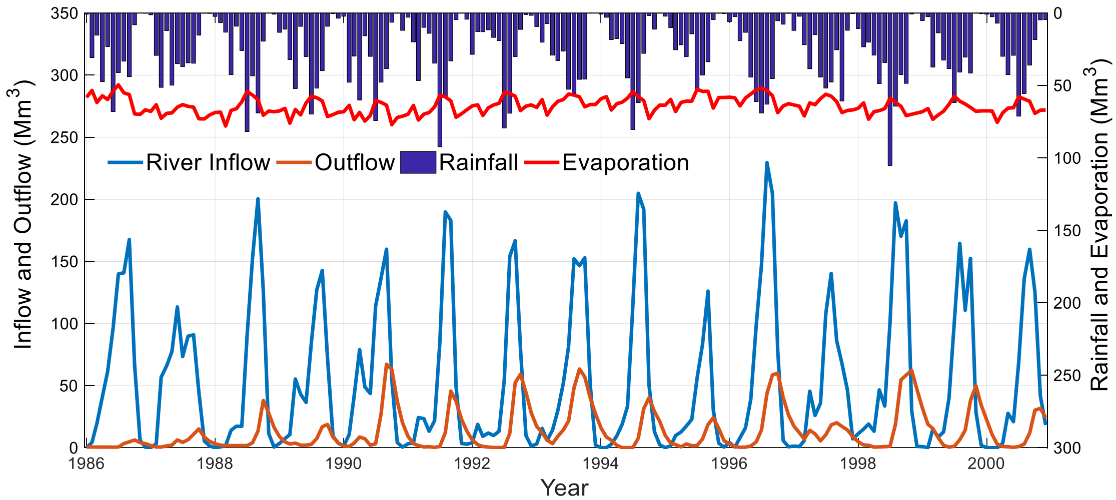

Figure 4.6. Monthly time series of lake inflow and outflow components from 1986-2000.

4.5.3 Lake Level Simulation

Figure 4.7(a) shows the simulated and observed lake levels from 1986 to 2014 on a monthly time step. The simulated monthly lake levels reasonably follow the pattern of the observed lake levels up to 2000. However, the simulated lake level significantly deviated from the observed from 2000 onwards. The 12 month moving average plot also clearly shows that the deviation of the simulated water level from observed level after 2000 onwards (Figure 4.7b).

The gap between the simulated and observed levels beginning from the end of 2000 could be most likely attributed to error in any of the water balance terms and human activities (e.g. pumping water abstraction for irrigation) which are not incorporated in our water balance model. For the natural period (1986-2000), the results of the lake level simulation revealed NSE of 0.67, R^2 of 0.75 and RVE of 3.41, with overall all performance of rated as good. The study shows that smaller error did not result a perfect lake level simulation. We note that the model performance efficiency slightly deteriorated for the recent human-induced period (2001-2014). The difference in model performance is likely to be influenced by the temporal aspects related to water abstraction.

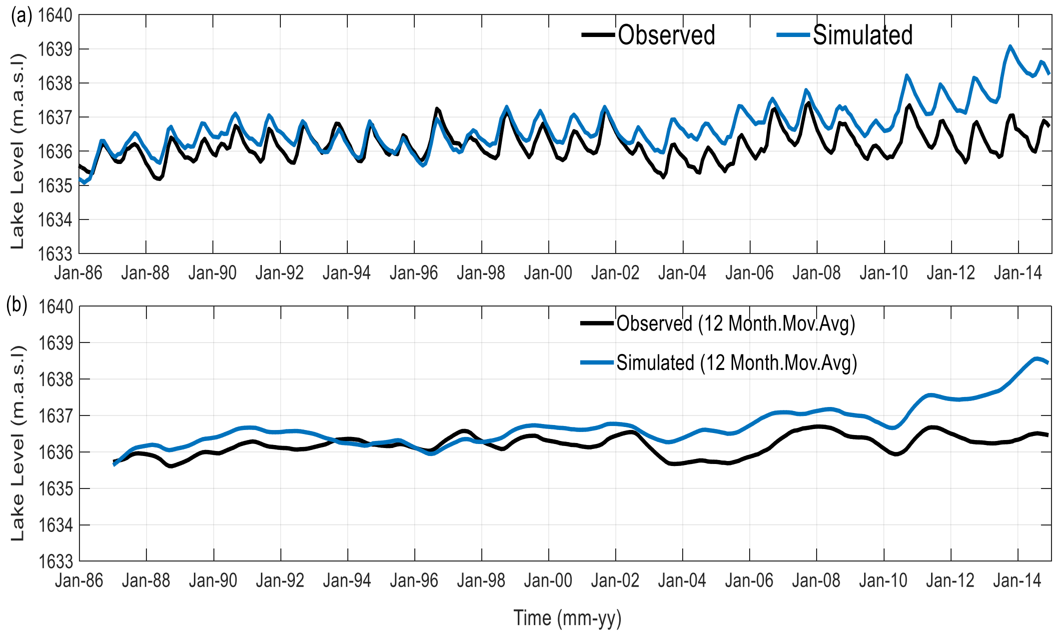

Figure 4.7. Comparison of monthly lake level between (a) observed and simulated lake level; (b) 12 months moving average, for a time series from 1986 to 2014

4.5.4 Impact of Water Abstraction

After the amount of water abstraction for all development pathways (Table 4. 2) and lake water balance component (Table 4. 3) were estimated, we simulated the lake volume using water balance modelling approach following Equation (4.3). Then, the simulated lake volume was converted to lake level using the bathymetric relationships. The simulated volume and lake level were compared with the baseline simulated counterparts to evaluate the impact of water abstraction. We assumed constant monthly water abstraction throughout the simulation period for the respective pathways.

Figure 4.8 present comparisons of the simulated lake volume for three development pathways and baseline condition for the period 1986-2000. The simulated monthly lake volume for the three development pathways was disagreed with the baseline condition over the simulation period. The disagreement becomes significant after 1990. The possible reason for this phenomenon might be attributed due to cumulative effect of water abstraction and also depends on variation of climatic regions. The simulation results show that the influence of water abstraction on the lake volume is significant. The difference of the simulated lake volume for existing development is relatively lower than the likely future and full potential development pathways.

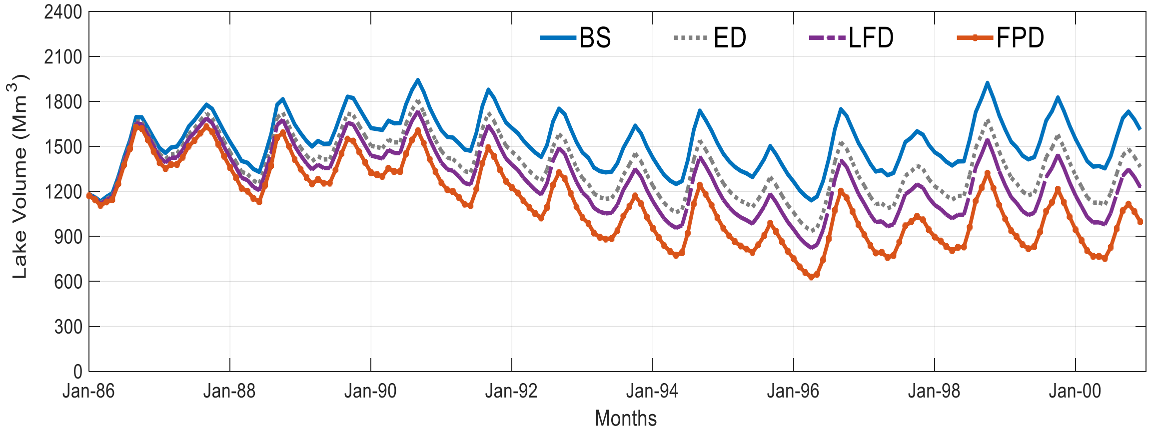

Figure 4.8. Comparison of baseline simulated and simulated lake volume for three development pathways around Lake Ziway from 1986-2000

Figure 4.9 shows the result of lake level simulation for baseline condition and the simulation including water abstractions for the three development pathways. The simulated monthly lake level for the three pathways is significantly lower than the baseline lake level over the simulation period. The results show that the influence of water abstraction on the water level of Lake Ziway is substantial. It has been found that the difference is noticeably large for likely future development and fully planned development pathways.

The full planned development exacerbates the drop in water level. For instance, in 2000 the lake level simulations drop up to 1.5 from the natural condition. The lake level during this period drops to 1634.5 m.a.s.l, which is below both the water stress and water scarcity levels. This consequently affects the lake outflow which in turn decline in Lake Abiyata inflow. Vallet-Coulomb et al. (2001) reported that a decrease by about 30% of river inflows to Lake Ziway would bring about a complete drying of the Bulbula River, which accounts about 42% of the input to Lake Abiyata. Therefore, any water level decline in Lake Ziway will reduce the downstream water level of Lake Abiyata.

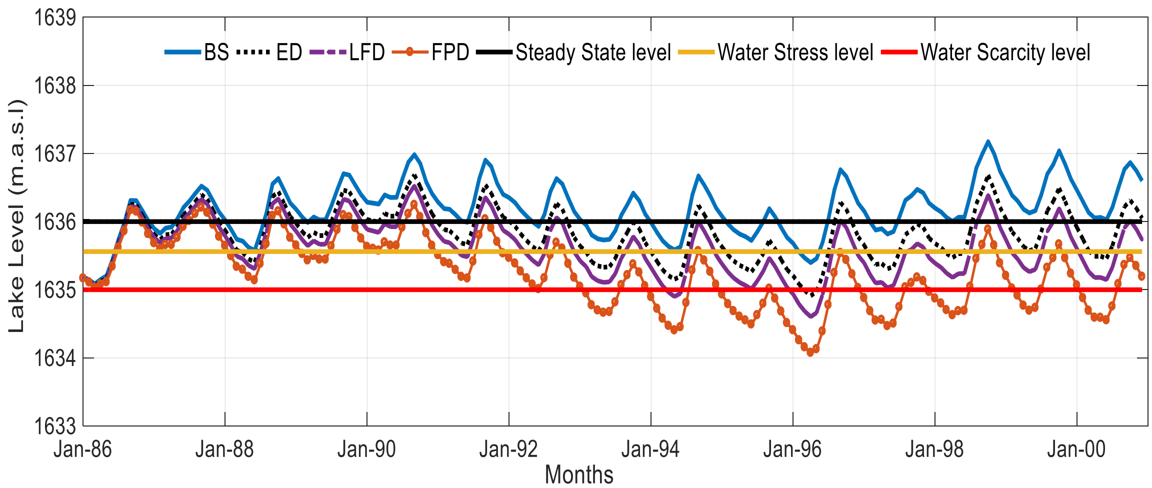

Figure 4.9. Comparison of baseline natural condition (BS) and simulated lake level for three pathways (ED, LFD, FPD) for Lake Ziway from 1986 to 2000

The existing water abstraction will not drop the lake level below the water stress level except a few dry years (March to May 1996). This indicates that existing water abstraction is reaching steady state condition. For the LFD, the water level drop below the water stress level up to 46% of the time and even below water scarcity level in 1996 mainly from January to May. This likely would have a significant impact on the ecology of the lake. However, if full development occurs then water level will significantly drop below the water stress level for 70% of the time and below water scarcity level for 31% of the time. This would have a very significant impact on shipping and fishing in the lake. Overall, we note that the lake water level drops below the steady state condition at about 70% of the time for ED, 80% for LFD and 92% of the time for FPD. This clearly indicates that the irrigation water abstraction from the lake has significant impact on the lake volume and level.

Table 4.5 shows the decline of mean annual lake level, volume and surface area of Lake Ziway as water abstraction in the lake increases. As expected the decline was higher during full planned potential and likely future development, respectively as compared to existing development. During existing development pathway, the mean annual water level of the lake drops by 0.36 m from the baseline. This translates to 4% reduction in lake surface area (Table 4-5). The likely future development pathway decreases the lake water level by 0.57 m, which yields 6.1% reduction in the surface area of the lake (Table 4.5).

The full planned potential development pathway further exacerbates the drop in the water volume and level. During this pathway, the mean annual lake water level is reduced by 0.94 m from the baseline. In this pathway, average surface area of the lake decreases by approximately 8.7%. A similar finding was also reported by Alemayehu et al. (2010) for Lake Tana in Ethiopia nearly from similar development pathways. Van Oel et al. (2013) showed that the influence of water abstraction around Lake Naivasha revealed substantial decline on the volume and water level of the lake. However, the current and ongoing status of the lake water abstraction amount was measured at major abstraction points which help for water pricing and conservation orientation. As a result of this, there is a coordinated institutional framework among responsible authorities and better management of water abstraction practice from the lake and its basin.

Table 4.5. Summary of simulation results for each pathway from 1986 to 2000

Pathway	Mean annual lake balance term			Change from the baseline		
	Water Level (m.a.s.l)	Area (km^2)	Volume (Mm^3)	Water level Change (m)	Area change (%)	Volume change (%)
BS	1636.18	442.24	1529.50			
ED	1635.82	424.35	1367.49	-0.36	-4.0	-10.6
LFD	1635.61	415.49	1278.53	-0.57	-6.1	-16.4
FPD	1635.25	403.95	1124.10	-0.94	-8.7	-26.5

In this study, we focused on the impacts of water abstraction from Lake Ziway on water volume level and surface area of the lake. The water balance modelling result indicate that water abstraction from the lake has significantly contributed to the change in the water volume and level of Lake Ziway. Previous studies also reported that the hydrology of Central Rift Valley lakes basin has been affected by both natural climate variability and human activities (Legesse et al., 2004; Seyoum et al., 2015; Desta et al., 2017). Desta et al. (2017) indicated human-induced impacts, such as sediment loads due to deforestation, soil erosion, uncontrolled water abstractions from the lake and its feeding rivers can also be one of the major causes for the lake volume and water level reduction. The results of this study share the view of the above studies. Hence, this calls serious action on integrated water management of lake. If the current situation continues without any intervention, the lake storage will decline at moderate to excessive levels which will likely damage to the lake hydro-ecological integrity as observed in Lake Alemaya (Lemma, 2003).

The reduction in the available water volume of Lake Ziway could be expected to decrease its services for a wide variety of ecosystems. Lake Ziway supports the largest fish stock in the CRV basin and serves as a principal source of commercial fishing in Ethiopia (Legesse and Ayenew 2006). We note that for full development the Lake water level (and corresponding volume) will reach water scarcity situation. This will significantly affect its service for fish and their food chain. Hence, the reduction in water volume will hinder its potential as a freshwater for fishery which in turn reduces economic income. The impact also goes to reduce its service for food and shelter for a wide variety of endemic birds and wild animals.

In this study, consideration was given only to the possible changes arising from water abstraction around Lake Ziway. However, the water resources of the lake are also vulnerable to climatic changes (rainfall and temperature). In a study of climate change on Lake Ziway watershed, it was reported that the total mean annual inflow volume into Lake Ziway will significantly decline which yield reduction in water level and surface area of the lake (Zeray, 2006). This could also affect both water availability and irrigation demand, which alter the allocation of water resources. Hence, in the future studies water allocation to the various water demands including the current and future water resources development under a changing climate covering the entire Lake Ziway watershed must be undertaken.

4.6 Conclusions

In this study, we evaluated the impact of water abstraction on the volume and level of Lake Ziway using water balance modelling approach. The CHIRP rainfall dataset was bias-corrected and used as input in rainfall-runoff simulation where the simulated river inflow served as input to Lake Ziway water level simulation. A water abstraction survey was conducted to estimate actual water withdrawal from the lake and three development pathways were simulated to evaluate the likely impact of future developments on the lake water balance. We chose to use the simulated lake volume and level from 1986 to 2000 as a reference period for baseline natural condition to evaluate the impact of water abstraction. The study is unique as it is couples the use of the satellite dataset, rainfall-runoff modelling and field survey data to evaluate human intervention impact on Lake Ziway.

Our results indicate that water abstraction for irrigation has substantial impact on the water balance of Lake Ziway. Under the likely future development pathway, irrigation water abstraction is estimated to be 57 Mm^3. Compared to the baseline situation, this will reduce the mean annual lake volume and water level by 262 Mm^3 and 0.57 m, respectively, which leads to a reduction of lake surface area by 27 km^2. If the full development pathway is to be implemented, then the water level and surface area of the lake will drop by an additional 0.37 m and 11 km^2, respectively. This consequently, will yield a significant reduction in the lake volume by 405 Mm^3 as compared the baseline situation. Hence, our findings indicate that existing and future water abstractions directly from the lake have a significant impact on the lake volume and level. We, therefore, recommend that implementation of future development plans should be reconsidered to limit their impacts on the lake storage to acceptable levels. This demands integrated action by all concerned stakeholders to achieve sustainable water use around the lake.

References

Adgolign, T. B, Srinivasa-Rao, G.V.R., Abbulu, Y. (2015). WEAP modeling of surface water resources allocation in Didessa sub-basin, West Ethiopia. Sustainable Water Resources Management, 2(1): 55–70. doi.org/10.1007/s40899-015-0041-4.

Alemayehu, T., McCartney, M., Kebede S. (2010). The water resource implications of planned development in the Lake Tana catchment, Ethiopia. Ecohydrology and Hydrobiology, 10: 211–221. doi.org/10.2478/v10104-011-0023-6.

Ayenew, T. (2004). Environmental implications of changes in the levels of lakes in the Ethiopian rift since 1970. *Regional Enviromnetal Change*, 4(4):192–204. doi.org/10.1007/s10113-004-0083-x.

Ayenew, T. (2007).Water management problems in the Ethiopian rift: challenges for development. Journal of African Earth Sciences, 48 (2/3): 222–36.

Chinnasamy, P., Bharati, L., Bhattari, U., Khadka, A., Dahal, V., Wahid S. (2015). Impact of planned water resource development on current and future water demand in the Koshi River Basin, Nepal. *Water International*, 40(7):1004-1020. doi.org/10.1080/02508060.201 5.1099192.

Deribessa, A. (2006). Groundwater and surface water interaction and geo-environmental changes in Ziway catchment. M. Sc. Thesis, Addis Ababa University.

Dessie, M., Verhoest, N.E. C, Pauwels, V.R.N., Adgo, E., Deckers, J., Poesen, J., Nyssen J. (2015). Water balance of a lake with floodplain buffering: Lake Tana, blue Nile basin, Ethiopia. *Journal of Hydrology*, 522: 174–86. doi.org/10.1016/j.jhydrol.2014.12.049.

Desta, H., Lemma, B., Gebremariam, E. (2017). Identifying sustainability challenges on land and water uses: the case of Lake Ziway watershed, Ethiopia. *Applied Geography*, 88: 130–43. doi.org/10.1016/j.apgeog.2017.09.005.

Döll, P., Hoffmann-Dobrev, H., Portmann, F.T., Siebert, S., Eicker, A., Rodell, M., Strassberg, G., Scanlon, B.R. (2012). Impact of water withdrawals from groundwater and surface water on continental water storage variations. *Journal of Geodynamics*, 59: 143–156

Funk, C., Verdin, A., Michaelsen, J., Peterson, P., Pedreros, D., Husak, G. (2015). A global satellite, assisted precipitation climatology. *Earth System Science Data* 7(2): 275-87. doi.o rg/10.5194/essd-7-275-2015.

Funk, C.C., Pete, J., Peterson, P.J., Landsfeld, M.F,, Pedreros, D.H., Verdin, J.P., Rowland, J.D., Romero, B.E., Husak, G. J., Michaelsen, J.C., Verdin, A. P. (2014). A quasi-global precipitation time series for drought monitoring. *U.S Geological Survey Data Series*, 832 (4).

Goshime, D. W., Absi, R., Ledésert, B. (2019). Evaluation and bias correction of CHIRP rainfall estimate for rainfall-runoff simulation over Lake Ziway watershed, Ethiopia. Hydrology, 6 (3):68: doi.org/10.3390/hydrology6030068.

Jansen, H., Hengsdijk, H., Legesse, D., Ayenew, T., Hellegers, P., Spliethoff, P. (2007). Land and water resources assessment in the Ethiopian Central Rift Valley project: ecosystems for water, food and economic development. *Alterra report, 1587*. Wageningen, The Netherlands.

Kebede, S., Travi, Y., Alemayehu, T., Marc, V. (2006). Water balance of Lake Tana and its sensitivity to fluctuations in rainfall, blue Nile basin, Ethiopia. *Journal of Hydrology*, 316(1–4): 233–47. doi.org/10.1016/j.jhydrol.2005.05.011.

Legesse, D., Ayenew, T. (2006). Effect of improper water and land resource utilization on the central main Ethiopian rift lakes. *Quaternary International*, 148(1): 8–18

Legesse, D, Vallet-Coulomb, C., Gasse., F. (2003). Hydrological response of a catchment to climate and land use changes in tropical Africa: case study south central Ethiopia. *Journal of Hydrology*, 275(1–2): 67–85. doi.org/10.1016/S0022-1694 (03)00019-2.

Legesse, D., Vallet-Coulomb, C., Gasse, F. (2004). Analysis of the hydrological response of a tropical terminal lake, Lake Abiyata (main Ethiopian rift valley) to changes in climate and human activities. *Hydrological Processes*, 18(3): 487–504. doi.org/10.1002/hyp.1334

Lemma, B. (2003). Ecological changes in two Ethiopian lakes caused by contrasting human intervention. *Limnologica*, 33(1): 44–53. doi.org/10.1016/S0075-9511 (03)80006-3.

Penman, H. L. (1948). Natural evaporation from open water, bare soil and grass. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 193(1032): 120–45. doi.org/10.1098/rspa.1948.0037

Rientjes, T.H.M., Perera, B.U.J., Haile, A.T., Reggiani, P., Muthuwatta, L.P. (2011). Regionalisation for lake level simulation–the case of Lake Tana in the upper blue Nile, Ethiopia. *Hydrology and Earth System Sciences*, 15(4): 1167–83. doi.org/10.5194/hess-15-1167.

Seyoum, W.M., Milewski, A.M., Durham, M. C. (2015) .Understanding the relative impacts of natural processes and human activities on the hydrology of the Central Rift Valley Lakes basins, East Africa: assessment of natural and human impacts on the hydrology of lakes. *Hydrological Processes*, 29(19): 4312-24. doi.org/10.1002/hyp.10490.

Vallet-Coulomb, C., Legesse, D., Gasse, F., Travi, Y., Chernet, T. (2001). Lake evaporation estimates in tropical Africa (Lake Ziway, Ethiopia). *Journal of Hydrology*, 245(1–4): 1–18.

Van Oel, P.R., Mulatu, D.W., Odongo, V.O., Meins, F.M., Hogeboom, R. J., Becht, R., Stein, A.,Onyando, J. O., Vander-Veen, A. (2013). The effects of groundwater and surface water use on total water availability and implications for water management: the case of Lake Naivasha, Kenya. Water Resources Management, 27(9), 3477–3492. doi. 10.1007/s11269-013-0359-3.

Wale, A., Rientjes, T.H.M., Gieske, A.S.M., Getachew, H. A. (2009). Ungauged catchment contributions to Lake Tana's water balance. *International Journal of Hydrological Processes*, 23(26), 3682–3693.

Zeray, L, A, Roehring, J., Chekol, A. D. (2006). Climate change impact on Lake Ziway watershed water availability, Ethiopia. C*onference on International Agricultural Research for Development*, University of Bonn, October 11-13.

5 Assessment of existing and future water demand on the Central Rift Valley Lakes basin of Ethiopia

Abstract: The water resources of Central Rift Valley lakes basin is largely used by various sectors. However, existing and future water demand and the impact of water resources development on the lake water balance are not quantified in the scientific literatures. The Water Evaluation and Planning (WEAP) model was used to assess existing and future water demand of the study area, based on water abstraction survey and CROPWAT software. Three water resources development pathways were simulated, namely current development (2009-2018), short-term development (2019-2028) and long-term development (2029-2038) to evaluate the likely impact of water resources development on the water level of three interconnected lakes i.e. Lake Ziway, Langano and Abiyata. The streamflow data of six catchments (Meki, Rinzaf, Katar, Chuifa, Sagure and Timala) were simulated using Hydrologiska Byråns Vattenbalansavdelning (HBV) model. The results show that the simulated streamflow better captured the observed hydrograph for most of the gauge stations. The WEAP simulation result show that the total water demands under the current development was 102.1 Mm^3, the demand increased to 149.4 Mm^3 under short-term development and to 223 Mm^3 under long-term water resources development pathways. The results reveled that for long-term development pathway to be implemented there is a total unmet water demand about 46.5 Mm^3 in the area. The study also found that there is unmet demand at most of the schemes with larger at Katar, Meki and Langano watersheds. Temporally, the most unmet water demand occurs from November-February, primarily in the dry seasons. Overall, this study indicated that the impact of current and future water demand directly from the lakes and its tributaries on water level is significant. Therefore, we suggest integrated water management of the lakes and their tributaries.

Keywords: Water demand; Central Rift valley; water level; WEAP, water resources development; Ethiopia

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This chapter is based on: Goshime, D.W., Haile, A.T., Absi, R., Ledésert, B., Rientjes, T.H.M., Tobias, S. Assessment of existing and future water demand on Central Rift Valley Lakes basin of Ethiopia, to be submitted to Journal of Advances in Water Resources, Elsevier.

5.1 Introduction

Increasing pressure on water resources development revealed competition among water sectors to satisfy their demand are the main challenging aspects at worldwide (UNESCO, 2009). The rising of demands for water resources will make its allocation struggle in the near future. The Central Rift Valley (CRV) Lakes basin in Ethiopia is one of the basin in which expansion of irrigation and industrial activities has been resulted in very high demand from the lakes and their feeding rivers (Ayenew, 2004; Jansen *et al*., 2007). The sub basin is one of environmentally vulnerable and rainfall deficit areas in Ethiopia, with the surrounding agro-climatic factors are believed to have significant impact on the hydrological system (Ayenew, 1998; Jansen et al., 2007).

According to Ministry of Water, Irrigation and Electricity of Ethiopia, water resources development plans are ongoing to be implemented in all major river basins of the country. Besides, there are also many other water demanding projects and investments at upstream and downstream areas (Awulachew et al., 2007). Furthermore, the policies of the Ethiopian government strongly support export-oriented irrigated horticulture and private floriculture as a means to increase foreign exchange earnings and employment opportunities. The CRV is a basin in Ethiopia where such policies have resulted in large-scale investments in floriculture greenhouses and strong growth in smallholder irrigation schemes. Such activities in the basin create stress on available water resources and hence may result for water claims and/or conflict between various water users.

Significant changes have been observed in the hydrology Rift Valley lakes in Ethiopia over the past decades. Jansen et al. (2007) reported that as a result of excessive expansion of smallholder irrigation the average level of Lake Ziway has decreased by approximately 0.5 m since 2002. The authors reported that this further revealed a decrease in the discharge of Bulbula River which resulting in a reduction in size of Lake Abiyata by more than 40% of its size. Seyoum et al. (2015) showed that the water level of Lake Abiyata tremendously changed as a result of both climate and human activities. They reported a reduction of approximately 4.5 m in water level was related to human activities whereas 2.5 m belongs to climatic variability. Therefore, if the water level of the lake continues to decline in such a manner, the lake water balance could be stresses to the threshold of ecological collapse that has been observed in Lake Alemaya (Alemayehu et al., 2007). These consequently will results shortage of water resources for irrigation and processing purposes. We note that the government of Ethiopia planned to stop any activity from Abiyata lakes as a result of significant decline.

Several studies have been investigated on the hydrology of Central Rift Valley Lakes basin (e.g. Vallet-Coulomb et al., 2001; Legesse et al., 2003, 2004; Ayenew, 2007; Jansen et al., 2007). Most of the previous studies mainly focused on the likely impact of socio-economic assessment of land and water resources at catchment level (Hengsdijk and Jansen, 2006; Legesse and Ayenew, 2006; Jansen et al., 2007). Only few studies are available on lake water balance estimation for natural condition without water abstraction incroprated in (Vallet-Coulomb., 2001; Legesse et al., 2003, 2004; Belete et al., 2016). Unfortunately, quantitative assessment to understand spatio-temporal existing and future water demand and the likely impact of upstream and downstream water resources development on the lake water levels is not available.

The main objective of the present study is to quantify existing and future demands in the CRV lakes basin and thereby evaluate the impact of different water resources development pathways on lake water balance. The study will help us to point out the spatio-temporal unmet demand of the water resources development schemes in the basin. This study was unique as it considers the water resources of three interconnected lakes (i.e. Ziway-Langano-Abiyata) using a combination of hydrological, water balance and water resources planning models from in-situ, satellite and survey datasets. The outcome of this study will provide information on the change occurring in the lake water balance for Ministry of Water, Irrigation and Electricity, Rift valley lakes basin authority of Ethiopia and any concerned person for integrated water management of the lakes and their watersheds.

5.2 Study area

The Central Rift Valley Lakes basin is located is the central section of the main Ethiopian Rift with a total drainage area of 10,685 km^2 situated between 7º10'- 8º30' N and 38º10'- 39º30' E. The basin is characterized by a chain of three interconnected lakes such as Lake Ziway, Langano and Abiyata. Table 5.1 shows the key characteristics of the three lakes in the CRV lakes basin based on historic data.

Table 5.1. Basic morophological charactersitcs of the selected CRV lakes

Lake	Lake Area (km^2)	Catchment area(km^2)	Elevation (m.a.s.l)	Mean Depth (m)	Maximum Depth (m)	Volume (Mm^3)
Ziway	445	7022	1636	3.0	8	1148
Langano	233	2006	1584	12.2	44.1	5565
Abiyata	148	10744	1580	7.3	13	1276

Lake Ziway receives most of its water from Meki and Katar major rivers, which drains the western and eastern plateaus, respectively. Meki River originates in the highlands of Gurage and travels a distance of about 100 km from the highlands at altitude ranging from 3600 m to 1600 m with a catchment area of 2824 km^2 including ungauge catchments. The river is supplemented by Rinzaf and Wijo minor tributaries before draining into Lake Ziway.The Katar River with a catchment area of 3750 km^2 rises from Arsi highlands drains to the east of the lake. The major tributaries that are contributing to the Katar Rivers include Chuifa, Sagure, Ashebeka, Timala, and Wolkesa. The catchments of Meki and Katar rivers cover a total of 6570 km^2 including ungauged catchments. Lake Ziway has an outflow through Bulbula River, which in turn flow to the downstream Lake Abiyata, being a terminal lake.

Lake Langano receives it water inflow from Gedemso River and other minor tributaries such as Huluka, Lepis and Boku rivers with a total drainage area of 2006 km^2. Lake Abiyata receives water from the Bulbula and the Horakelo Rivers with a drainage area of 1495 km^2. Lake Ziway and Langano are open lakes with overflow towards Lake Abiyata whereas Lake Abiyata is closed lake without surface water outflow. The basin is bounded to the east and west by the escarpment of the rift valley and the highlands. The elevation of the area is characterized by mountainous terrain with an altitude ranging from 4200 m.a.s.l at extreme western and eastern escarpments to 1580 m.a.s.l at central rift valley floor (Figure 5.1).

The main water demand from the lake and its tributaries are water used for irrigation, domestic, and industrial production. Irrigation water abstraction from Lake Ziway and its tributary rivers primarily used for production of horticulture and flowers in addition to intensive smallholder irrigation farmers. Industrial water abstraction from Lake Abiyata mainly used for soda ash production. Lake Langano and its contributing catchments use the water for irrigation and recreation activities. In addition, they also support the livelihoods for commercial fish farming, shipping and habitat for a wide variety of endemic wild animals such as birds (Ayenew, 2007). The basin climate is mainly characterized by semi-arid to sub-humid climatic condition. The major land uses in the basin includes intensive and moderately agriculture lands with onion, tomato, maize, cabbage, green beans and pepper are the dominant crops grown in the study area. The water system of Central Rift Valley lakes is preferred by various water sectors due to suitable for irrigation and industrial activities.

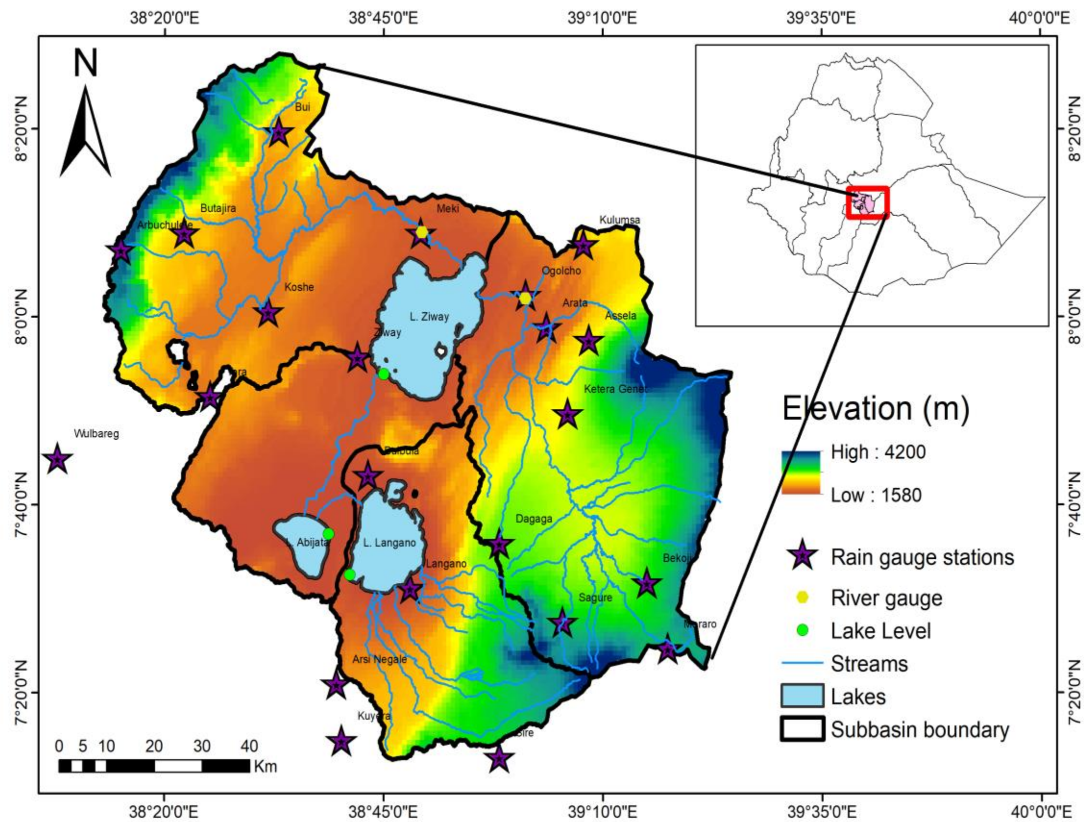


Figure 5.1. Location map of the study area showing digital elevation, hydro-meteorological stations, lake level along with contributing tributary rivers and their stream networks

5.3 Data Availability

In this study, hydro-meteorological time series, demand sites and supply sources data were used. The hydro-meteorological dataset includes streamflow, satellite rainfall and climate data required for estimation of evapotranspiration. We used daily satellite and ground observation rainfall dataset obtained from Climate Hazard Group (CHG) and National Meteorological Agency (NMA) database, respectively.

The rain gauge observations were coupled with the CHIRP satellite rainfall estimate at daily temporal and 5.5 × 5.5 km spatial resolution for the period from 1984 to 2018 as a reference for bias correction. Refere Goshime et al. (2019a) for bias-correction of the satellite rainfall estimate merging with ground observations. Daily rain gauge data for 20 meteorological stations for Lake Ziway watershed and 6 stations for Abiyata and Langano watershed from 1984 to 2018 were used. After data analysis, 20 stations out of 26 were used in this study for bias correction and evaporation estimation.

Streamflow and lake water level data were obtained from the Ethiopian Ministry of Water, Irrigation and Electricity of Ethiopia. Streamflow supply data was made available at Meki, Katar, Bulbula, Horakelo and Gedemso from the major rivers and Rinzaf, Chuifa, Sagure and Timala from minor tributaries for a period from 1984-2010. Lake water level (Ziway, Langano and Abiyata) for the period 1986-2014 were obtained from MoWiE. The observed datasetfor streamflow and lake water level were used as a reference to compare and calibrate the hydrological and water balance models.

Irrigation demand sites were identified by a field survey and consultation of relevant governmental organizations. The field survey was undertaken for 6 days from 16-21 September 2019. In the present study, the field survey covers Lake Ziway contributing catchments (i.e. Meki and Katar), Bulbula River, Langano and Abiyata lakes. The survey includes the location of demand sites, type of scheme, water sources, potential irrigated area, crop type, cropping pattern and intensity. The survey data was used to estimate site-specific crop water requirement in the study area. In addition, data obtained from water and agricultural offices of the study area, master plan, feasibility and design documents were used. For water demand from Lake Ziway water abstraction survey data collected by our previous study were directly used in this study to estimate water demand directly from the lake (Goshime et al., 2019b).

The Digital Elevation Model of ASTER GDEM V2 with a spatial resolution of 30m × 30m was used to delineate the spatial feature of the basin for the location of the demand sites. Land use/ land cover map were obtained from MoWiE for the year 1992and 1996. We note that intensive agriculture cultivation land, water bodies and wetlands are the major land use over the study area. The lake bathymetric maps conducted by Ministry of Water, Irrigation and Electricity of Ethiopia for the three lakes were used. For Lake Ziway the bathymetric survey was for 1984 and 2013 years whereas 1984 survey data was used for Lake Langano and Abiyata.

5.4 Methods

This study is mainly based on WEAP model in which data from multiple sources (such as satellite, field survey, and master plan and design documents) served as model inputs. In this study, we followed the following steps: First, we calibrated and simulated streamflow using the HBV rainfall-runoff model for the period from 1984 to 2018 for 6 river gauge stations at major and minor tributaries. Then, we assessed the available water supply and demand sites in the study area. Next, the water demand was estimated using a water abstraction survey, CROPWAT software and literature reviews. Then, we evaluated existing and future water demand in the basin using WEAP model. Finally, we evaluated the likely impacts of three water resources development pathways on the upstream and downstream water availability and on volume, water level, and surface areas of three interconnected lakes (i.e. Lake Ziway, Langano and Abiyata).

5.4.1 Model calibration and simulation

The water supply sources in CRV basin are the lakes, Meki and Katar, Fite, Bulbula, Horakelo and Gedemso major rivers and other minor tributaries. However, the observed streamflow time series covers relatively a short period with substantial missing records. This shortage of streamflow data was compensated by the use of Hydrologiska Byråns Vattenbalansavdelning (HBV) rainfall-runoff model for Lake Ziway watershed. For this, we calibrated the HBV model at 6 river gauge stations. The model was calibrated from 1986 to 1991 and validated from 1996-2000 with a 2 year warm-up period (1984-1985) to initialize the model. For detail description of HBV model reference is made to Johansson (2013). Then, we simulated the river head streamflow time series from 1986 to 2018 for input to the WEAP model. Note that for Bulbula, Abiyata and Langano, the surface water inflows were specified from river gauge data.

Bias-corrected satellite rainfall was used as input to HBV rainfall-runoff model to simulate streamflow at gauged and ungauged catchments of the subbasin. The rainfall over the catchment and lake surface of Lake Ziway is obtained from bias-corrected CHIRP rainfall estimate. Reference is made to Goshime et al. (2019a) for detailed description of CHIRP data and the applied bias-correction approach. Available rain gauge stations neaby the lake were used to estimate the rainfall over Lake Langano and Abiyata. Meteorological observations at 10 stations in the study area (Figure 5-1) were used to estimate potential evapotranspiration (PET) using the Penman-Monteith (Allen et al., 1998), which were then used as input to the hydrological model.

The land cover map obtained from MoWIE for 1992 and 1996 years over the study area were used for HBV model inputs.

The model performance was then evaluated in terms of visual inspection of the simulated hydrographs compared to observed counterparts. In addition to graphical comparison, three quantitative statistical measures such as Nash-Sutcliffe efficiency (NSE), relative volumetric error (RVE) and coefficient of determination (R^2) were used for model evaluation.

NSE measure the relative magnitude of the residual variance of the simulated flow compared to observed flow, which indicates how well fits the plot of two datasets (Nash and Sutcliffe, 1970). RVE measures the average tendency of the simulated streamflow to be larger or smaller than the observed counterparts (Gupta et al., 1999). The coefficient of determination (R2) is the measure the fraction of the variation in the observed streamflow data that is replicated in the simulated streamflow data (Moriasi et al., 2007). Table 5.2 summarizes the equation for all performance statistical measures and their descriptions are depicted.

Table 5.2. HBV model performance measures used for model evaluation

S. no	Performance Measures	Equations	Value range	Best fit Value
1	NSE	$NSE = 1 - \frac{\sum_{i=}^{n}(Q_{sim,i} - Q_{obs,i})^2}{\sum_{i=1}^{n}(Q_{obs,i} - \overline{Q_{obs}})^2}$	$-\infty$ to 1	• 1 perfect fit • 0.75 and 1 is very good
2	RVE	$RVE = \left[\frac{\sum_{i=1}^{n}(Q_{obs,i} - Q_{sim,i})}{\sum_{i=1}^{n} Q_{obs,i}}\right]$	$-\infty$ to ∞	• ±5% to ±10% well performance
3	R^2	$R^2 = \frac{\left[\sum_{i=1}^{n}(Q_{sim,i} - \overline{Q_{sim}}) \times (Q_{obs,i} - \overline{Q_{obs}})\right]^2}{\left[\sum_{i-1}^{n}(Q_{sim,i} - \overline{Q_{sim}})\right]^2 \times \left[\sum_{i=1}^{n}(Q_{obs,i} - \overline{Q_{obs}})\right]^2}$	0 to 1	• 1 best fit • 0..5 to 0.9 satisfactory to very good

where: Q_{sim} and Q_{obs} represent simulated and observed streamflow, respectively (m^3s^-1) and the over-bar symbol denotes the mean of the observed and simulated streamflow values; *i* is the time step; *n* is the number of sample size.

5.4.2 Water demand assessment

5.4.2.1 Irrigation demand

In this study, irrigation water demand was estimated using a combination of water abstraction survey and CROPWAT 8.0 program developed by Joss Swennenhuis for the water resources development and management service of Food and Agricultural Organization of the United

Nations (FAO). CROPWAT calculates reference evapotranspiration (ETO), crop water requirement (CWR), irrigation scheduling, and irrigation requirement (IR) using rainfall, soil, crop, and climate datasets. A CROPWAT input includes reference evapotranspiration, rainfall, and crop type and crop pattern. Ten (10) selected meteorological stations which are located close to the demand sites were used to estimate reference evapotranspiration using Penman-Monteith method which is considered a standard method (Allen et al., 1998) and rainfall amount at each demand sites for crop water requirement.

Based on our field survey the major selected crops over the study area include onion, tomato, maize, cabbage, green beans, pepper, alfalfa and grapes. The survey also includes the irrigation pattern (planting and harvesting stage) of each crop over the study area. In addition, crop coefficient, growth stage, depletion and soil data inputs required for irrigation water demand were obtained from FAO 56, Irrigation and Drainage paper, the basin master plan and irrigation project design documents.

5.4.2.2 Domestic water demand

The domestic water supply for Ziway and Bulbula towns is obtained from Lake Ziway and Bulbula River, respectively. We estimated the domestic water demand using the population size, population growth rate and water use (litres per capita per day) data. The water use rates were then multiplied by the population to estimate the domestic water demand. The 2007 population and housing census of Ethiopia showed that the population of Ziway and Bulbula towns was 43,660 and 5000, respectively (Central Statistical Agency of Ethiopia, CSA).

For current period, the water supply authorities of the two towns are distributing 3450 and 430 m^3/day of water for Ziway and Bulbula towns, respectively (personal communication). Water source for Ziway town will shift to the spring water at Telo area which is located at 37 km from the town due to concerns about the water quality of the lake. In this study, the current domestic water withdrawal from Lake Ziway is kept constant for all development pathways.

5.4.2.3 Industrial water demand

The Soda Ash factory has been pumping water from Lake Abiyata since 1985. The factory was established by the government of Ethiopia to produce soda ash ($Na_3H\ (CO_3)2.2H_2O$). The average annual water use rate that amounts to be 150 m^3 per ton of water were obtained from the sectoral water demand (personal communication). Then, WEAP model was used to interpolate into monthly time steps. According to Rift Valley master plan, it is reported that a total of 25,000 ton of soda ash was produced from Lake Abiyata for the current development period. In this study, an increment of 15,000 ton per each development pathway was used to construct the future production capacity (master plan report).

5.4.2.4 Environmental flow requirement

The environmental flow is required to sustain the aquatic environment to protect the natural and the ecosystem. The environmental flow requirements were expressed as a percentage of the mean annual flow. In this study, environmental flow requirement at downstream of Bulbula river were placed to control downstream flow to Lake Abiyata. However, there is no strict provision for environmental flow for other rivers and hence kept as zero. Several studies indicated that 15-20% of mean annual flow was used as environmental flow as downstream water requirement using Tennant (1976) method. Hence, in this study 20% of the mean annual flows were used for environmental flow estimation following (Shumet and Mengistu, 2016) who applied in the same study area.

5.4.3 Water Evaluation and Planning (WEAP) model

The WEAP model was developed by Stockholm Environment Institute at Boston, USA to evaluate water demands, associated priorities and water supply for current and future periods. The WEAP model used to simulate alternative scenarios (i.e., plausible futures based on “what if” questions) to assess the impact of different development and management options. The model optimizes water use in the catchment with the objective of which is to maximize the water delivered to demand sites, according to a set of user-defined priorities. The demand sites are assigned a priority between 1 and 99, where 1 is the highest priority and 99 the lowest.

WEAP integrates water supplies generated through the watershed hydrological processes with a water management model driven by various water demands and environmental requirements using linear programming to solve water allocation problems (Yates et al., 2005). The WEAP model was selected in this study due to its proven applicability in various countries for water resources planning and management studies such as (Arranz and McCartney, 2007; Alemayehu et al., 2010; Mounir et al., 2011; McCartney and Girma, 2012; Mehta et al., 2013; Adgolign et al., 2016; Polpanich et al., 2017; Hassan et al., 2019).

The input data required for WEAP are water supply or river head flows, water use (demand site), water levels, elevation-storage-area relationship and the spatial location of the water system. The WEAP model was used to optimize the spatial and temporal water use in the study area using a linear programming algorithm as per the demand priorities, supply preferences, mass balance and other constraints. For more detail description about WEAP model see (Sieber, 2005; SEI, 2015). Figure 5.2 shows the schematization of the CRV lakes basin using existing and planned water demand and supply sources which were specified for WEAP model simulation. In the schematization, we considered the type of scheme, supply sources and the location of the demand sites.

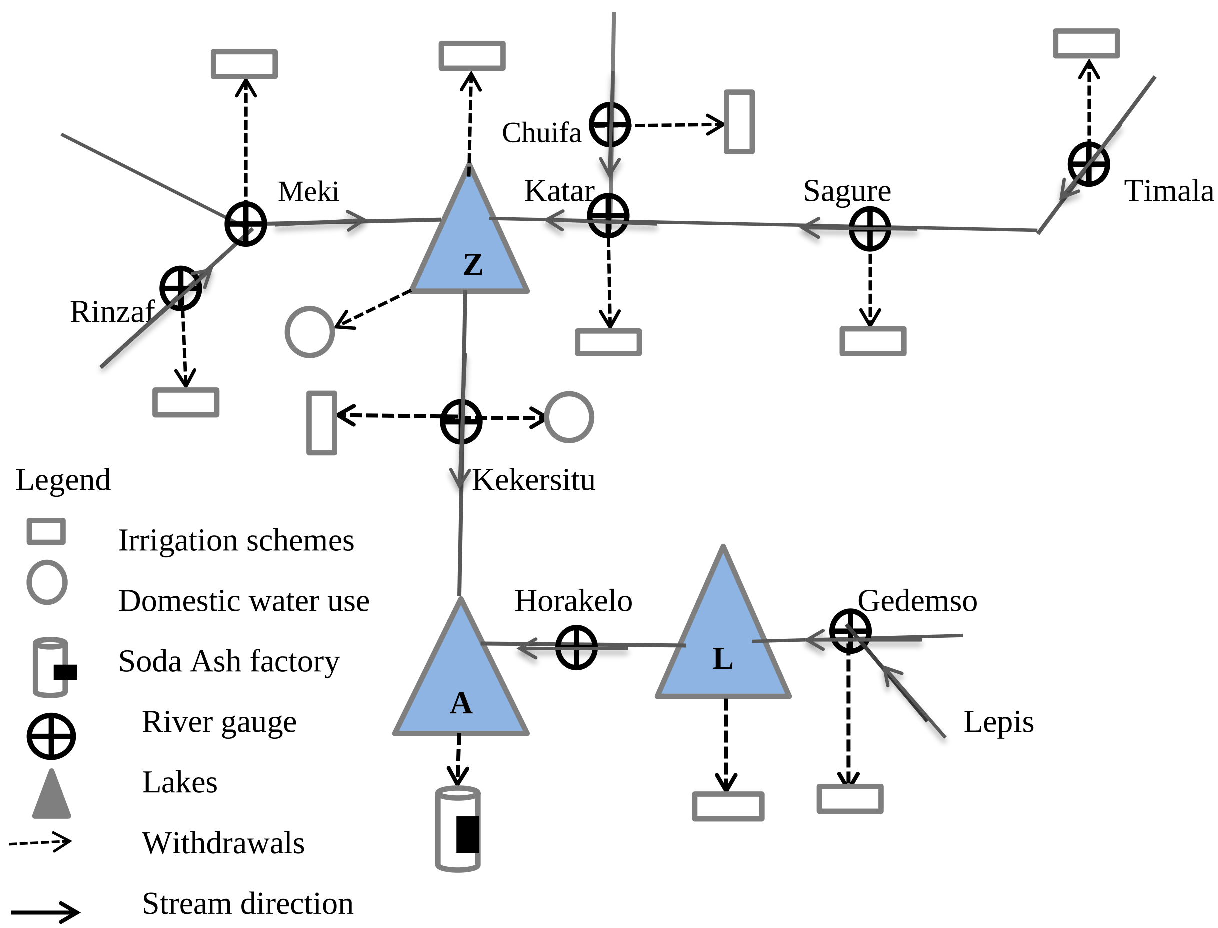


Figure 5.2. Schematic of WEAP model for the CRV lakes basin (letter Z, A and L denotes Lake Ziway, Abiyata and Langano, respectively. The triangle, rectangle, circle, broken and solid lines represents; the three lakes, irrigation schemes, water supply, withdrawals and river system, respectively

The demand priority was assigned considering the existing situation in the basin is that the most upstream demand sites withdraw water until its demand is met than the downstream users. Hence, the highest priority should be given to the most upstream demand sites first; the next priority will be assigned to the next demand sites and so on (priority varies from upstream to downstream). Accordingly, the upstream Lake Ziway catchment demand sites receive the highest priority 1 and demand sites directly from Lake Ziway for irrigation assigned priority 2. Then, Bulbula irrigation demand sites were assigned priority 3, Langano tributary and lake water use received priority 4 and 5, respectively and we assigned priority 6 for Abiyata soda ash factory. In terms of water use domestic water supply receives the highest priority than irrigation. Hence, Ziway and Bulbula town's water supply demand sites were assigned the highest priority.

5.4.4 Water Resources Development Pathway

In this study, three water resources development pathways were considered based on the current and future stages of the basin water resources development. Three development pathways were built considering 10-year development period. These pathways include current development (2009-2018), short term development (2019-2028) and long term development (2029-2038) pathways.

The pathways are constructed based on the information from Rift Valley Lakes basin master plan, feasibility studies, design documents and consultation of stakeholders during the field survey. The current account year was specified using the water abstraction in 2007 (Jansen et al., 2007). This period was selected to due detail water abstraction survey during master plan studies. Table 5.3 shows the summary and descriptions of each water resources development pathways. The variations of domestic water withdrawal with respect to time were based on the population growth rate of 2.9% of the two towns.

Table 5.3. Summary of the water resources development pathways for this study

Development Pathways	Time Frame	Descriptions
Base year	2007	The 2007 water use rate withdrawing water for 5,534 ha of irrigated lands and 15,000 ton of Abiyata soda ash
Current Development	2009-2018	The 2007 water use rate plus additional irrigation expansion up to 3,150.5 ha (total irrigated area=8,684.5 ha) and 25,000 ton of Abiyata soda ash industrial expansion.
Short term Development	2019-2028	Current development plus additional expansion of up to 4,195.5 ha of irrigated lands from schemes that are expected to be operational for short period of time (total irrigated area=12,880 ha) and 50,000 ton soda ash production.
Long term Development	2029-2038	Short term development plus all full potential scheme development to be operational in the study area with an additional expansion of 6,390 ha of irrigated area (total irrigated area=18,919 ha) and 75,000 ton soda ash.

Note: Domestic water demand for Ziway, Bulbula town and environmental flow at Bulbula River for downstream Abiyata also considered in each development pathway.

5.4.5 Impact of water resources development

After determining the amount of water demand for all development pathways, the water level simulation was performed to quantify the impact of water resources development on Lake water level. For this, we first estimated the monthly water balance of the three lakes under natural condition for a period of 15 years (1986-2000) which served as a baseline for comparison of changes by each development pathways. This period was selected because it represents the natural water level regime with minimum water withdrawal from lake and its tributaries. Furthermore, it represents the period before construction of outflow regulator at Bulbula River. Besides, Goshime et al. (2019) indicated significant water abstraction for the period 2001-2014, hence the period from 1986-2000 assumed the natural water level regime. Therefore, the impact of each development pathway could be compared with the natural water level regime of the lake. Then, the impact of the three development pathways was evaluated using water balance modelling approach to quantify the impact of existing and future water demand on lake level, volume and surface area. Furthermore, water scarcity threshold levels were established for the three lakes to evaluate the impact of water resources development on the situation of water availability on the lake.

5.5 Results and Discussion

5.5.1 Streamflow simulation

The HBV model was calibrated using daily discharge data for a period of 1986-1991 and validated from 1996-1998 at 6 (six) gauge stations in the study area. The rainfall input data was obtained from CHIRP satellite estimate bias-corrected using rain gauge data. Figure 5.3 shows a comparison of the simulated and observed streamflow hydrograph for the calibration period (1986-1991) at Meki and Rinzaf gauging stations with drains to the lake from the western side. The model reasonably captured the pattern of the observed hydrograph (including recession and rising limbs) of both catchments. However, it did not satisfactorily capture most of the observed peak flows especially for Rinzaf gauge station. The agreement between the simulated and observed streamflow was better for Meki catchments than Rinzaf catchments. The latter has relatively smaller watershed size and hence was not easy to model the high streamflow variability and flashy peaks. Streamflow was observed only two times per day which limits the accuracy of the observed hydrograph to provide an accurate data on streamflow volume. The effect of observation interval becomes significant for small catchments where the streamflow can be highly variable.

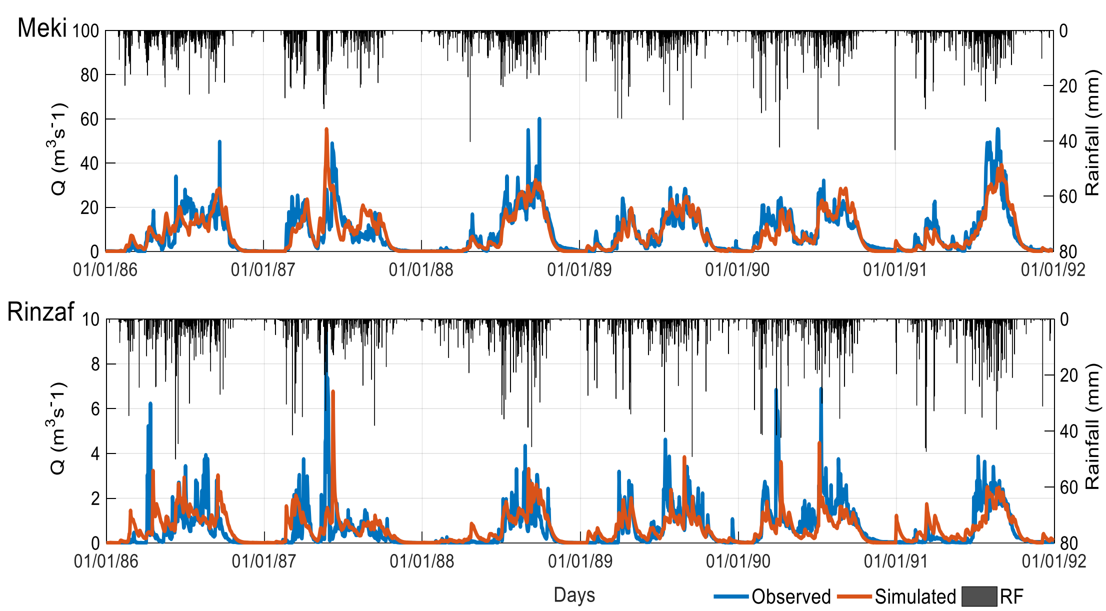


Figure 5.3.The simulated and observed hydrographs of Meki and Rinzaf catchments for the calibration period (1986-1991) which both flowing from western direction

Figure 5.4 shows the simulated and observed streamflow for the calibration period (1986-1991) at Katar, Chuifa, Sagure and Timala gauge stations which drain in to the lake from the eastern plateaus. HBV well captured the overall pattern of the observed hydrograph in most of the gauge stations. However, the rapidly varying part of the observed hydrograph was not satisfactorily captured some of the observed small flow magnitudes. The model better captured the observed flow for the Katar catchment which has highest streamflow. However, for smaller tributary some observed peaks were not satisfactory captured for instance for Fite and Chuifa river gauge stations.

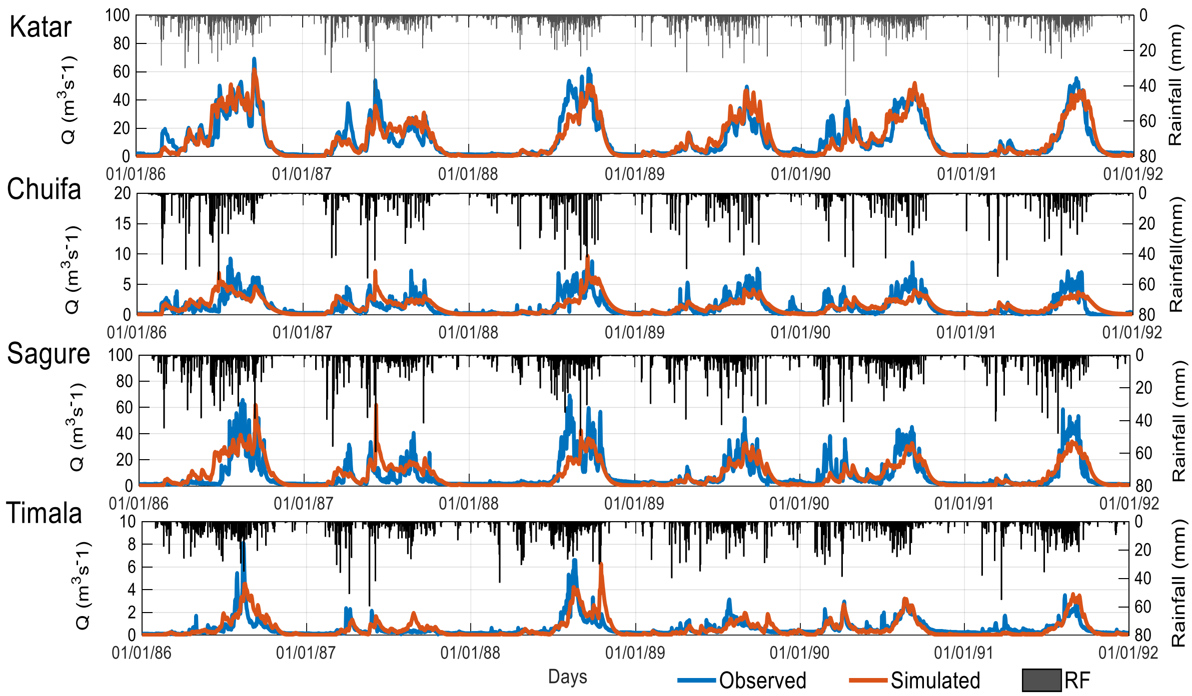


Figure 5.4. The simulated and observed hydrographs of Katar, Chuifa, Sagure and Timala catchments for the calibration period (1986-1991) which all flowing from eastern direction

Table 5.4 presents the calibrated values of the model parameters and objectives functions. The calibrated values of Alfa, K4 and CFLUX do not significantly vary across the catchments (Table 5.4). The parameter K4 distributes the estimated discharge in time, which influences the shape of the hydrographs. Alfa is used in order to fit the higher peaks into the hydrograph. The most sensitive parameter such as FC, BETA, Khq and LP values shows variation with the catchments (Table 5.4). This typically suggests the catchments variation in their storage capacity and catchment area. The higher Khq results in higher peaks and a more dynamic response in the hydrograph. We also kept the PERC values larger to capture the dry season flow for smaller catchments. Overall, the slight variation of the calibrated model parameter among the gauge stations might contribute the disagreement between the simulated and observed hydrograph with the catchments.

The HBV model performance when evaluated using objective functions revealed satisfactory performance for most of the gauge stations during calibration periods. The results indicate that the model performance for Meki and Katar gauge stations better than other minor tributaries with NSE greater than 0.7%, RVE of less than 5% and a R^2 greater than 0.7. When evaluated for an independent validation period the model performance deteriorated for most river gauges but with noticeable magnitude especially for small catchments such as Rinzaf and Timala. This phenomenon mostly related to the quality of observed streamflow data for these two stations.

Table 5.4. Calibrated values of model parameters for considered gauged catchments and objective functions

Parameter	Meki	Rinzaf	Katar	Chuifa	Sagure	Timala
FC	860	840	820	860	830	870
BETA	1.96	1.2	3.05	2.2	2.8	3.15
LP	0.5	0.6	0.7	0.9	0.52	0.4
K4	0.1	0.1	0.1	0.05	0.08	0.1
Khq	0.1	0.08	0.12	0.04	0.20	0.15
Alfa	0.8	0.5	1.1	1.0	1.2	1.05
CFLUX	0.01	0.02	0.005	0.002	0.002	0.002
PERC	1.15	5.8	2.75	5.5	3.2	5.5
Calibration						
NSE	0.71	0.35	0.80	0.52	0.57	0.50
RVE	-1.47	1.51	-1.28	-2.08	-0.13	-1.04
R^2	0.73	0.38	0.82	0.53	0.58	0.58
Validation						
NSE	0.64	0.30	0.74	0.48	0.50	0.35
RVE	3.84	-14.3	3.04	-12.2	-14.8	-2.47
R^2	0.65	0.32	0.75	0.50	0.54	0.38

5.5.2 Water demand and development pathway

Figure 5.5 shows existing and future demand sites for water demand in the subbasin. The water demands which are considered in this study include irrigation, domestic, industrial and environmental flow requirement for downstream. Irrigation demands were from both smallholder and modern to large irrigation schemes. Figure 5.5 shows an intensive water abstraction directly from Lake Ziway in the three districts (Adami Tulu, Dugda and Ziway Dugda). As expected, water abstraction from the lake was through pump diversion. The canal diversions are situated at Katar, Meki and Langano tributary rivers. Particularly, the canal diversions are very dense along the most downstream stretch of Meki and Katar Rivers.

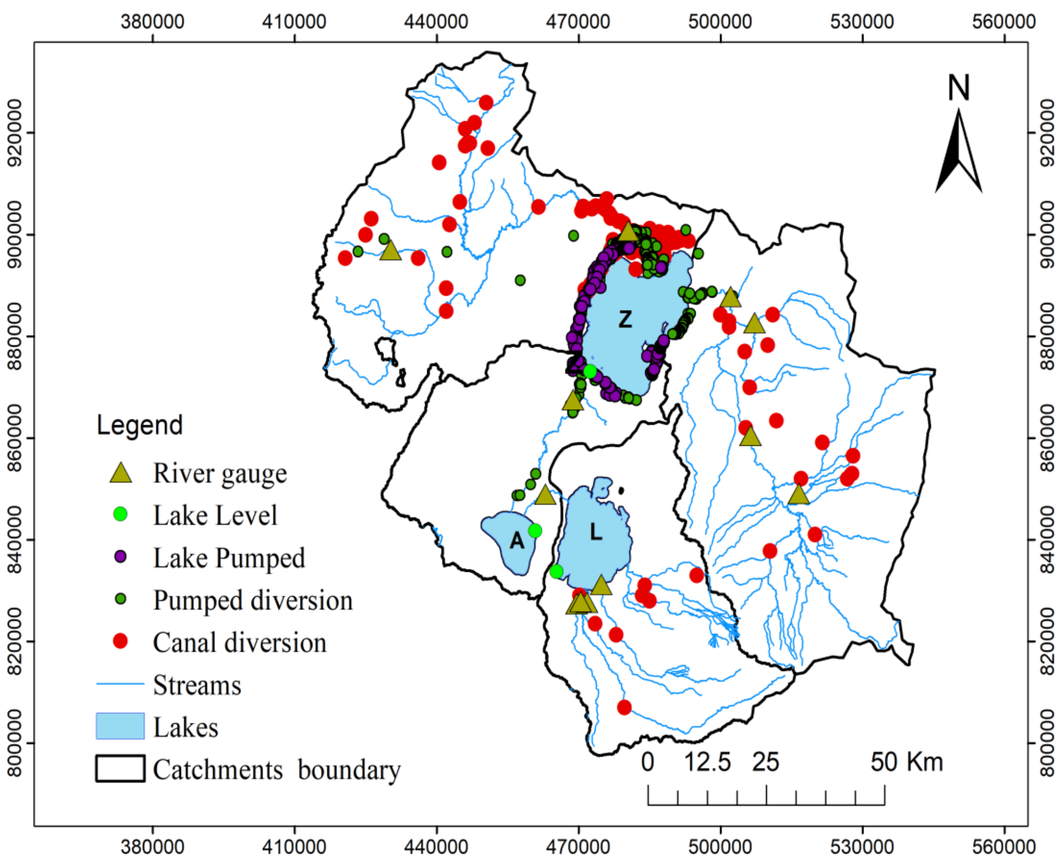


Figure 5.5. Water resources demand sites in the Central Rift valley lakes basin (letter Z, L and A represents Lake Ziway, Langano and Abiyata, respectively)

Table 5.5 shows the major demand sites and their corresponding irrigated area and demand for three water resources development pathways. The surface water system of the study area for the base year (2007) was supplying water to a total irrigated area of 5,534 ha. The Katar, Meki and Bulbula rivers irrigates the largest lands in the sub basin, respectively. In addition, the annual activity level also includes water demand for soda ash, domestic and environmental flow at Bulbula River for downstream Lake Abiyata. A larger irrigated area is dominated at upstream

Lake Ziway mainly at three administrative woredas and at contributing major tributaries. This is mainly due to the presence of intensive smallholder irrigated farmers, flower farms and modern irrigation schemes especially around Lake Ziway.

Compared to the base year, we note that the irrigated areas increased by 36, 57 and 71% for the current, short term and long term development pathways, respectively. The largest increase in irrigated areas and water demands were exist during long term development pathways. We note that irrigation water abstraction is the largest water user activity in the sub basin. The domestic water demand and environmental flow remains almost nearly the same for the three development pathways.

Table 5.5. Summary of water resources development pathways in CRV lakes basin. Irrigation water demand is shown in ha whereas other demands in Mm^3.

S.No	Water resources development	Water source	Development Pathways			
			Base year (2007)	Current (2009-2018)	Short term (2019-2028)	Long term (2029-2038)
I	**Size of Irrigated area (ha)**					
1	Meki Irrigation	Meki	645	918	1330	2206
2	Rinzaf Irrigation	Rinzaf	80	230	302	372
3	Katar Irrigation	Katar	781	1490	1965	3110
4	Chuifa Irrigation	Chuifa	65	123	223	423
5	Sagure Irrigation	Fite	212	750	1000	1500
6	Timala Irrigation	Sagure	335	850	1865	2200
7	Ziway flower farm	Ziway	500	640	944	1292
8	Lake Ziway Irrigation	Ziway	863	1144.5	1756	2958
9	Meki-Ziway Pump Irrigation	Ziway	128	216	400	750
10	Bulbula pumped Irrigation	Bulbula	1095	1235	1683	2000
11	Langano Tributary Irrigation	Gedemso	800	1040	1352	2028
12	Lake Langano Irrigation	Langano	30	48	60	80
II	**Domestic water demand (Mm^3)**					
1	Ziway town Ws	Ziway	1.26	1.41	1.45	1.49
2	Bulbula town WS	Bulbula	0.15	0.16	0.17	0.18
III	**Industrial water demand (Mm^3)**					
1	Lake Abiyata Soda Ash	Abiyata	3.63	7.06	7.5	10.5
IV	**Environmental Flow (Mm^3)**					
1	Abiyata minimum flow	Bulbula	3.62	3.62	3.62	3.62

Table 5.6 shows the monthly water demand for current development (2009-2018) for water resources schemes in the sub basin. The water demand for each month of the years between 2009-2018 was estimated for irrigation area obtained from survey and consultation. This estimate demand time series was then used as input to WEAP. The annual water demand of the sub-basin for current development was estimated to be about 102.1 Mm^3. We note that water user from Lake Ziway are the highest water users from the lake at three districts (Adami Tulu, Dugda and Ziway Dugda) including flower and domestic water use. The water use from Bulbula, Katar and Meki are the highest water users from the rivers. Overall, the water withdrawal from the rivers is larger than the lake. Water withdrawal from Katar River was larger than Meki due to larger irrigated area and river gauge stations.

Table 5.6. Mean monthly water demand for current development from 2009-2018 (all unit in Mm^3).

Demand sites	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Annual
Meki Irrigation	1.14	1.05	1.64	0.99	1.02	0.52	0.03	0.00	0.22	0.82	1.23	1.22	9.88
Rinzaf Irrigation	0.20	0.11	0.13	0.17	0.19	0.04	0.00	0.00	0.04	0.21	0.32	0.29	1.69
Katar Irrigation	1.83	1.86	1.79	1.40	1.39	0.66	0.08	0.00	0.10	1.20	1.95	2.01	14.28
Chuifa Irrigation	0.13	0.09	0.15	0.13	0.03	0.00	0.00	0.00	0.01	0.12	0.18	0.17	1.03
Sagure Irrigation	0.65	0.43	0.49	0.52	0.49	0.14	0.00	0.00	0.02	0.56	0.93	0.89	5.13
Timala Irrigation	0.71	0.44	0.52	0.48	0.47	0.12	0.00	0.00	0.05	0.47	0.94	0.95	5.16
Flower farms	0.84	0.78	0.84	0.82	0.84	0.82	0.84	0.83	0.82	0.84	0.82	0.84	9.94
Lake Ziway	2.03	1.73	2.03	1.88	2.03	0.90	0.99	0.99	1.89	2.03	1.88	2.03	20.42
Meki-Ziway Pump	0.53	0.48	0.53	0.52	0.54	0.23	0.23	0.22	0.50	0.54	0.53	0.54	5.38
Bulbula Irrigation	1.00	1.30	1.40	1.55	1.44	0.67	0.36	0.00	0.41	1.25	1.80	1.67	12.85
Langano Tributary	1.69	1.05	1.34	1.21	1.09	0.21	0.08	0.00	0.21	0.71	1.48	1.53	10.61
Lake Langano	0.08	0.08	0.06	0.06	0.05	0.01	0.00	0.00	0.00	0.02	0.05	0.07	0.50
Ziway WS	0.12	0.11	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	1.41
Bulbula WS	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.16
Soda Ash	0.31	0.28	0.31	0.30	0.31	0.30	0.30	0.31	0.30	0.31	0.30	0.31	3.63
Sum	11.2	9.60	11.3	10.2	10.1	4.84	3.06	2.50	4.73	9.31	12.54	12.6	102.1

Figure 5.6 shows the summary of annual water withdrawal from the main water sources in the sub basin for the base year (2007). The figure indicates that Lake Ziway is the largest water users in the sub basin as compared to other water sources. Katar and Bulbula water sources withdraw water second and third, respectively next to Lake Ziway. This is mainly related to largest irrigated area at Lake Ziway, Katar and Bulbula, respectively during this year.

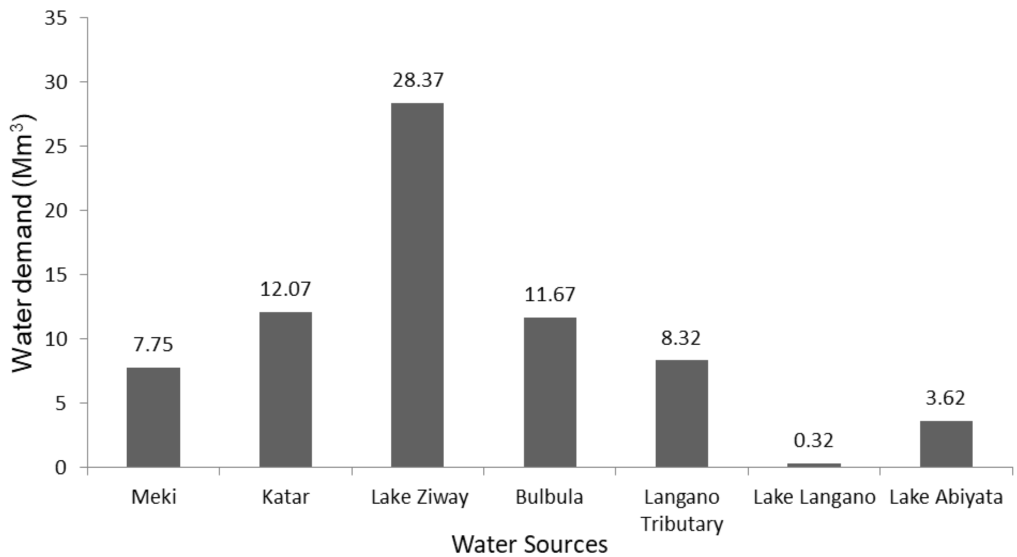


Figure 5.6. Annual water withdrawal for the base year (2007) from the main water sources in the sub basin

The summary of total annual water demand, supply and unmet demand for the three development pathways is presented in Table 5.7. The annual water demand for short-term development pathway (2019-2028) will be 149.4 Mm^3, which corresponds to 46% increase as compared to the demand under current development. If all the planned long-term water resources development will be fully implemented, the annual water demand amount will increase by 2.2 folds (i.e. 223 Mm^3) as compared to the current development. This is mainly because of the irrigated area increase by two folds during this period. The annual water supply does not match the demand for all the development pathways. Table 5.7 also indicated that unmet demand will increase in the long-term development pathway approximately by three folds (i.e. 46.5 Mm^3) from the current development (Table 5.7).

Table 5.7. Annual water demand and supply delivered for three development pathways (Mm^3)

Pathways	Water Demand	Supply Delivered	Unmet Demand
Current Development	102.1	86.83	15.27
Short term Development	149.41	122.03	27.37
Long term Development	223.02	176.56	46.46

Table 5.8 presents the water demand, supply delivered and unmet demand across the watersheds for the three development pathways at the major water sources in the study area. The table illustrates there is unmet demand for all development pathways from the river supply sources. Whereas there is no unmet demand from Lake Ziway, Langano and Abiyata for all development pathways as excpecetd due the presence of water in the lake to meet the demand required all the time. The unmet demand was larger for long term development for all demand sites which has unmet demand. We note that Katar, Langano tributary and Meki irrigation demand sites are the most unmet, respectively. Eventhough, we assigned the highest priority to the most upstream demand sites, larger unmet demand was revealed at upstream demand sites than downstream. The water demand in Katar watershed is the most unmet. This is mainly due to larger water demand and irrigated areas in Katar watersheds. The annual water demand of Katar watershed including all minor tributary demand sites is unmet by about 27.7 Mm^3 for long term development.

The percentage of unmet demand was aslo higher for demand sites with largest water demand. For long term development, we obtained a maximum of up to 50% of Katar irrigation schemes, 44% of Langano tributary and 33% of Meki irrigation schemes was unmet as compared to total water demand (Table 5.8). The results indicate that the percentage of unmet demand was higher for larger water demand sites. Overall, this study indicates that there is unmet demand in the entire sub-basin for river water supply schemes especially larger for long term development plans to be implemented.

Table 5.8. Summary of spatial annual unmet demands across watersheds for the three pathways

S.no	Watershed	Pathways	Volume (Mm^3) Demand	Supply Delivered	Unmet Demand	% of unmet demand
1	Meki	Current	11.57	9.03	2.54	22
		Short term	16.23	12.05	4.18	26
		Long term	25.61	17.49	8.12	32
2	Katar	Current	25.66	16.99	8.67	34
		Short term	38.45	21.43	17.02	44
		Long term	55.94	28.22	27.72	50
3	Lake Ziway	Current	37.13	37.13	0.00	0
		Short term	56.13	56.13	0.00	0
		Long term	89.74	89.74	0.00	0
4	Bulbula	Current	13.01	11.91	1.10	8
		Short term	17.32	15.84	1.48	9
		Long term	20.38	18.59	1.79	9
5	Langano	Current	11.11	8.14	2.97	27
		Short term	14.21	9.52	4.69	33
		Long term	20.85	12.02	8.83	42
6	Lake Abiyata	Current	3.63	3.63	0.00	0
		Short term	7.06	7.06	0.00	0
		Long term	10.50	10.50	0.00	0

Figure 5.7 presents the summary of monthly temporal unmet demand for the three development pathways. The result indicates that the demand for all development pathways will be fully met for 3 months which stretch from July-September, which corresponds to the main rainy season. During the remaining seasons, there is varying amount of unmet demand across all pathways. The unmet demand for November to February is noticeable mainly due to this period is the driest season. The unmet demand in the small rainy season (March-May) is relatively smaller compared to the dry season.

The total annual unmet demand under the current development was about 15.3 Mm^3, which accounts 6.7 % of the total water demand. This amount increased by a factor of 1.8 (i.e. 27.4 Mm^3) for the short-term development. At the end of the long-term development pathway, the annual unmet water demand amount will increase by three folds (i.e. 46.5 Mm^3) as compared to the current development. This is due to most of the demand sites are unmet at larger amount during this development pathways.

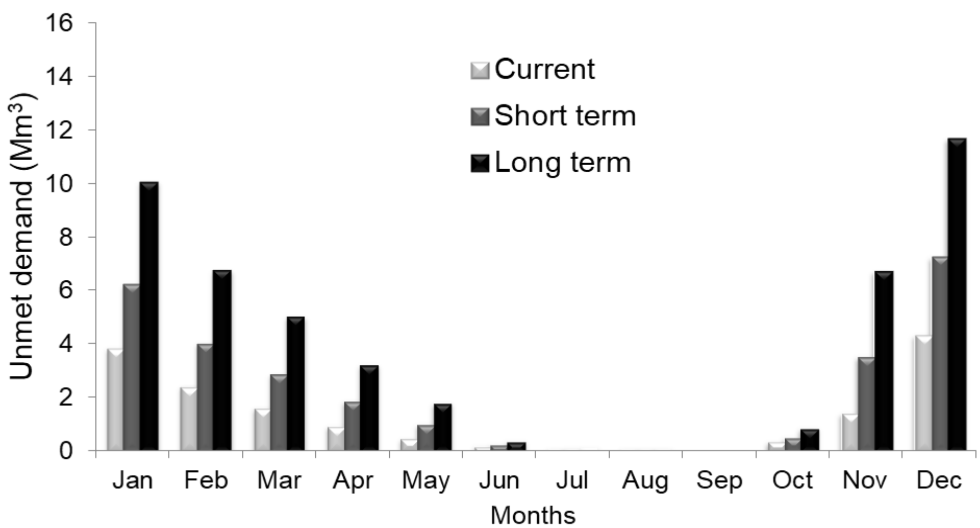


Figure 5.7. Monthly temporal unmet demands for the three development pathways

5.5.3 Impact of water resources development

The results of annual water balance components from natural condition for the period 1986-2000 for the three interconnected lakes are shown in Table 5.9. The results of our estimate of the annual water balance components are comparable with most of other previous (e.g. Vallet-Coulomb et al., 2001; Ayenew, 2004; Legesse and Ayenew, 2006; Jansen et al., 2007; Desta et al., 2017). The results indicate that lake rainfall, river inflow and evaporation are the major components of the water balance of the CRV lakes. Note that the amount of water abstraction for Lake Ziway was significantly larger than Lake Langano and Abiyata.

Table 5.9. Estimated mean annual water balance of CRV lakes from 1986-2000 (all unit in Mm^3)

	Water Inflow			Water Outflow		Water Abstraction	
Lake	R_i	Q_{in}	Q_{un}	Evap	Q_{out}	Q_{abs}	ΔV
Ziway	338.4	613.8	80.8	832.1	170.9	37.2	-7.2
Langano	195.5	231.9	27.2	466.6	52.9	11.1	-76
Abiyata	114.9	219.5	-	328	-	15.0	-8.6

Note: R_i, rainfall on the lake surface; Q_{in}, river inflow; Q_{un}, inflow from ungauged catchment; Evap, evaporation from the lake surfaces, and Q_{out}, lake outflow in the river outlet.

Figure 5.8 shows the long-term water level of three CRV lakes for the period 1986-2014. We note that the water level fluctuations of the three lakes exhibited similar temporal trend with a noticeable reduction during recent periods (Figure 5.8). Lake Abiyata exhibited a visible water level reduction with its reduction coincides with low water level record in Lake Ziway. In addition, the water level reduction also in line with intensive water abstraction from Lake Ziway and production of Soda Ash from the lake itself. The range of lake level variations in Lake Ziway is slightly lower than Lake Abiyata. This is mainly due to wide and shallow lake with surface outflow doesn't exhibit a large variation of seasonal lake level changes (Ayenew and Becht, 2008).

In contrast, Lake Langano which has no direct link with Lake Ziway experienced small seasonal and inter-annual water level variations compared to other lakes (Ayenew, 2001; Vilalta, 2010).This is phenomenon is mainly related to relatively smaller irrigation water abstraction around the lake and its tributaries. The water level change after 2001 was significant, which can be attributed to both natural and human-induced water abstraction. The lowest water level recorded ranging from 2003 to 2007, which is typical a drought years in much part of Ethiopia and intensive water abstraction directly from the lakes and their catchments. As a result of low water level, outflow of upstream Lake Ziway is regulated then after by a barrage constructed at Bulbula River near Lake Ziway.

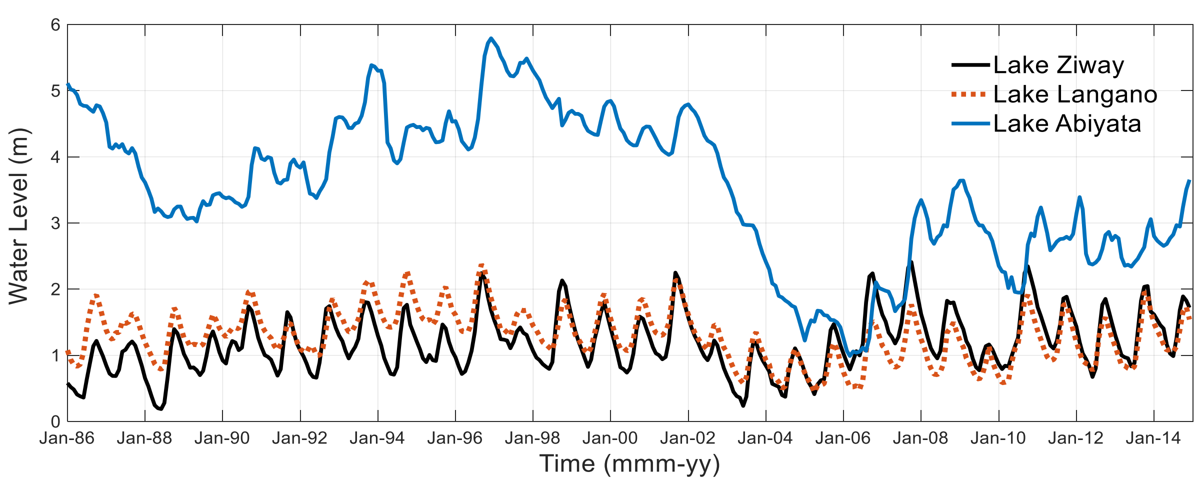


Figure 5.8. Long- term water level fluctuation of CRV lakes for the period 1986-2014

Figure 5.9 presents the result of lake level simulation for baseline natural condition and the three development pathways. The results indicate that the simulated lake level for the three development pathways was lower than the natural water level over the simulation periods. Lake Ziway exhibited water level decline as a result of water resources development from feeding rivers as well as direct pumping from the lake. We note that a maximum of up to 3 m water level decline occasionally will occur during long-term development. In terms of threshold water level, the water level of Lake Ziway drops below the water scarcity level for most of the development pathways.

In contrast, Lake Langano indicated lower change with the lake water level unlikely to drop below the water scarcity level most of the time except during the lowest water level periods. This phenomenon is related to less irrigation water diversions from its tributary rivers. The water level fluctuations in Lake Abiyata follow the same trend as observed in Lake Ziway. The results show that the lake level significantly drops below the water scarcity level for all development pathways as well as for natural condition. We found up to a maximum of 4.2 m water level decline will occur in Lake Abiyata as a result of water resources development. The finding of this study was in agreement with that reported in (Ayenew, 2007; Seyoum et al., 2015).

Overall, the results of this study show that the influence of water resources development on the water levels is substantial. There is large difference between the water level under the current development and baseline period. The shift from current to short-term development will exacerbates the drop in the water level. However, the lake water level indicated the largest decline when the development pathway shifted from the short-term to long term development. During this development, the water levels significantly drop below the water scarcity level for most of the time for Lake Ziway and Abiyata. This likely would have a significant impact on shipping, fishing and ecology of the lake and might cease water abstraction from the lake.

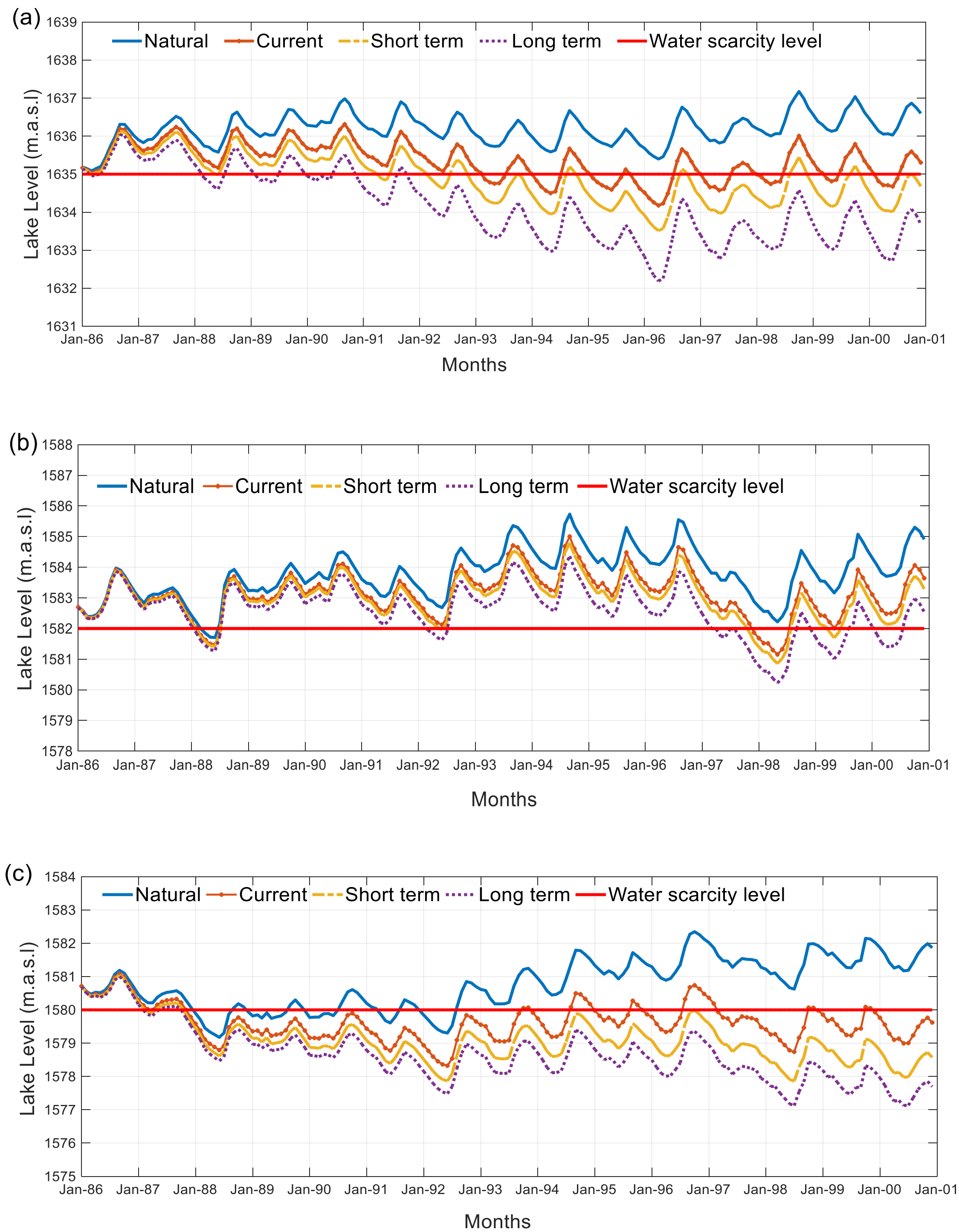


Figure 5.9. Comparison of the natural and simulated lake levels for the three development pathway (a) Lake Ziway (b) Lake Langano (c) Lake Abiyata

To further evaluate the impact of Lake Ziway on that of downstream Lake Abiyata an average water level change of each year of the two lakes from 1986-2000 with the first year as a reference (Figure 5.10). The figure illustrates there is direct relationship on the water level change of Lake Ziway and Abiyata. For instance, a 0.5 m annnual reduction in water level of Lake Ziway will result 1.8 m drop in Lake Abiyata. Furthermore, at 2000 for 3 m reduction in Lake Ziway water level revealed 4.5 m reduction in water level of Lake Abiyata. Therefore, any water level decline in Lake Ziway will result a greater decline in downstream Lake Abiyata. Similar findings were reported in (Vallet-Coulomb et al., 2001; Seyoum et al., 2015) studies.

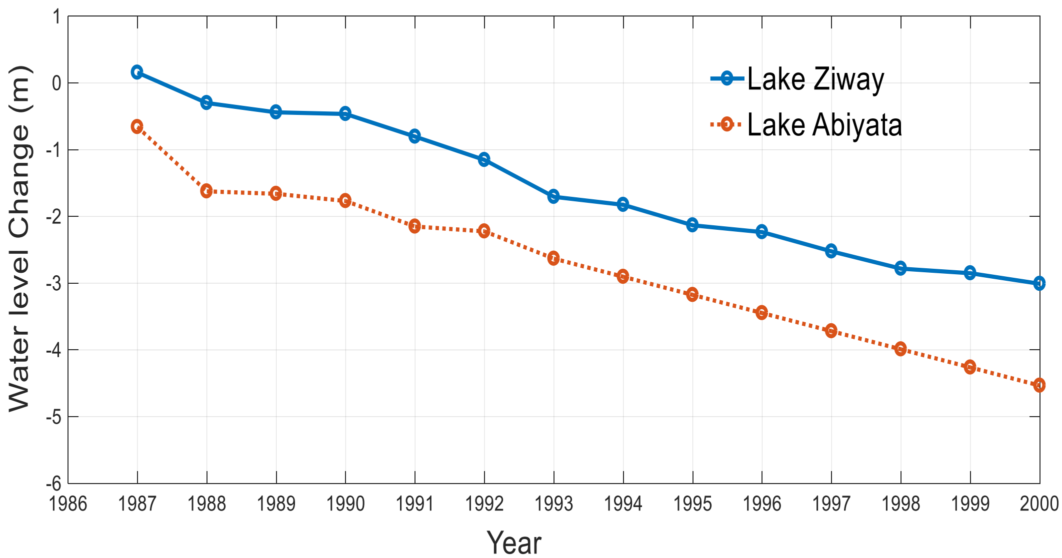


Figure 5.10. Annual water level change of Lake Ziway and Abiyata from 1987-2000 with 1986 as a reference

Seyoum et al. (2015) reported that approximately up to 4.5 m reduction in water level of Lake Abiyata was observed between 1986 and 2006 due to human influences. In this study, the water level reduction in downstream Lake Abiyata was significant. The possible cause of water level reduction of Lake Abiyata is related to: First, since Abiyata Lake is terminal lake without surface outflow it is more vulnerable to water balance changes. The water budget of Lake Abiyata depends on season rainfall, river inflow mainly from Bulbula and Horakelo Rivers, which are the largest inflowing river into the lake. Hence, any intervention either from Lake Ziway or Bulbula River contributes to the water budget reduction of Lake Abiyata. Secondly, intensive irrigation water abstraction is ongoing at upstream reach of Lake Ziway and its tributaries, and the Bulbula rivers for the production of horticulture, vegetables, and flowers. As a result, the water level of Lake Ziway and water flow into Bulbula River is reduced. This consequently will result significant water level decline of Lake Abiyata.

In addition, Abiyata soda ash could be the other possible anthropogenic causes for the water level reduction. Since the water withdrawal from the lake for soda ash production does not return to the lake, the shore of Lake Abiyata has receded each year (personal communication). Fetahi (2016) reported that Lake Abiyata shore run away 3 km from its pumping station and soda ash production has reduced because of the loss of water in Lake Abiyata. Therefore, this study suggests appropriate measures should be taken by decision makers and any concerned stakeholders for water management of the CRV lakes.

In this study, the water availability was simulated for current development and constantly used for the future development pathways. However, the future water availability might change due to the effect of future global climate changes. Therefore, for future water resources planning and management of the lake and its tributaries, the projected impacts of climate change using comparative advantage of global and regional climate model need to be considered.

5.6 Conclusions

In this study, we assessed existing and future water demand and the likely impact of water resources development on the water balance of CRV lakes and their contributing catchments. This study is unique as it considers the spatial and temporal water resources developments of the sub basin using a combination of HBV rainfall-runoff, water balance and water resources planning models from ground observation, satellite and field survey datasets. The Water Evaluation and Planning (WEAP) model was used to assess existing and future water demand and thereby to evaluate the likely impact of three water resources development pathways on the water balance of Lake Ziwa, Langano and Abiyata. The water demand for irrigation, domestic, industrial and environmental were estimated using water abstraction survey, CROPWAT and, literatures reviews. The HBV rainfall-runoff model was used to simulate streamflow at six (6) river gauge stations. The simulated streamflow from HBV hydrological model better captured the observed hydrographs for most of the gauge stations except deterioration of the objective functions for Rinzaf and Sagure stations during validation period. This phenomenon partly related to the quality of the observed streamflow data at both stations.

The WEAP simulation results revealed that for current development 102.1 Mm^3 of water demand will be diverted for irrigation, domestic and industrial purpose. This amount increased to 223 Mm^3 if long term water resources development is implemented. These will results unmet demand at various spatial and temporal scales. The demand sites at Katar, Meki and Langano watersheds are the most unmet demands for all development pathways, respectively. Temporally, the most unmet demand is from November-February, which is typical the main dry season.

The simulated lake level for long-term water resources development pathways yields a reduction on average water level by 1.87, 0.97 and 2.1 m for Lake Ziway, Langano and Abiyata, respectively. The study indicated that any water resources development on upstream catchments will result significant impact on the downstream Lake Abiyata. Overall, our results indicate that existing and future water demand around the lake and its feeding rivers has substantial impact on the water balance of the three interconnected lakes. Hence, our study suggests integrated water resources management among all stakeholders towards achieving sustainable water abstraction management around the lake and its tributaries. Future studies should consider the future projected climate change using comparative advantage of various ensemble climate models to further explore the report changes.

References

Adgolign, T. B., Rao, G. V. R. S., Abbulu, Y. (2015). WEAP modeling of surface water resources allocation in Didessa Sub-Basin, West Ethiopia. *Sustainable Water Resources Management*, *2*(1), 55–70.

Alemayehu, T., Furi, W., & Legesse, D. (2007). Impact of water overexploitation on highland lakes of eastern Ethiopia. *Environmental Geology*, 8.

Alemayehu, T; McCartney, Matthew; Kebede, S. (2010). Modelling to evaluate the water resource implications of planned infrastructure development in the Lake Tana sub-basin, Ethiopia. *Ecohydrology and Hydrobiology*, 10: 211–221.

Allen, R. G., Pereira, L. S., Raes, D., Smith, M. (1998). Crop evapotranspiration-Guidelines for computing crop water requirements. *FAO Irrigation and drainage paper* 56, *Rome*, Italy, 9, *300*.

Arranz, R., McCartney, M. (2007). Application of the water evaluation and planning (WEAP) model to assess future water demands and resources in the Olifants catchment, South Africa. *IWMI Working Paper, 116. Colombo, Sri Lanka: International Water Management Institute.*

Awulachew, S. B., Yilma, A. D., Loulseged, M., Loiskandl, W., Ayana, M., Alamirew, T. (2007). *Water resources and irrigation development in Ethiopia*, Vol. 123. International Water Management Institute(IWMI).

Ayenew, T. (1998). The hydrogeological system of the Lake District Basin, Central Main Ethiopian Rift. PhD Thesis, Free University of Amsterdam. The Netherlands.

Ayenew, T. (2004). Environmental implications of changes in the levels of lakes in the Ethiopian Rift since 1970. *Regional Environmental Change*, *4*(4), 192-204.

Ayenew, T. (2007). Water management problems in the Ethiopian rift: Challenges for development. *Journal of African Earth Sciences*, *48*(2/3), 222–236.

Ayenew,T and Becht, R.(2008) . Comparative assessment of the water balance and hydrology of selected Ethiopian and Kenyan Rift Lakes. Lakes & Reservoirs: Research and Management, 13: 181–196.

Belete, M., Diekkrüger, B., Roehrig, J. (2016). Characterization of Water Level Variability of the Main Ethiopian Rift Valley Lakes. *Hydrology*, *3*(1), 1.

Desta, H., Lemma, B., Gebremariam, E. (2017). Identifying sustainability challenges on land and water uses: The case of Lake Ziway watershed, Ethiopia. *Applied Geography*, *88*, 130–143.

Fetahi, T. (2016). Greening a Tropical Abijata-Shala Lakes National Park, Ethiopia- A Review. *Journal of Ecosytem and Ecography*, 6: 179.

Goshime, D. W., Absi, R., Ledésert, B. (2019a). Evaluation and Bias Correction of CHIRP Rainfall Estimate for Rainfall-Runoff Simulation over Lake Ziway Watershed, Ethiopia. *Hydrology*, *6*(3), 68.

Goshime, D. W., Absi, R., Ledésert, B., Dufour, F.N., Haile, A.T. (2019b). Impact of water abstraction on the water level of Lake Ziway, Ethiopia. *WIT Transactions on Ecology and the Environment*, Vol 239. *5th International Conference on Water and Society*, Valencia, Spain.

Gupta, H. V., Sorooshian, S., Yapo, P. O. (1999). Status of automatic calibration for hydrologic models: Comparison with multi-level expert calibration. *Journal of Hydrologic Engineering, 4(2), 135-143.*

Hassan, D, Rais, M. N, Ahmed, W, Bano, R., Burian, S.J, Ijaz, M.W, Bhatti, F.A. (2019). Future water demand modeling using water evaluation and planning: a case study of the Indus Basin in Pakistan. *Sustainable Water Resources Management*.

Hengsdijk, H., Jansen, H. (2006). Agricultural development in the Central Ethiopian Rift valley: A desk-study on water-related issues and knowledge to support a policy dialogue. *Plant Research International B.V,* Wageningen, 1–25.

Jansen, H. C., Hengsdijk, H., Legesse, D., Ayenew, T., Hellegers, P., Spliethoff, P. C. (2007). Land and water resources assessment in the Ethiopian Central Rift Valley: Project: Ecosystems for water, food and economic development in the Ethiopian Central Rift Valley. *Alterra report, 1587*. Wageningen, The Netherlands.

Johansson, B. (2013). *IHMS Integrated Hydrological Modelling System Manual*. 144.

Legesse, D., Ayenew, T. (2006). Effect of improper water and land resource utilization on the central Main Ethiopian Rift lakes. *Quaternary International*, *148*(1), 8–18.

Legesse, D., Vallet-Coulomb, C., Gasse, F. (2003). Hydrological response of a catchment to climate and land use changes in Tropical Africa: Case study South Central Ethiopia. *Journal of Hydrology*, *275*(1–2), 67–85.

Legesse, D., Vallet-Coulomb, C., Gasse, F. (2004). Analysis of the hydrological response of a tropical terminal lake, Lake Abiyata(Main Ethiopian Rift Valley) to changes in climate and human activities. *Hydrological Processes*, *18*(3), 487-504.

Lindström, G., Johansson, B., Persson, M., Gardelin, M., Bergström, S. (1997). Development and test of the distributed HBV-96 hydrological model. *Journal of Hydrology*, *201*(1–4), 272–288.

McCartney M. P., Girma, M. M. (2012). Evaluating the downstream implications of planned water resource development in the Ethiopian portion of the Blue Nile River. *Water International*, 37(4):362–379.

Mehta, V. K, Haden, V.R, Joyce, B.A, Purkey, D.R, Jackson, L. E. (2013). Irrigation demand and supply, given projections of climate and land-use change, in Yolo County, California. *Agricultural Water Management, 117:70–82*.

Mounir, Z.M, Ma, C.M, & Amadou, I. (2011). Application of water evaluation and planning (WEAP): a model to assess future water demands in the Niger River (In Niger Republic). *Modern Applied Science*, *5(1):38–49*. Published by Canadian Center of Science and Education.

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D., Veith, T. L. (2007). Model evaluation guidelines for systemic quantification of accuracy in watershed simulations. *Transactions of American Society of Agricultural and Biological Engineering*, 50, 885–900.

Nash, J. E., J. V. Sutcliffe. (1970). River flow forecasting through conceptual models: Part 1. A discussion of principles. *Journal of Hydrology*, 10(3): 282-290.

Polpanich, O., Lyon, S.W., Krittasudthacheewa, C., Angela, L., Bush, Eric, K-B. (2017). Modelling impacts of development on water resources in the Huai Sai Bat sub-basin in north-eastern Thailand with a participatory approach. *International Journal of Water Reso urces Development*.

Seyoum, W. M., Milewski, A. M., Durham, M. C. (2015). Understanding the relative impacts of natural processes and human activities on the hydrology of the Central Rift Valley lakes, East Africa: Assessment of Natural and Human Impacts on the Hydrology of Lakes. *Hydrological Processes*, *29*(19), 4312–4324.

Shumet, A. G., Mengistu, K. T. (2016). Assessing the Impact of existing and future water demand on economic and environmental aspects (Case study from Rift Valley Lake Basin.*International Journal Waste Resources*, *6*(2).

Sieber, J., Yates, D., Huber Lee, A.,Purkey, D. (2005). WEAP a demand, priority, and preference driven water planning model: Part 1, model characteristics, *Water International*, 30(4), 487–500.

Tennant, D. L. (1976). Instream flow regimens for fish, wildlife, recreation and related environmental resources, fisheries, 1:4, 6-10.

Vallet-Coulomb, C., Legesse, D., Gasse, F., Travi, Y., Chernet, T. (2001). Lake evaporation estimates in tropical Africa (Lake Ziway, Ethiopia). *Journal of Hydrology*, *245*(1–4), 1–18.

Vilalta, E.R. (2010). Water resources management in the central Rift Valley of Ethiopia. Master’s Thesis, Civil Engineering, Barcelona, Spain.

Yates, D., Purkey, D., Sieber, J., Huber-Lee, A., Galbraith, H. (2005). WEAP21—A Demand-, Priority-, and Preference-Driven Water Planning Model. *Water International*, *30*(4), 501–512.

6 General Discussion

6.1 General

The aim of thesis was to assess the water resources of the CRV lakes basin integrating a high resolution satellite and ground observation rainfall data using model based approach. The study uses Climate Hazards InfraRed Precipitation (CHIRP) satellite rainfall estimate to evaluate rainfall-runoff modelling where simulated runoff served as input to lake water balance and Water Evaluation and Planning (WEAP) model. The study area is the Central Rift valley Lakes basin of Ethiopia with scarce data and poorly gauged region. The water system of the basin is highly interested to water users as it plays a key role in ensuring food security and support export-oriented irrigation activities. However, the contribution of river inflow, water withdrawal, climate and land cover change has not been quantified mainly due to lack of continoues datasets. Therefore, this study aim to provide assessment of water resources of CRV lakes basin based on satellite, ground observation and field survey data.

To address the aim of this study first we evaluated the performance of CHIRP satellite rainfall estimate at various temporal and spatial scales in Chapter 2 which would help as check the applicability of the satellite estimate for streamflow simulation. Then, we applied the bias-corrected CHIRP satellite rainfall estimate for water balance components and water level simulation in Chapter 3. Next, the modelling approach was combined with water abstraction survey data to estimate actual water withdrawal from Lake Ziway and the impact on lake water balance. This part of the study was discussed in Chapter 4. Finally, the thesis further extend the application of WEAP model to assess existing and future water demand using water abstraction survey, CROPWAT model and literature review to evaluate the likely impact of three water resources development pathways on the water level of Lake Ziway, Langano and Abiyata in Chapter 5. This part of the study uses the output of the hydrological model (Chapter 2), water balance components (Chapter 3), and water abstraction survey (Chapter 4) around the lake and additional water abstraction survey on upstream Lake Ziway catchments, Bulbula River, Langano tributaries and Lake Abiyata.

6.2 Satellite Rainfall Estimate

In this study, we applied a high-resolution satellite rainfall (0.05^0 x 0.05^0) estimate and available rain gauge stations as a reference for bias correction. The systematic error in the original CHIRP satellite estimate was bias-corrected using a non-linear power bias correction method. Hence, we believe that the results of our study benefited from the use of bias-corrected satellite rainfall on the lake surface and its basin to accurately quantify the water balance components and lake level simulation. The results of performance analysis of CHIRP satellite-only product show that the estimate has systematic bias at various temporal and spatial scales. However, improvements where clearly seen when bias-corrected satellite data replaced the uncorrected estimate for both rainfall and streamflow simulation. The results are discussed in Chapter 2 using different performance indices.

The bias-corrected CHIRP satellite rainfall estimate better captured the pattern of the observed rainfall and the performances of the statistical measures are also significantly improved after bias correction (Table 2.5). However, there are still some mismatches between the satellite and observed rainfall amount outside the bias calibration period (Figure 3.3). This mismatch might be related a number of factors among them: (i) uncertainty related to rain gauge data and (ii) uncertainty related to the satellite estimate and bias-correction algorithms to capture the seasonal rainfall at different period. The earlier case is mainly related to limitation and quality of ground observation datasets in less developed countries like Ethiopia (Ashenfi and Hailu, 2014; Fuka et al., 2014; Gebremicheal et al., 2014). Haile et al. (2013) indicated that rain gauge networks have inadequate coverage and density over upper Blue Nile basin, which represent point scale estimate only. The authors also reported that most of the stations suffer from problem related to data quality and inconsistency. Gebere et al. (2015) reported that rain gauge station installation over most parts of Ethiopia are located mainly in towns and therefore, do not adequately represent the spatial rainfall over the study area. Furthermore, this ground data might also fail to provide timely information and reliable data. We note that similar situation share in the CVR lakes basin.

The second case related to bias of CHIRP satellite rainfall at seasonal time scale and caused by the ineffectiveness of the bias correction algorithm to capture the difference in rainfall characteristics at different period.We note that CHIRP don't capture statsifactorly the rainy season rainfall amount (Goshime et al., 2019). Khandu et al. (2016) indicated that CHIRP satellite performed slightly better in the higher rainfall region over Bhutan. Hence, the above aforementioned factors might contribute slight mismatches between the satellite and observed rainfall amount. Overall, our study shows that bias correction significantly improved the bias of the satellite rainfall data and streamflow simulation even when validated outside the bias correction period. Therefore, in this study we applied to use a high-resolution CHIRP satellite estimate integrating with available ground observation in the basin as a reference for bias correction.

The lake rainfall estimation in this study has benefited from the use of bias-corrected satellite rainfall on the lake surface. Whereas other previous study rely only on rain gauge data avialable at the study area (Vallet-Coulomb et al., 2001; Ayenew, 2004; Jansen et al., 2007; Desta et al., 2017). The Lake evaporation computation also benefited from the air temperature data of stations near the lake especially with the additional two stations (i.e Ogolcho & Arata) considered in the western side of the lake. The river inflow from the gauged catchments was estimated by the use of conceptual rainfall-runoff model using bias-corrected satellite rainfall as input. However, other previous studies simply estimated from river gauge data (Vallet-Coulomb et al., 2001; Ayenew 2004; Jansen et al. 2007). Furthermore, in this study the uncertainties of river inflow to the lake from ungauged catchments were reduced by applying area-ratio methods.

In this study, a distinction was made between the natural and human-induced period to estimate the water balance components. This helps to quantify the magnitude of attribution due to human-influances on the lake water balance compared with the results obtained for the natural condition. Furthermore, it also helps to avoid the difference in the years considered for studying the water balance among different studies for comparison of each component. Refer Table 3.7 for comparison of the water balance components obtained by this study with other previous studies in the area.

The water balance of Lake Ziway for natural condition resulted in a mean lake rainfall depth of 760 mm, open water evaporation depth of 1870 mm, river inflow depth of 1561 mm and outflow discharge depth from the lake of 384 mm. The simulated lake levels were compared with the observed lake levels revealed better agreement for the natural period (1986-2000). However, the simulated lake levels were in disagreement with the observed lake level for the human-induced period from 2001-2014. The result of this study was in agreement with the previous studies of Desta & Lemma (2017) for Lake Ziway and Seyoum et al. (2015) for Lake Abiyata situated within the same climatic zone. Table 6.1 shows comparison of lake water balance components estimated by this study and with that of the other studies for each lake.

Table 6.1. Comparison of water balance components of CRV lakes among different studies in Mm^3

	Inflow			Outflow		Abstraction
Water Balance Components	R	Q_{in}	Q_{ung}	Evap	Q_{out}	Q_{abs}
Lake Ziway						
Vallet-Coulomb et al. (2001)	335	691	50	832	157	-
Ayenew (2004)	323	657	48	890	184	28
Desta et al. (2017)	356	656	-	854	-	41
This study (2019)	338	613	81	832	171	37.3
Lake Langnao						
Ayenew (2004)	186	212	-	463	46	-
This study (2019)	196	232	27.2	467	53	11.1
Lake Abiyata						
Ayalew (2003)	97.2	180	-	291	0	0
Ayenew (2004)	113	230	15	372	0	13
This study (2019)	115	219.5	-	328	0	15

Although, better quality of datasets both at time and space and approaches followed in this work, still there are several sources of uncertainty and errors in the water balance components. For instance, open water evaporation was estimated using Penman method (Penman, 1984) using available meteorological stations near to the lake. However, pan water evaporation data is not available in the study area for accurate evaporation loss estimation. Hence, this may result uncertainties in the magnitude of lake open evaporation. Furthermore, we assumed that the lake-groundwater interaction is negligible due absence of detailed data in the lake and its basin. This study, unlike the previous water balance studies, is more comprehensive by providing a rainfall-runoff modelling for streamflow simulation from gauge catchments and area-ratio transformation for ungauged catchments using bais-corrected CHIRP satellite estimate. This is an improvement on the water balance of Lake Ziway and the results also contribute to better water resources management of the lake and its tributaries.

We also infer that the impacts of intensive human activities and land use changes (conversion of woodlands in to agricultural lands and settlement areas) during recent periods will affect the water balance of the lakes (Legesse et al., 2003; Seyoum et al., 2015; Desta et al., 2017). Therefore, future studies should consider distributed hydrological model that take into account the land use, sediment inflow and socio-economic aspects of the study area. Althougth, we found that area-ratio method is reliable to estimate flow contribution from ungauge catchments in the study area due to large part of the cathcmnet is gauged. However, note that in future studies other regionalization methods should be taken into consideration by increasing the gauge catchments. Overall, to minimize the uncertainty and errors in the water balance components we recommend comparative advantage of various satellite rainfall estimate and bias correction algorithms (Wale et al., 2009; Rientjes et al., 2011; Dessie et al., 2015). Therefore, in future studies we suggest to better understand each hydrological process and to apply more advanced model calibration procedures to further explore the reported changes.

6.3 Water abstraction

In most of the previous studies water abstraction was estimated using CROPWAT model from crop that requires a highest amount of water. However, in reality this estimate may overestimate the water demand and hence may not yield the actual amount of water withdrawal from the water system. Previous studies reported that either site specific crop water demand or dominant crops in the area should be considered to estimate the actual amount of abstracted (Alemayehu et al., 2010; Adgolign et al., 2015; Chinnasany et al., 2015).

In this study, water abstraction field survey was applied for the most of the water users around the lakes and their tributaries. Furthermore, site-specific dominant crops were collected for the remaining irrigated schemes for use in CROPWAT software. Hence, in this study improvement in the estimation of actual water water abstraction from the water system were made for refined water allocation. Accordingly, our assessment revealed annual water abstraction amount to be 38 MCM for existing situation for irrigation and domestic water directly from Lake Ziway. This value is approximately comparable with other previous studies (Ayenew, 2004; Desta et al., 2017). This value increased by 2.5 times when the future planned development is implemented. This will result the abstraction of water has lead to the situation of water stress and scarcity. Hence, this would have a very significant impact on shipping and fishing from the lake which might result irrigation water abstraction to cease at certain period of time. This calls integrated water management to achieve sustainable water use around the lakes and their tributaries.

6.4 WEAP model

A WEAP model was employed to evaluate existing and future water demand in the subbasin considering spatial and temporal scales. Furthermore, we quantified the likely impact of three water resources development pathways on the water balance of Lake Ziway, Langano and Abiyata. Unlike other previous studies, in this study we used site-specific water demand assessment considering the spatial location of each demand sites using field survey. This study is unique as it couple satellite rainfall, ground observation, rainfall-runoff and water balance modelling, water abstraction and water evaluation and planning model for detail assessment of the water resources of the CRV Lakes basin.

This study considered the spatio-temporal assessment in comparison to most other previous studies which they focus at specific part of the study area. The use of WEAP-based water resources development simulation in this study indicated that water shortage at various spatial and temporal scales.The water demands for current development revealed 102.1 Mm^3. However, this amount increases by an additional 121 Mm^3 amount during long term development pathway. The likely impacts of this water resources development will result a reduction in water volume, level and surface area of Lake Ziway, Langano and Abiyata. The study showed that the impact on downstream water resources development is substantial. Therefore, any intervention on upstream catchments affects the water budget of the downstream Lake Abiyata. This indicates water abstraction management of each lake and their upstream catchments.

6.4 Conclusions

The main objective of this PhD research work is to assess the water resources of CRV lakes basin in scarce data regions of Ethiopia. In this study, we evaluated the performance of Climate Hazards InfraRed Precipitation (CHIRP) at various temporal and spatial scales for water budget studies. To this end, our research strategy and approach combine the use of finer resolution satellite data with a dense network of rain gauge stations. The observed rain gauge stations were used to drive the bias correction algorithms. The HBV model was applied to simulate streamflow from gauge, uncorrected and bias-corrected CHIRP satellite rainfall estimate. The study area is located in the Central Rift Valley Lakes basin of Ethiopia, which plays an important role in the national development plan of the country.

The following conclusions were drawn based on the findings of this study:

i. The performance evaluation of CHIRP satellite rainfall revealed that the CHIRP satellite contain biases at various spatio-temporal over the study area. The result showed that a percentage bias (PBIAS) varies between -16 to 20% and lower correlation performance at daily time step. However, the performance of monthly and areal catchment scales relatively improved than daily and point scales. The systematic errors in CHIRP satellite estimate distinctly spread in streamflow simulations via the HBV model. A change of up to 63% was obtained for model parameters controlling the water balance when uncorrected CHIRP rainfall inputs. However, this study indicated that a power transformation bias correction of satellite rainfall estimate using rain gauge data as a reference effectively reduced the rainfall bias and resulted in improved streamflow simulations. Hence, our study show that the potential of bias-corrected CHIRP satellite estimate in streamflow simulations over Lake Ziway watershed.

ii. The bias-corrected CHIRP rainfall estimate was then further applied for water level simulation where simulated river inflow using HBV rainfall-runoff model served as input into the lake water balance. The result revealed that rainfall, river inflow and evaporation constitute 33, 67 and 83% of the water balance, respectively. The water balance closure error of Lake Ziway is 67.5 mm for the natural condition from 1986-2000, which accounts for 2.9% of the total annual lake inflow by rainfall and river inflow. Overall, the simulated and observed lake levels fits well for the natural condition. However, for recent periods from the year 2001 onwards the simulated and observed lake levels do not agreed well. This attribution may be explained interms of the climate variability and combined effects of anthropogenic influences such as water abstraction and land use change (i.e. woodland to agricultural lands and settlement areas), which might be affected by temporal variation of any of the water balance components. Due to such factors a water level fluctuation of up to 2.3 m and 381 MCM volume changes has been observed in Lake Ziway. The findings of this study indicate a significant human impact on lake level and volume and the study suggests appriorate water management of lakes and its tributaries.

iii. The study also assess the impact of water abstraction on the water balance of Lake Ziway.The study aim towards estimating the actual water withdrawal through water abstraction survey and water balance model. The study indicated that actual estimate of water abstraction can be made using water abstraction survey data and finally using a water balance model. The results shows that the amount of water diverted for irrigation around Lake Ziway have substantial impact on the lake water balance. The simulation results indicated that if the future planned development fully implemented, the water level and surface area of the lake will drop by 0.94 m and 38 km^2, respectively. This is related to an isolated annual volume change of 405 Mm^3 compared to the baseline natural condition. The findings of this study indicated that existing water abstraction from the lake is substantial and exacerbate in the future. Therefore, the study suggests integrated water management of the lake water resources.

iV. This PhD research work concludes by assessing existing and future water demand and thereby evaluating the likely impact of three water resources development on the water balance of three interconnected CRV lakes. Our result indicated that for current development 102.1 Mm^3 of water diverted from the basin for irrigation, domestic and industrial purpose. However, when the future long term development to be implemented the water required increased to 223 Mm^3 of water.This will translates the average water level decline by 1.87, 0.97 and 2.1 m for Lake Ziway, Langano and Abiyata, respectively. The impact is significant for the downstream Abiyata lake water level. The study also indicated that there is unmet demand at various spatial and temporal scales over the basin. Overall, this study suggests that existing and future water demand around the lake and its feeding rivers has significant impact on the lake water balance of each lake.

6.5 Future outlook

Future study should focus on modelling of the hydrological processes of the basin including (i) impact of future climate change using multimodel climate models (ii) the contribution of groundwater and sediment inflow to the lakes (iii) comparative advantage of various satellite rainfall products and bias correction algorithms, (iv) suitable integrated water management and allocation strategies to better manage the decline in water resources of the basin and to further explore the attribution of the reported changes on the lakes and their tributaries, and (v) scaling up of the lesson’s obtained in the current work from this area to other study area.

References

Adgolign, T. B., Rao, G. V. R. S., Abbulu, Y. (2015). WEAP modeling of surface water resources allocation in Didessa Sub-Basin, West Ethiopia. *Sustainable Water Resources Management*, *2*(1), 55–70.

Alemayehu, T; McCartney, Matthew; & Kebede, S. (2010). Modelling to evaluate the water resource implications of planned infrastructure development in the Lake Tana sub-basin, Ethiopia. *Ecohydrology and Hydrobiology,* 10: 211–221.

Ashenafi, Y., Hailu, D. (2014). Assessment of the use of remotely sensed rainfall products for runoff simulation in the Upper Blue Nile basin of Ethiopia. *Zede Journal*, 31, 1–9.

Ayalew, E. (2003). Application of Stable Isotopes in the Study of Lake Dynamics in Ziway-Shalla Basin. Master's Thesis, Addis Ababa University, Addis Ababa, Ethiopia.

Ayenew, T. (2004). Environmental implication of changes in the levels of lakes in the Ethiopian Rift since 1970. *Regional Environmental Change, 4(4)*, 192-204.

Chinnasamy, P., Bharati, L., Bhattari, U., Khadka, A., Dahal, V, S. (2015). Impact of planned water resource development on current and future water demand in the Koshi River Basin, Nepal. *Water International*, 40(7):1004-1020.

Dessie, M., Verhoest, N. E., Pauwels, V. R., Adgo, E., Deckers, J., Poesen, J., Nyssen, J. .(2015). Water balance of a lake with floodplain buffering: Lake Tana, Blue Nile Basin, Ethiopia. *Journal of Hydrology*, *522*, 174–186.

Desta, H., Lemma, B., Gebremariam, E. (2017). Identifying sustainability challenges on land and water uses: The case of Lake Ziway watershed, Ethiopia. *Applied Geography*, *88*, 130–143.

Desta, H., Lemma, B. (2017). SWAT based hydrological assessment and characterization of Lake Ziway sub-watersheds, Ethiopia. *Journal of Hydrology: Regionl studies*, *13*, 122–137.

Fuka, D. R., Walter, M. T., MacAlister, C., Degaetano, A. T., Steenhuis, T. S., Easton, Z. M. (2014). Using the climate forecast system reanalysis as weather input data for watershed models. *Hydrological Processes*, *28*(22), 5613–5623.

Gebremichael, M.; Bitew, M.M.; Hirpa, F.A.; Tesfay, G.N. (2014). Accuracy of satellite rainfall estimates in the Blue Nile Basin: Lowland plain versus Highland Mountain. *Water Resources Research*, *50*, 8775–8790.

Gebere, S. B., Alamirew, T., Merkel, B. J., Melesse, A. M. (2015). Performance of high resolution satellite rainfall products over data scarce parts of Eastern Ethiopia. *Remote Sensing*, *7*(9), 11639–11663.

Goshime, D. W., Absi, R., Ledésert, B. (2019). Evaluation and bias correction of CHIRP rainfall estimate for rainfall-runoff simulation over Lake Ziway watershed, Ethiopia. Hydrol 6 (3) 68.

Haile, A. T., Habib, E., & Rientjes, T. (2013). Evaluation of the climate prediction center (CPC) morphing technique (CMORPH) rainfall product on hourly time scales over the source of the Blue Nile River. *Hydrological processes*, *27*(12), 1829–1839.

Jansen, H. C., Hengsdijk, H., Legesse, D., Ayenew, T., Hellegers, P., Spliethoff, P. C. (2007). Land and water resources assessment in the Ethiopian Central Rift Valley :*Alterra report, 1587*. Wageningen, The Netherlands.

Legesse, D, Vallet-Coulomb, C., Gasse, F. (2003). Hydrological response of a catchment to climate and land use changes in tropical Africa: case study south central Ethiopia. *Journal of Hydrology*, *275(1–2), 67–85*.

Penman, H. L. (1948). Natural evaporation from open water, bare soil and grass. *Proceedings of the Royal Society. A: Mathemtical, Physicaland Engineering Sciences, 193(1032), 120-145*.

Rientjes, T. H. M., Perera, B. U. J., Haile, A. T., Reggiani, P., Muthuwatta, L. P. (2011). Regionalisation for lake level simulation – the case of Lake Tana in the Upper Blue Nile, Ethiopia. *Hydrology and Earth Sytem Sciences*, 15(4), 1167-1183.

Seyoum, W.M., Milewski, A.M., Durham, M. C. (2015) .Understanding the relative impacts of natural processes and human activities on the hydrology of the Central Rift Valley Lakes basins, East Africa: assessment of natural and human impacts on the hydrology of lakes. *Hydrological Processes, 29(19), 4312-24*.

Vallet-Coulomb, C., Legesse, D., Gasse, F., Travi, Y., Chernet, T. (2001). Lake evaporation estimates in tropical Africa (Lake Ziway, Ethiopia). *Journal of Hydrology, 245(1–4), 1–18*.

Wale, A., Rientjes, T. H. M., Gieske, A. S. M., Getachew, H. A. (2009). Ungauged catchment contributions to Lake Tana's water balance. *International Journal of Hydrological processes, 23(26), 3682–3693.*

Appendices

Annex-A

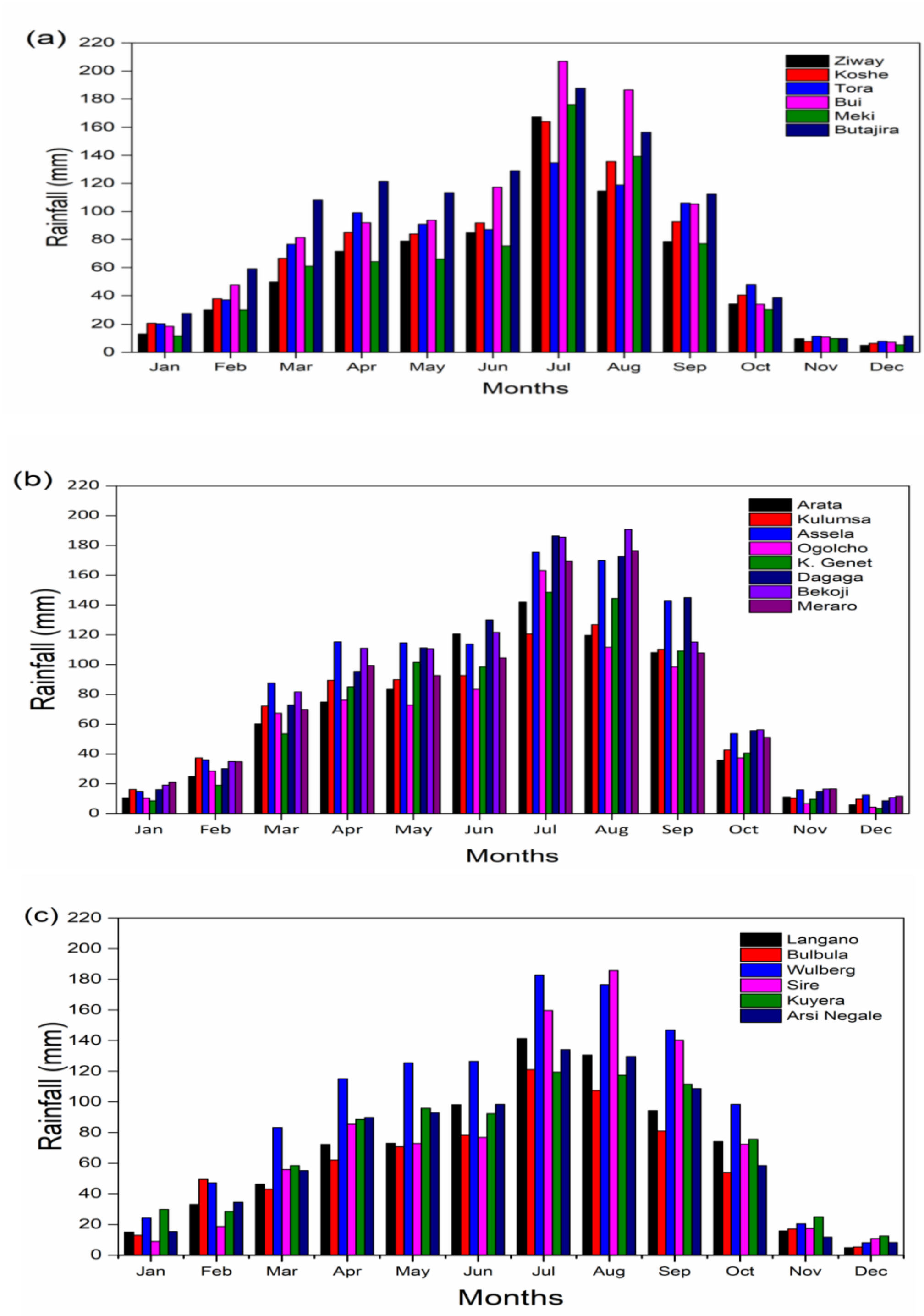


Figure 1-A: Mean monthly summary of rainfall of the study area **(a)** Meki catchment **(b)** Katar catchment **(c)** Langano and Abiyata catchment

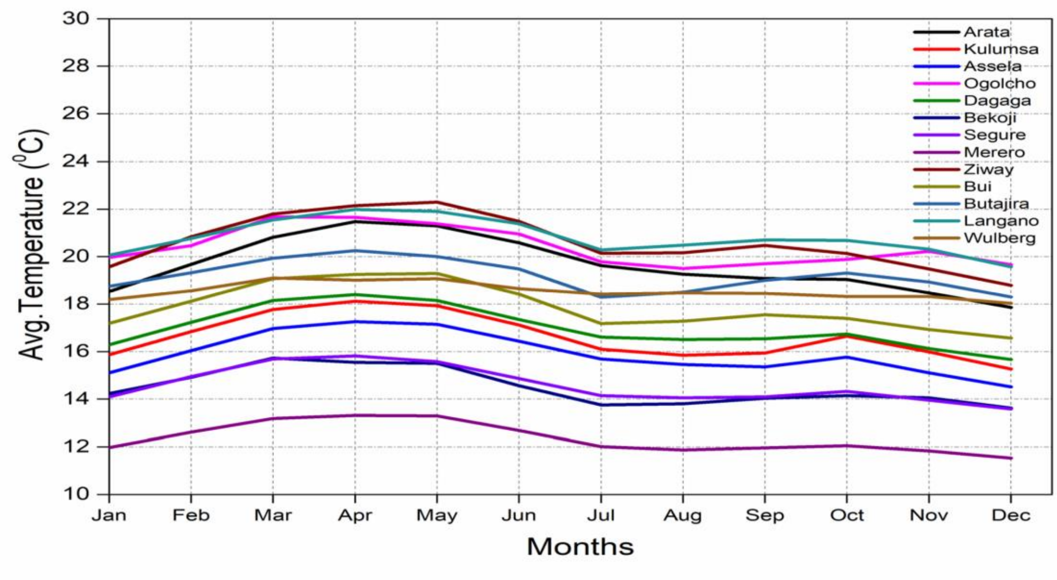


Figure 2-A: Mean monthly summary of average Temperature of the study area

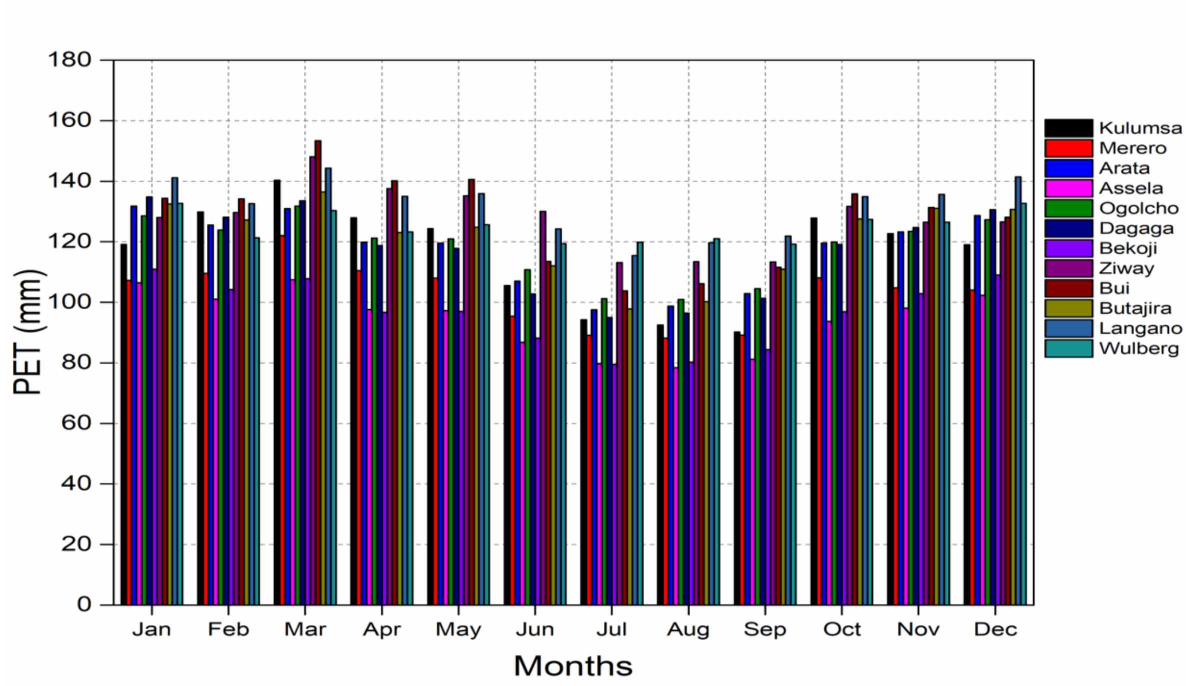


Figure 3-A: Mean monthly Potential Evapotranspiration (PET) of the study area

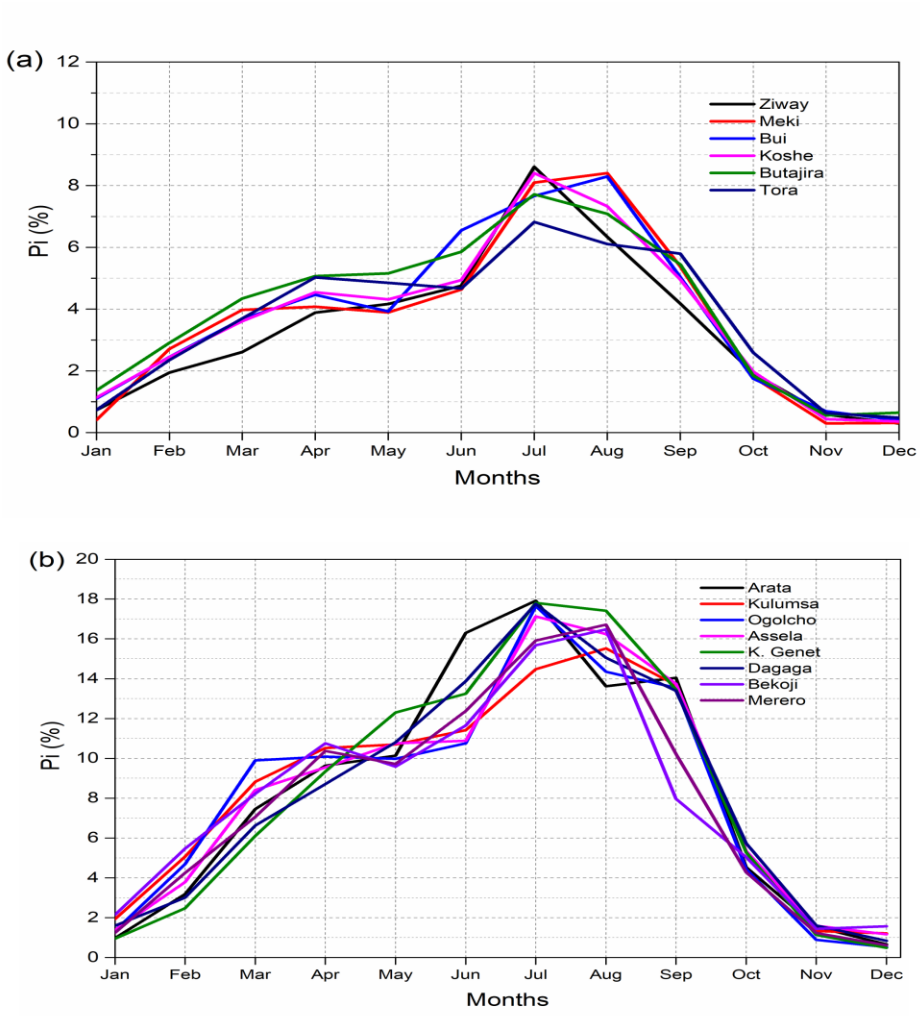


Figure 4-A: Non-dimensionalzed rainfall for (**a**) Meki catchment, (**b**) Katar catchment

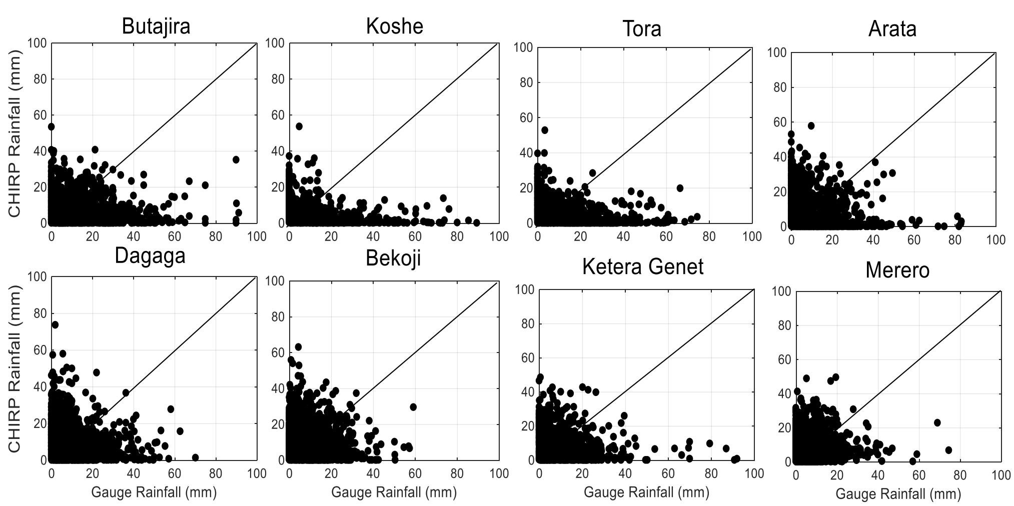
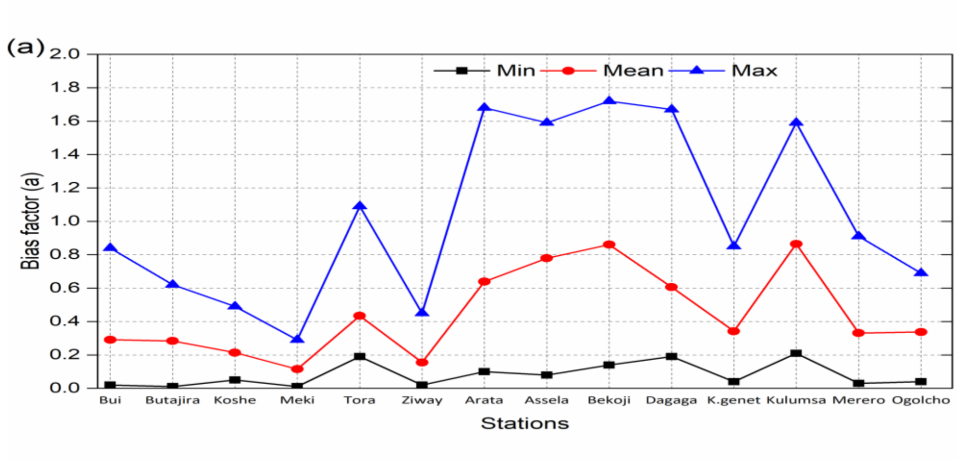


Figure 5-A. Scatter plots of daily CHIRP satellite rainfall estimate against gauge rainfall at eight weather stations for Meki and Katar catchment from 1984-2007



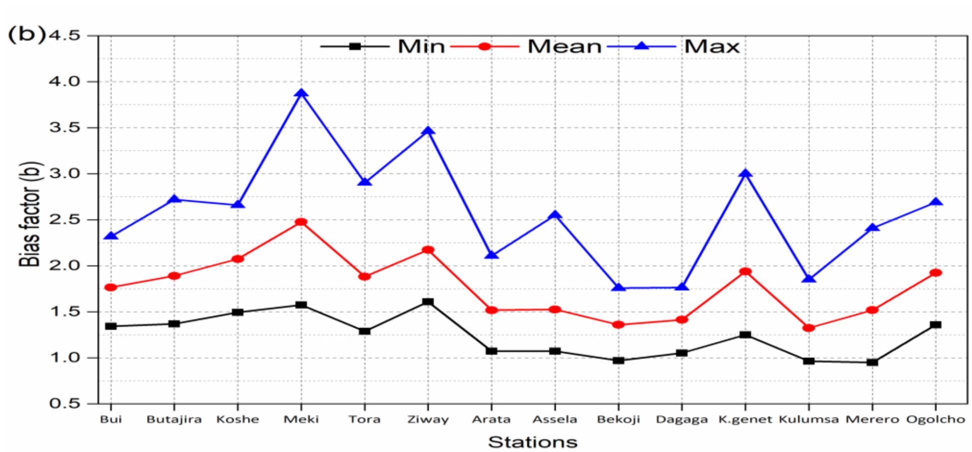


Figure 6-A. Mean, minimum and maximum monthly bias factors evaluated from ensemble of 14 rain gauge stations from 1984-2000 **(a)** bias factor a **(b)** bias factor b.

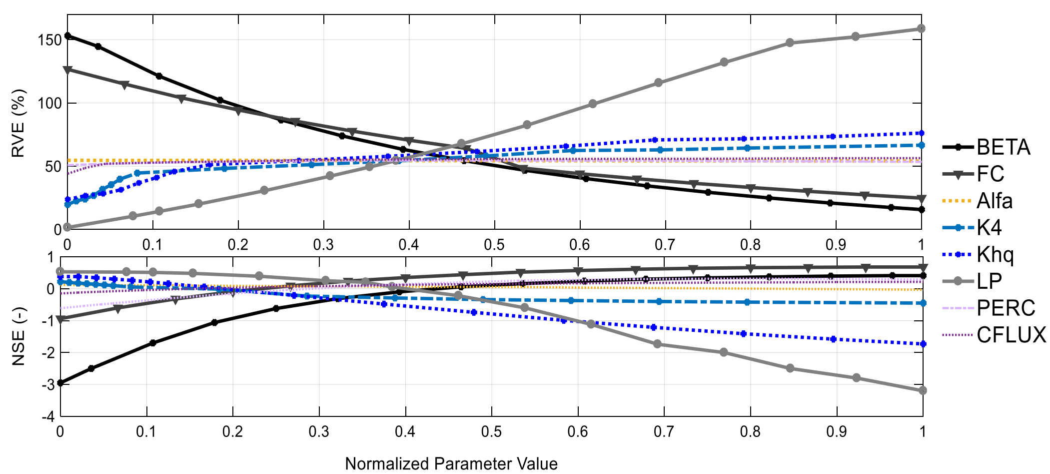


Figure 7-A**.** Sensitivity analysis results for Katar catchment with respect to NSE and RVE objective functions

Annex-B

Table 1-B: Selected meteorological stations for the study area

S.no	Station Name	Altitude (m)	Location		Data Type			Annual RF (mm)
			Lat. (N)	Long. (E)	RF	Tmax	Tmin	
1	Adami Tulu	1653	7.85	38.70	yes	yes	yes	701
2	Arbachulele	2480	8.12	38.25	yes	No	No	1038
3	Butajira	2000	8.15	38.37	yes	yes	yes	1233
4	Bui	2054	8.33	38.55	yes	yes	yes	1039
5	Chelelketu	1623	7.88	38.37	yes	No	No	1251
6	Digello	1772	7.75	39.33	yes	yes	yes	656
7	Kersa	2700	7.52	38.97	yes	No	No	927
8	Koshe	1878	8.01	38.53	yes	No	No	788
9	Meki	1400	8.15	38.82	yes	No	No	731
10	Tora	2001	7.86	38.42	yes	No	No	853
11	Ziway	1640	7.93	38.70	yes	yes	yes	734
12	Arata	1777	7.98	39.06	yes	yes	yes	747
13	Assela	2413	7.96	39.14	yes	yes	yes	1078
14	Bekoji	2388	7.53	39.25	yes	yes	yes	1056
15	Dagaga	2787	7.60	38.97	yes	yes	yes	1042
16	K. Genet	2400	7.83	39.10	yes	No	No	754
17	Kulumsa	2200	8.13	39.13	yes	yes	yes	816
18	Meraro	2940	7.45	39.37	yes	yes	yes	940
19	Ogolcho	1682	8.04	39.02	yes	yes	yes	728
20	Segure	2480	7.46	39.09	yes	yes	yes	756
21	Bulbula	1606	7.72	38.65	yes	No	No	649
22	Langano	2700	7.54	38.68	yes	yes	yes	784
23	A. Negale	1913	7.35	38.66	yes	yes	yes	1196
24	Wulberg	1800	7.67	38.35	yes	yes	yes	956
25	Sire	2037	7.24	38.74	yes	No	No	855
26	Kuyera	2870	7.30	38.65	yes	Yes	yes	837

Table 2-B: Mean monthly PET of selected meteorological station from 1984-2015

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Bui	134.4	134.2	153.3	140.2	140.6	113.5	103.8	106.2	111.6	135.9	131.4	128.1
Butajira	132.6	127.2	136.5	123.1	124.8	112.0	97.8	100.2	110.9	127.6	131.0	130.7
Ziway	128.1	129.7	148.1	137.6	135.2	130.1	113.1	113.4	113.4	131.7	126.5	126.5
Arata	131.8	125.6	131.0	119.8	119.6	107.0	97.5	98.8	102.8	119.5	123.3	128.7
Assela	106.5	101.0	107.5	97.7	97.3	86.8	79.7	78.4	81.2	93.7	98.1	102.3
Bekoji	111.0	104.3	107.8	96.7	96.9	88.2	79.5	80.2	84.4	96.9	102.9	109.1
Dagaga	134.8	128.1	133.6	118.8	117.8	102.7	95.0	96.4	101.3	119.1	124.7	130.6
Kulumsa	119.1	129.9	140.3	127.9	124.3	105.5	94.3	92.5	90.2	127.9	122.7	119.0
Merero	107.2	109.6	122.1	110.5	108.0	95.4	89.1	88.1	89.1	108.1	104.8	104.0
Ogolcho	128.6	123.9	131.8	121.2	120.9	110.8	101.2	100.9	104.5	119.9	123.4	127.3
Langano	141.2	132.6	144.3	135.0	136.0	124.3	115.4	119.7	121.9	134.9	135.6	141.5
Wulberg	132.7	121.3	130.3	123.3	125.7	119.4	119.9	121.0	119.2	127.4	126.5	132.8

Table 3-B: Lake Ziway-Langano-Abiyata bathymetric relationships

Lake Ziway	Elevation (m.a.s.l)	1627	1628	1629	1630	1631	1632	1633	1634	1635	1636	1637	1638		
2013	Area (km2)	0	0.2	2.4	8.0	19.1	40.8	136.0	392.4	752.3	1148.0	1582.7	2077.7		
	Volume (Mm3)	0	0.6	3.8	7.6	15.2	30.1	173.2	326.9	382.6	407.8	481.9	504.1		
1984	Elevation (m.a.s.l)	1627	1628	1629	1630	1631	1632	1633	1634	1635	1636	1637			
	Area (km2)	0	6.0	18.0	40.0	104.0	250.0	320.0	394.0	440.0	492.0				
	Volume (Mm3)	0	10.0	30.0	80.0	180.0	420.0	750.0	1120.0	1580.0	2050.0				
Lake Langano	Elevation (m.a.s.l)	1538	1545	1548	1555	1575	1577	1578	1579	1582	1583	1584	1584	1584.5	1585
1984	Volume (Mm3)	0.0	262.5	510.0	1210.0	3810.0	4130.0	4305.0	4490.0	5105.0	5330.0	5446.0	5565.0	5686.3	5810.0
	Area (km2)	0	75	90	110	150	170	180	190	220	230	235	240	245	250
Lake Abiyata	Elevation (m.a.s.l)	1568	1572	1574	1576	1577	1578	1579	1580	1581	1582	1583	1584		
1984	Volume (Mm3)	0.0	167.7	346.2	546.3	654.5	768.2	887.2	1011.7	1141.5	1276.8	1417.5	1563.7		
	Area (km2)	0.0	125.8	142.0	158.3	166.4	174.5	182.6	190.8	198.9	207.0	215.1	223.3		

Table 4-B: Major abstraction schemes from Lake Ziway with irrigable area and abstraction amount under existing condition

Abstraction point	Irrigable area (ha)			Annual gross water abstraction (Mm^3)		
	ED	LFD	FPD	ED	LFD	FPD
Sher Ethiopia	500	750	1000	8.09	12.13	16.18
AQ Rose	30	40	60	0.44	0.58	0.88
Ziway Rose	40	60	100	0.61	0.92	1.54
Braam Flower	22	22	30	0.32	0.32	0.44
Herburg Flower	40	60	80	0.58	0.88	1.17
ET Seeds	6.5	10	20	0.07	0.10	0.20
Meki-Ziway	216	400	750	5.56	10.30	19.32
Federal Farm	20	40	68	0.50	0.99	169
Flora Veg.	1	2	2	0.003	0.01	0.01
Agro Processing	16.5	30	60	0.49	0.89	1.78
Adami Tulu	467	720	1245	8.30	12.79	22.12
Meki Dugda	375	566	965	7.62	11.50	19.61
Ziway Dugda	266	400	620	3.92	5.89	9.14

Table 5-B: Mean monthly water demand for current development from 2009-2018 (Mm^3)

S.no	Schemes	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1	Adami Tulu Lake irrigation	0.90	0.76	0.90	0.85	0.90	0.42	0.45	0.45	0.84	0.90	0.84	0.90	9.10
2	Bulbula Irrigation	1.00	1.30	1.40	1.55	1.44	0.67	0.36	0.00	0.41	1.25	1.80	1.67	12.85
3	Dugda Lake Irrigation	0.75	0.63	0.75	0.69	0.75	0.32	0.36	0.36	0.69	0.75	0.69	0.75	7.49
4	Sagure Irrigation	0.66	0.44	0.49	0.53	0.49	0.15	0.00	0.00	0.02	0.57	0.95	0.90	5.20
5	Flower farms	0.84	0.78	0.84	0.82	0.84	0.82	0.84	0.83	0.82	0.84	0.82	0.84	9.94
6	Katar Diversion Irrigation	0.91	0.87	0.77	0.96	0.97	0.53	0.08	0.00	0.10	0.86	1.28	1.30	8.63
7	Katar Pumped Irrigation	0.86	0.81	0.92	0.51	0.53	0.21	0.00	0.00	0.03	0.42	0.68	0.67	5.65
8	Langano Tributary Irrigation	1.69	1.05	1.34	1.21	1.09	0.21	0.08	0.00	0.21	0.71	1.48	1.53	10.61
9	Meki Diversion Irrigation	0.52	0.47	0.98	0.62	0.64	0.37	0.03	0.00	0.20	0.52	0.74	0.73	5.82
10	Meki Pumped Irrigation	0.62	0.58	0.66	0.37	0.38	0.15	0.00	0.00	0.02	0.30	0.49	0.48	4.06
11	Meki Ziway Pump	0.53	0.47	0.53	0.51	0.53	0.22	0.24	0.24	0.51	0.53	0.51	0.53	5.38
12	Soda Ash factory	0.31	0.28	0.31	0.30	0.31	0.30	0.30	0.31	0.30	0.31	0.30	0.31	3.63
13	Bulbula WS	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.16
14	Chuifa Irrigation	0.13	0.09	0.15	0.13	0.03	0.00	0.00	0.00	0.01	0.12	0.18	0.17	1.03
15	Langano Lake Irrigation	0.08	0.08	0.06	0.06	0.05	0.01	0.00	0.00	0.00	0.02	0.06	0.07	0.50
16	Rinzaf Irrigation	0.20	0.11	0.13	0.17	0.19	0.04	0.00	0.00	0.04	0.21	0.32	0.29	1.69
17	Timala Irrigation	0.71	0.44	0.52	0.48	0.47	0.12	0.00	0.00	0.05	0.47	0.94	0.95	5.16
18	Ziway Dugda Lake Irrigation	0.38	0.32	0.38	0.35	0.38	0.17	0.18	0.18	0.35	0.38	0.35	0.38	3.82
19	Ziway WS	0.12	0.11	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	1.41
	Sum	**11.24**	**9.60**	**11.27**	**10.24**	**10.14**	**4.84**	**3.06**	**2.50**	**4.73**	**9.31**	**12.54**	**12.63**	**102.10**

Table 6-B: Mean monthly water demand for short term development from 2019-2028 (Mm^3)

S.no	Schemes	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1	Adami Tulu Lake irrigation	1.38	1.17	1.38	1.30	1.38	0.64	0.68	0.68	1.28	1.38	1.28	1.38	13.94
2	Bulbula Irrigation	1.34	1.73	1.87	2.08	1.92	0.89	0.48	0.00	0.55	1.66	2.40	2.23	17.16
3	Dugda Lake Irrigation	1.10	0.93	1.10	1.02	1.10	0.48	0.53	0.53	1.02	1.10	1.02	1.10	11.04
4	Flower farms	1.22	1.12	1.22	1.18	1.22	1.18	1.22	1.21	1.18	1.22	1.18	1.22	14.35
5	Katar Diversion Irrigation	1.19	1.15	1.01	1.26	1.27	0.70	0.10	0.00	0.14	1.14	1.68	1.71	11.35
6	Katar Pumped Irrigation	1.11	1.04	1.19	0.66	0.68	0.28	0.00	0.00	0.04	0.54	0.87	0.87	7.28
7	Langano Tributary Irrigation	2.16	1.35	1.71	1.55	1.40	0.27	0.11	0.00	0.27	0.91	1.89	1.96	13.59
8	Meki Diversion Irrigation	0.69	0.63	1.30	0.83	0.85	0.49	0.04	0.00	0.27	0.69	0.99	0.98	7.76
9	Meki Pumped Irrigation	0.96	0.90	1.02	0.57	0.59	0.24	0.00	0.00	0.03	0.46	0.75	0.75	6.27
10	Meki Ziway Pump	0.97	0.85	0.97	0.93	0.96	0.41	0.43	0.43	0.92	0.97	0.93	0.97	9.72
11	Timala Irrigation	1.53	0.94	1.12	1.03	1.02	0.27	0.00	0.00	0.10	1.02	2.02	2.04	11.11
12	Soda Ash factory	0.60	0.55	0.60	0.58	0.60	0.58	0.59	0.60	0.58	0.60	0.58	0.60	7.06
13	Bulbula WS	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.16
14	Chuifa Irrigation	0.23	0.16	0.27	0.23	0.06	0.00	0.00	0.00	0.02	0.22	0.33	0.31	1.82
15	Sagure Irrigation	0.87	0.58	0.65	0.70	0.65	0.19	0.00	0.00	0.03	0.75	1.25	1.20	6.88
16	Langano Lake Irrigation	0.10	0.10	0.07	0.07	0.07	0.01	0.00	0.00	0.00	0.03	0.08	0.09	0.62
17	Rinzaf Irrigation	0.27	0.14	0.17	0.23	0.24	0.05	0.00	0.00	0.05	0.27	0.41	0.38	2.20
18	Ziway Dugda Lake Irrigation	0.56	0.47	0.56	0.52	0.56	0.25	0.27	0.27	0.52	0.56	0.52	0.56	5.63
19	Ziway WS	0.12	0.11	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	1.45
	Sum	**16.43**	**13.94**	**16.36**	**14.86**	**14.73**	**7.05**	**4.59**	**3.86**	**7.12**	**13.67**	**18.31**	**18.48**	**149.41**

Table 8-B: Mean monthly water demand for Long term development from 2029-2038 (Mm^3)

S.no	Schemes	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1	Adami Tulu Lake Irrigation	2.36	2.00	2.36	2.21	2.36	1.09	1.17	1.17	2.19	2.36	2.19	2.36	23.79
2	Dugda lake Irrigation	1.84	1.56	1.84	1.70	1.84	0.80	0.89	0.89	1.70	1.84	1.70	1.84	18.47
3	Sagure Irrigation	1.30	0.86	0.97	1.05	0.97	0.29	0.00	0.00	0.04	1.12	1.87	1.79	10.26
4	Flower farms	1.65	1.51	1.65	1.59	1.65	1.59	1.65	1.63	1.59	1.65	1.59	1.65	19.39
5	Katar Diversion Irrigation	1.94	1.86	1.64	2.05	2.07	1.14	0.17	0.00	0.22	1.85	2.73	2.79	18.46
6	Katar Pumped Irrigation	1.64	1.53	1.75	0.98	1.01	0.41	0.00	0.00	0.05	0.79	1.29	1.28	10.73
7	Langano Tributary Irrigation	3.19	1.99	2.53	2.29	2.07	0.40	0.16	0.00	0.40	1.34	2.79	2.89	20.03
8	Meki Diversion Irrigation	1.20	1.09	2.27	1.44	1.49	0.85	0.07	0.00	0.47	1.20	1.71	1.70	13.50
9	Meki Pumped Irrigation	1.44	1.34	1.53	0.86	0.88	0.36	0.00	0.00	0.05	0.70	1.13	1.12	9.40
10	Meki Ziway Pump	1.79	1.57	1.79	1.72	1.78	0.75	0.79	0.79	1.71	1.79	1.72	1.79	17.99
11	Timala Irrigation	1.80	1.11	1.32	1.22	1.20	0.31	0.00	0.00	0.12	1.20	2.38	2.41	13.08
12	Soda Ash factory	0.89	0.82	0.89	0.86	0.89	0.86	0.88	0.89	0.86	0.89	0.86	0.89	10.50
13	Bulbula Irrigation	1.58	2.04	2.20	2.45	2.26	1.05	0.57	0.00	0.65	1.96	2.83	2.63	20.21
14	Bulbula WS	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.17
15	Chuifa Irrigation	0.43	0.30	0.51	0.43	0.11	0.00	0.00	0.00	0.04	0.41	0.61	0.58	3.41
16	Langano Lake Irrigation	0.13	0.13	0.10	0.09	0.09	0.01	0.00	0.00	0.00	0.04	0.10	0.12	0.82
17	Rinzaf Irrigation	0.33	0.17	0.21	0.28	0.30	0.06	0.00	0.00	0.06	0.34	0.51	0.46	2.70
18	Ziway Dugda Lake Irrigation	0.86	0.72	0.86	0.79	0.86	0.38	0.41	0.41	0.79	0.86	0.79	0.86	8.60
19	Ziway WS	0.13	0.12	0.13	0.12	0.13	0.12	0.13	0.13	0.12	0.13	0.12	0.13	1.49
	Sum	**24.52**	**20.76**	**24.56**	**22.13**	**21.96**	**10.50**	**6.89**	**5.92**	**11.08**	**20.48**	**26.94**	**27.28**	**223.02**

Table 9-B: Mean monthly streamflow of Meki gauge stations from 1986-2018 (Mm^3)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1986	0.3	1.3	2.3	12.7	6.8	25.9	63.2	76.8	48.1	5.1	0.5	0.1	242.9
1987	0.0	0.7	20.6	47.3	46.2	37.9	20.1	16.8	18.9	6.7	1.0	0.1	216.4
1988	0.1	1.0	0.4	8.0	5.9	7.9	42.0	62.3	58.2	33.8	7.6	2.5	229.5
1989	0.4	5.9	8.8	25.0	7.9	10.1	40.6	41.1	47.3	26.0	4.3	2.4	219.8
1990	0.9	27.5	54.1	57.0	14.1	15.0	45.7	53.0	39.3	17.2	4.8	2.3	331.0
1991	1.3	6.3	19.2	7.4	2.4	9.8	65.5	93.5	52.2	9.3	2.3	1.8	271.0
1992	2.4	13.5	5.8	12.9	11.3	8.5	18.4	136.7	84.9	33.4	7.7	4.2	339.5
1993	2.5	2.4	2.7	34.9	47.0	32.0	67.5	144.1	51.6	57.1	11.6	2.4	455.6
1994	2.2	1.2	1.6	0.8	1.0	11.2	63.2	153.9	121.3	4.6	2.6	0.6	364.2
1995	1.8	2.0	22.4	12.7	10.0	6.6	28.3	72.1	82.6	6.4	3.4	1.9	250.1
1996	6.5	0.6	19.7	24.6	51.6	86.3	109.1	149.7	63.5	14.9	5.2	3.2	535.0
1997	0.8	0.7	2.7	25.8	7.8	11.3	44.5	44.5	14.0	14.4	16.0	2.5	184.8
1998	4.3	1.8	32.5	8.5	31.5	13.6	74.0	187.8	75.8	61.9	6.6	1.1	499.3
1999	0.2	0.2	7.6	0.3	1.4	7.4	55.3	60.1	26.3	85.1	32.3	4.7	280.8
2000	1.3	0.9	0.4	1.7	8.6	6.8	43.3	85.0	67.3	53.5	21.5	9.3	299.4
2001	0.4	1.0	16.2	9.5	23.6	60.0	112.3	129.7	73.2	8.6	3.0	2.3	439.7
2002	13.2	9.4	5.3	3.6	1.7	13.2	41.0	57.0	31.2	5.8	4.4	1.6	187.3
2003	2.3	1.2	21.0	16.2	5.2	12.0	112.8	125.8	54.1	9.8	0.8	3.8	365.1
2004	2.2	0.7	1.9	1.9	0.7	2.0	18.5	56.2	21.3	8.7	0.4	0.1	114.7
2005	0.1	0.1	2.3	3.1	29.3	14.5	35.5	47.3	52.3	16.4	2.4	0.2	203.5
2006	0.0	0.5	5.5	39.1	34.0	28.3	66.0	75.6	71.5	14.2	7.9	0.9	343.4
2007	0.0	1.8	1.4	7.0	6.7	30.3	51.8	74.8	84.9	25.6	1.6	0.0	285.7
2008	0.0	0.0	0.0	0.0	1.4	10.2	29.3	55.2	32.1	10.8	28.3	1.4	168.7
2009	1.5	0.7	0.3	3.5	0.9	0.5	12.7	21.8	21.9	22.4	3.6	0.4	90.2
2010	0.3	3.8	10.6	22.4	35.6	27.1	44.2	53.3	75.3	19.9	0.9	0.3	293.8
2011	0.3	0.0	1.4	0.3	8.7	16.3	33.9	60.6	40.5	9.1	1.3	0.0	172.4
2012	0.0	0.0	0.0	9.7	9.9	7.4	35.3	71.0	74.6	24.4	9.4	0.7	242.5
2013	0.1	1.4	3.9	10.0	9.8	33.0	81.0	91.8	65.6	36.8	4.6	0.4	338.5
2014	0.4	3.2	6.2	7.8	9.6	8.4	15.2	28.6	46.2	16.7	1.7	0.1	144.1
2015	0.1	0.7	1.8	3.9	5.4	10.3	16.5	30.8	26.0	11.3	1.3	0.0	108.1
2016	0.0	0.5	2.6	7.2	18.8	11.1	34.2	38.4	24.5	11.7	2.0	0.1	151.1
2017	0.0	0.3	1.5	2.1	2.1	1.5	15.2	24.9	58.0	9.3	0.3	0.0	115.2
2018	0.0	0.0	0.7	3.4	7.0	19.5	30.8	31.7	56.0	12.2	0.9	0.0	162.2
Mean	**1.4**	**2.8**	**8.6**	**13.0**	**14.1**	**18.0**	**47.5**	**74.3**	**53.4**	**21.3**	**6.1**	**1.6**	**262.0**
Max	**13.2**	**27.5**	**54.1**	**57.0**	**51.6**	**86.3**	**112.8**	**187.8**	**121.3**	**85.1**	**32.3**	**9.3**	**535.0**
Min	**0.0**	**0.0**	**0.0**	**0.0**	**0.7**	**0.5**	**12.7**	**16.8**	**14.0**	**4.6**	**0.3**	**0.0**	**90.2**

Table 10-B: Mean monthly streamflow of Rinzaf gauge stations from 1986-2018 (Mm^3)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1986	0.0	0.0	0.2	3.0	0.9	3.8	3.5	5.7	2.0	0.4	0.0	0.0	19.5
1987	0.0	0.1	1.9	8.0	12.3	6.3	1.7	2.1	1.0	0.6	0.1	0.0	34.0
1988	0.0	0.1	0.0	0.1	0.1	0.3	2.7	4.1	4.0	2.1	0.1	0.0	13.6
1989	0.0	0.2	0.4	3.6	0.8	0.8	5.0	3.2	5.2	2.7	0.3	0.3	22.5
1990	0.1	1.6	8.9	4.1	1.7	2.7	6.9	5.1	3.7	1.4	0.3	0.1	36.4
1991	0.1	0.2	0.7	0.3	0.1	0.6	5.8	7.1	3.5	0.5	0.1	0.1	19.3
1992	0.2	2.4	1.2	1.4	1.1	1.4	4.6	8.5	6.9	5.0	1.2	0.5	34.4
1993	0.7	1.1	0.3	3.8	8.6	4.5	6.5	6.1	2.7	3.1	1.3	0.3	38.9
1994	0.2	0.1	0.4	0.4	1.4	0.6	1.4	1.9	5.0	0.8	0.1	0.0	12.2
1995	0.0	0.2	0.6	0.3	0.3	0.5	0.8	2.8	1.3	0.1	0.0	0.0	6.8
1996	0.3	0.0	26.8	0.5	4.4	4.8	5.4	9.3	2.6	0.6	0.2	0.1	54.9
1997	0.3	0.1	0.2	2.6	0.2	0.4	1.3	1.3	1.2	1.7	1.5	0.3	11.2
1998	0.5	1.0	0.8	0.4	1.1	0.6	1.7	2.2	1.8	1.6	0.5	0.0	12.1
1999	0.1	0.0	0.8	0.3	0.4	0.7	1.5	1.5	0.8	1.2	0.5	0.1	7.7
2000	0.0	0.0	0.0	0.1	0.7	0.4	1.3	1.4	1.0	1.1	0.3	0.1	6.4
2001	0.0	0.1	0.1	0.2	0.4	2.0	2.5	3.1	2.9	0.7	0.0	0.0	12.2
2002	0.0	0.0	0.2	0.0	0.1	0.4	1.8	2.9	1.0	0.1	0.0	0.0	6.5
2003	0.1	0.0	0.1	0.4	0.4	0.4	0.9	1.3	1.1	0.3	0.0	0.1	5.0
2004	0.1	0.0	0.0	3.5	0.2	0.3	0.9	7.3	2.0	0.7	0.0	0.0	15.0
2005	0.0	0.0	0.4	2.9	6.7	1.0	10.7	4.5	4.2	0.4	0.1	0.0	31.0
2006	0.0	0.2	0.4	1.3	0.8	0.8	1.9	2.3	2.5	1.1	1.2	0.2	12.8
2007	0.1	0.4	0.3	1.0	0.8	2.6	3.1	3.8	4.5	1.4	0.1	0.0	18.3
2008	0.0	0.1	0.1	0.2	0.3	1.1	2.3	3.3	1.8	1.1	4.4	0.3	15.0
2009	0.2	0.3	0.2	2.4	0.6	0.5	1.3	1.5	1.1	2.7	0.6	0.7	12.0
2010	0.4	1.5	2.8	3.8	3.4	1.7	2.4	5.2	5.4	1.5	0.3	0.1	28.4
2011	0.2	0.2	0.5	0.2	1.1	1.2	1.7	2.7	2.4	0.6	0.3	0.1	11.1
2012	0.0	0.1	0.1	1.2	0.6	0.4	1.9	2.9	2.8	0.9	0.5	0.1	11.4
2013	0.1	0.3	0.5	0.7	0.5	2.4	4.5	3.8	2.2	1.3	0.2	0.0	16.4
2014	0.1	0.4	0.7	0.6	0.7	0.6	0.7	1.3	2.2	0.7	0.1	0.0	8.2
2015	0.1	0.2	0.3	0.5	0.5	0.7	0.8	1.4	1.0	0.6	0.1	0.0	6.4
2016	0.1	0.2	0.4	0.7	1.2	0.5	1.6	1.4	0.9	0.6	0.2	0.0	7.8
2017	0.0	0.4	0.7	0.6	0.5	0.6	1.6	1.6	2.5	0.6	0.1	0.0	9.2
2018	0.1	0.3	0.7	0.9	1.0	2.0	2.1	1.6	1.9	0.7	0.2	0.0	11.4
Mean	**0.1**	**0.4**	**1.6**	**1.5**	**1.6**	**1.4**	**2.8**	**3.5**	**2.6**	**1.2**	**0.4**	**0.1**	**17.2**
Max	**0.7**	**2.4**	**26.8**	**8.0**	**12.3**	**6.3**	**10.7**	**9.3**	**6.9**	**5.0**	**4.4**	**0.7**	**54.9**
Min	**0.0**	**0.0**	**0.0**	**0.0**	**0.1**	**0.3**	**0.7**	**1.3**	**0.8**	**0.1**	**0.0**	**0.0**	**5.0**

Table 11-B: Mean monthly streamflow of Katar gauge stations from 1986-2018 (Mm^3)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1986	5.0	6.7	9.1	13.2	15.4	25.7	75.5	138.0	89.5	35.2	8.8	6.7	428.7
1987	4.9	4.4	13.0	47.0	26.2	38.3	26.8	51.8	44.2	19.7	6.1	5.4	288.0
1988	5.0	5.3	5.4	6.0	6.7	7.1	61.6	266.3	89.5	54.4	13.4	7.2	527.8
1989	6.4	5.7	6.2	16.6	15.5	10.2	34.4	67.1	75.6	32.4	8.9	10.7	289.7
1990	0.8	29.3	53.6	57.1	14.2	11.5	76.4	88.6	67.9	28.7	8.3	10.7	447.1
1991	5.8	5.4	10.1	14.0	7.4	8.9	37.6	122.6	93.5	16.5	6.6	6.2	334.6
1992	5.4	6.2	4.7	7.9	8.2	8.4	21.9	176.7	139.9	67.2	11.8	7.6	465.9
1993	7.3	15.9	5.9	13.2	30.8	30.0	44.0	141.5	92.5	53.9	18.6	7.2	460.7
1994	5.7	4.6	4.4	4.0	-	11.1	61.4	184.5	127.2	18.8	7.3	5.5	434.6
1995	4.2	3.8	21.3	18.7	14.6	6.6	33.8	129.7	153.8	12.3	6.1	5.7	410.4
1996	6.6	4.2	7.7	10.2	18.0	46.5	57.6	171.7	63.2	22.9	6.3	5.8	420.8
1997	6.4	4.0	4.2	15.5	7.0	7.1	36.3	56.2	28.7	14.9	18.0	7.9	206.3
1998	5.9	8.4	13.4	6.2	16.0	9.5	35.9	185.3	128.6	77.4	17.5	6.3	510.4
1999	5.3	1.0	4.6	4.3	4.5	8.3	45.5	90.7	55.0	119.1	19.3	6.3	363.9
2000	4.2	4.0	4.2	3.9	12.5	7.1	26.1	132.1	74.4	67.7	22.6	6.7	365.3
2001	4.7	3.7	5.8	6.7	20.3	35.8	91.9	214.4	98.1	28.0	6.3	4.8	520.6
2002	4.9	4.6	7.4	5.4	7.5	8.9	19.5	71.2	34.8	8.9	3.8	5.1	182.2
2003	6.5	3.4	4.2	10.2	10.2	6.3	44.5	139.1	75.2	20.1	4.8	5.0	329.3
2004	3.9	3.4	3.6	22.6	9.4	8.6	53.7	101.9	69.5	36.3	5.8	3.8	322.5
2005	1.8	1.0	4.1	6.7	49.2	24.7	62.4	93.3	104.9	34.1	5.8	1.0	389.0
2006	0.0	0.6	1.8	8.0	9.1	10.3	52.6	74.6	70.5	25.8	16.3	2.5	272.2
2007	0.1	3.6	2.9	5.6	8.4	42.7	83.3	105.3	147.7	57.7	5.3	0.3	462.9
2008	0.0	0.0	0.0	1.1	5.0	15.5	36.2	82.5	77.5	26.6	55.2	3.4	303.1
2009	3.1	2.6	0.9	7.4	5.1	5.5	18.8	56.3	64.4	44.5	8.6	1.8	218.9
2010	1.0	6.4	22.0	37.5	97.7	93.5	123.9	131.4	176.5	51.8	12.4	3.7	757.9
2011	0.5	0.3	3.4	2.5	12.0	21.9	49.4	110.1	167.9	41.5	11.5	3.7	424.7
2012	0.2	0.0	0.4	14.0	13.3	9.3	54.1	107.2	137.8	39.4	7.2	1.2	384.1
2013	0.2	0.6	2.7	14.2	19.7	45.6	119.9	149.3	132.0	137.0	19.8	3.3	644.3
2014	1.1	3.9	6.9	10.1	22.9	15.4	26.1	56.5	94.5	49.4	8.3	1.5	296.7
2015	0.6	0.5	2.1	4.3	9.9	17.7	28.5	48.5	66.2	29.2	5.4	1.1	213.9
2016	1.0	0.2	3.5	34.6	77.9	53.0	102.4	116.0	94.4	45.2	3.2	1.3	532.5
2017	0.1	5.2	5.0	7.3	9.7	8.3	19.6	27.7	77.7	22.8	2.8	0.3	186.6
2018	0.0	0.5	3.1	4.7	13.8	48.5	55.1	57.7	63.7	20.1	4.0	0.4	271.5
Mean	**3.3**	**4.5**	**7.5**	**13.3**	**18.7**	**21.4**	**52.0**	**113.5**	**93.2**	**41.2**	**11.1**	**4.5**	**383.9**
Max	**7.3**	**29.3**	**53.6**	**57.1**	**97.7**	**93.5**	**123.9**	**266.3**	**176.5**	**137.0**	**55.2**	**10.7**	**757.9**
Min	**0.0**	**0.0**	**0.0**	**1.1**	**4.5**	**5.5**	**18.8**	**27.7**	**28.7**	**8.9**	**2.8**	**0.3**	**182.2**

Table 12-B: Mean monthly streamflow of Sagure gauge stations from 1986-2018 (Mm^3)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1986	3.3	3.5	4.1	6.9	7.4	4.5	59.7	119.8	64.9	20.0	4.7	4.1	302.7
1987	3.7	3.3	9.4	35.4	23.9	21.1	14.9	56.7	21.8	10.7	4.1	4.0	209.2
1988	3.9	4.4	4.4	5.5	5.6	6.1	67.5	236.4	71.5	76.1	12.7	8.3	502.4
1989	6.7	6.0	6.2	14.0	9.6	9.5	32.8	62.4	62.3	14.9	7.9	9.1	241.5
1990	6.2	26.9	43.4	44.4	13.6	8.4	27.7	116.9	63.5	11.9	5.1	4.3	372.3
1991	3.9	4.4	7.5	7.9	4.9	5.3	22.5	122.4	73.7	7.1	3.5	3.3	266.3
1992	3.4	4.1	3.2	5.6	4.7	4.7	14.8	172.4	77.0	37.0	6.8	5.5	339.0
1993	4.7	12.0	4.4	10.6	23.3	27.6	38.0	179.9	70.6	41.5	10.0	5.7	428.3
1994	5.2	4.0	4.8	5.0	8.0	9.1	69.5	27.8	30.2	7.7	6.8	6.5	184.6
1995	12.2	10.7	16.4	56.0	3.6	5.1	12.7	25.0	43.7	9.2	1.7	0.6	196.9
1996	10.1	7.7	12.8	11.6	21.8	43.5	67.6	229.9	63.4	24.3	10.8	11.5	515.1
1997	15.3	11.6	12.8	22.5	14.9	15.3	43.8	73.9	26.5	21.1	25.0	13.0	295.6
1998	15.2	17.4	20.8	22.4	26.8	17.2	70.2	238.2	142.1	104.4	24.0	15.1	713.9
1999	13.9	10.1	15.4	11.4	12.1	16.8	72.5	120.4	74.5	122.4	23.8	13.8	507.1
2000	12.6	10.2	13.8	20.8	77.8	98.6	117.5	251.1	89.0	104.5	31.8	16.2	843.7
2001	5.3	0.7	2.6	1.9	3.2	6.2	13.8	283.6	84.3	19.7	6.4	5.5	433.3
2002	16.0	11.6	17.3	17.8	18.3	24.0	10.5	28.6	27.4	5.1	0.9	1.0	178.5
2003	0.9	0.2	1.3	4.2	4.5	7.2	25.7	69.7	58.5	13.6	2.3	3.1	191.2
2004	2.4	1.7	1.6	21.0	5.6	7.5	72.3	110.4	50.0	9.0	1.1	0.3	283.0
2005	0.7	0.4	1.0	1.7	16.1	7.3	17.9	29.3	36.0	10.8	1.9	0.4	123.5
2006	2.2	4.2	10.5	37.2	40.9	23.9	20.6	44.5	47.4	14.8	9.2	1.7	256.9
2007	2.8	3.5	2.4	6.5	6.9	20.8	67.4	230.5	128.3	18.1	1.6	0.2	488.8
2008	0.1	0.1	0.1	0.4	2.4	10.0	23.9	56.2	45.6	12.8	52.7	3.9	208.0
2009	7.0	5.9	1.3	9.6	5.0	3.8	15.0	33.6	29.5	27.6	5.1	6.5	149.9
2010	1.0	2.5	6.3	13.4	26.3	19.8	23.5	59.0	73.6	15.0	3.1	1.8	245.4
2011	1.5	0.5	3.2	1.8	7.6	13.6	31.7	82.5	123.4	23.2	9.5	2.8	301.2
2012	0.4	0.2	0.3	9.7	8.0	5.1	35.5	77.3	80.5	18.0	3.2	0.7	238.8
2013	0.4	0.6	1.4	8.3	11.0	36.7	101.3	128.4	86.7	100.9	15.6	3.3	494.6
2014	1.3	3.8	5.5	7.3	18.6	11.4	17.7	42.4	59.5	30.8	5.8	1.2	205.2
2015	0.6	0.4	1.0	2.2	4.7	9.0	15.0	27.5	31.7	12.3	2.6	0.7	107.6
2016	0.3	0.6	1.0	4.3	17.5	10.9	31.6	36.9	22.9	27.5	6.3	1.2	161.1
2017	0.5	1.3	2.3	4.4	8.6	7.0	13.4	18.2	52.0	16.4	2.2	0.4	126.8
2018	0.2	0.8	3.6	4.3	18.6	56.2	47.5	35.5	43.8	16.2	3.5	0.5	230.7
Mean	**5.0**	**5.3**	**7.3**	**13.2**	**14.6**	**17.4**	**39.9**	**103.9**	**62.3**	**30.4**	**9.4**	**4.7**	**313.4**
Max	**16.0**	**26.9**	**43.4**	**56.0**	**77.8**	**98.6**	**117.5**	**283.6**	**142.1**	**122.4**	**52.7**	**16.2**	**843.7**
Min	**0.1**	**0.1**	**0.1**	**0.4**	**2.4**	**3.8**	**10.5**	**18.2**	**21.8**	**5.1**	**0.9**	**0.2**	**107.6**

Table 13-B: Mean monthly streamflow of Chuifa gauge stations from 1986-2018 (Mm^3)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1986	0.4	1.2	4.5	2.7	2.1	3.4	10.8	11.3	16.6	5.2	1.4	1.0	60.7
1987	0.7	0.7	2.6	5.3	4.1	4.1	4.2	6.5	7.2	2.1	0.7	0.8	39.0
1988	0.7	0.8	0.5	1.0	0.8	1.3	8.6	17.3	12.9	6.5	1.5	0.8	52.7
1989	0.8	0.6	0.8	4.3	1.5	2.0	6.7	9.0	11.5	4.5	0.8	2.6	45.0
1990	0.7	3.1	4.9	4.8	2.2	1.2	6.3	12.0	10.8	4.1	0.9	0.6	51.6
1991	0.6	0.6	1.7	1.2	0.7	0.8	6.2	12.8	9.7	0.1	0.0	0.4	34.8
1992	1.0	2.0	1.0	2.2	1.7	1.5	4.3	26.5	20.7	10.7	1.4	0.7	73.7
1993	0.7	0.7	0.5	2.8	5.0	4.2	11.9	18.5	16.8	13.0	2.9	0.7	77.7
1994	0.6	0.6	0.9	0.6	0.8	2.6	17.5	22.2	20.2	5.2	1.9	1.5	74.7
1995	1.4	0.6	1.4	4.5	1.7	0.9	6.9	17.2	15.9	1.8	0.5	0.8	53.5
1996	1.0	0.4	2.4	3.1	5.0	14.5	15.2	24.5	13.5	3.2	0.6	0.5	83.9
1997	0.6	0.5	0.8	3.9	1.2	1.6	9.9	12.2	7.7	2.8	3.0	0.9	44.9
1998	0.7	0.7	2.0	0.8	2.0	1.5	6.3	23.7	13.6	13.5	2.7	0.9	68.2
1999	0.6	0.4	0.6	0.5	0.5	1.3	8.0	12.5	10.9	16.3	2.7	0.8	55.2
2000	0.5	0.4	0.4	0.5	4.3	2.5	7.8	19.0	12.4	11.5	3.7	1.1	64.1
2001	0.9	0.7	0.5	0.4	0.6	6.7	15.7	23.2	13.8	2.7	1.2	1.1	67.4
2002	1.0	0.8	1.5	1.0	0.9	0.4	2.1	9.6	6.9	1.4	0.5	0.5	26.7
2003	0.6	0.4	0.4	0.3	0.9	2.0	9.6	16.9	13.1	1.2	0.3	0.2	45.8
2004	0.7	0.4	0.6	2.6	0.9	1.4	7.9	13.7	16.1	10.0	1.2	0.8	56.3
2005	0.7	0.5	2.3	2.5	9.6	2.9	11.0	13.7	12.2	3.3	0.8	0.4	59.8
2006	0.4	0.5	1.9	6.4	2.1	2.9	15.5	21.3	15.5	4.7	1.4	0.6	73.2
2007	0.8	1.0	1.0	12.7	1.1	5.8	10.2	8.6	13.5	6.7	1.7	0.4	63.6
2008	0.2	0.1	0.2	0.3	1.1	3.4	5.7	10.0	9.4	5.2	9.0	2.2	46.8
2009	1.2	1.8	0.7	4.1	2.1	1.3	2.6	5.1	5.5	6.6	2.7	1.6	35.4
2010	0.8	1.8	4.8	6.2	9.2	7.6	7.6	11.7	17.1	6.6	1.6	0.5	75.6
2011	0.2	0.3	0.9	0.8	2.5	4.0	5.5	7.4	12.3	5.8	2.0	0.8	42.4
2012	0.3	0.2	0.3	3.7	3.1	2.0	6.5	10.5	13.6	6.5	2.4	0.7	49.8
2013	0.3	0.3	0.8	2.5	2.6	5.6	13.0	12.8	12.1	11.4	3.6	1.0	65.9
2014	0.4	0.8	1.4	1.5	2.2	2.0	1.9	3.1	7.0	4.6	1.4	0.4	26.8
2015	0.2	0.2	0.4	0.7	1.6	2.7	3.1	3.0	4.1	2.5	0.8	0.3	19.6
2016	0.1	0.2	0.4	1.0	2.8	2.5	4.9	3.9	3.0	2.8	1.0	0.4	22.9
2017	0.1	0.7	1.1	1.7	2.2	2.3	2.9	3.6	8.6	4.9	1.7	0.6	30.4
2018	0.2	0.4	1.3	1.6	3.4	8.5	8.8	6.5	7.8	4.5	1.9	0.6	45.4
Mean	**0.6**	**0.7**	**1.4**	**2.7**	**2.5**	**3.3**	**8.0**	**13.0**	**11.9**	**5.8**	**1.8**	**0.8**	**52.5**
Max	**1.4**	**3.1**	**4.9**	**12.7**	**9.6**	**14.5**	**17.5**	**26.5**	**20.7**	**16.3**	**9.0**	**2.6**	**83.9**
Min	**0.1**	**0.1**	**0.2**	**0.3**	**0.5**	**0.4**	**1.9**	**3.0**	**3.0**	**0.1**	**0.0**	**0.2**	**19.6**

Table14-B: Mean monthly streamflow of lower Timala gauge stations from 1986-2018 (Mm^3)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1986	0.3	0.3	0.4	0.5	0.6	0.8	3.6	8.4	2.7	1.3	0.4	0.4	19.7
1987	0.3	0.3	0.9	2.1	1.6	1.3	0.8	0.9	0.9	0.9	0.4	0.5	11.0
1988	0.5	0.7	0.5	0.8	0.7	0.9	1.5	5.2	3.9	2.7	0.9	0.6	18.8
1989	0.5	0.6	0.6	1.9	0.8	1.6	4.3	3.2	2.0	1.2	0.7	0.9	18.5
1990	0.8	1.4	2.2	3.1	1.4	1.1	2.2	5.6	4.1	1.7	0.8	0.7	25.2
1991	0.6	0.7	1.3	1.5	1.0	0.7	2.3	5.0	3.5	0.8	0.5	0.6	18.5
1992	0.6	0.5	0.5	0.9	1.2	1.1	1.6	18.4	5.3	1.8	0.8	0.8	33.6
1993	1.1	1.6	0.6	1.9	2.4	1.2	1.8	6.0	3.1	1.8	1.0	0.6	23.0
1994	0.5	0.4	0.5	0.5	0.5	0.8	5.1	15.5	4.0	1.3	0.7	0.6	30.3
1995	0.5	0.5	0.8	0.8	0.7	0.6	8.2	10.6	6.3	1.1	0.7	0.3	31.1
1996	0.2	0.0	0.2	0.6	0.8	1.6	3.3	12.0	2.9	0.9	0.1	0.0	22.6
1997	0.6	0.4	0.4	0.9	0.4	0.7	2.2	1.7	0.8	0.9	1.0	0.5	10.3
1998	0.5	0.7	1.4	0.6	1.9	0.7	3.0	6.5	7.4	5.0	1.3	1.0	30.0
1999	0.7	0.4	0.4	0.3	0.4	1.0	3.6	3.7	2.7	3.2	1.2	0.5	18.0
2000	0.3	0.2	0.2	0.3	0.4	0.4	1.1	13.9	3.4	1.7	0.8	0.3	23.2
2001	0.0	0.1	0.3	0.2	0.6	1.4	1.6	2.0	2.8	0.7	0.2	0.1	9.9
2002	0.1	0.1	0.3	0.4	0.6	1.0	1.1	2.5	2.9	0.6	0.1	0.1	9.7
2003	0.0	0.0	0.1	0.3	0.3	0.3	1.2	2.8	3.2	1.2	0.1	0.2	9.8
2004	0.3	0.1	0.1	0.6	0.3	0.5	1.3	2.7	4.8	4.1	0.5	0.2	15.5
2005	0.4	0.3	0.7	1.0	1.6	0.9	0.7	1.1	0.9	1.4	0.5	0.4	10.0
2006	0.5	0.5	0.5	1.9	1.9	1.1	7.8	4.9	9.0	1.7	0.8	0.7	31.3
2007	0.6	0.7	0.7	1.2	1.1	2.2	6.3	9.4	7.2	1.7	0.8	0.7	32.7
2008	0.0	0.0	0.0	0.0	0.2	0.4	1.2	2.9	3.8	1.4	2.1	0.1	12.2
2009	0.2	0.2	0.1	0.4	0.3	0.1	0.8	2.8	3.8	1.5	0.2	0.1	10.4
2010	0.0	0.1	0.6	1.2	2.6	2.8	3.8	3.8	6.0	1.7	0.4	0.1	23.2
2011	0.0	0.0	0.2	0.1	0.5	0.6	1.2	2.5	3.2	1.1	0.4	0.2	10.2
2012	0.0	0.0	0.0	0.1	0.1	0.1	1.1	2.9	4.4	1.3	0.1	0.1	10.2
2013	0.0	0.0	0.1	0.3	0.4	0.4	1.7	2.8	1.7	1.8	0.4	0.0	9.6
2014	0.0	0.0	0.1	0.1	0.2	0.5	1.8	5.6	4.1	4.2	0.3	0.0	17.0
2015	0.0	0.0	0.1	0.4	0.5	1.3	1.7	2.2	3.7	1.4	0.2	0.0	11.5
2016	0.0	0.0	0.1	0.9	1.9	1.3	3.0	3.4	3.0	1.5	0.1	0.1	15.3
2017	0.0	0.1	0.2	0.4	0.6	0.4	1.0	1.6	4.3	1.4	0.3	0.1	10.4
2018	0.0	0.0	0.1	0.2	0.8	2.5	2.4	2.2	2.6	1.2	0.4	0.1	12.6
Mean	**0.3**	**0.3**	**0.5**	**0.8**	**0.9**	**1.0**	**2.6**	**5.3**	**3.8**	**1.7**	**0.6**	**0.3**	**18.0**
Max	**1.1**	**1.6**	**2.2**	**3.1**	**2.6**	**2.8**	**8.2**	**18.4**	**9.0**	**5.0**	**2.1**	**1.0**	**33.6**
Min	**0.0**	**0.0**	**0.0**	**0.0**	**0.1**	**0.1**	**0.7**	**0.9**	**0.8**	**0.6**	**0.1**	**0.0**	**9.6**

Table 15-B: Mean monthly streamflow of Kekersitu gauge stations from 1986-2018 (Mm^3)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1986	0.2	0.2	0.2	0.2	0.2	0.2	0.2	1.3	1.9	2.4	1.6	1.3	10.0
1987	1.8	0.6	0.6	1.5	2.2	6.3	4.4	6.5	10.9	15.2	8.6	5.2	63.9
1988	3.2	2.2	1.7	1.8	1.7	1.7	1.8	4.0	13.4	38.1	27.9	16.5	114.1
1989	9.0	4.8	3.0	3.8	2.1	2.1	2.7	7.5	17.0	18.8	8.6	3.9	83.2
1990	1.4	1.1	3.7	8.7	7.3	2.0	3.2	27.2	67.3	63.1	37.5	20.0	242.5
1991	9.3	3.3	1.8	0.7	0.8	0.3	1.1	12.3	45.7	37.6	23.1	13.5	149.4
1992	6.4	2.5	1.1	0.6	0.2	0.1	0.3	11.6	52.4	59.2	44.6	28.2	207.2
1993	17.2	12.1	6.2	3.4	9.3	14.3	21.5	48.3	63.4	57.2	40.2	27.3	320.4
1994	16.0	8.7	6.1	2.0	0.1	0.1	0.1	7.7	31.5	40.3	29.2	21.2	162.9
1995	10.0	3.7	2.6	0.7	3.1	1.6	1.8	7.1	18.6	24.2	15.6	5.7	94.7
1996	3.2	0.9	0.4	0.5	1.4	4.7	14.4	42.9	22.6	61.2	40.5	26.6	219.3
1997	17.5	12.1	7.0	14.0	11.2	5.6	10.4	18.4	20.1	17.2	14.3	9.0	156.8
1998	4.8	2.3	2.0	0.5	0.7	0.9	1.2	19.1	54.7	21.9	62.8	46.9	217.7
1999	31.9	19.0	15.5	8.1	2.0	0.5	1.2	6.5	14.2	38.2	49.8	34.3	221.2
2000	22.4	10.6	2.9	1.0	0.8	0.3	1.0	3.0	11.8	30.3	31.7	24.3	140.2
2001	17.1	12.8	6.8	5.0	2.0	0.8	7.5	15.0	56.4	54.8	30.4	25.8	234.2
2002	19.9	12.0	7.5	3.9	1.8	1.8	2.6	3.2	4.7	2.5	1.8	1.6	63.2
2003	1.0	0.4	0.3	0.3	0.4	0.5	0.4	1.2	3.2	3.0	1.8	1.0	13.6
2004	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.5	3.3	3.1	1.1	0.7	8.9
2005	0.6	0.2	0.1	0.0	0.1	0.1	0.3	4.5	9.8	9.3	6.4	4.3	35.8
2006	2.0	0.6	0.6	2.1	4.0	1.8	1.5	10.8	20.8	22.6	38.5	22.0	127.3
2007	11.2	10.9	7.7	2.9	2.3	2.6	12.5	42.1	58.1	69.4	50.2	30.9	300.8
2008	19.6	4.6	2.8	1.7	1.2	1.1	4.6	16.9	38.3	10.5	10.0	7.0	118.5
2009	5.2	6.0	2.2	5.9	7.3	2.8	0.4	1.1	1.8	2.0	1.6	1.0	37.4
2010	0.7	1.0	5.6	5.6	10.3	13.7	23.5	43.2	67.4	64.6	49.4	42.7	327.7
2011	33.4	22.3	20.1	13.5	10.2	8.8	11.5	24.5	43.5	38.0	27.2	20.7	273.7
2012	15.8	11.3	7.1	5.3	4.6	3.4	5.8	19.3	34.7	33.7	22.8	18.1	182.0
2013	13.5	7.3	6.3	5.3	4.7	4.4	12.7	29.7	47.4	48.0	28.7	23.8	231.5
2014	18.4	14.3	12.4	10.1	7.0	5.4	5.8	10.1	17.4	29.1	25.3	20.7	176.0
2015	17.0	11.7	9.5	6.6	5.0	4.2	0.6	1.1	1.8	2.5	2.6	1.9	64.3
2016	17.0	11.7	9.5	6.6	5.0	1.3	1.5	1.9	2.3	2.2	1.7	1.2	61.7
2017	6.9	5.9	4.6	3.9	2.6	2.1	2.2	3.8	6.7	10.9	9.8	7.7	67.0
2018	6.3	4.8	3.5	2.5	1.8	1.1	0.6	1.1	1.8	2.5	2.6	1.9	30.7
Mean	**10.9**	**6.7**	**4.9**	**3.9**	**3.4**	**2.9**	**4.8**	**13.7**	**26.2**	**28.3**	**22.7**	**15.7**	**144.2**
Max	**33.4**	**22.3**	**20.1**	**14.0**	**11.2**	**14.3**	**23.5**	**48.3**	**67.4**	**69.4**	**62.8**	**46.9**	**327.7**
Min	**0.2**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.5**	**1.8**	**2.0**	**1.1**	**0.7**	**8.9**

Table 16-B: Mean monthly streamflow of Gedemso river from 1986-2018 (Mm^3)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1986	0.2	0.1	0.1	0.2	0.9	0.9	3.3	18.7	10.4	9.4	1.5	0.4	46.2
1987	0.2	0.2	0.1	0.2	0.9	0.9	3.3	18.7	10.4	9.4	0.5	0.4	45.2
1988	0.4	0.1	1.1	0.5	0.6	1.3	1.2	4.3	4.1	1.5	0.4	0.3	15.8
1989	0.2	0.1	0.2	0.8	0.7	0.3	1.2	4.3	4.1	1.0	0.5	0.1	13.4
1990	0.0	0.0	0.0	1.2	0.4	1.4	3.7	5.1	3.9	3.3	0.6	0.2	19.8
1991	0.2	0.0	0.0	1.2	1.4	0.7	3.5	11.1	10.1	1.0	0.5	0.1	29.8
1992	0.1	0.1	0.1	1.2	1.8	4.4	12.7	7.7	2.5	1.8	0.6	0.4	33.2
1993	0.2	0.1	0.1	0.2	0.5	0.7	5.4	4.8	8.0	1.8	0.6	0.4	22.8
1994	0.2	0.1	0.1	0.2	0.9	0.9	3.3	18.7	10.4	9.4	1.5	0.4	46.2
1995	0.2	0.2	1.0	5.8	4.1	3.4	1.9	18.7	10.4	9.4	0.5	0.4	55.9
1996	0.4	0.1	1.1	0.5	0.6	1.3	1.2	4.3	4.1	1.5	0.4	0.3	15.8
1997	1.4	0.4	0.5	1.2	1.0	0.8	7.5	11.5	3.9	2.7	1.9	1.0	33.9
1998	0.6	0.6	0.9	0.7	4.2	0.8	7.9	8.6	6.7	6.8	4.4	2.1	44.4
1999	1.3	0.8	2.8	1.4	1.5	2.2	8.4	15.7	10.1	12.4	2.8	1.0	60.4
2000	0.5	0.3	0.3	0.5	2.4	2.4	8.9	17.2	20.6	15.1	3.9	1.1	73.2
2001	0.2	0.2	0.1	0.2	0.9	0.9	3.3	18.7	10.4	9.4	0.5	0.4	45.2
2002	1.1	0.3	1.1	0.5	0.6	1.3	3.1	11.6	10.7	3.9	1.1	0.8	36.1
2003	0.4	0.2	0.5	2.1	1.8	0.3	1.2	4.3	4.1	1.0	1.3	0.3	17.4
2004	0.1	0.1	0.1	3.0	1.0	3.7	9.8	13.7	10.2	8.9	1.6	0.5	52.5
2005	0.4	0.0	0.0	1.2	1.4	1.7	9.4	19.8	26.2	2.8	1.2	0.3	64.5
2006	0.2	0.1	0.2	3.2	4.7	11.5	15.9	20.7	6.4	4.9	1.5	1.0	70.2
2007	0.6	0.3	0.2	0.5	1.4	2.1	14.6	13.1	8.0	1.8	0.6	0.4	43.6
2008	0.2	0.1	0.1	0.2	0.9	0.9	3.3	18.7	10.4	9.4	1.5	0.4	46.2
2009	0.2	0.2	0.1	0.2	0.9	0.9	3.3	10.7	8.4	7.4	0.5	0.4	33.2
2010	0.4	0.1	1.1	0.5	0.6	1.3	1.2	4.3	4.1	1.5	0.4	0.3	15.8
2011	0.2	0.1	0.2	0.8	0.7	0.3	1.2	4.3	4.1	1.0	0.5	0.1	13.4
2012	0.0	0.0	0.0	1.2	0.4	1.4	3.7	5.1	3.9	3.3	0.6	0.2	19.8
2013	0.2	0.0	0.0	1.2	1.4	0.7	3.5	11.1	10.1	1.0	0.5	0.1	29.8
2014	0.1	0.1	0.1	1.2	1.8	4.4	12.7	7.7	2.5	1.8	0.6	0.4	33.2
2015	0.2	0.1	0.1	0.2	0.5	0.7	5.4	4.8	8.0	1.8	0.6	0.4	22.8
2016	0.2	0.0	0.0	1.2	1.4	0.7	3.5	11.1	10.1	1.0	0.5	0.1	29.8
2017	0.1	0.1	0.1	1.2	1.8	4.4	12.7	7.7	2.5	1.8	0.6	0.4	33.2
2018	0.2	0.1	0.1	0.2	0.5	0.7	5.4	4.8	8.0	1.8	0.6	0.4	22.8
Mean	**0.3**	**0.2**	**0.4**	**1.0**	**1.3**	**1.8**	**5.6**	**11.0**	**8.1**	**4.6**	**1.1**	**0.5**	**35.9**
Max	**1.4**	**0.8**	**2.8**	**5.8**	**4.7**	**11.5**	**15.9**	**20.7**	**26.2**	**15.1**	**4.4**	**2.1**	**111.3**
Min	**0.0**	**0.0**	**0.0**	**0.2**	**0.4**	**0.3**	**1.2**	**4.3**	**2.5**	**1.0**	**0.4**	**0.1**	**10.4**

Table 17-B: Mean monthly streamflow of Horekalo river from 1986-2018 (Mm^3)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1986	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.2	0.2	0.2	0.2	0.2	1.5
1987	0.2	0.6	0.9	1.7	1.8	3.3	3.3	3.2	4.0	4.0	2.2	0.4	25.7
1988	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.4	7.3	5.9	3.2	18.8
1989	1.5	0.6	0.0	0.1	0.3	0.1	0.1	0.7	2.7	5.9	3.6	1.5	17.0
1990	0.2	0.1	0.1	0.1	0.1	0.1	2.1	8.5	13.0	12.7	7.4	4.4	48.7
1991	2.3	1.1	0.9	0.2	0.0	0.0	0.1	0.3	1.6	1.8	0.1	0.0	8.5
1992	0.1	0.4	0.1	0.0	0.0	0.0	0.1	0.1	1.6	5.3	4.7	1.8	14.2
1993	1.1	1.0	0.4	0.1	0.1	0.0	0.1	0.9	9.6	11.7	9.4	5.6	40.0
1994	2.5	2.2	2.4	2.4	1.4	0.1	0.8	8.5	17.5	29.3	12.2	7.9	87.1
1995	5.3	3.6	3.2	3.1	3.8	3.4	4.0	7.3	17.6	18.6	11.7	8.3	89.7
1996	5.3	3.8	3.1	1.9	2.2	4.4	7.6	24.4	33.8	30.1	15.7	8.9	141.1
1997	2.0	1.5	1.1	0.7	0.8	1.7	2.8	9.1	13.0	11.2	6.1	3.3	53.5
1998	4.4	2.1	1.5	0.3	0.2	0.1	0.0	1.8	5.9	13.3	13.8	8.1	51.6
1999	4.7	1.9	1.3	0.3	0.1	0.0	0.0	0.7	2.3	5.0	5.3	3.0	24.6
2000	0.9	0.9	0.9	0.9	0.5	0.0	0.3	3.2	2.5	10.0	11.1	8.8	40.2
2001	6.5	4.0	2.5	2.0	2.0	2.6	4.6	11.5	20.6	21.2	15.4	12.2	105.0
2002	9.9	5.1	3.6	2.1	1.3	0.9	0.6	3.1	5.0	4.6	2.4	0.9	39.4
2003	0.2	0.0	0.0	0.0	0.0	0.0	0.1	0.4	2.2	3.2	1.6	0.6	8.3
2004	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.3	0.0	0.0	0.4
2005	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.4	0.0	0.7
2006	0.0	0.0	1.3	0.8	0.5	0.3	0.2	1.2	1.9	1.7	3.6	2.4	14.0
2007	1.0	0.3	1.2	0.4	1.4	0.2	0.0	0.9	2.0	1.7	1.4	0.9	11.5
2008	0.9	0.9	0.9	0.9	0.5	0.0	0.3	3.2	2.5	3.7	4.3	3.3	21.6
2009	2.4	1.7	0.9	0.8	0.7	1.0	1.7	4.3	7.9	7.9	6.0	4.5	39.9
2010	3.7	2.1	1.3	0.8	0.5	0.3	0.2	1.2	1.9	1.7	0.9	0.3	15.0
2011	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.8	1.2	0.6	0.2	3.1
2012	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.2
2013	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.2	0.0	0.5
2014	0.0	0.0	1.3	0.8	0.5	0.3	0.2	1.2	1.9	1.7	1.4	0.9	10.3
2015	0.4	0.3	1.2	0.4	1.4	0.1	0.0	0.3	2.0	1.7	1.4	0.9	10.1
2016	2.0	1.5	1.1	0.7	0.8	1.7	2.8	9.1	13.0	11.2	6.1	3.3	53.5
2017	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.8	1.2	0.6	0.2	3.1
2018	0.4	0.3	1.2	0.4	1.4	0.1	0.0	0.3	2.0	1.7	1.4	0.9	10.1
Mean	**1.8**	**1.1**	**1.0**	**0.7**	**0.7**	**0.6**	**1.0**	**3.2**	**5.8**	**7.0**	**4.8**	**2.9**	**30.6**
Max	**9.9**	**5.1**	**3.6**	**3.1**	**3.8**	**4.4**	**7.6**	**24.4**	**33.8**	**30.1**	**15.7**	**12.2**	**141.1**
Min	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.1**	**0.0**	**0.0**	**0.2**

Table 18-B: Mean monthly Lake Ziway water level from 1986-2014 (m), datum level 1635 m.a.s.l

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1986	0.58	0.52	0.48	0.41	0.38	0.36	0.63	0.89	1.14	1.22	1.10	0.99	0.72
1987	0.85	0.72	0.69	0.69	0.78	1.06	1.08	1.16	1.21	1.15	1.00	0.85	0.94
1988	0.65	0.53	0.39	0.25	0.20	0.19	0.28	0.67	1.13	1.40	1.33	1.19	0.68
1989	1.02	0.92	0.81	0.82	0.78	0.70	0.77	0.99	1.26	1.36	1.22	1.05	0.97
1990	0.92	0.88	1.09	1.22	1.19	1.08	1.11	1.46	1.74	1.68	1.48	1.27	1.26
1991	1.12	1.00	0.98	0.93	0.82	0.69	0.79	1.25	1.65	1.57	1.35	1.17	1.11
1992	1.07	0.98	0.87	0.74	0.67	0.66	0.89	1.28	1.71	1.74	1.57	1.41	1.13
1993	1.30	1.21	1.07	0.95	1.05	1.13	1.25	1.60	1.80	1.80	1.65	1.47	1.36
1994	1.29	1.15	0.96	0.84	0.72	0.71	0.82	1.33	1.71	1.76	1.46	1.34	1.17
1995	1.21	1.09	0.95	0.90	1.01	0.93	0.91	1.20	1.47	1.41	1.20	1.06	1.11
1996	0.97	0.83	0.72	0.76	0.89	1.07	1.35	1.84	2.24	2.16	1.89	1.68	1.37
1997	1.53	1.40	1.24	1.24	1.22	1.11	1.20	1.36	1.42	1.34	1.31	1.18	1.30
1998	1.06	0.96	0.93	0.87	0.83	0.79	0.90	1.44	1.97	2.13	2.04	1.78	1.31
1999	1.56	1.37	1.23	1.09	0.96	0.82	0.94	1.23	1.43	1.65	1.81	1.60	1.31
2000	1.41	1.22	1.03	0.82	0.79	0.74	0.80	1.02	1.40	1.58	1.55	1.41	1.15
2001	1.27	1.12	1.03	1.00	0.94	0.97	1.21	1.70	2.25	2.15	1.93	1.75	1.44
2002	1.57	1.41	1.30	1.20	1.08	0.99	0.93	1.03	1.22	1.15	0.97	0.81	1.14
2003	0.68	0.58	0.45	0.38	0.36	0.24	0.37	0.86	1.17	1.19	1.03	0.92	0.69
2004	0.84	0.76	0.57	0.55	0.52	0.40	0.37	0.74	0.95	1.11	1.01	0.90	0.73
2005	0.74	0.60	0.53	0.41	0.56	0.62	0.63	0.99	1.38	1.47	1.33	1.16	0.87
2006	1.02	0.89	0.79	0.92	1.06	1.00	1.17	1.80	2.19	2.24	2.01	1.79	1.41
2007	1.61	1.51	1.34	1.28	1.18	1.28	1.49	1.91	2.32	2.41	2.14	1.87	1.70
2008	1.62	1.45	1.28	1.11	1.02	0.95	1.07	1.47	1.82	1.79	1.80	1.64	1.42
2009	1.51	1.39	1.22	1.13	0.95	0.82	0.77	0.99	1.14	1.16	1.09	0.97	1.10
2010	0.86	0.79	0.84	0.83	0.98	1.13	1.27	1.74	2.25	2.35	2.17	1.98	1.43
2011	1.73	1.59	1.45	1.30	1.15	1.10	1.21	1.47	1.86	1.89	1.71	1.58	1.50
2012	1.44	1.20	1.03	0.94	0.84	0.67	0.80	1.33	1.77	1.85	1.67	1.49	1.25
2013	1.30	1.15	1.00	0.97	0.95	0.83	0.88	1.36	1.83	2.04	2.05	1.66	1.34
2014	1.62	1.53	1.46	1.41	1.16	1.03	0.99	1.26	1.68	1.89	1.83	1.72	1.46
Mean	**1.19**	**1.06**	**0.96**	**0.89**	**0.86**	**0.83**	**0.93**	**1.29**	**1.62**	**1.68**	**1.54**	**1.37**	**1.18**
Max	**1.73**	**1.59**	**1.46**	**1.41**	**1.22**	**1.28**	**1.49**	**1.91**	**2.32**	**2.41**	**2.17**	**1.98**	**1.75**
Min	**0.58**	**0.52**	**0.39**	**0.25**	**0.20**	**0.19**	**0.28**	**0.67**	**0.95**	**1.11**	**0.97**	**0.81**	**0.58**

Table 19-B. Mean monthly Lake Langano water level from 1986-2014 (m), datum level 1582.1 m.a.s.l

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1986	1.08	0.93	0.86	0.83	0.86	1.04	1.40	1.66	1.86	1.91	1.75	1.56	1.31
1987	1.38	1.27	1.24	1.34	1.35	1.51	1.48	1.50	1.63	1.61	1.48	1.33	1.43
1988	1.19	1.09	0.99	0.87	0.81	0.79	0.83	1.17	1.48	1.72	1.64	1.43	1.17
1989	1.27	1.22	1.13	1.17	1.16	1.13	1.17	1.31	1.47	1.62	1.53	1.41	1.30
1990	1.33	1.28	1.35	1.41	1.42	1.40	1.53	1.76	1.96	1.98	1.80	1.62	1.57
1991	1.46	1.37	1.31	1.26	1.15	1.08	1.17	1.27	1.46	1.49	1.33	1.20	1.30
1992	1.09	1.06	1.04	1.14	1.12	1.00	1.00	1.11	1.40	1.71	1.86	1.73	1.27
1993	1.61	1.56	1.44	1.35	1.36	1.45	1.55	1.78	2.06	2.13	2.11	1.94	1.69
1994	1.77	1.62	1.52	1.44	1.42	1.43	1.56	1.85	2.12	2.28	2.10	1.92	1.75
1995	1.75	1.62	1.55	1.51	1.55	1.46	1.53	1.73	1.96	2.03	1.86	1.68	1.69
1996	1.61	1.49	1.36	1.36	1.36	1.49	1.77	2.19	2.37	2.29	2.05	1.86	1.77
1997	1.70	1.55	1.39	1.39	1.35	1.30	1.45	1.62	1.69	1.67	1.68	1.56	1.53
1998	1.45	1.38	1.30	1.20	1.17	1.12	1.08	1.27	1.51	1.78	1.84	1.66	1.39
1999	1.48	1.31	1.25	1.17	1.08	1.03	1.12	1.33	1.53	1.84	1.93	1.73	1.40
2000	1.55	1.38	1.21	1.10	1.12	1.07	1.09	1.24	1.52	1.82	1.85	1.72	1.39
2001	1.54	1.42	1.34	1.31	1.30	1.36	1.49	1.86	2.14	2.12	1.96	1.76	1.63
2002	1.61	1.46	1.35	1.26	1.18	1.13	1.09	1.28	1.46	1.44	1.25	1.12	1.30
2003	1.04	0.91	0.81	0.71	0.64	0.58	0.66	0.98	1.27	1.35	1.18	1.06	0.93
2004	0.92	0.86	0.67	0.66	0.60	0.50	0.53	0.78	0.98	1.09	1.00	0.86	0.79
2005	0.73	0.63	0.56	0.44	0.54	0.55	0.57	0.78	1.06	1.19	1.09	0.90	0.75
2006	0.74	0.63	0.52	0.52	0.54	0.49	0.63	1.06	1.42	1.52	1.45	1.29	0.90
2007	1.15	1.10	0.95	0.87	0.82	0.85	0.95	1.22	1.57	1.77	1.60	1.40	1.19
2008	1.24	1.11	0.93	0.81	0.72	0.71	0.75	0.89	1.35	1.41	1.50	1.35	1.06
2009	1.22	1.12	0.96	0.88	0.76	0.67	0.64	0.72	0.89	1.14	0.91	0.78	0.89
2010	0.67	0.59	0.59	0.61	0.88	1.09	1.17	1.50	1.82	1.91	1.73	1.54	1.18
2011	1.38	1.24	1.10	0.98	0.92	0.94	1.02	1.37	1.76	1.77	1.59	1.38	1.29
2012	1.20	1.04	0.91	0.88	0.86	0.77	0.85	1.28	1.50	1.57	1.41	1.26	1.13
2013	1.13	0.99	0.85	0.84	0.80	0.78	0.83	1.17	1.48	1.96	1.91	1.66	1.20
2014	1.48	1.37	1.29	1.17	1.08	1.09	1.06	1.13	1.38	1.66	1.73	1.54	1.33
Mean	**1.30**	**1.19**	**1.10**	**1.05**	**1.03**	**1.03**	**1.10**	**1.34**	**1.59**	**1.72**	**1.62**	**1.46**	**1.29**
Max	**1.77**	**1.62**	**1.55**	**1.51**	**1.55**	**1.51**	**1.77**	**2.19**	**2.37**	**2.29**	**2.11**	**1.94**	**1.85**
Min	**0.67**	**0.59**	**0.52**	**0.44**	**0.54**	**0.49**	**0.53**	**0.72**	**0.89**	**1.09**	**0.91**	**0.78**	**0.68**

Table 20-B: Mean monthly Lake Abiyata water level from 1986-2014 (m), datum level 1576.1 m.a.s.l

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1986	5.11	5.02	5.00	4.94	4.80	4.77	4.77	4.72	4.68	4.78	4.76	4.66	4.83
1987	4.52	4.15	4.12	4.19	4.14	4.19	4.08	4.05	4.13	4.05	3.85	3.69	4.10
1988	3.61	3.50	3.37	3.17	3.22	3.18	3.11	3.09	3.10	3.21	3.25	3.25	3.25
1989	3.12	3.06	3.07	3.08	3.02	3.21	3.33	3.27	3.28	3.42	3.44	3.45	3.23
1990	3.40	3.37	3.39	3.36	3.31	3.29	3.24	3.27	3.40	3.88	4.13	4.12	3.51
1991	3.97	3.95	4.00	3.98	3.76	3.61	3.60	3.65	3.65	3.90	3.96	3.87	3.83
1992	3.84	3.92	3.68	3.44	3.43	3.38	3.48	3.56	3.66	4.07	4.30	4.58	3.78
1993	4.60	4.60	4.54	4.44	4.43	4.50	4.52	4.62	4.82	5.20	5.39	5.36	4.75
1994	5.30	5.30	5.11	4.22	4.13	3.94	3.90	3.96	4.22	4.44	4.47	4.48	4.46
1995	4.45	4.45	4.40	4.44	4.43	4.30	4.22	4.22	4.25	4.51	4.69	4.53	4.41
1996	4.54	4.42	4.24	4.17	4.11	4.14	4.29	4.57	5.08	5.53	5.72	5.79	4.72
1997	5.72	5.65	5.52	5.43	5.30	5.22	5.22	5.27	5.42	5.42	5.49	5.39	5.42
1998	5.30	5.23	5.16	5.02	4.90	4.82	4.74	4.81	4.88	4.47	4.56	4.67	4.88
1999	4.70	4.65	4.65	4.62	4.48	4.39	4.36	4.34	4.33	4.55	4.76	4.83	4.55
2000	4.85	4.76	4.59	4.43	4.37	4.25	4.20	4.17	4.17	4.31	4.43	4.46	4.42
2001	4.45	4.36	4.28	4.17	4.10	4.06	4.03	4.06	4.32	4.60	4.72	4.77	4.33
2002	4.79	4.72	4.68	4.59	4.46	4.32	4.24	4.22	4.18	4.05	3.85	3.69	4.32
2003	3.61	3.50	3.37	3.17	3.10	2.98	2.97	2.97	2.96	2.88	2.69	2.54	3.06
2004	2.41	2.30	2.09	2.05	1.90	1.87	1.83	1.80	1.75	1.73	1.57	1.40	1.89
2005	1.22	1.41	1.53	1.51	1.67	1.67	1.61	1.60	1.54	1.53	1.50	1.43	1.52
2006	1.25	1.07	0.99	1.06	1.04	1.05	1.12	1.07	1.27	1.77	2.10	2.02	1.32
2007	2.00	1.98	1.96	1.85	1.67	1.74	1.78	1.85	2.20	2.76	3.07	3.24	2.17
2008	3.35	3.22	3.06	2.76	2.68	2.78	2.82	2.97	2.95	3.24	3.51	3.55	3.07
2009	3.64	3.64	3.49	3.38	3.19	3.03	2.96	2.96	2.87	2.84	2.73	2.54	3.11
2010	2.35	2.27	2.25	2.02	2.18	1.96	1.95	1.95	2.10	2.67	2.84	2.80	2.28
2011	3.09	3.23	3.06	2.85	2.59	2.65	2.72	2.76	2.76	2.79	2.76	2.83	2.84
2012	3.14	3.39	3.21	2.53	2.39	2.37	2.40	2.46	2.60	2.82	2.87	2.74	2.74
2013	2.81	2.77	2.48	2.35	2.37	2.34	2.40	2.46	2.55	2.63	2.92	3.06	2.60
2014	2.80	2.73	2.69	2.65	2.68	2.77	2.82	2.97	2.95	3.24	3.51	3.65	2.96
Mean	**3.72**	**3.68**	**3.59**	**3.44**	**3.37**	**3.34**	**3.33**	**3.37**	**3.45**	**3.63**	**3.72**	**3.70**	**3.53**
Max	**5.72**	**5.65**	**5.52**	**5.43**	**5.30**	**5.22**	**5.22**	**5.27**	**5.42**	**5.53**	**5.72**	**5.79**	**5.48**
Min	**1.22**	**1.07**	**0.99**	**1.06**	**1.04**	**1.05**	**1.12**	**1.07**	**1.27**	**1.53**	**1.50**	**1.40**	**1.19**

About the Author

Demelash Wondimagegnehu Goshime obtained his Bachelor of Science in Water Resources and Irrigation Enrineering in 2008 and MSc in Hydraulic and Hydropower Engineering in 2011 from Arba Minch Univerisity. In 2014, he received postgraduate diploma in Enviromental Hydrology in arid and semi-arid regions at Hydraulics research institute in Egypt. Besides, he also participated in different training such as GIS and remote sensing (UNESCO-IHE, The Netherlands), Global water challenges (ETH Zurich, Switzerland), Dam safety (ICH, Norway), Enviromental and resource protection (AMU-Rostock, Ethiopia), QGIS (Nairobi, Kenya), Regional climate and impact modelling (AAU, Ethiopia), Groundwater modelling (AMU, Ethiopia) among others. After working for five year as teaching, research and post graduate coordinator at Arba Micnh university institute of technology, he started his PhD in 2017 at CY Cergy Paris University, France as part of sandwich exchange program funded by Ethio-France goverement. His PhD research focuses on integration of satellite and ground-based rainfall data for water resources assessment of centreal rift valley lakes basin of Ethiopia towards a high-resolution and model based approach. As part of his PhD research, he had the opportunity to work and collaborate with the Ministry of Water, Irrigation and Electricity of Ethiopia who financially supported his PhD research. His research interests span across field of water resources, hydrology, satellite rainfall estimate, climate change, water abstraction and water allocation among them to mention.

Publications

Goshime, D.W., Absi, R., Ledésert, B. (2019). Evaluation and bias correction of CHIRP rainfall estimate for rainfall-runoff Simulation over Lake Ziway Watershed, Ethiopia. MDPI Journal of Hydrology, 6(3), doi.org/10.3390/hydrology6030068.

Goshime, D.W., Absi, R., Haile, A.T., Ledésert, B, Rientjes. T. (2020). Bias-corrected CHIRP satellite rainfall estimate for water level simulation, Lake Ziway, Ethiopia. Accepted by ASCE Journal of Hydrologic Engineering.

Goshime, D.W., Haile, A.T., Absi, R., Ledésert, B. (2020). Impact of water abstraction on the water balance of Lake Ziway, Ethiopia. Condiotional accepted by Journal of Sustainable Water Resources Management (SWAM), Springer.

Goshime, D.W., Haile, A.T., Absi, R., Ledésert, B., Rientjes, T.H.M., Tobias, S. (2020) Assessment of existing and future water demand on Central Rift Valley Lakes basin of Ethiopia, to be submitted to Journal of Advances in Water Resources, Elsevier.

Goshime, D.W, Absi, R., Ledésert, B., Dufour, F., Haile, A.T. (2019). Impact of water abstraction on the water level of Lake Ziway, Ethiopia.Vol. 239 of the WIT Transactions on Ecology and the Environment (ISSN: 1743-3541), 12, 67-68.

Conference abstracts

Goshime, D. W., Absi, R., Ledesert, B., Haile, A. (2018). Evaluating the value of bias correction of high-resolution satellite rainfall product (CHIRP) to simulate streamflow into Lake Ziway, Ethiopia. 4th Remote Sensing and Hydrology Symposium (ICRS-IAHS), 8-10, May, 2018, Cordoba, Spain.

Goshime, D.W, Absi, R., Ledésert, B., Haile, A.T., Dufour, F., (2019). Impact of water abstraction on the water level of Lake Ziway, Ethiopia. 5th International conference on water and society, 2-4 October 2019, Valencia, Spain.

Goshime D. W., Haile, A.T. Absi, R., Ledésert, B., (2019). Impact of water abstraction on the water balance of Lake Ziway, Ethiopia. 4th International electronic conference on water sciences, managing water resources from aquifers, Rivers and Lakes from 13-19 November 2019.

Teaching and supervision activity

Teaching 'Dam and Reserviors'' course for MSc Hydrulaic Enginering summer and regular student of Arba Minch Univeristy School of Graduate studies (2018).

Co-supervision of MSc student thesis entitled on "Hydrologic Evaluation of High-Resolution Satellite Precipitation Products": case study on Dabus watershed, Abbay Basin, Ethiopia (2018).

Co-supervision of MSc student thesis entitled on "Surface water availability and water demand under climate and development scenarios, case study of Keleta Catchment, Ethiopia, (2019).