OPTIMAL ALLOCATION OF WATER RESOURCES TO COMPETING DEMANDS UNDER DIFFRENT SCENARIOS IN THE KATAR SUB-BASIN, CENTRAL RIFT VALLEY BASIN, ETHIOPIA

By

Saliha Muhammedamin

A Thesis Submitted to the Department of Water Resources Engineering, School of Civil Engineering and Architecture

Presented in Partial Fulfillment of the Requirements for the Degree of Master's in Water Resources Engineering (Specialization in Irrigation Engineering)

Office of Graduate Studies
Adama Science and Technology University

Jan, 2022

Adama, Ethiopia

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DECLARATION

I hereby declare that this Master Thesis entitled "**Optimal Allocation of Water Resources to Competing Demands under Different Scenarios in the Katar Sub-Basin, Central Rift Valley Basin, Ethiopia**" is my original work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation

Saliha Muhammedamin Yusuf	____________________	________________
Name of the student	Signature	Date

RECOMMENDATION OF THE ADVISOR

I, the advisor of this thesis, hereby certify that I have read the revised version of the thesis entitled "**Optimal Allocation of Water Resources to Competing Demands under Different Scenarios in the Katar Sub-Basin, Central Rift Valley Basin, Ethiopia**" prepared under my guidance by Saliha Muhammedamin Yusuf submitted in partial fulfillment of the requirements for the degree of Mater's of Science in Water Resources Engineering (Specialization in Irrigation Engineering) Therefore, I recommend the submission of revised version of the thesis to the department following the applicable procedures.

_________________________	_________________________	_______________
Name of Advisor	Signature	Date

APPROVAL PAGE OF THE MSC THESIS

I, the advisors of the thesis entitled "**Optimal Allocation of Water Resources to Competing Demands under Different Scenarios in the Katar Sub-Basin, Central Rift Valley Basin, Ethiopia**" and developed by Saliha Muhammedamin Yusuf, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

Abdulkerim Bedewi, (PhD) ________________ ________________

Advisor Signature Date

We, the undersigned, members of the Board of Examiners of the thesis by Saliha Muhammedamin Yusuf have read and evaluated the thesis entitled "Optimal Allocation of Water Resources to Competing Demands under Different Scenarios in the Katar Sub-Basin, Central Rift Valley Basin, Ethiopia" and examined the candidate during open defence. This is, therefore, to certify that the thesis is accepted for partial fulfilment of the requirement of the degree of Master of Science in Master's in Water Resources Engineering (Specialization in Irrigation Engineering) ______________________________ ________________ ________________

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ACRONYMS AND ABBREVIATIONS

AGNPS	Agricultural Non-Point Source model
CRV	Central Rift Valley
DDS	Decision Support System
DEM	Digital Elevation Model
EFR	Environmental Flow Requirement
FAO	Food and Agriculture Organization
GDP	Gross Domestic Product
GIRD	Generation Integrated Rural Development
GIS	Geographic Information System
GW	Ground Water
GWP	Global Water Partnership
IHA	Indicators of Hydrologic Alteration
IWRM	Integrated Water Resource Management
L/c/d	Litre Per Capita Per Day
m.a.s.l	Meters Above Sea Level
MCM	Million Cubic Meter
MODSIM	Modular Simulation Model
MoWIE	Ministry of Water, Irrigation and Electricity
NGOs	Non-Governmental Organizations
NSE	Nash Sutcliffe Simulation Efficiency
PGM	Plant Growth Model
RIBASIM	River Basin Simulation Model
SEI	Stockholm Environment Institute
SRTM	Shuttle Rader Topographic Missions
SWAT	Soil and Water Assessment Tool
TLU	Tropical Livestock Unit
UN	United Nation
UNCSD	United Nations, Commission on Sustainable Development
UNESCAP	United Nations, Economic and Social Commission for Asia and the Pacific
UNEP	United Nations Development Program
UNESCO	United Nations Educational, Scientific and Cultural Organization
WAGRI-SIM	Water Resources Graphical Interface – Simulation Tool
WEAP	Water Evaluation and Planning
WMO	World Meteorological Organization

ABSTRACT

As water is significant forever, analysis of both available and water demand within the basin is critical. This will enable to formulate water allocation strategies and allocation principles for present and future planning. Lack of sufficient knowledge about available water resources, unbalance between supply and demand coordination in water resources management, conflicts among different water use sectors, and improper distribution of available water resource in the river watershed are still a serious problem in the world including Ethiopia. Therefore the major goal of this study was to estimate the current and future demand and supply of water and water allocation scenario for Katar River sub-basin. To achieve this, evaluation of water demands were modeled using the WEAP model. Future water demand was estimated using three different scenarios namely short-term, medium term, and long-term scenario. According to the result obtained from the model, the total estimated mean annual surface runoff that leaves the basin is 289.61MCM. Both the calibration and validation result showed a very good performance with a value of R2 and NSE of 0.96, and 0.85 for calibration and 0.98, and 0.99 for validation respectively. The estimated mean annual actual evapotranspiration, precipitation, interflow, and Base flow is 2649.72 MCM, 3095.67 MCM, 78.74 MCM and 77.60 MCM respectively. Total available annual stream flow at the outlet Point of Katar River is 445.95 MCM. Current water demand for Domestic, Industrial, Livestock, and Irrigation was 45.13 MCM. The water demand result shows there is no shortage of water in the current situation. To forecast water demand up to the year 2050 three basic scenarios were formulated. The first scenario, short term scenario has not much effect on future water demand. In the medium term and long-term scenario, the development of irrigation activities and expansion of industries in the catchment was applied. In the medium and long-term scenario shortage of water demand will happen in Industrial and irrigation. Based on the result of this research it has been recommended that both water supply and demand side management measures should be well implemented in an integrated manner.

Keywords: *Katar sub-basin; WEAP; Water Allocation; Supply and Demand; Scenario Development*

1. INTRODUCTION

1.1 Background

Water is necessary for all forms of human, animal, and plant life. It is essential for overall human well-being and supports all aspects of human livelihoods. Furthermore, water plays an important role in supporting productive human activities such as agricultural, energy, and industrial production, sanitation, transportation services, fishing and tourism (UNEP, 2009). The global water demand will primarily grow due to population and economic growth, rapid urbanization, and the increasing demand for food and energy (GWP and INoBO, 2009). Therefore, assessing water resource availability of relevant spatial and temporal scales is of importance (Yang and Zehnder, 2007) as well as an ability to assess the availability of freshwater resources has been an issue of importance in most countries for many decades (WMO, 2012).

The growing pressure on the world′s fresh water resources which is enforced by population growth can lead to conflicts between demands for different uses (Tessema, 2011). The conflict is mainly between the environment and other purposes like irrigation for agriculture, hydropower, domestic and industrial water supply. As the demand for water increases across the world, the availability of fresh water in many regions is likely to decrease due to population growth, industrialization, landuse, and climate change. Hence, the utilization of integrated water resources management is an optimum way to handle the question of water resource management and planning. It is a way of analyzing the change in demand and operation of water institutions that evaluates a variety of demand and supply-side management measures to determine the optimal way of providing water services (Sonjica, 2004).

Due to high water demand from population growth, degradation of the rivers and pollution of surface and groundwater sources, and the loss of potential sources of fresh water supply since of old and unsustainable water, management practices (UNCSD, 1994; Wang, 2005). The scientists and practitioners were forced to establish appropriate water allocation approaches and associated management institutions and policies in IWRM. Therefore, the water allocation approach becomes more important as a mechanism to prevent conflict originating in increasing scarcity and competition for basin water resources.

In the context of a river basin, allocation priority becomes important when the full water rights of all water users cannot be supplied. A prioritized system allows the water managers to take control over the water use in a river basin by allocating water in a preferred order. This preferential order could be based on regional or national objectives (Weragala, 2010). In the context of water management, decision makers in the arid and semi-arid states face a question about how much water should be allocated among competing uses. Around one-fifth of the world's population currently lives in water scarce areas, and more than two-thirds will live in areas with physical or economic water scarcity by 2025 (UNWATER, 2007). Water resources management becomes increasingly critical and as new, local and national sources of water become scarce, limited, expensive and difficult to exploit. Many countries in the arid and semi-arid regions that are facing water crisis will be increasingly forced to consider the possibilities of utilizing the water that is available in river basins.

Water allocation has received considerable attention in the recent past years by the scientific community. Quba'a *et al*. (2002) discussed the optimal allocation of water between market uses but did not directly consider management to maximize benefits from the distribution of water among consumptive and non-consumptive uses. The complexity of the water allocation task and the increasing pressure on water (increasing demand and variability) have stimulated the revision of water allocation goals and means in many countries (Roa-García, 2014). Therefore, the appropriate water allocation and management requires an understanding of water availability and reliability with considering equity, efficiency, and sustainability as the key principles in water allocation (UNESCAP, 2000). The sustainable management of water resources requires a clear understanding of the water resources in the basin to meet the growing demand of the world‘s population for water and to achieve secure and sustainable water in the future.

Currently, the Central Rift Valley (CRV) basin has been facing challenges for satisfying ever-growing demands for water, domestic use, irrigation, and the requirement for environmental flow to maintain ecosystem health (Alemayehu *et al*., 2006; Ayenew, 2007; Legesse and

Ayenew, 2006; Pascual-ferrer *et al*., 2013). Consequently, competition has steadily tightened for Lake Ziway water abstraction among many water users (Pascual-Ferrer *et al*., 2014). Besides, the sustainability of water resources has become more challenged under potential impacts of human-induced changes such as land development and climate change. Effective water resources management depends on a thorough understanding of the quantity and quality of available water in the sub-basin (Lorenz and Ziegeweid, 2016).

The Katar River is used as an important source for food, domestic water supply, agriculture, wildlife, grazing, water for livestock, and as a repository for human and agricultural. This makes the issue of water resource availability very crucial for effective water resources management and improves livelihoods. In Ethiopia, where agriculture serves as a backbone of the economy as well as ensures the wellbeing of the people, the availability of water resources is quite essential.

Water allocation models are useful because, by simulating scenarios of situations encompassing complicated hydrological, environmental and socio-economic factors, they can provide insights into the likely impacts of different development options (Mccartney and Arranz, 2007). This study described the use of the Water Evaluation and Planning (WEAP) model to evaluate scenarios of water resource development in the Katar watershed. The model assess water availability and investigate the impacts of different water allocation scenarios (water demand management strategies) to meet various sectorial water demands in the Katar watershed.

1.2 Statement of the Problem

The processes of population increase, urbanization and industrialization has resulted in a rapid demand increase for water resources in the developing world. Due to this reason, water managers in the river basins of the developing world face the increasingly difficult task of allocating the limited water resources among competing users. As a result, the difference between available water resources and water demands is ever increasing (Weragala, 2010; Thuo, 2013).

The Ethiopian water resource management policy aims at developing the water resource of the country for the economic and social benefits of the people on equitable and sustainable basis with the widely accepted IWRM (integrated water resource management) principles, the climate change impact on flow volume and an increasing population growth affected the stream flow volume of the river. Impact on flow volume put their negative side to trust the earlier water demand assessments to know the demands of water for a specific project to meet the needs that the project aims.

The Katar sub-basin's primary economy is agriculture and there is a desperate need to increase water uses for food, industries and other uses, therefore water allocation among competing water users are urgently required to avoid a water-based conflict, over utilization of the rivers' scarce water resources, and to address the challenges facing the basins common forms of resource management.

The Katar River is currently adequate in water; however, due to urbanization, industrail growth, irrigationn and mismanagement, water scarsity will take place in the future. As cited by Desta and Lemma (2017) in their findings, Katar sub-basin is an important source of the economic growth and social development of the communities in the sub-basin because it is an important source of water for irrigation, domestic, and livestock purposes. However, the Katar River is currently faced the declining of water due to rapid population, urbanization, climate change and industrial growth. This increases in demand, competition, and conflicts among different water use sectors and this causes the unbalance between the demand and supply of the catchment.

In Katar sub-basin there is insufficient knowledge of available water resources, lack of coordination in water resources allocation and management, estimated future water demand, water requirement for different users, and supply and demand interaction in the sub-basin because the catchment is one of the potential future development areas. These indicate there is a need to analyze the water availability and demand of the catchment and to formulate water allocation strategies and allocation for present and future planning. Therefore, this study fills the gaps between the demand and supply of the catchment; specifically, consider the current and future development scenarios and improving the optimal allocation in the Katar sub-basin using the WEAP model.

1.3. Objective

1.3.1. General objective

The overall objective of this study was to allocate the water resources to demanding sectors in a sustainable manner for social, economic, and environmental benefits in the Katar River sub-basin.

1.3.2. Specific objectives

- → To assess the available surface water for appropriate water allocation to different users
- → To analyses water demand of various water competing users in the Katar sub-basin
- → To develop current and future water allocation under different development scenarios.

1.4. Research Questions

- → How much the available surface water in the watershed is for appropriate water allocation to different users?
- → What are the water demands of various water competing users in the Katar sub-basin?
- → How much is the current and future water allocation under different development scenarios?

1.5. Significances of the Study

The research is highly significant for the body responsible to allocate and manage the water resource of the sub-basin under study by providing the current and future demands for water. The water demands under different scenarios are used to visualize the balance with the water supply so as to analyze the future reliability of the water resources of the sub-basin and to undertake different water demand management measures. In addition, it is very important for further study to evaluate the effects of future irrigation developments, and population increase on the water resources availability of the catchment.

The Katar sub-basin is a potential area for cereal-based double cropping. For example, the Katara farming center is an institution that produces a huge amount of cereal-based cash crops within the watershed. The local farmers and individuals are also producing abundant food crops and generating adequate income for their livelihood using the green water in the watershed. Therefore, this research is critical in determining the water resources potentials, and in assessing the available water in the sub-basin for present and future agricultural uses. The results of this study can also be used as bases for equitable water allocation and distribution especially during water crises and towards the rational utilization of available water in the watershed. Moreover, the results of the study are valuable to farmers, researchers, the local institutions, the government as well as NGOs involved in water management, environmental conservation, planning, and development. It also helps all relevant stakeholders at the ground level to use water resources in an efficient and sustainable manner while giving consideration such as social, economic, and environmental benefits.

1.6. Scope and Limitation of the Study

This research was restricted only to the Katar watershed which is situated at $7^{0}21'34''$ to $8^{0}9'55''$ North latitudes and $38^{0}53'57''$ to $39^{0}24'46''$ East longitudes. The study focused on current, future water demand and optimal allocation using the WEAP model. It also covers selected demands such as (domestic, irrigation, livestock, industrial and environmental flow) for water allocation. The Groundwater, Climate change, Land use and Land cover are not considered to be researched on because of data and time constraints.

1.7. Thesis Organization

This study report was organized with seven chapters. Chapter one provides a brief introduction of the study, a statement of the problem, objectives of the research, research questions, and significance of the study. Chapter two deals with about literature survey in the subject area. In chapter three, a detail description of the study area, and dataset and data sources for WEAP Model are presented. Chapter four is explaining the results and discussion part of the study. Conclusions and recommendations are presented in chapter five. The last two chapters are references and appendix.

2. LITRATURE RIVEW

The chapter describes water resource availability assessment, water demand assessment, optimal water allocation mechanism and criteria for water allocation, WEAP model and different Decision Support System (DSS) tools for analysing allocation of water resources used by different researchers around the world.

2.1 Water Resources Availability Assessment

The eradication of poverty and hunger in rural areas is closely related to fair and equitable access for the most vulnerable people with basic livelihood assets (including land and water) for most domestic and productive uses (UN, 2006).

Water resource management is one of the most important challenges the world is facing today. In order to meet the demands of different users, efforts should be intensified on the efficient use of all water resources (surface water, groundwater, and rainfall) and also on water allocation plans that maximize the resultant economic returns to limited water resources and, at the same time, protect the fragile ecosystem (Adeboye and Alatise, 2008).

Surface water is water that is on the Earth's surface, such as in a stream, river, lake, or reservoir. Surface water is a valuable resource that can be used for public, industrial and agricultural supply purposes. Surface water courses also provide important natural habitats, environmental and leisure resources. Therefore, understanding surface water resources is a key aspect of water resource assessment and evaluation (Tadesse, 2006).

Quantifying the amount of surface water available for irrigation and determining the exact locations to which water can be economically transported are important in the decision to expand its use. Where possible, the water source should be located above the command area so that the entire field can be irrigated by gravity (Ganole, 2010). The water resource assessment and sustainable water resource management practices rely heavily on the accurate modeling of hydrological processes. The water resource in the catchment is a paramount importance not only for irrigation development planning but for a variety of fields, such as for industry, engineering structure design/hydropower/flood control, water resources utilization/households, and Ecohydrological services (Gebrekristos, 2015).

The surface water availability assessment in this study was undertaken for surface irrigation development at woreda's administration level. According to FAO (1997), assessment of surface water resources can only be done at basin level. An important consideration in water resource assessment is to estimate how much adequate amount of surface water potential is available in the catchment for the intended irrigation method and crops to be grown in the identified irrigable areas. As a result, the availability of water both spatially and temporally is a major factor for the feasibility of any irrigation development.

2.2 Water Demand Assessment

Water demand is increasing as a result of the rapid population growth, agricultural expansion, industrial development, and higher standards of living in addition to climate change. Awash Basin is one of the largest basins in the country with high population pressure, degradation of land and highly dependent on agricultural economy. This increase in demand for the limited water resources puts pressure to improve the allocation of scarce water. Because irrigation is the major water consumer sector in the world, so it is important to ensure efficient water allocation (Ahmed and Sayed, 2015).

Factors affecting water demand are size of the city, living standard of the people, climate condition, quality of water, industrial and commercial activities etc. water consumption in a community is characterized by several type of demand including domestic, commercial and industrial and public institution. Water demand forecasting is component based and the demand is broken down into different components and a baseline demand in every component is assessed from a base year to a particular data in the future (Sutherland *et al*., 2000).Water demand assessment is the amount of water needed to supply population, i.e. the assessment requires data collection on existing water consumption patterns, number and types of facilities and levels of service in use, potential demand for future upgrading, operation and maintenance arrangements (Rooijen and Taddesse 2009; Allan *et al.*, 2001).

2.2.1 Irrigation water demand

While there are significant differences within the sector, agriculture is often the sector that is best placed to accommodate variability in water availability. Many of the inputs to agricultural production are annual rather than fixed capital costs, meaning that production levels can be increased and decreased on an annual basis with less significant losses. Important exceptions to this exist, including high-value permanent crops such as grapes and fruit trees. Conversely, and for the same reasons, the agricultural sector is often well placed to make productive use of additional water in years of surplus. At the same time, agriculture is typically the least economically productive user of water, and consequently, reductions in agricultural production have a less economic impact than reductions in other sectors (Sonjica, 2007).

Irrigation water demand is particularly important because it comprises nearly 70 to 80 % of total water demand on a global scale (Raskin *et al*., 1997; Shiklomanov, 2003). The most important drivers of irrigation water demand are the extent of irrigated areas (Kundzewicz *et al*., 2008) and food production (Leff *et al*., 2004; Ramankutty *et al*., 2008). Estimated a global cropland of about 15 million km^2 (an area roughly the size of South America) on global scale.

In Africa, the total amount of water withdrawn for irrigation use is 85% (UNWA, 2003). Although irrigation in Africa has the potential to boost agricultural productivities by at least 50 percent, food production on the continent is almost entirely rain-fed. The area equipped for irrigation, currently slightly more than 13 million hectares, make up just 6 percent of the total cultivated area (You *et al*., 2010).

Agricultural activity is by far the largest consumer of water in Ethiopia. An estimated 93% of all water withdrawals in the country (surface water and groundwater) are for agriculture use, much higher than the global average of 70%. However, water withdrawn for agriculture represents only an estimated 4% of the overall country's available renewable water resources. While Ethiopia has relatively abundant water resources, it is considered water-stressed due to rapid population growth over the last decade (USAID, 2020).

The irrigation water demand is calculating using the CROPWAT model: it is a DSS developed by the Land and Water Development Division of the FAO for planning and management of irrigation (FAO, 1992). It is a practical tool to carry out standard calculations for reference evapotranspiration, CWR, IWR, and more specifically the design and management of irrigation schemes. CWR and irrigation timing are particularly important in water resources management. Michael (2013), stated that estimating irrigation water requirement is important for water project planning, management, and maintaining crop evapotranspiration (ETc) when precipitation is insufficient or available. It can be determined using the CROPWAT model and has been applied for the calculation of CWR and irrigation schedule for water resources management.

2.2.2 Industrial water demand

Industrial water demand amounts to about 20% (World Bank, 2006) of total water demand on a global scale. It is less than a half of agricultural water demand however it often comprises more than a half of the total water demand in developed (i.e. industrialized) countries.

In Africa the total amount of water withdrawn for industrial use is 6% (UNWA, 2003). Africa still accounts for a very low share of global manufacturing. The share of the region in global manufacturing value-added fell from 1.2% in 2000 to 1.1% in 2008. In developing Asia, it rose from 13% to 25% and in developing countries in Latin America; it fell from 6% to 5% over the same period. There has also been no significant change in the region's share of global manufacturing exports in recent years, although Africa's share of global manufacturing exports rose slightly from 1% in 2000 to 1.3% in 2008 (UN, 2013).

In Ethiopia the total amount of water withdrawn for industrial use is 2% (MFA, 2016). The Ethiopian economy has been on a continuous and high growth trajectory since 2003/04, registering an average annual growth of 10.6% between then and 2010/11. This is about double the average growth rate of 5.2% recorded for sub-Saharan Africa (SSA) over the same period. The industry sector grew by more than 10% annually averaged over the same period. Despite its recent impressive growth performance, Ethiopia remains among the world's poorest countries. Agriculture continues to be the main source of livelihood employing 85% of the country's labor force. The industry contributes to the economy remains at about 14%, far below the average for SSA countries (Gebre-eyesus, 2016).

The most important drivers of industrial water demand are economic and technological development and a type of industry (Kundzewicz *et al*., 2008). A large amount of industrial water is used for cooling thermal and nuclear power generation (Shiklomanov, 2000).

2.2.3 Domestic water demand

Domestic water demand consists of water use by households and municipalities. The most important drivers of domestic water demand are population and economic development (Kundzewicz *et al*., 2008). Domestic water demand typically ranges from 500 to 800 liter/capita/day (about 300 m^3/capita/year) in developed countries and from 60 to 150 liter/capita/day (about 20 m^3/capita year) in developing countries (UNESCAP, 2000). In some regions in Africa where access to safe water is not guaranteed, domestic water demand ranges only from 20 to 60 liter/capita/day (about 10 m^3/capita/ year (UNESCAP, 2000).

2.2.4 Livestock water demand

The livestock sector is the fastest-growing agricultural sector, which has led to increasing industrialization and, in some cases, reduced environmental constraints. In rising economies, growing involvement in livestock is associated with enhancing rural wealth and increasing consumption of animal protein. Water usage for livestock production should be considered an integral part of agricultural water resource management, taking into account the type of production system (e.g. grain-fed or mixed crop-livestock) and scale (intensive or extensive), the species and breeds of livestock, and the social and cultural aspects of livestock farming in various countries. Limited availability of water or the presence of contaminants in the supply has a significant impact on animal health and productivity. The water demands of livestock can also compete with the ones of the human population and water required for crop production. Crops can make direct use of rainfall or saved water through irrigation, while animals consume vegetation or pastures, main to ability reductions in water efficiencies for food production. This water must be added to the water directly consumed by the animals to maintain life as well as to the water used during product processing. This apparent ‘inefficiency’ of water use has been highlighted in recent accounting models of global water use (Schlink *et al*., 2010).

2.3 Optimal Water Allocation Models

Based on the trend of the past data (i.e., observations, statistics, questionnaires, and remote sensing), we can derive or develop different policies for present and future situations. The future policies could be alternatives for policy makers to choose and implement. For this reason, different hydrologic models are available now adays.

Several hydrologic models are broadly used for allocation. The Modular Simulation Model (MODSIM) simulates water allocation in the system at each time step through the sequential solution of a network flow optimization problem where nonlinearities (i.e. evaporation, groundwater return flows and channel losses) are assessed within a successive approximation solution procedure (Sechi and Sulis, 2010). MODSIM is a generic system management DSS originally conceived in the late 1970s at the Colorado State University, United State, and continuously maintained.

Water Evaluation and Planning (WEAP) model is a generic simulation model developed at the Stockholm Environment Institute, Boston, Massachusetts. It integrates some physical hydrological processes with the management of demands and infrastructure to allow for multiple scenario analyses, including alternative climate scenarios and changing anthropogenic stressors. WEAP model simulations are constructed as a set of scenarios with different simulation time steps. The physical hydrology model updates the hydrologic state of the system at each time step, and thus provides mass balance constants used in the allocation phase within the same time step. A groundwater module in WEAP allows for the water transfer between stream and aquifer. The main point of the water management analysis in WEAP is the analysis of water demand configuration. These demand scenarios are applied deterministically to a linear programming allocation algorithm where each demand and source is assigned a user-defined priority. The linear program solves the water allocation problem by trying to maximize the satisfaction of demand, subject to supply preferences and demand priorities, and using reservoir operating policies to minimize the distance to ideal conditions. The water allocation problem is solved at each time step using an iterative, computationally expensive approach. Traditional target storage levels, multiple zones, and reduced releases by a buffer coefficient are implemented in WEAP.

MODSIM and WEAP are models where optimization methods are developed on a single time period and results are used as an efficient mechanism for performing simulations, whereas WAGRI-SIM and RIBASIM are simulation-only models based on a more conventional if-then approach and give lower values of performance system index. Operating policies in WAGRI-SIM and RIBASIM are fixed whereas operating policies in MODSIM and WEAP are defined as a combination of system states and hydrologic conditions and can be linked to some more detailed higher-dimensional models (e.g. QUAL2E, MODFLOW) to provide comprehensive modeling of water quality conditions and effect of groundwater (Sechi and Sulis, 2010).

MODSIM and WEAP have better advantages over the other models and are equally important to model water demand in the study area; MODFLOW is not an easy task as it needs an extensive calibration phase. Therefore, the WEAP model is easy and best suited to model water demand as it can be licensed online annually free of cost.

Actually, there are numerous criteria that can be used for choosing the right water demand model. These criteria are always project-dependent, since every project has its own specific requirements and needs. Further, some criteria are also user dependent, such as personal preference for graphical user interface, computer operation system, input/output management, and structure, or users add on expansibility. Among the various project-depended selection criteria, there are four main common, fundamental ones that must always be considered (Cunderlik, 2003).

To select which hydrologic model can be used for choosing the right, the following key points are the governing criteria. These are; physical detail, user-friendliness, water quality assessment ability, spatial scale, data demanding, support, price, and similar issues that have to be seen carefully.

Beven (2012) suggested four criterions for selecting model. They are,

1. Availability of the model on minimum investment of time and cost.
2. Ability of the model to produce the intended output to meet the objective of the project.

3. Ability of the model considered to produce the outputs needed to meet the aims of a particular project.
4. Possibility to prepare a list of assumptions made by the model and ability to check the assumptions likely to be limiting in terms of known response of the catchment.
5. Ability to make a list of inputs required by the model and deciding whether all the information required by the model can be provided with in time and cost constraints.

Therefore, based on these criteria, the WEAP model was selected as the best suitable to model the water demand by many researchers and hence selected for this study analysis purpose.

2.4 Water Evaluation and Planning (WEAP) model

WEAP model, an object-oriented computer-modeling package, is an Integrated Water Resources Management (IWRM) tool designed for simulation of water resources systems and trade-off analysis. The tool considering that water supply is defined by the amount of precipitation that falls on a watershed or a series of watersheds, with the supply progressively becoming depleted through natural watershed processes, human demands, and interventions, or enhanced through watershed accretions. These processes are governed by a water balance model concept that defines watershed-scale evaporative demands, rainfall-runoff processes, groundwater recharge, and irrigation demands (Yates *et al*., 2005).

The model simulates water system operations within a river system with basic principles of water accounting on a user-defined time step, usually a month. Simulation allows the prediction and evaluation of “what if” scenarios and water policies such as water conservation programs, demand projections, hydrologic changes, new infrastructure, and changes in allocations or operations. Thus, WEAP is considered as an integrated water management tool for evaluating water use and allocation with a greater focus on balancing supply and demand in a swift and transparent way.

WEAP is comprehensive, straightforward, and easy-to-use, and attempts to assist rather than a substitute for the skilled planner. As a database, WEAP provides a system for maintaining water demand and supply information. As a forecasting tool, WEAP simulates water demand, supply, flow, and storage, and pollution generation, treatment, and discharge. As a policy analysis tool, the WEAP evaluates a full range of water development and management options, and takes account of multiple and competing uses of water systems (Sieber *et al*., 2012). Hence, WEAP model becomes a powerful tool to assess the water demand in this study area.

In WEAP, the typical scenario modelling effort consists of three steps. First, a "Current Accounts" year is chosen to serve as the base year of the model; Current Accounts has been what you have been adding data to in the previous modules. A "Reference" scenario is established from the Current Accounts to simulate the likely evolution of the system without intervention. Finally, "what if" scenarios can be created to alter the "Reference Scenario" and evaluate the effects of changes in policies and/or technologies (SIE, 2015).

In general, the WEAP model is an integrated water resources planning system, it is the GIS-based model (it has drag and drop interface), it has basic methodologies for conceptual simulation of water demands and supplies, it has scenario management capabilities, it has a financial cost/benefit analysis capability, and it has links to spread sheets and other models.

2.5 Water Allocation

Water allocation is the process of distributing water supplies to meet the various requirements of a community. Determining how to allocate water supplies requires the consideration of certain factors, including the source of the water and methods for obtaining it. Water resources can be neither developed nor controlled rationally without an evaluation of the quantity and quality of water available. Water resources assessment (WRA) is a tool to evaluate water resources in relation to a reference frame, or to evaluate the dynamics of the water resource in relation to human impacts or demand. Water allocation systems serve to equitably apportion water resources among users; protect existing water users from having their supplies diminished by new users; govern the sharing of limited water during droughts when supplies are inadequate to meet all needs; and facilitate efficient water use (Speed *et al*., 2013).

2.5.1 Criteria for water allocation

Appropriate means of resource allocation are necessary to achieve optimal allocation of the resource. Several criteria are used to compare forms of water allocation introduced by

Weragala and Neelanga (2010) such as: Flexibility in the allocation of supplies, Security of tenure for established users, real opportunity cost of providing the resource is paid by the users, Predictability of the outcome of the allocation process, Equity of the allocation process and Political and public acceptability.

2.5.2 Optimal water allocation mechanism

Dinar *et al*. (1997) talk the ideas of four basic mechanisms for water allocation: user-based allocation, marginal cost pricing, public allocation, and water markets allocation.

User-Based Allocation: Many researches have proven a huge variant of policies for allocation inside such systems; through timed rotation, the depth of water, a place of land, or shares of the flow (Yoder, 1994). User-based allocation requires collective movement establishments with authority to make selections on water rights (Dinar *et al*., 1997).

Water Markets: Water markets allocate water by tradable water use rights and sell efficient water utilization through permitting customers to promote and purchase their water rights freely. Furthermore, it argues that water markets are uncommon in truth and are not truly free markets. Due to the transaction costs, technological constraints, political constraints, and many special reasons the real-worldwide water markets do now no longer benefit from first-best allocations. The absence of properly described water rights is likewise seeing as a major obstacle in formulating water markets inside the growing world (Rosegrant and Gazmuri, 1994).

Marginal cost pricing (MCP): A marginal cost pricing (MCP) mechanism, in principle, objectives a rate for water to equal the marginal cost of providing the final unit of that water. A rate is described as located rate (marginal value) of water on a demand curve, which corresponds to located quantity (i.e. Reference quantity). An allocation that equates the water‘s unit rate (the marginal cost of water) with the marginal cost is taken into consideration an economically efficient, or socially optimal, allocation of water resources. The limitation of MCP, however, is it is hard to implement at a river basin level because, it is difficult to collect sufficient information to estimate the correct volume of water (Malual, 2015).

Public (Administrative) Water Allocation: Public allocation promotes equitable water use, can guard the poor, and may preserve environmental needs. But frequently results in inefficient use of water and failure to create incentives for water customers to preserve water, enhance use performance, and permit tradable water transfers to attain most blessings in an entire river basin and additionally public allocation mechanisms frequently cause waste and miss-allocation of water, in addition to fragmented funding and control of the present resource. The amount primarily based totally administrative allocation is the maximum common water allocation mode in the growing international today (Meinzen and Mendoza, 2015; Molle, 2004). In general, state managed administrative allocation (public allocation) has more than one target and is greater involved with equity, sovereignty, and satisfying more public good (Dinar *et al.*, 1997).

2.6 Previous Studies Made on Surface Water Demand Assessment

Gao *et al*. (2019) assessed surface water resources in the Big Sunflower River Watershed; in the case of the U.S, the researcher applied the coupled Soil and Water Assessment Tool–Modular Groundwater Flow model (SWAT–MODFLOW). The results of the author showed that the average monthly total stream resources (MSR = 8.8 × 107 m^3) in growing seasons is greater than in non-growing seasons (MSR = 11.0 × 107 m^3), and monthly pond resources (MPR from 30,418 to 30,494 m^3) varied less than stream resources. The proportion of sub-basins with stream water resources greater than 700 mm was 21% in dry years (229 to 994 mm) while this increased to 35% in normal years (296 to 1141 mm) and 57% in wet years (554 to 991 mm). Surface water resources might be supplementary irrigation sources to mitigate the water resources scarcity in this region.

Koech (2013) assessed surface water resources and water demand assessment in Nyando catchment, Kenya using the SWAT model. The obtained results showed that the output water balance components are actual evaporation and transpiration, deep aquifer recharge, and river runoff at the outlet of the study area with mean annual values of 1253 mm, 71 mm, and 244 mm respectively. Rainfall is the main input water balance component with a mean annual value of 1569 mm and annual change in water storage range between ±200 mm. Planning and management of water resources in the catchment is required to reduce water shortage in the future.

Talila *et al*. (2018) estimated surface water potential based on watershed modeling: in the case of Sor watershed, Ethiopia the Geographic Information System (GIS) based Soil and Water Assessment Tool (SWAT) had been used. The result obtained from the SWAT model shows that, the watershed receives a mean annual rainfall of 1700.7mm, surface water runoff of the watershed 338.84 mm, and lateral soil flow is 143.73 mm. From a total watershed area of 1963.512 km^2, 665.32MCM runoff was generated by the model from a catchment annually.

Adeba *et al*. (2015) assessed assessment of water scarcity and its impacts on sustainable development in Awash basin, using SWAT model. The result showed that the annual average surface water available is estimated around 4.64 Billion Cubic Meters (BCM) as compared to the estimated demand of about 4.67 BCM in the basin for 1980–2012. This shows that on an average, the demand exceeds the availability by 0.03 BCM during the study period. Seasonal water deficit is even serious. A detailed seasonal analysis for the last 2 years (2011–2012) shows that the demand exceeds supply by 1.27 and 2.82 BCM during December–April of 2011 and 2012, respectively. However, there is a surplus supply of 1.67 and 3.16 BCM during June–September months of the same year.

Desta and Lemma (2017) studied the assessment and characterization of Lake Ziway using the SWAT model. The results showed that infiltration, surface runoff, base flow, and aquifer recharge were large in the Katar sub-watershed while ET and lateral flow were large in the Meki sub-watershed. However, surface and base flows showed decreasing trends in both sub-watersheds, yet the Katar sub-watershed showed a major contribution of water to Lake Ziway. The model estimated Lake Ziway and its watershed mean annual ETs as 1920 mm and 674 mm respectively, but plantation showed more ET than other land cover types in the watershed. Generally if the current trends in irrigation development continue in the region, it is suspected that Katar and Meki Rivers are likely to cease to exist after seven decades, and so is then Lake Ziway to dry out.

2.7 Previous Studies Made on Water Demand Assessment

Metobwa *et al*. (2018) studied Water Demand Simulation Using the WEAP model in the case of the Mara River Basin, Kenya. The results showed that the total water demand within the basin under the reference scenario was 4.91 BCM, the demand dropped to 4.1 BCM under the Demand Management Strategy (DMS) scenario and to 3.5 BCM under the Enhanced Policy Implementation and DMS scenario. Furthermore, the results showed that, the proposed DMS could increase water sustainability by reducing water demands at the basin.

Amin *et al*. (2018) Analyzed current and future water demands in the Upper Indus Basin under IPCC climate and socio-economic scenarios using Water Evaluation and Planning (WEAP) modeling. The authors generate different scenarios for external driving factors (population growth, urbanization, and living standards) and the impact of climate change to evaluate their effect on the current water supply system. The results indicated that the future unmet water demands is likely to reach 134 MCM by the year 2050 and that the external driving factors are putting more pressure on the supply service.

Kerim *et al*. (2016) studied water allocation for existing and future demands under changing climate condition in case of upper Awash Sub River Basin using WEAP model. The results revealed that the future water availability from 2006 to 2031 in sub-basin was 1001 MMC and the highest supplied volume is about 479.4 MCM annually. The annual water demand and supplied for the reference period found to be 1716.3 MCM while the demand increases to 1953.3 MCM for the future scenario with no unmet demand.

Gedefaw *et al*. (2019) made study on water resources allocation systems under irrigation expansion and climate change scenario in case of Awash River Basin using WEAP model. The study showed that the total extent of water needed to meet the irrigation demands of all the stations was 306.96 MCM from 1980 to 2016. The seasonal unmet demand is observed in all months, which ranged from 6 × 106 m^3 to 35.9 × 106 m^3 in August and May respectively. The prevention of future water shortages requires the implementation of water-saving measures and the use of new water supply technologies.

Shumet and Mengistu (2016) assessed the impact of existing and future water demand on economic and environmental aspects in the case of Rift Valley Lake Basin: Meki-Ziway Sub Basin, Ethiopia by using the WEAP model. The simulation result indicated that, the total average annual inflow volume into the study area is declining significantly and water availability is limited in the months of January (17 MCM) and December (171 MCM) while in the other months the availability is efficient and all users have 100% coverage. Except for Langano irrigation site that has between 33.33% and 86.5% coverage in average during the month of Feb to May 2.57 MCM and April in Bulbula 95.2% coverage, others get full coverage.

Abdi and Ayenew (2021) evaluated the WEAP model in the simulation of sub-basin hydrology in the Central Rift Valley basin of Ethiopia. The results showed that the monthly measured and simulated stream flow statistics showed a positive strong relationship with R^2 of 0.82, NSE of 0.80, and IA of 0.95; and with R^2 of 0.91, NSE of 0.91, and IA of 0.98 for calibration and validation periods respectively. Model performance evaluation statistics show a very good agreement between measured and simulated stream flow. The model has demonstrated the capability to represent the hydrologic dynamics of the sub-basin.

3. MATERIALS AND METHODS

This chapter describes the methods and procedures used in the study. It focuses mainly on the hydrological and characteristics of the study catchment, input data preparation, conceptual modeling processes and scenario developments. A current account was set to 1994-2019 and the reference years of 2020-2050 were analyzed according to three scenarios: (1) short-term development scenario (2020-2030); (2) medium-term development scenario (2031-2040); and (3) long-term development scenario (2041-2050). WEAP21 represents one supply source (e.g. rivers) and the water demands of four water use sectors (domestic, industrial, livestock, and irrigation).

3.1. Description of the Study Area

3.1.1. Location of the study area

The study area, Katar River catchment, is sub-catchment of the Ethiopian CRV basin. This watershed is located in the Oromia Regional State of Ethiopia and the northern part of CRV catchment in the part of the Ziway Shala basin. In terms of geographic coordinate system, the watershed lies between 7^0 21' 34" to 8^0 9' 55" North latitudes and 38^0 53' 57" to 39^0 24' 46" East longitudes. The Katar River and its tributaries start from the Eastern parts of mountains Chilalo, Galema, and Kakka in Arsi Zone, drain to Lake Zuway and the overflow of Lake Zuway drains to Lake Abiyata. Topographically, the Katar catchment shows variation with altitude ranging from around 1673m near Abura (at gauging Station) to about 4181m above mean sea level on the high volcanic ridges along the eastern watershed. The total area of the watershed, upstream of the gauging station is estimated to be 3466.59 km^2. The Location of the study area is shown in the figure 3.1

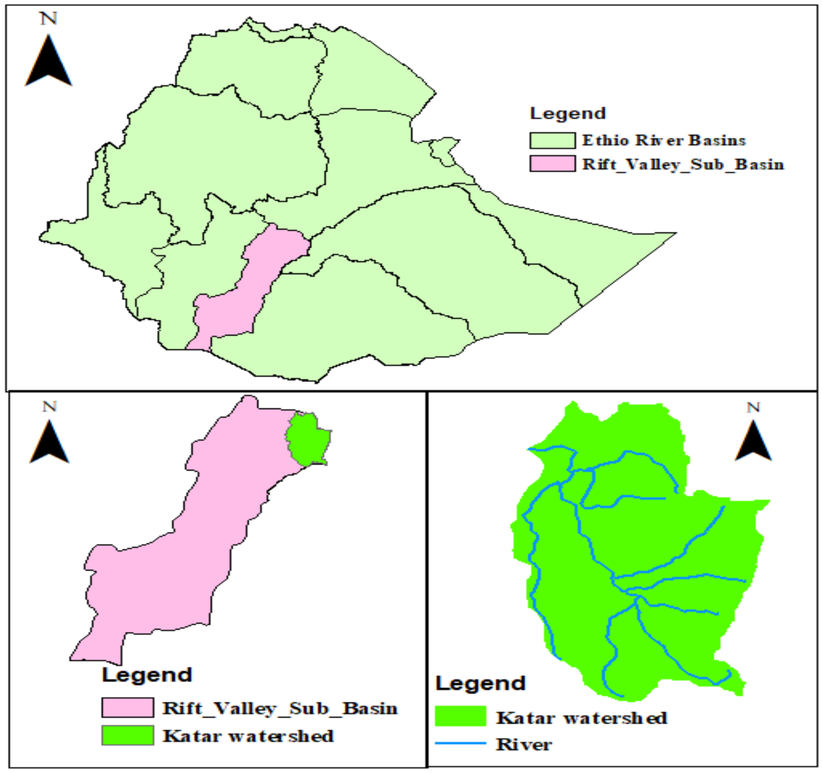

Figure 3.1: Location map of the study area

3.1.2. Climate characteristics of the study area

According to Ethiopian zone classification based on altitude, the climate zone of the Katar watershed is categorized by the sub-humid-to semi-arid climate Zone. Since the altitude of the catchment ranges from 1673 to 4181 m.a.s.l, the mean annual rainfall was from 283.6 mm to 1397.1 mm. The maximum monthly average rainfall of 249.17 mm was recorded in July. While the minimum average monthly rainfall was recorded in January and December. The recorded maximum average monthly temperature was 27.03 °C and the minimum average monthly temperature was 5.28 °C.

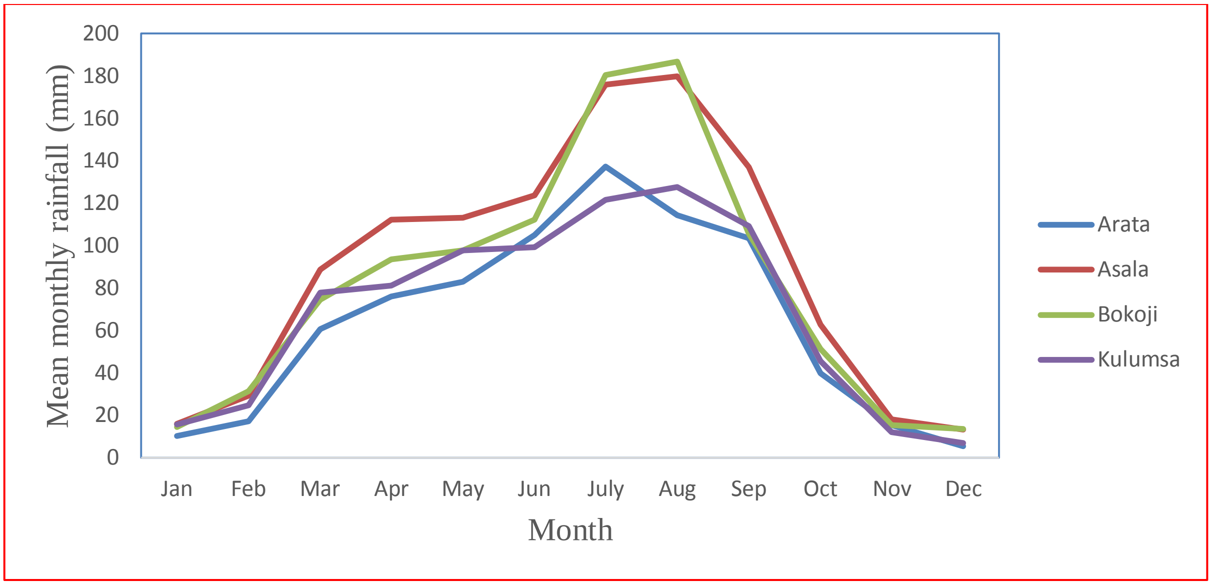

Figure 3.2: Mean monthly rainfall characteristics of selected weather stations

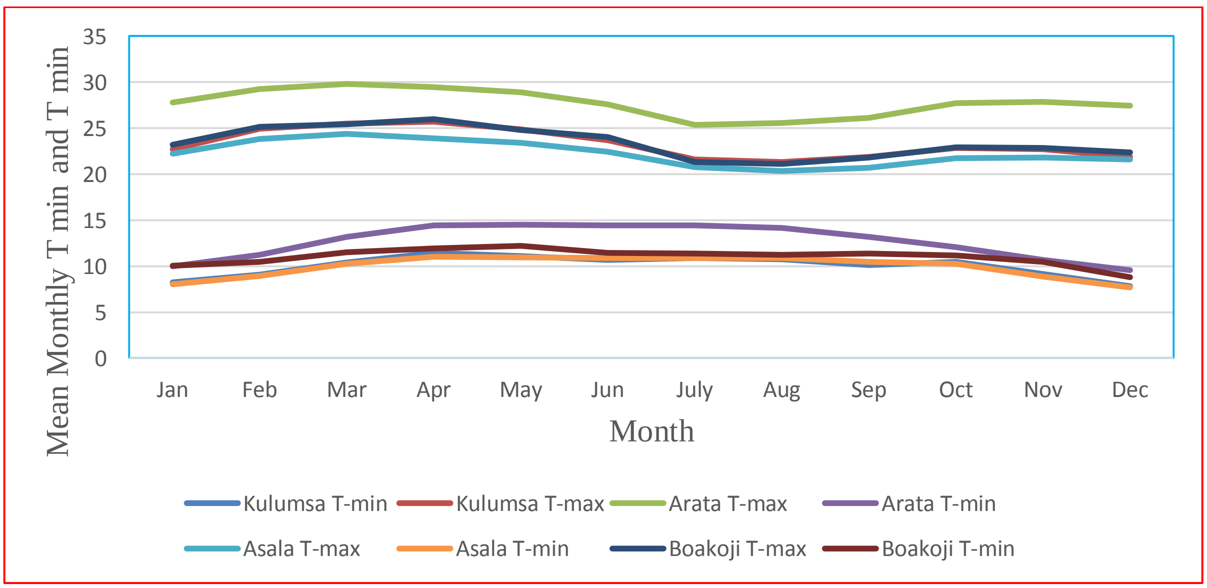

Figure 3.3: Mean monthly maximum and minimum temperature characteristics of selected weather stations

3.1.3. Land use /land cover condition of the study area

The dominant land use in the Katar watershed is agriculture. The basin is as a whole intensively cultivated and different crops are grown in the basin using both rain and irrigation. The main crops produced in this scheme are onion, cabbage, potato, carrot, etc. Crops like teff, maize, and bean are also cultivated during the rainy season. The catchment provides water for domestic (rural and urban water supply) and agriculture sectors. Detail land cover distribution of the study area is presented in Table 1 and Figure 4 below

Table 3.1: Katar Land covers distribution of the study area (source:**http**://www.**globallandcover**.com)

Land Cover	Area (km^2)	% Distribution
Bare Land	8.37	0.24
Built up Areas	0.56	0.02
Cultivated Land	2102.11	60.64
Forest Land	263.62	7.60
Grass Land	878.05	25.33
Shrub Land	212.81	6.14
Water Body	1.03	0.03
Total	3466.59	100.00

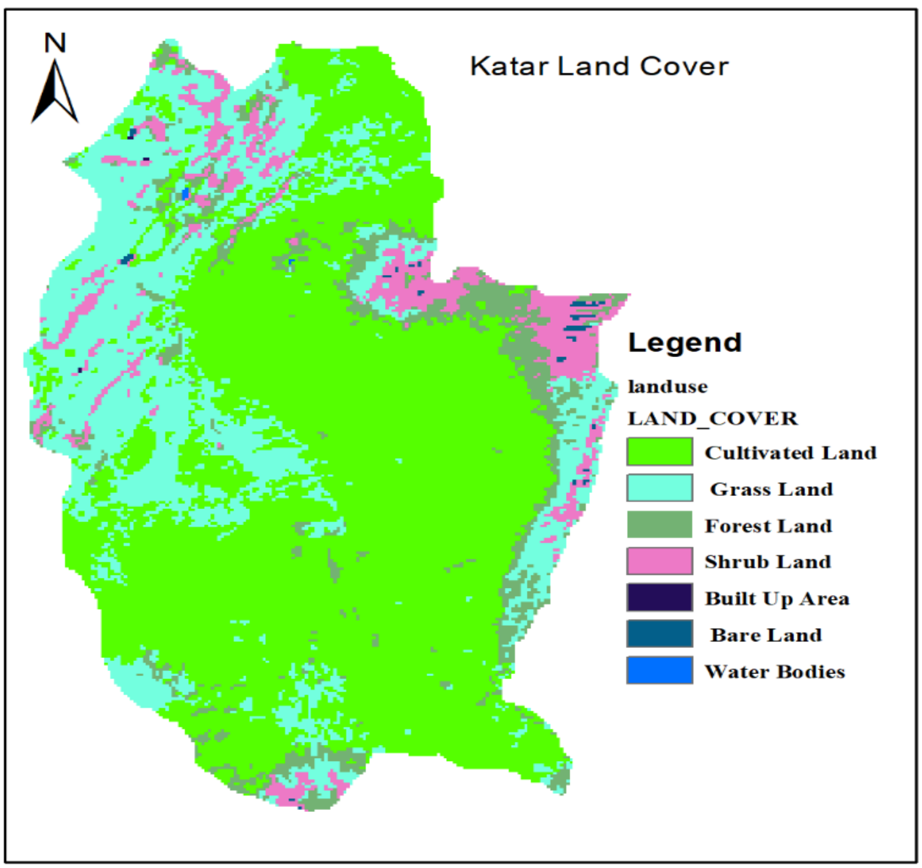

Figure 3.4: Land covers distribution of the study area

3.1.4. Soil types of the study area

Soil data is an important parameter to model catchment hydrology. The property of water holding capacity of soil affects the generation of surface runoff from the meteorological data like rainfall. Classification of soil units is based on the combined description of geomorphic and soils characteristics. According to the FAO/UNESCO soil classification system, the study comprises five major soil types like (1) Dystric regosols is a deep, well drained, medium textured, non-differentiated mineral soil that has minimal expression of diagnostic horizons. (2) Eutric Nitosols is a deep, red, well-drained soil with a clay content of more than 30% and a blocky structure. (3) Haplic Xerosols is soils having a weak ochric a horizon and an aridic moisture regime. Lithosols is soils having a weak ochric a horizon and an aridic moisture regime. And Pellic Vertisols is soils having a weak ochric a horizon and an aridic moisture regime. They are characterized by the strong development of structure frequently with shiny aggregate faces. They are originated from basic and intimate rocks or sediments derived under relatively intense weathering conditions in tropical and sub-tropical climates. The dominant soil groups in the Katar catchment are shown in Table 2 below with their percentage coverage.

Table 3.2: Soil distribution of the study area (source: FAO 56)

Soil Group	Area (Km^2)	% age
Lithosols	7.30	0.21
Hablic Xerosols	736.97	21.26
Eutric Nitosols	2258.41	65.15
Dystric Regosols	307.09	8.86
Pellic Vertisols	156.82	4.52
Total	3466.59	100.00

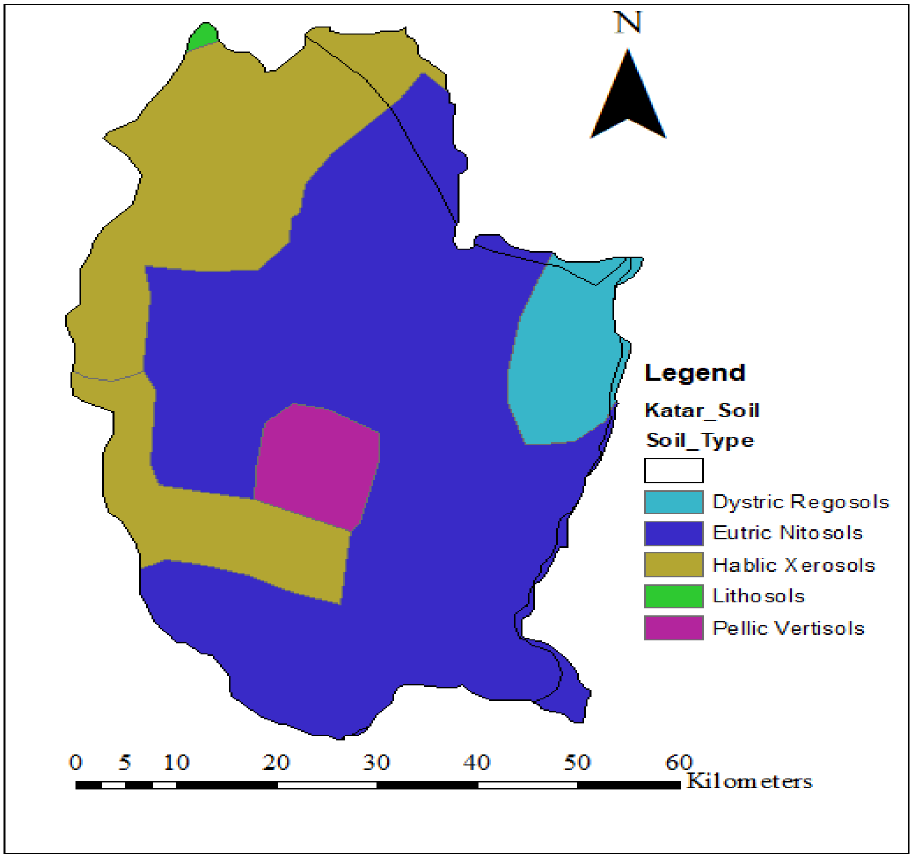

Figure 3.5: Soil distribution of the study area

3.2. Materials and Softwares Used

The materials and softwares used in this study were DEM, Arc GIS 10.4, CROPWAT 8.0, WEAP model and Microsoft excel to effectively execute and to compete demands considering current and future development scenarios and its optimal allocation. Arc-GIS software was used for delineation of water shade. CROPWAT 8.0 software was used to determine the crop water requirements of selected crops in the watershed. Finally, WEAP was used to allocate water for different uses.

3.3. Data Collection and Sources

In the development of any research, the primary task of the study was getting/collecting relevant information or data of the study area. This section identified and discussed the types and sources of data required for the study. Primary and Secondary data sources are used for the study. A secondary data source was very important for the study to accomplish the objectives. Primary data collections include: field observation and interviews of experts and farmers. Furthermore, meteorological data (rainfall, maximum and minimum temperature, relative humidity, wind speed, and sunshine hour) for four stations (Kulumsa, Asela, Arata, and Bokoji) for the year 1994-2019 were collected from the National Meteorology Agency (NMA) of Ethiopia. Stream flow data for Katar River station was recorded from 1994-2015, spatial data (topographic, soil data, land use land cover data) and digital elevation model (DEM) of Rift valley basin were collected from the Ministry of Water, Irrigation and Electricity (MoWIE). All water consumption like livestock, domestic, industries, irrigation, major crops, and areas were obtained from Arsi Zone Agricultural Offices.

Table 3.3: Data required and its sources

Data Type	Sources of Data		Description
Meteorological Data	National Metrological Service Agency (NMSA) of Ethiopia and design document		Temperature, rainfall, humidity, wind speed and Evaporation
Hydrological Data	Ministry of Water, Irrigation and Electricity of Ethiopia Department of water resources and hydrology		Gauging Station Data, Stream Flow Data
Spatial Data	Ministry of Water, Irrigation and Electricity of Ethiopia		Shape files of Digital elevation Model (DEM), Topographic, land use land cover and soil type
Water Demand Data	Domestic Irrigation	Arsi Zone Agricultural Offices	Water use rate Water consumption Agricultural sector
Socio-economic data	Central Statics Agency		Population data

3.4. Data processing and Checking Data Quality

Collected data may contain errors due to the failures of the measuring devices or the recorder. Therefore, before using the data for specific purposes, checking for missed data and removing errors is very essential. In this study, rainfall data was filled using the arithmetic mean method, detecting rainfall data variability was performed through homogeneity test and data consistency checking was performed by a double mass curve.

3.4.1. Filling missing rainfall data

Before using the rainfall record of a station, it is necessary first to check the data for continuity and consistency. To fill missing rainfall data, the normal rainfall was used as a standard of comparison. Normal rainfall is the average value of rainfall at a particular date, month, or year over a specified 2-year period. Simple arithmetic mean and normal ratio methods were the common methods used for filling missing rainfall data. To calculate the percentage of difference to decide whether to use the arithmetic mean or normal ratio method, the following equation was used.

$$\text{Per cent difference} = \left(\frac{Nx - Ni}{Nx}\right) * 100 \tag{3.1}$$

Where, Nx = the normal annual rainfall amount from the missing data station,

Ni = the normal annual rainfall amount from one of the nearby stations.

For this study, the missing values of recorded rainfall were computed by using the Arithmetic mean method. This method could be used to calculate monthly as well as annual missing rainfall values. The missing data estimated by;

$$Px = \frac{1}{M}(P1 + P2 + P3 + \cdots Pm) \tag{3. 2}$$

Where, Px = missing rainfall data at station x,

P1, P2, P3 and P4 = precipitation at surrounding gauges station,

M = the number of nearby gauge stations.

3.4.2. Homogeneity test

Homogeneity is used to detect the variability of data. When the data is homogeneous, it means that the measurement of the data is taken at the time with the same instruments and environments. The method to check the homogeneity of the stations in the catchment is non-dimensional rainfall records and plotted to compare the stations to each other. Non-dimensional values of the monthly precipitation of each station can be computed by

$$P_i = \frac{P_{i\,av}}{P_{av}} * 100 \qquad (3.\,3)$$

Where,

P_i is non-dimensional values of precipitation for the month in station i.

$P_{i\,av}$ is over year's averaged monthly precipitation for the station i

P_{av} is over year's averaged yearly precipitation of the station

When the rainfall patterns are spatially identical or vary with range, they are considered as homogenous. Appendix Figure 1 shows the homogeneity of rainfall stations plotted in the study area.

3.4.3. Consistency test

Consistency of time series data analyzed based on the theory that a plot of two cumulative quantities measured for the same time period should be a straight line and their proportionality is unchanged, and this is represented by slope. Therefore, inconsistency of the record was done by the double-mass curve technique. This technique is based on the principle that when each recorded data comes from the parent population they are consistent.

The double mass curve compares data for a single station with that of a pattern composed of the data from other stations. The data of the annual rainfall of the doubtful station and the average rainfall of the group of base stations covering a long period was arranged in reverse chronological order. To check the degree of consistency provided the value of the coefficient of correlation as follows:

Table 3.4: Correlation coefficients

Range of correlation coefficient	Description
r =1	Direct linear correlation
o.6≤ r <1	Good direct correlation
0 < r < 0.6	Insufficient reciprocal correlation
r = -1	reciprocal linear correlation

Graphical inspection of the double mass curves (Appendix Figure 2) shows the consistency of rainfall stations plotted in the study area.

3.5. Watershed Delineation

The process of locating and drawing the boundaries of a watershed is called watershed delineation. The first step in doing any kind of hydrologic modelling involves delineating streams and watersheds and getting some basic watershed properties such as area, slope, flow, and length and stream network density. Traditionally, this was done manually using topographic/contour maps. Topographic map features are helpful for watershed delineation. With the availability of Digital Elevation Models (DEM) and GIS tools, watershed properties can be extracted through automated procedures. The processing of DEM to delineate watersheds is referred to as terrain pre-processing. There are several tools available for terrain pre-processing. ArcSWAT compatible with ArcGIS 10.4 software package was applied towards processing a DEM to delineate the watershed boundary, stream, network and some other watershed characteristics that collectively describe the drainage patterns of Katar gauged catchment. The Shuttle Rader Topographic Mission (SRTM) DEM having a spatial resolution of 30 m was used to delineate the boundaries of the Katar sub-basin. The results from this procedure were used to create input files for the WEAP model setup in the catchment modelling.

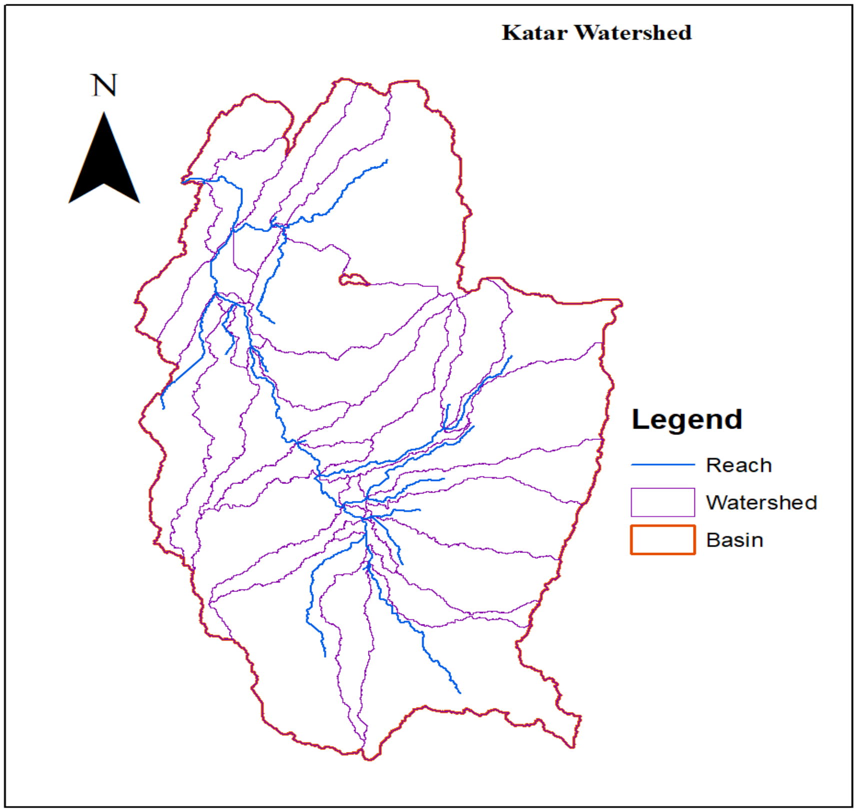

Figure 3.6: Katar sub-basin

3.6. Estimation of Surface Water Availability

The surface water availability of the Katar sub-basin was estimated by using the WEAP model. To determine surface water resources in the sub-basin, the model followed long-term average climate data like (rainfall, mean of high and low temperature, humidity, and wind speed), monthly mean values of stream flow, land use land cover of the catchment, and average Kc value. The Kc value was obtained from FAO paper 56. The average Kc value of the Katar sub-basin was portrayed in appendix table 15.

3.7. Modelling Hydrological Processes of Katar Sub-Basin

There is a choice among five methods to simulate processes such as evapotranspiration, runoff, infiltration, and irrigation demands. These methsods include (1) the rainfall-runoff and (2) irrigation demands only versions of the simplified coefficient Approach, (3) the Soil Moisture Method, (4) the MABIA Method, and (5) the Plant Growth Model or PGM. The choice of method should be depend on the complexity desired for representing the catchment process and data availability (Sieber and Purkey, 2015).

To model Katar sub-basin, the soil moisture method was selected due to its more complexity, representing the sub-basin with two soil layers. In the upper soil layer, it simulates evapotranspiration considering rainfall and irrigation on agricultural and non-agricultural land, runoff and shallow interflow, and soil moisture. The lower soil layer is meant to represent groundwater recharge and base flow processes, and its parameters remain the same for the entire catchment. This method allows for the characterization of land use and soil type impacts to this process. The parameters of this model include the water holding capacity of the layer as well as the water movement between them. A watershed unit can be divided into N fractional areas representing different land uses/soil types, and a water balance is computed for each fractional area, j of N. Climate is assumed uniformly over each sub-catchment, and the water balance is given as:

$$Rd_j \frac{dZ_{1,j}}{dt} = P_e t - PET(t)K_{c,j}(t)\left(\frac{5Z_{1,j} - 2Z_{1,j}^2}{3}\right) - P_e(t)Z_1^{RRF_j}{}_{,j} - f_j K_{s,j} Z_{1,j}^2 - (1 - f_j)K_{s,j}Z_{1,j}^2$$

(3. 4)

Where $Z_{1,\,j}$ = [1, 0] is the relative storage given as a function of total effective storage of the root zone (mm) for land cover fraction, j. the effective precipitation, P_e. includes snowmelt from accumulated snowpack in the sub-catchment. PET is potential evapotranspiration, $K_{c,j}$ is the crop/plant coefficient for each fractional land cover. The third term represents surface runoff, where RRFj is the runoff resistance factor of the land cover. Higher values of RRFj lead less surface runoff. The fourth and fifth terms are the interflow and deep percolation terms respectively. Where the parameter $K_{s,j}$ is an estimate of the root zone saturated conductivity (mm/time), Rdj is soil water holding capacity of land use j [mm], and f_j as a partitioning coefficient related to soil, land cover type, and topography that fractionally partitions water both horizontally and vertically.

The total surface and interflow runoff, RT from each sub-catchment at time t is

$$T(t) = \sum_{j=1}^{N} A_j(P_e\,(t)Z_{1,j}{}^{RRF,j} + f_j k_{s,j} Z_{1,j}{}^2) \qquad (3.\,5)$$

Where no return flow link is created from a catchment to a groundwater node, base flow emanating from the second bucket will be computed as:

$$S_{max}\frac{dZ_2}{dt} = \left[\sum_{j=1}^{N}(1-f_j)K_{s,j}{Z_{1,j}}^2\right] - Ks_2{Z_2}^2 \tag{3. 6}$$

Where the inflow to this storage S_{max} is the deep percolation from the upper storage and Ks_2 is the saturated conductivity of the lower storage (mm/time).

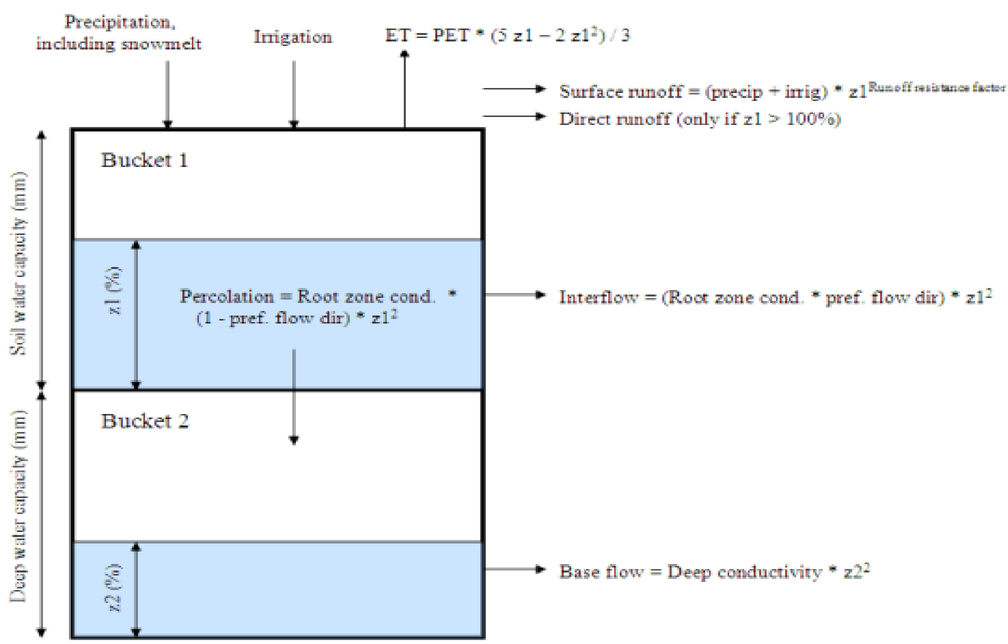

Figure 3.7: Diagram and equations in the soil moisture method (Sieber and Purkey, 2015)

3.8. WEAP Model Setup and Key Assumptions made

The WEAP model was developed by SEI to enable the evaluation of planning and management issues associated with water resources development. The WEAP model can be applied to both municipal and agricultural systems and can address a wide range of issues including sectarian demand analysis, water conservation, water rights and allocation priorities, stream flow simulation, reservoir operation, ecosystem requirements, and project cost-benefit analyses. WEAP model has two primary functions (Arranz and Mccartney, 2007).

i. Simulation of natural hydrological processes (e.g., evapotranspiration, runoff, and infiltration) to enable assessment of the available of water within the catchment.
ii. Simulation of anthropogenic activities superimposed on the natural system to influence water resources and their allocation (i.e., consumptive and non-consumptive water demands) to enable evaluation of the impact of human water use.

The modeling of a watershed using the WEAP consists of the following key assumption (Mayol, 2015).

i. Define the study area and time frame. The setup of the time frame includes the last year of scenario creation (last year of the analysis) and the initial year of application.
ii. Create the current, which is more or less the existing water resources situation of the study area. Under the current account, available water resources and various existing demand nodes are specified.
iii. Create scenarios based on future assumptions and expected increases in the various indicators. This forms the core or the heart of the WEAP model since this allows for possible water resources management processes to be adopted from the results generated from running the model. The scenarios are used to address a lot of "what is scenarios'', like what if there is a population increase, what if irrigation activities increase. Scenario creation can take into consideration factors that change with time.

Evaluate the scenarios about the availability of the water resources for the study area. Results generated from the creation of scenarios can help the water resources planner in the decision-making process.

3.9. Water Demand Assessment over the Katar Sub-Basin

Demand is defined as a set of water users that share a physical distribution system that is all within a defined region or that share an important withdrawal supply point. With the increasing population including urbanization, economic growth, industrial production, agricultural and livestock production, water demand increased rapidly over the years.

Water is a resource, which appears in different forms of surface stream, groundwater, lakes, and reservoirs. The developments of these resources for various purposes like water supply, irrigation, and hydropower are the basis for the socio-economic development of society. The effective utilization of countries water resources heavily depends on the estimation of the quality and quantity of the available water resource. In a very general way, water demand can broadly classify into off-stream and in-stream use. In stream, use refers to the water that is used but not withdrawn from groundwater or surface water for purposes such as hydroelectricity and navigation while off-stream refers to water that is withdrawn and diverted from a source. Forecasting water demand is an essential input for decision-making in water resources planning and management. The most influential factors affecting water demand and use are related to the population level of services, tariffs, demand management measures as well as climatic conditions. Demand site is classified into domestic, irrigation, and livestock. Each demand site has a transmission link to its source and where applicable a return link directly to a river.

3.9.1. Domestic water demand

Domestic water demand includes water used for basic needs such as drinking, cooking, washing clothes, and cleaning houses. The average amount of water used per person per capita varies from country to country and as well as from place to place within a country. The major important factors for these variations are the level of water supply service to be provided, location and climatic conditions, level of socio-economic development, water quality standards.

The amount of water used per person per day is known as per capita water demand. The per capita water demand is varies depending on the size of a town, the level of development, the type of water supply schemes, the cost of the water system of sanitation, and the climatic condition of the area. According to WHO (2003), the per capita per person per day is about 100 litters. But according to Ethiopian transformation plan-1, rural and urban water supply targets were 15 and 20 liters per capita per day respectively. The country develops a new standard of quantity supplied 25 liters per capita per day for rural and 40-100 liters per capita per day for urban (GTP-2, 2015).

The design of water supply project is done based on the projected population at the end of the design period. Otherwise, a present scheme will be inadequate in the near future. The standard method by which the forecasting of population is done include: the Arithmetical increase method, geometrical increase method, simple graphical method, and the logistic curve method. The geometrical increase method is mostly applicable for developing towns and rural areas having a possibility of growth. This method is based on the assumption of the percentage increase in population from decade to decade remains constant. If the present population is P and the average percentage growth is K, the population at the end of n decade is calculated based on the equation given by (Getu, 2015).

$$P_n = P_0(1+k)^n \tag{3. 7}$$

Where P_o = initial population, P_n = population at n decades, n = decades and k = percentage (geometric) increase. The total water consumptive for Katar watershed is forecasted for the year 2020 from the 2007 census data.

Based on the Ethiopian Central Statistics Authority (ECSA), the Woreda level of urban and rural population distribution over the watershed is presented in Appendix Table 16. Besides, annual domestic water consumption for urban and rural population is shown in Appendix Table 17.

3.9.2. Livestock water demand

Livestock is major component of the livelihood of both pastoralists in the arid and semi-arid lowlands of Ethiopia and the crop-livestock farmers in the highlands. The water resource is pertinent and vital for the existence and development of the livestock sector. Water requirement for livestock appears to be very individual and specific characteristics. Water for livestock is an essential basis for subsistence and the development of population and used as income. Ethiopia is the home of about 35 million tropical livestock units (TLU), and on average one, TLU requires about 25 liters of water per day (Sileshi, 2008). Livestock population type is presented in Tropical Livestock Unit (TLU).

The total water requirement for basin livestock was calculated based on the population of Livestock multiplied by TLU and unit water requirement of each livestock.

According to the 2020 livestock census data from the Arsi zone Bureau of Agriculture, the livestock population distribution over the watershed has been assessed as shown in Appendix Table 18. Generally, the water consumption for livestock in the watershed is calculated based on values indicated in Appendix Table 19.

3.9.3. Industrial water demand

Industries require water for different purposes such as production and cooling processes. Currently, in Katar catchment especially around Assela town, there are food complex industries. In coming years different Agro-processing, mining and tannery industries are expected to be established, and functional. However, for the purpose of water allocation, the annual water use for industries was determined from different literatures as 12.9 MCM per year (BeSBO, 2016).

3.9.4. Irrigation water demand

One of the best alternatives to consider for reliable and sustainable food security development is expanding Agricultural development on various scales through river diversion, constructing micro dams water harvesting structures, etc. (Lambisso, 2015). Agriculture is one means by which agricultural production can be increased to meet the growing demands in Ethiopia. Ethiopia has a significant agricultural potential identified from both available land and water resources. The country has developed irrigation schemes in many parts of the country at different scales (Awulachew *et al.*, 2007).

Irrigation water demand is varying considerably from month to month depending on the variation of crop type. Crop water demand is calculated using CROPWAT8.0 which is developed by FAO to estimate irrigation water demand for the proposed irrigation scheme by multiplying the crop water requirement by the total area covered by crop pattern. Crop water requirement is calculated using Reference crop evapotranspiration (ETo), crop coefficient (Kc), and effective precipitation (Peff).

$$ET_c = ET_o * K_c \tag{3. 8}$$

Reference evapotranspiration (ETo): It was calculated from climatic data using the FAO penman-monteith method using the following equation (3.9).

$$ETo = \frac{0.408\Delta(Rn-G)+\frac{900\gamma}{T+27.}*U2(es-ea)}{\Delta+\gamma(1+0.34U2)} \tag{3.9}$$

Where, ETo = reference evapotranspiration [mm/day]

Rn = net radiation at the crop surface [MJ/day m2]

G = soil heat flux density [MJ/day m2]

T = Mean daily air temperature at 2m height [O C]

U2 = wind speed at 2m height [m/s] es saturation vapor pressure [k Pa]

Ea = actual vapor pressure [k Pa]

es –ea = saturation vapor pressure deficit [k Pa]

Δ = Slope vapor pressure curve [k Pa/ O C]

γ = Psychrometric constant [k Pa/ O C]

Net irrigation requirement (NIR): Depends on the climate and cropping pattern. The mean monthly rainfall data and Hydro-Meteorological data are used in calculating the net irrigation requirements for dominant crops in the study area. The different losses such as runoff, seepage, evaporation and percolation take place during the application and transport of irrigation water. Operations such as leaching, transplantation and land preparation require certain amounts of water. Thus, CWR includes ET, losses during the application of water needed for these purposes (Salam *et al.*, 2019).

$$NIR = ETc - Pef \tag{3.10}$$

Where, NIR = the net irrigation requirement of crops (mm)

ETc = crop Evapotranspiration (mm/day)

Pef = effective rainfall (mm).

Effective rainfall (Pef) is the portion of rain, falling during the growing period of the crop, which is available to meet the consumptive water need or the evapotranspiration the requirement of the crop. It is the part of the rainfall that is effectively used by the crop after losses by surface runoff and deep infiltration. The average rainfall for 16 years is used and the data on the monthly basis was given in CROPWAT for calculating effective rainfall. Rainfall data from 2000-2015 was taken to calculate effective rainfall and USDA Soil Conservation Service method was selected from the four methods(Fixed percentage, dependable rain empirical formula, USDA Soil Conservation Service) given in CropWat 8.0 model.

$$IWR = ET_c - P_{eff} \tag{3. 11}$$

Where, ET_c= crop evapotranspiration (mm/period)

IWR=irrigation water requirement in (mm/period)

Gross irrigation water requirements (GIWR): GIWR of the crops at the identified potential irrigable sites were estimated based on efficiency from the source to the identified command area. Then, gross irrigation water requirement was computed using the following formula.

$$GIWR = \frac{NIWR}{E} * A \tag{3. 12}$$

Where, GIWR= Gross irrigation water requirement (m^3/s)

NIWR= Net irrigation water requirement (l/s/ha)

A= Area (ha)

E= Efficiency

3.10 Environmental Flow Requirement

The Environmental (in stream) flow refers to the flow regime in a river that ensures conservation of a river ecosystem. It is the minimum monthly flow required along a river to meet water quality, fish, navigation, recreation, downstream, and other requirements. Depend on its demand priority an environmental flow requirement will be satisfied before, after, or at the same time as other demands on the river (Ayele, 2014). McCartney *et al.*(2010) conducted a study to estimate the environmental flow requirement downstream of Chara Chara weir on

Lake Tana. They estimate an average annual allocation of 22% of the mean annual flow for environmental flow requirements. For Katar watershed 20% of mean annual runoff is kept for the river ecosystem and downstream water users.

3.11 Model Calibration and Validation

Calibration is an iterative exercise used to establish the most suitable parameter in modelling studies. It is very important because reliable values for some parameters can only be found by calibration. It involves the identification of the most important model parameters and changing the parameter set. Model calibration can be manual, automatic and a combination of the two methods. The manual calibration uses trial and error techniques in parameter adjustment through a number of simulations runs. It is subjective to the modeler's assessment and can be time-consuming. Computer-based automatic calibration involves the use of a numerical algorithm that finds the extreme of a given numerical objective function. Model performance is assessed statistically by comparing the model output and observed flow values. The statistical measures commonly used are the coefficient of determination (R^2), Nash-Sutcliffe Efficiency (NSE), and Percent bias (Tadesse, 2016).

Model validation is the process of representing that a given site-specific model is capable of making accurate predictions. This was done by applying the calibrated model using a different data set out of the range of calibration without changing the parameter values. The model is said to be validated if its accuracy and predictive capability in the validation period have been proven to lie within acceptable limits. Observed and simulated hydrograph values were gained compared as in the previous calibration procedure.

Simulated model results were compared with the observed flows for each control station. These comparisons were carried out taking into account the statistical parameters mentioned in previous sections. For this research, observed stream flows from Katar station near Abura located at the outlet of the Katar River were compared with the simulated outputs of the model and the two data's results should be overlapped monthly. This shows that the model simulates the output from the catchment land use and land cover should be matched with the recorded stream flow data. In Katar catchment, there is one gaging station namely Katar near Abura. The mean monthly stream flow is calibrated and validated by Parameter Estimation Tool

(PEST) in WEAP. The calibration was made for ten years from 2001 to 2010 and the validation was made from 2011 to 2015 monthly time step for Katar stream flow depends on the full record of gage data. The calibration is done by comparing the simulated result of the model and the observed stream flow of the catchment.

3.12 Model Performance Evaluation

There are different ways of evaluating the goodness of fit measures between the simulated and observed values during both calibration and validation processes. The three numerical model performance measures are the common ones. These are coefficient of determination (R^2) Nash Sutcliffe simulation efficiency (NSE) and Percent Bias.

R^2 outlines the degree of collinearity between simulated and measured data and describes the proportion of variance in measured data explained by the model. It ranges from 0 to 1, given higher values indicating less error variance. Values which are greater than 0.5 are considered as acceptable.

NSE is normalized statistics that determine the relative magnitude of the residual variance compared to the measured data variance. It indicates how well the plot of observed versus simulated data fits the 1:1 line. NSE ranges between -∞ and 1, with NSE equal to one being optimal value. Values between 0 and 1 are generally viewed as acceptable levels of performance, whereas values less than 0 indicate that the mean observed value is a better predictor than the simulated value which indicates the unacceptable performance

PBIAS measures the average tendency of the simulated data to be larger or smaller than their observed counterparts. The optimal value of PBIAS is 0.0, with low-magnitude values indicating accurate model simulation. Positive values indicate model underestimation bias, and negative values indicate model overestimation bias.

$$R^2 = \left[\frac{\sum_{i=1}^{n}\left(\left(Y_i{}^{sim} - \bar{Y}^{sim}\right)\left(Y_i{}^{obs} - \bar{Y}^{obs}\right)\right)}{\sqrt{\sum_{i=1}^{n}(Y_i{}^{sim} - \bar{Y}^{sim})^2 * \sum_{i=1}^{n}\sum_{i=1}^{n}(Y_i{}^{obs} - \bar{Y}^{obs})^2}} \right] \qquad (3.13)$$

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}({Y_i}^{obs} - {Y_i}^{sim})^2}{\sum_{i=1}^{n}({Y_i}^{obs} - \bar{Y}^{obs})^2}\right] \tag{3. 14}$$

$$\mathrm{PBIAS} = \left[\frac{\sum_{i=1}^{n}\left({Y_i}^{obs} - {Y_i}^{sim}\right) * 100}{\sum_{i=1}^{n} {Y_i}^{obs}}\right] \tag{3. 15}$$

Where, Y_i^{sim} The i^th simulated stream flow

$\bar{Y}^{sim}$ The mean of simulated stream flow

Y_i^{obs} : The i^th observed stream flow

$\bar{Y}^{obs}$ The mean of observed stream flow

3.13 Water Supply and Demand of Katar Sub-Basin

Configuration of the entire demand and supply system of the Katar sub-basin, including the links between supplies and demands is important. In order to inform WEAP how the demand is satisfied, the user needs to connect to the supply system that has been identified previously to each demand site. To understand how supply fits the demand in different scenarios in the katar sub-basin, four consumptive demand users namely domestic water demand, Livestock water demand, Industrial water demand, and Agriculture water demand from Katar River and one reservoir is connected in the WEAP configuration to perform water allocation.

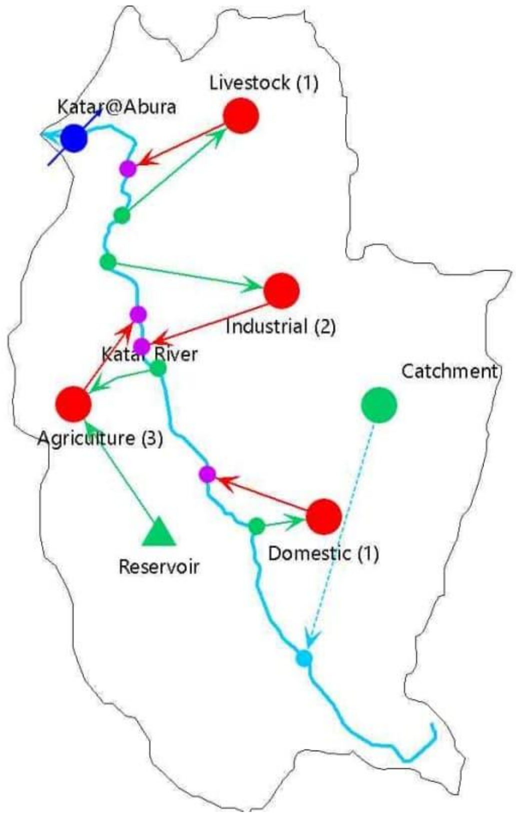

Figure 3.8 : WEAP model configuration showing the supply and demand sites in the Katar river sub-basin

3.14 Developing Current and Future Water Allocation Scenarios

A scenario can be defined as a plausible description of how the future may develop, based on a coherent and internally consistent set of assumptions about key relationships and deriving forces (Arranz and Mccartney, 2007). Scenarios are self-consistent storylines of how a future system might evolve in a particular socio-economic setting and under a particular set of policy and technology conditions. Using WEAP, scenarios be built and then compared to assess their water requirements. The scenarios can address a broad range of "what if" questions (Sieber and Purkey, 2015).

The basin-wide development scenarios under current consideration contain a range of economically-driven water-related developments that will or may be taken up within short term, medium-term, and long-term development and management scenarios through the year 2050. The scenarios have been formulated based on the current and future Katar catchment water resource related development conditions within the future three 10 year time-horizons; of (2020-2030), (2031-2040), and (2041-2050). In addition to the base period (current year) development conditions and prospective development potential of the catchment, the short-term scenario mainly shares the development goals, objectives, and strategies of the current national development plan.

The current accounts year is chosen to serve as a base year of the model where we feed basic data. With WEAP; we first create Current Accounts of the water system under study. The Current Account is chosen based on the data available in that year. Based on a variety of economic, demographic, hydrological, and technological trends, a "reference" scenario projection is established called reference scenario. The reference scenario is developed from the current account to simulate the likely evolution of the system without intervention. This scenario serves as a reference to all other scenarios created to show different trends. Hence, every scenario developed to show its own trend on the model result is compared to the reference scenario as there are interventions in the reference scenario other than projecting the current account year to the future year. In this study, the reference scenario from the year 1994-2020 is considered.

3.14.1 Scenario 1: Short Term development scenario

The short-term scenario is the definite future situation of the cumulative impacts of major sector development plans in the next ten years (2020-2030). Each scenario was formulated to represent different combinations of nationally or regionally planned sector developments, with a focus on going development interventions in the catchment, strategic direction of national development plans.

Within this time horizon, agricultural irrigation schemes would be expanding. According to Gurara (2020), depending on its soil texture, drainage, depth, slope, and proximity to river the 34.08% of the Katar sub-basin area is highly suitable for irrigation potential. For the coming ten years, in addition to base case irrigation development, 1000 ha land at Katar sub-basin would be developed. This would contribute to the total utilization of 1507 ha of irrigable land. By the year, 2030 the population increment in the sub-basin is projected to reach 660,302 in total, out of this total, 326,224 are rural while 334,078 are urban dwellers. Depending on population size, the per capita domestic water demands are projected to be 80 liters in 2025, 90 liters in 2035, and 100 liters in 2045 (GIRDC, 2020). Depending on the above projected demand for this study it is forecasted up to 2050. Currently, the livestock agricultural activity is traditional. If properly managed, the livestock production would highly increase in quantity in this time horizon, and products of the livestock would possibly expand. The implication for water resource management is that as the number of livestock increases, the volume of water required for the livestock would increase, and the environment and hence the water resource quality degradation would be higher. In the STS time horizon livestock production will be increased from 525,718 to 706,519.

3.14.2 Scenario 2: Medium Term Development Scenario

This level of scenario focuses on the foreseeable future situations that are assessing the additional cumulative impacts of water resources-related development plans through 2040, inclusive of the short-term scenario, and the additional changes on the sub short term scenarios within 10 additional years (2031-2040). Each scenario was formulated to represent different combinations of nationally or regionally planned sector developments. These are also those identified by the stakeholders as most important for water resources-related developments and management. Under this development and management key result area, various scenarios are expected to be executed and contribute to socioeconomic wellbeing and poverty reduction in the catchment through 2040.

Within this time horizon, in addition to Short Term Scenario, some agricultural irrigation schemes would be there, and irrigation productivities would increase at a high level. In addition to STS additional 3000 ha of land at Katar sub-basin will be irrigated; increasing the irrigation development to 4500 ha during the scenario period by adding Katar reservoir to store water in the rainy season and to irrigate the irrigation command area. By the year 2040, the population increment in the catchment is expected to reach 887,392 of which rural population accounts for 438,419, urban 448,973. Therefore, the sub-basin development plan should consider this demand according to the prepositions of this scenario. Also, some industrial development would be expected. The government promotes industrial developments, on the basis that rural production can support and be supported by such industries as, agro-processing industries and other value-adding enterprises.

3.14.3 Scenario 3: Long Term Development Scenario

This level of scenario focus on the long-term future situations that is assessing the addition cumulative impacts of water resources related development and managements through 2050, inclusive of the medium-term scenario, and the additional changes on the sub medium-term scenarios within 10 additional years (2041-2050). Each scenario was also formulated to represent different combinations of nationally or regionally planned sector developments which are identified by the stakeholders as most important for water resources-related developments and managements.

The initial scenario identified by the stakeholders summarizes that all the Katar sub-basin population would be accessed to adequate domestic water supply by the end of 2050. And hence, at this stage adequate domestic water supply will be accessed to all populations in the catchment. By the year 2050, the population increment in the sub-basin is expected to reach 1,192,581 of which rural population accounts for 589,198, urban 603,383. In this LTS period, additional industrial development would be expected and increased the number of industries to 2 in the time span. In this regard, the government promotes industrial developments, on the basis that rural production can support and be supported by such industries as agro-processing industries and other value-adding enterprises. From 2041 -2050, the livestock production and productivity would highly increase, In the LTS time horizon livestock production also will be increased from 973,022 to 127,6054. Within this time horizon, the large, medium and small scale agricultural irrigation schemes would be implemented in a stable way. Based on the availability of water resources and climate variability the 7000 ha irrigable land will be developed. Within this time horizon irrigation productivities would increase at a high level.

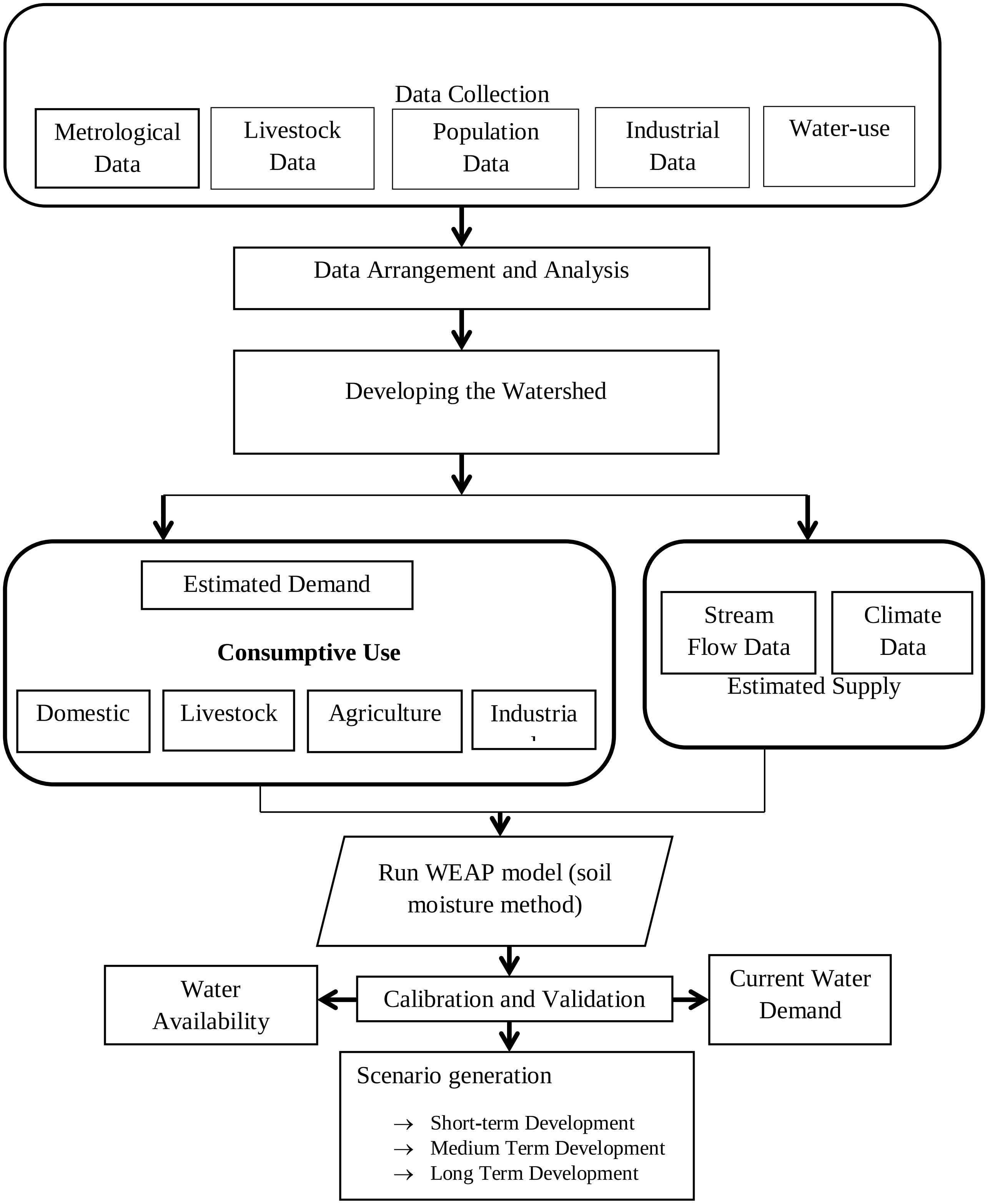

Figure 3.9: The overall methodological frame work for developing optimal water resources allocation scenarios in the study area

4. RESULTS AND DISCUSSION

The WEAP model was set up for water demands with the baseline year of 2020 and was run up to 2050. The scenario analysis approach was used for allocation and situation for the projected period from 2020 up to 2050. The analysis was based on three main scenarios. Under each scenario, the projected water demand was computed and the unmet demands were analysed.

4.1 Evaluation of WEAP Model Performance

Before starting with the actual calibration and validation procedure, it is necessary to understand the influence potential of calibration and validation parameters on model performance. Therefore, the parameters were adjusted in variable possible ranges to overlap the mean monthly observed stream flow with the model simulated data and the model response was evaluated.

Table 4.1: Range of values for the estimated sensitive parameters used in the WEAP model for the Katar River sub-basin

Parameters	Description	Range in values
KC	Crop coefficient	0-1.5
SWC	Soil water capacity	>=0
DWC	Deep water capacity	>=0
RRF	Runoff resistance factor	0-1000
RZC	Root zone conductivity	>=0
DC	Deep conductivity	>=0.1
PF	Preferred flow direction	0-1
Z_1	Relative storage of upper layer	(0 -100)%
Z_2	Relative storage of lower layer	(0 -100)%

4.2 WEAP Model Calibration and Validation Result

The calibration result of WEAP model between observed and simulated stream flow in the study area indicates very good capability to simulate historical stream flow with R^2 of 0.96, NSE of 0.85 and PBIAS of -7.51 while R^2 of 0.98, NSE 0.88 and PBIAS -12.41 during validation period as indicated in Table 4.2. When we compare this results with previous study made by Abdi and Ayenew (2021), the calibration result shows that R^2 and NSE of 0.82 and 0.80 respectively and for the validation the R^2 and NSE of 0.91 and 0.91 respectively. The result shows very slight difference which could be the length of data that we used. Similarly, many studies have confirmed the capability of the WEAP hydrologic model in reproducing catchment hydrology processes in a different part of Ethiopia. Among these, in Awash Gedefaw *et al*. (2019), from four gauging stations ranging values of R^2 = 0.73 to 0.89, NSE = 0.65 to 0.83, R^2 = 0.63 to 0.91 and NSE = 0.50 to 0.84 for calibration and validation respectively were achieved between measured and simulated average monthly flows. Generally, it was inferred from the results that the validation result is greater than calibration because there were a lot of missing data treated and used for calibration than validation.

Based on the graphical inspection (Figures 10-13) and statistical model performance evaluation indices values (Table 6), WEAP model has very good ability to simulate historical stream flow in the Katar river watershed in Ethiopia

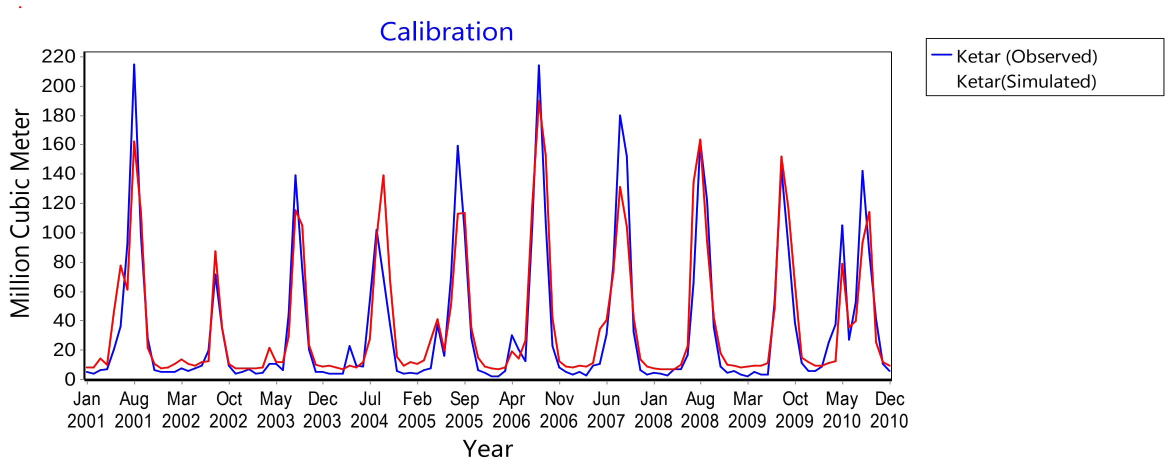

Figure 4.1: WEAP model calibration (2001 to 2010) for Katar river watershed

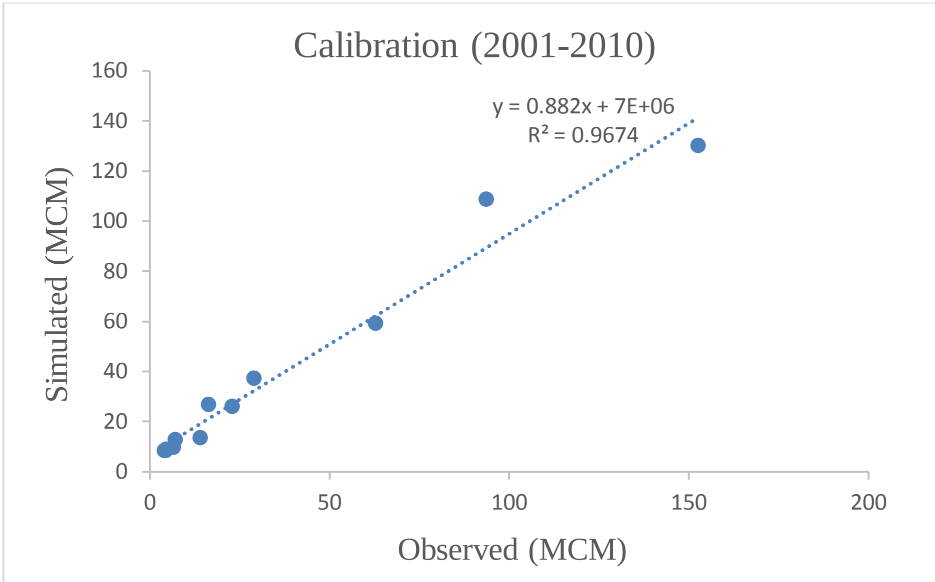

Figure 10: Scatter plot between observed and simulated flow during calibration period

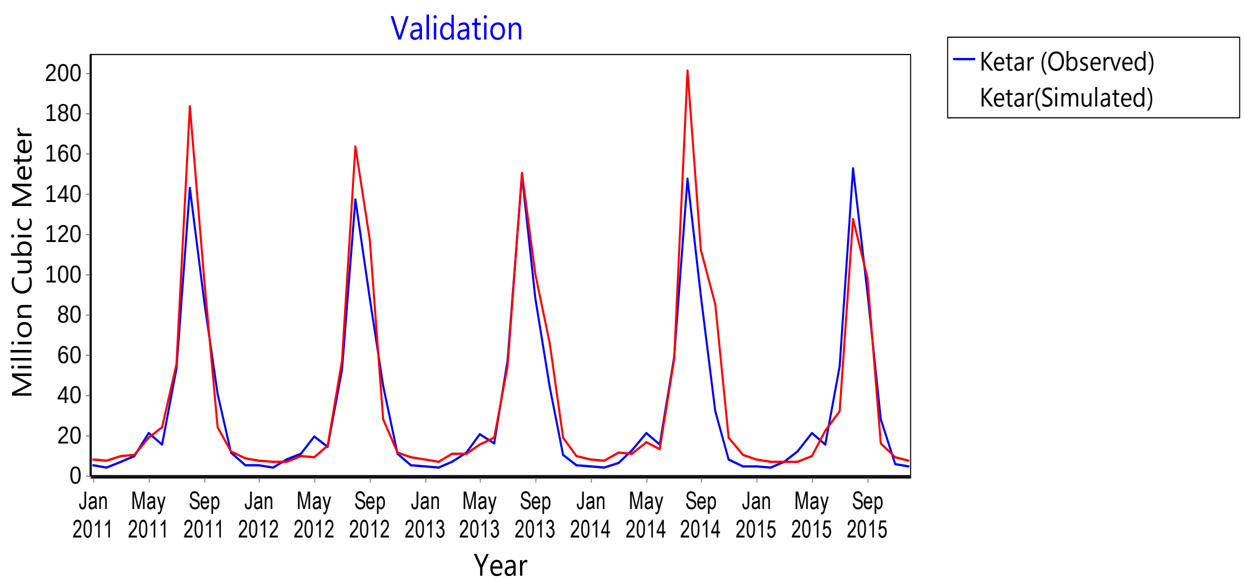

Figure 4.3: WEAP model validation (2011 to 2015) for Katar river watershed

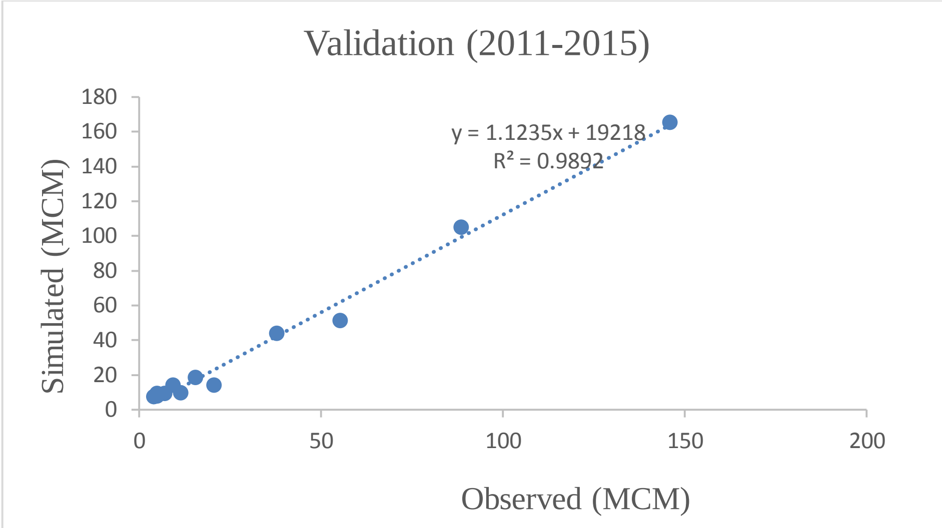

Figure 4.4: Scatter plot between observed and simulated flow during validation period

Table 4.2: Calibration and validation results of WEAP model in Katar river watershed

Parameter	Calibration	Validation
R^2	0.93	0.96
NSE	0.85	0.88
PBIAS	-7.51	-12.41

4.3 Hydrological Processes

Mean annual, seasonal, and monthly scale or bases hydrological processes of katar catchment was analysed. From long term mean annual precipitation the catchment gets 3095.67 MCM. The catchment simulation of the WEAP model shows that the surface runoff generated from the whole catchment in the Katar watershed is 289.61 MCM. The mean annual actual evapotranspiration, interflow, and Base flow are 2649.72 MCM (85.56%), 78.74 MCM (2.54%), and 77.60 MCM (2.51%). The maximum and minimum surface runoff was occurred in August and December respectively. From the total estimated precipitation, 9.36% was converted to surface runoff as indicated in figure 4.5. When we compare this result with previous study made by Abdi and Ayenew (2021), they gates the precipitation, evapotranspiration, interflow, and base flow of the catchments are 3041.75 MCM, 2612.73

MCM, 46.19 MCM, and 45.60 MCM respectively. The study indicates that slight difference that could be due to increase area in the delineation of a sub-basin.

Another study by Desta and Lemma (2017), using the SWAT model shows lower values as compared to the current study precipitation is 3226.22 MCM. The relative proportion of the three components of the runoff (base flow, interflow, and surface runoff) depends on the physical characteristics of the watershed, the land use, soil, topography, geomorphology, and geology characteristics. But it shows slight difference that could be attributed to climate change, variation of the method and increase area in the delineation of a sub-basin. Due to the variation of digital elevation model the watershed area is vary.

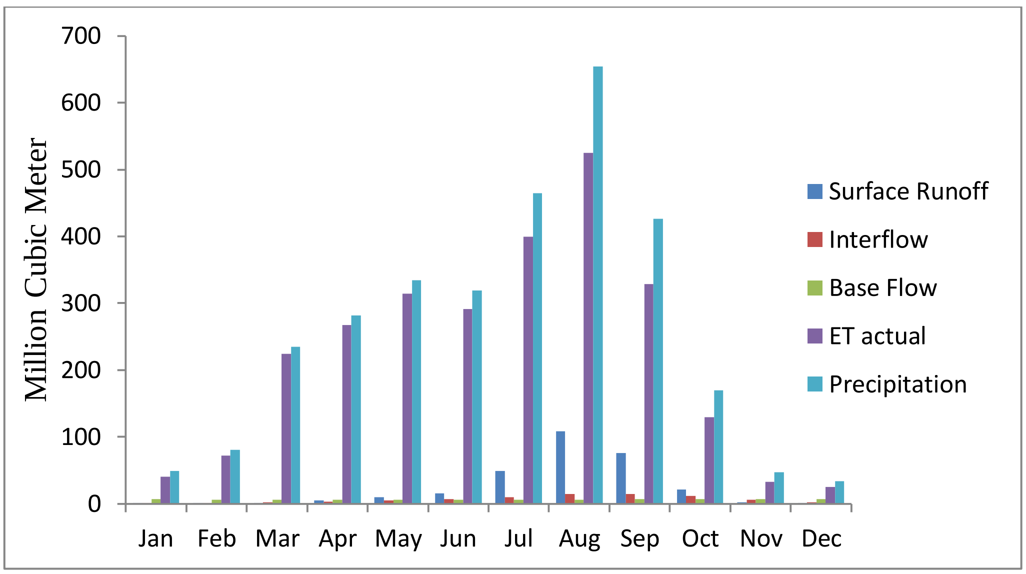

Figure 4.5: Monthly hydrologic components in the Katar sub-basin.

4.4 Surface Water Availability

Planning and allocation of water resources to completely different uses inside the sub-basin are one among the fundamental activities of water resource management to fill the gaps in water use, drought and flood protection, environmental stability, and increasing agricultural production. This has supported the procedures of the water use and allocation to work out water needs and allocations for domestic, livestock, industrial, and agricultural use at every stage of the event position. This analyses into under consideration of the increasing demands for water ensuing from an increasing population and irrigation space below cultivation, and has then balanced these needs with the abstractions required for different consumptive and non-consumptive uses.

The water use and allocation are based on the procedures to determine water requirements for Domestic, Livestock, Industrial, and Irrigation. To estimate river flow at Katar sub-basin 25 years of meteorological data based on a monthly basis were used. The mean annual river flow from the Katar sub-basin at the outlet point is 445.95 MCM. The watershed has a maximum and minimum flow volume of 129.57 MCM in August and 7.81 MCM in February respectively as indicated in Table 4.3. When we compare this result with previous study by Abdi and Ayenew (2021), the stream flow in the sub-basin is 423.59 MCM with a watershed area of 3271.6 Km^2. Furthermore, the stream flow which leaves the katar sub-basin is increased by 5.27%. The result shows slight differences for the determination of stream flow and the area of the watershed have a high effect on the result. The area of the watershed in this study increases with 194.99 km^2.

Table 4.3: Monthly stream flow in the Katar sub-basin

Month	Stream flow (MCM)
Jan	8.07
Feb	7.81
Mar	10.16
Apr	14.89
May	20.84
Jun	28.29
Jul	65.82
Aug	129.57
Sep	97.47
Oct	39.72
Nov	14.29
Dec	9.03
Total	445.95

4.5 Water Allocation Scenarios

WEAP model uses annual activity levels and annual water use rates to model the water demand in the basin. The water demand in the basin receives water from the simulated stream flow from the Katar catchment. For this study, there are four demand consumptives' users; Domestic water demand, Industrial water demand, Livestock water demand, and Irrigation water demand in the catchment were modeled. WEAP model was set up for demand allocation in Katar catchment to simulate the base year (current account year) 2020. Three subsequent scenarios, the Short-Term Development Scenario, the Medium-Term Development Scenario, and the Long-Term Development Scenario are analysed. Under each scenario, the projected water demand was computed and the demand coverage and unmet demands were analysed.

WEAP determines the allocation order to follow when allocating water demand. Demand sites with higher priorities are processed first by the WEAP Allocation Algorithm. These priorities are useful in representing a system of water rights and also important during a water shortage (Stockholm Environment Institute, 2016). Supply preferences indicate the preferred supply source where there is more than one source to a demand site. The allocation order represents the actual calculation order used by WEAP for allocating water. According to Ashin (2019) the priority order of domestic and livestock is higher than that of industrial and irrigation. Priority order for the specified demand sites is portrayed in the Table 4.4.

Table 4.4: Demand priority

Demand	Priority
Domestic	1
Livestock	1
Environmental Flow Requirements	1
Industrial	2
Irrigation	3

4.6 Current (Base year) Water Demand

The base year account comprises current hydrological, environmental, and socio-economic conditions against which future developments can be compared in the catchment. This has been agreed based on the hydrological situation of (1994-2019), and the environmental and socio-economic situation of the year 2020.

The current account of the model was developed using the demand data of 2020 and simulated stream flow data (Supply) at the outlet of Katar River near Abura is 445.95 MCM. The watershed has four consumptives' users namely Domestic, Irrigation, Industrial, and Livestock. Based on water allocation and demand priority the demand coverage of current water demand showed 100% and there is no unmet demand for all water demand sites as indicated in Table 4.6. The current total water consumption for the four consumers (Domestic, Livestock, Industrial, and Irrigation) within the sub-basin is estimated to be 49.68 MCM per year as indicated in Table 4.5. Therefore, the water withdrawal in Katar is around 11.14% of the total water available in the catchment, which is 445.95 MCM per year. Comparing the water requirements with the available surface water, Katar had a capacity to utilize only 11.14% of the current water available in the sub-basin for consumptive uses.

Table 4.5: Average monthly water demand in (MCM)

Month	Irrigation	Domestic	Industrial	Livestock
Jan	1.66	0.73	1.09	1.75
Feb	1.98	0.66	1.02	1.58
Mar	2.01	0.73	1.09	1.75
Apr	0.68	0.70	1.06	1.69
May	0.25	0.73	1.09	1.75
Jun	0.00	0.70	1.06	1.69
Jul	0.00	0.73	1.09	1.75
Aug	0.00	0.73	1.09	1.75
Sep	0.00	0.70	1.06	1.69
Oct	0.04	0.73	1.09	1.75
Nov	0.15	0.70	1.06	1.69
Dec	0.87	0.73	1.09	1.75
Total	7.64	8.56	12.90	20.58

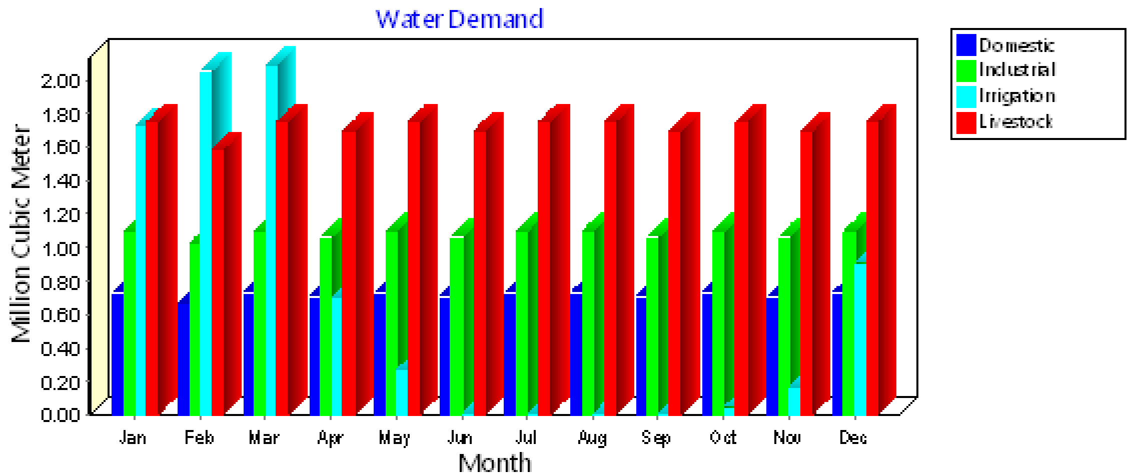

Figure 4.6: Current water demands for different water competing users in the study area.

Table 4.6: Current year total water demand, unmet demand and demand coverage in (MCM)

Month	Demand	Unmet Demand	Demand Coverage (%)
Jan	5.23	0.00	100
Feb	5.23	0.00	100
Mar	5.58	0.00	100
Apr	4.13	0.00	100
May	3.82	0.00	100
Jun	3.45	0.00	100
Jul	3.57	0.00	100
Aug	3.57	0.00	100
Sep	3.45	0.00	100
Oct	3.61	0.00	100
Nov	3.61	0.00	100
Dec	4.44	0.00	100
Total	49.69	0.00	

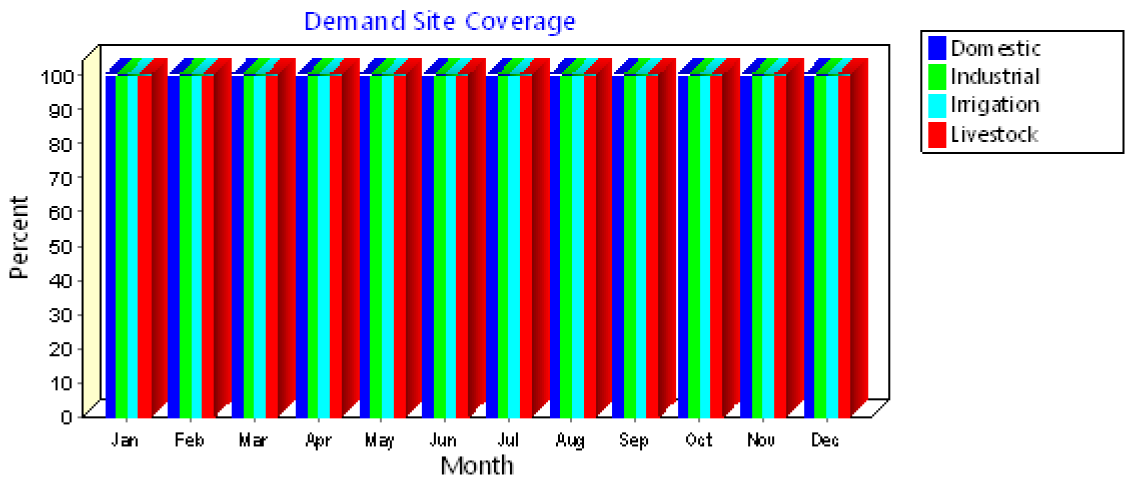

Figure 4.7: Current year demand coverage for Katar sub-basin

4.7 Environmental Water Demand

Environmental flow requirement is used to keep the natural ecosystem and for downstream water users in the basin. It is one of the different types of water demand that need to allocate to reserve water for basic human need and ecosystem sustainability. Its allocation is the first priority before other water demands are allocated and satisfied in the sub-basin. In Katar sub-basin 20% of mean annual river flow is reserved for Environmental flow requirement. The 20% mean annual river flow of Environmental flow requirement is used for navigation, and wildlife. In Katar sub-basin, annually 88.95 MCM of water is needed for the Environmental flow requirement.

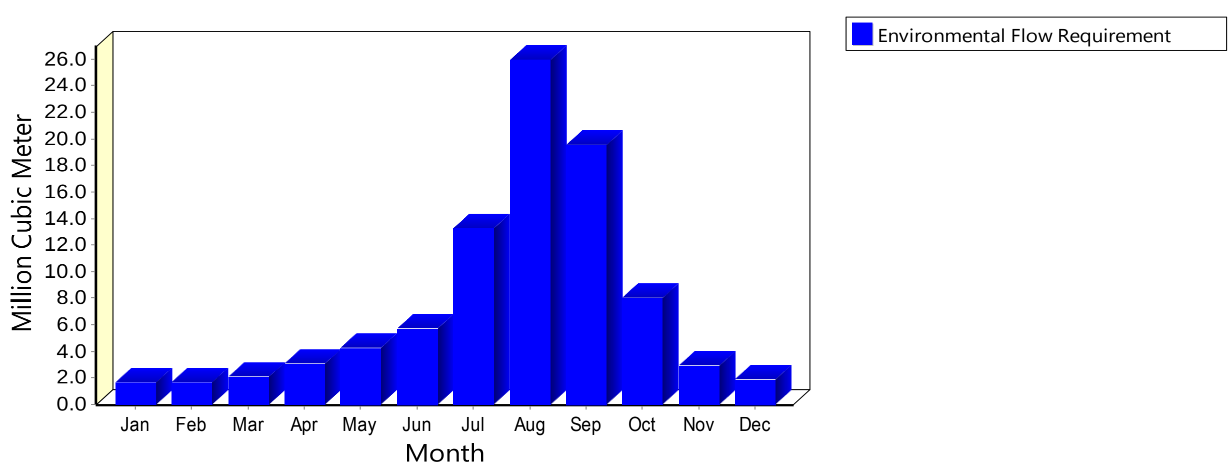

Figure 4.8: Environmental flow requirement

4.8 Future Water Demand

Future water demand is determined based on three basic scenarios. The first scenario is short term scenario, the second scenario is a medium-term scenario and the third is long term scenario. The above scenarios are discussed separately as below.

4.8.1 Short Term development (2020-2030) Scenario

Scenarios are self-consistent storylines of how a future system might evolve in a particular socio-economic setting and under a particular set of policy and technology conditions (Sieber and Purkey, 2015). The annual population growth rate of 3% for humans, livestock and 1000ha irrigation command area is involved under this scenario. The total water demand under this scenario for the year 2030 is 69.12 MCM as indicated in figure 4.9.

The water resource in the catchment implies that the number of human population, livestock population, and the irrigation command area is increasing also the volume of water required for humans, livestock and irrigation is also increasing. From the reference scenario, the total water demand by domestic, livestock, industrial, and irrigation for the year 2020 is 49.69 MCM. Comparing this result with a short-term scenario for the year 2030 the demand increased by 39.1%. Considering the water resource of the Katar catchment, there is no unmet demand for short term scenario and the demand coverage is 100% for all demand sites as indicated in Table 4.7.

Table 4.7: Total annual water demand under short term scenario

Year	2020	2025	2030
Demand (MCM)	49.69	58.96	69.12
Unmet Demand (MCM)	0.00	0.00	0.00

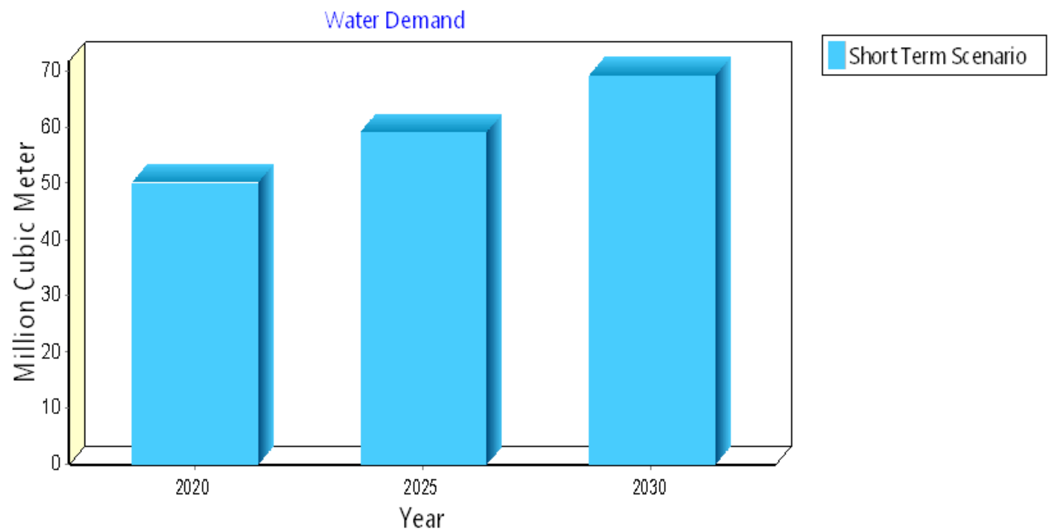

Figure 4.9: Total Annual water demands

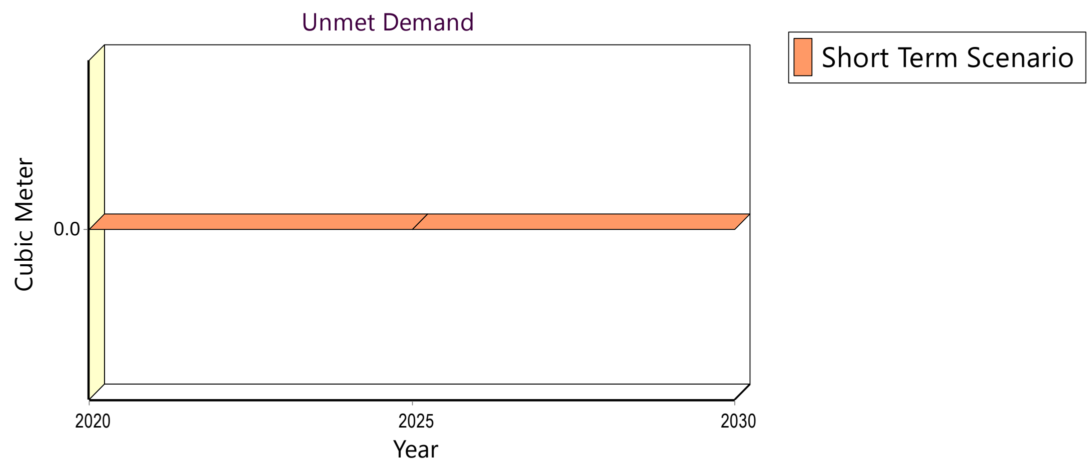

Figure 4.10: Unmet demands for short term development scenario

Table 4.8: Monthly water demand under short term development scenario in (MCM)

Month	Irrigation	Domestic	Industrial	Livestock
Jan	3.05	1.23	1.10	2.35
Feb	3.62	1.11	0.99	2.12
Mar	3.68	1.23	1.10	2.35
Apr	1.24	1.19	1.06	2.27
May	0.47	1.23	1.10	2.35
Jun	0.00	1.19	1.06	2.27
Jul	0.00	1.23	1.10	2.35
Aug	0.00	1.23	1.10	2.35
Sep	0.00	1.19	1.06	2.27
Oct	0.07	1.23	1.10	2.35
Nov	0.28	1.19	1.06	2.27
Dec	1.60	1.23	1.10	2.35
Total	14.02	14.53	12.90	27.66

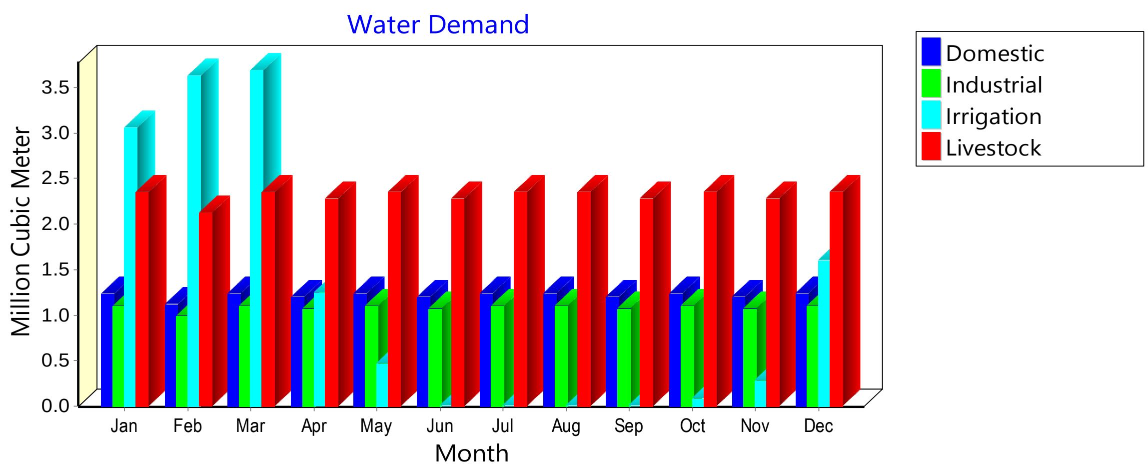

Figure 4.11: Monthly water demands under short term development scenario

4.8.2 Medium Term Development (2030-2040) Scenario

The demands considered in the medium-term scenario are development activities mentioned in short term scenario and additional 3000 ha irrigation and two industry are applied. The total water demand in the medium-term scenario for the year 2040 is 126.56 MCM. The supply delivered to each demand site depends on the available water source and the demand requirements for the site. If the available water source is sufficient to cover all the demands of the site, then the supply delivered and supply requirement are equal. Otherwise, there will be unmet demands. For the medium-term scenario, the supply requirement and supply delivery are equal for all monthly average values and the demand coverage is 100% up to the year 2039. For the coming 19 years, the current surface water resource is sufficient to perform sustainable water supply, Industries, and irrigation activities. But for the year 2040 there is unmet demand. Comparing the demand users under medium-term scenario Industrial consumption is higher than irrigation, domestic, and livestock as indicated in figure 4.12.

Table 4.9: Demand and unmet demand

Year	2030	2035	2040
Demand (MCM)	99.96	114.09	126.56
Unmet Demand (MCM)	0.00	0.00	0.33

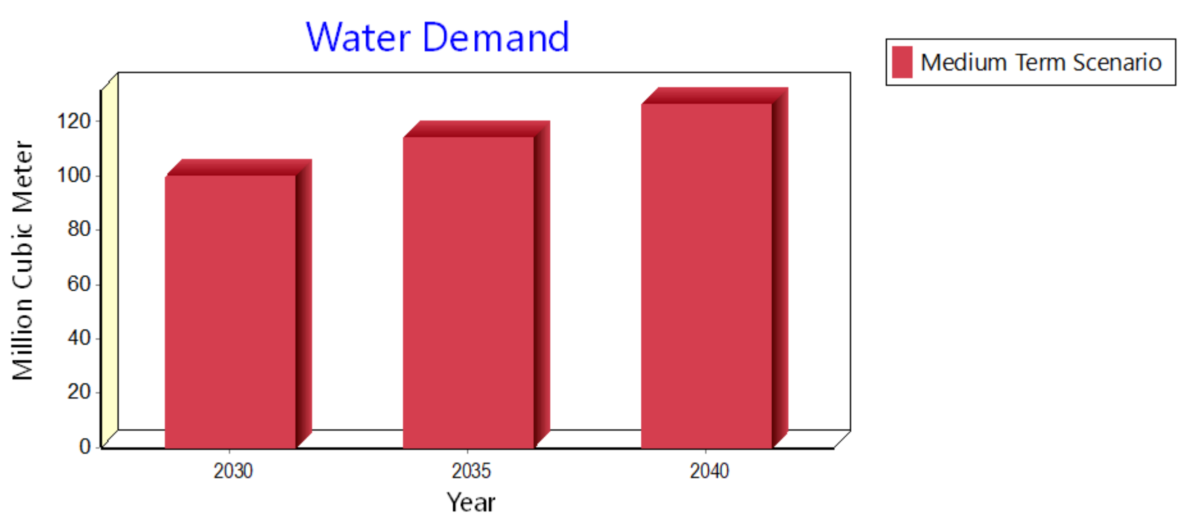

Figure 4.12: Water demand under medium term development scenario

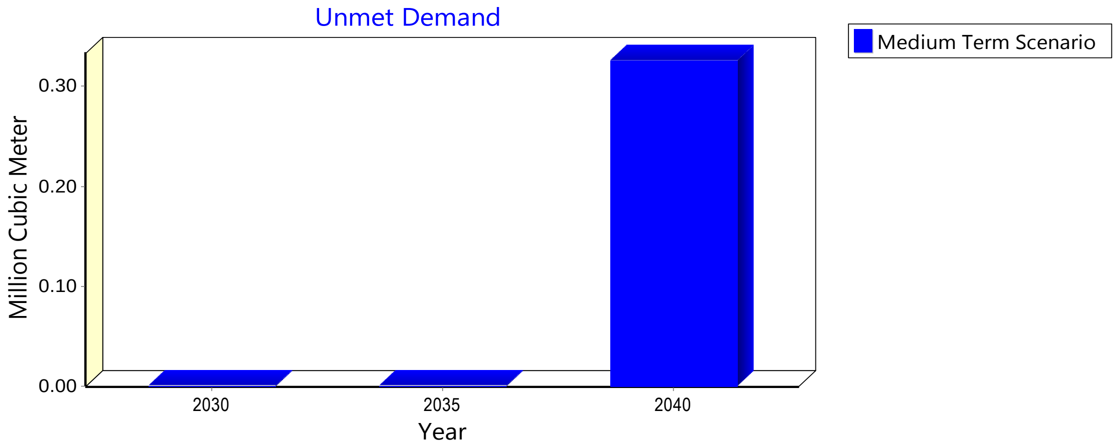

Figure 4.13: Unmet demands under medium term development scenario

Table 4.10: Monthly water demand under medium term development scenario

Month	Irrigation	Domestic	Industrial	Livestock
Jan	6.05	1.93	3.29	3.17
Feb	7.18	1.75	2.97	2.86
Mar	7.29	1.93	3.29	3.17
Apr	2.45	1.87	3.18	3.07
May	0.92	1.93	3.29	3.17
Jun	0.00	1.87	3.18	3.07
Jul	0.00	1.93	3.29	3.17
Aug	0.00	1.93	3.29	3.17
Sep	0.00	1.87	3.18	3.07
Oct	0.15	1.93	3.29	3.17
Nov	0.56	1.87	3.18	3.07
Dec	3.16	1.93	3.29	3.17
Total	27.76	22.76	38.69	37.34

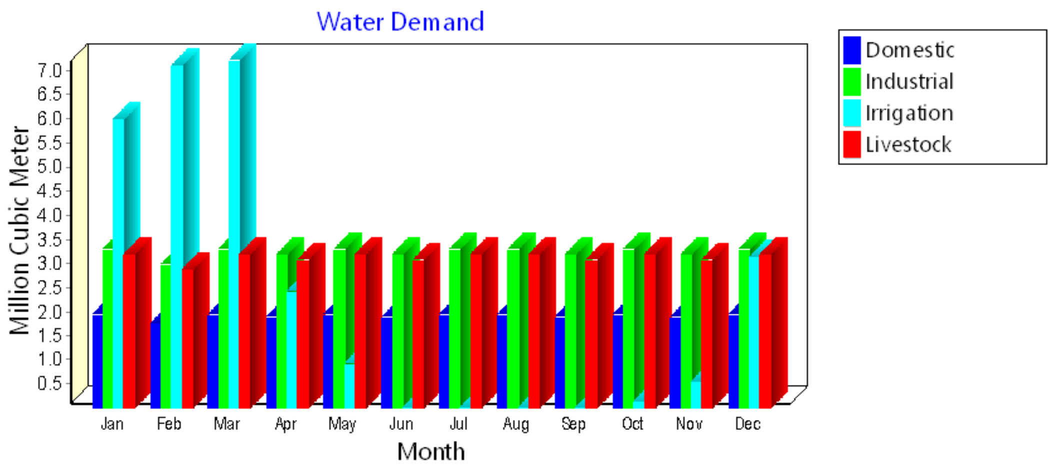

Figure 4.14: Monthly water demands under medium term development scenario

4.8.3 Long Term Development (2040-2050) Scenario

In the long-term scenario, the considered development plans are those plans mentioned in the medium-term scenario as well as other potential irrigable land and one additional industry in the area. Additional potential irrigable land of 2500ha in Katar catchment is expected to be studied and considered in this scenario. The total annual water demand under a long-term scenario by the year 2050 is 179.68 MCM. Comparing this result with short-term, and medium-term scenario the water demand increase by 154% from short-term scenario and 42% from medium term scenario.

The supply delivered to the demand sites is less than the supply requirement of all demands; there is a water deficit to perform future irrigation and industrial development under full potential. The unmet demand occurs in industrial and irrigation demands because both of them have priority orders of two and three. Domestic and Livestock demands have higher priority than irrigation and industrial water demand. The unmet demand is increased substantially from 2040 up to 2050. This is due to the increased irrigation command areas in the catchment.

Table 4.11: Demand and unmet demand under long term development scenario

Year	2040	2045	2050
Demand (MCM)	138.17	156.88	179.68
Unmet Demand (MCM)	2.11	9.22	21.43

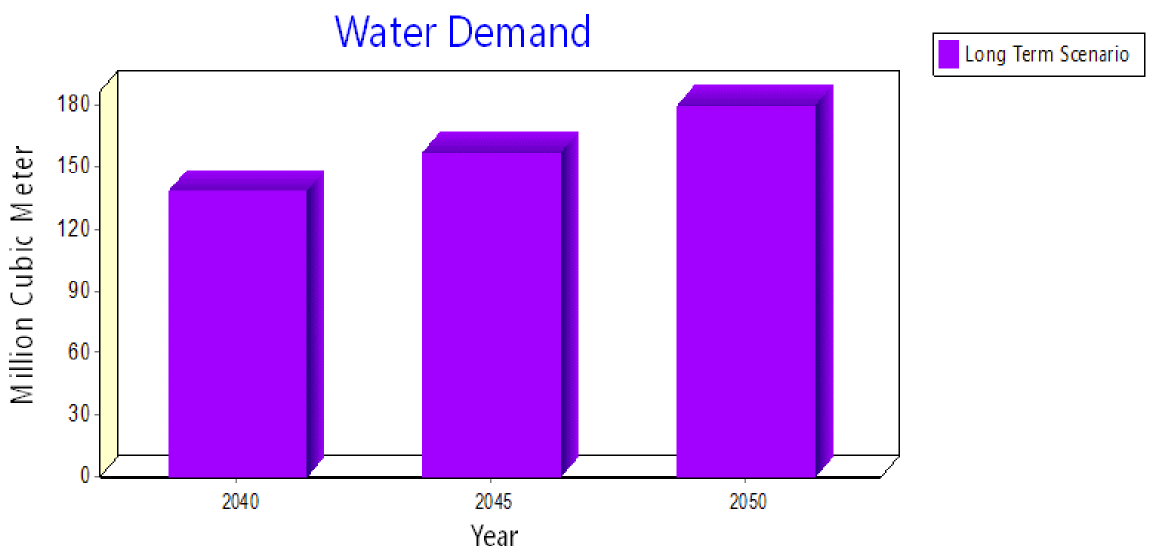

Figure 4.15: Annual water demands

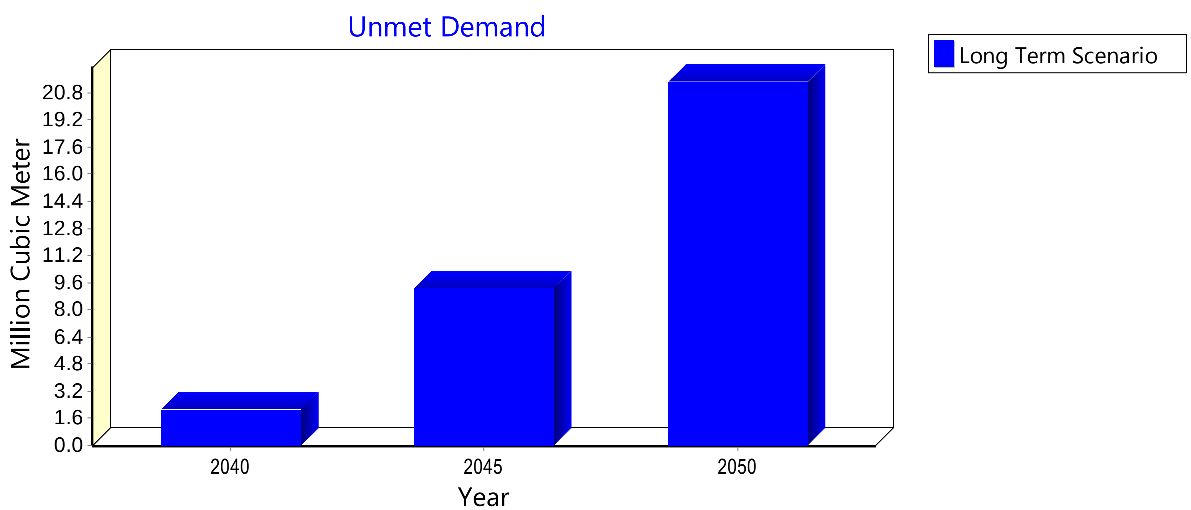

Figure 4.16: Unmet demands under long term development scenario

Table 4.12: Monthly water demand under long term development scenario

Month	Irrigation	Domestic	Industrial	Livestock	Total
Jan	9.41	2.97	4.38	4.24	21.00
Feb	11.16	2.68	3.96	3.83	21.64
Mar	11.35	2.97	4.38	4.24	22.94
Apr	3.82	2.87	4.24	4.11	15.04
May	1.44	2.97	4.38	4.24	13.03
Jun	0.00	2.87	4.24	4.11	11.22
Jul	0.00	2.97	4.38	4.24	11.59
Aug	0.00	2.97	4.38	4.24	11.59
Sep	0.00	2.87	4.24	4.11	11.22
Oct	0.23	2.97	4.38	4.24	11.82
Nov	0.86	2.87	4.24	4.11	12.09
Dec	4.92	2.97	4.38	4.24	16.51
Total	43.19	34.95	51.59	49.96	179.68

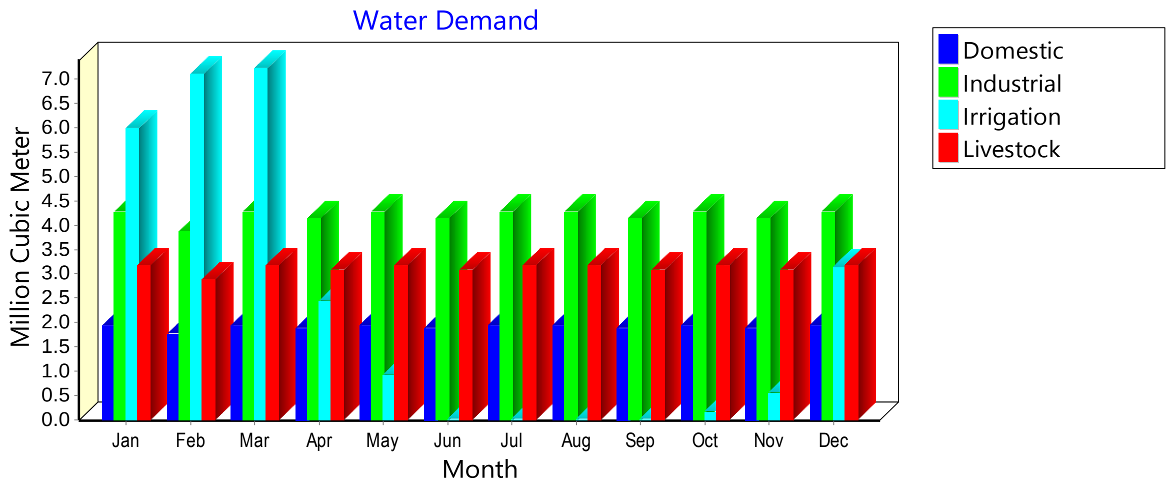

Figure 4.17: Monthly water demands under long term development scenario

To summarize the above three scenarios, the result shows that the water demand is increased from short term scenario to long term scenario. The water demand in short term scenario is minimum compared to a medium-term and a long-term scenario, this is because of expansion of Irrigation and Industries are applied in a medium-term and long-term scenario. In the short term scenario there is no unmet demand but for the medium-term and long-term scenario the water demand is not fully satisfied due to the unmet demand is occurred. Finally, to use the water resource of the Katar sub-basin efficiently, equitably, and sustainably additional storage is needed to store water in the rainy season and to use for irrigation in the dry season.

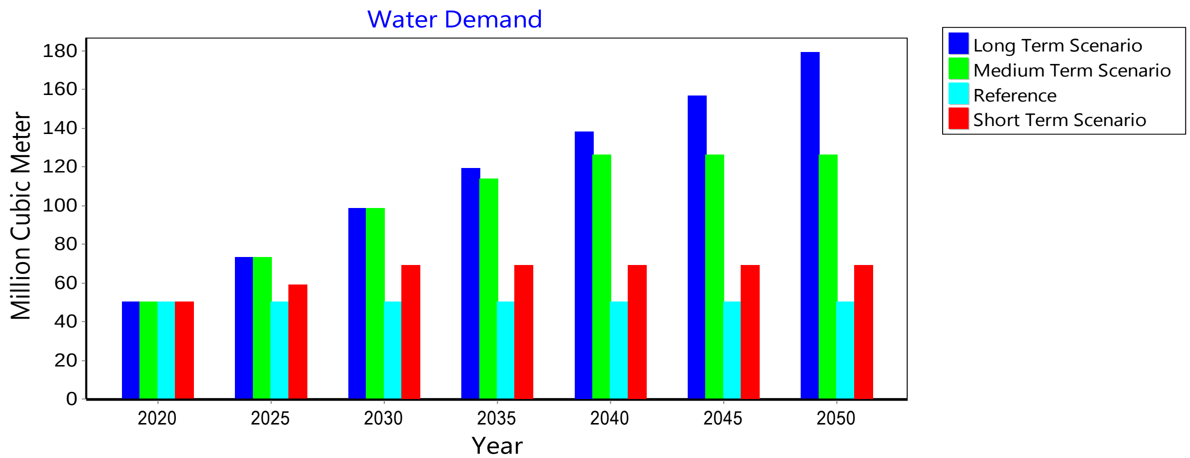

Figure 4.18: Water demand under all development scenarios

5. CONCLUSION AND RECOMMENDATIONS

5.1. Conclusion

In this study, the Water Evaluation and Planning (WEAP) model was applied to assess surface water availability and the current and future water demand. Evaluation of future water demand was made based on three scenarios namely short-term scenario, medium-term scenario, and long-term scenario. The catchment simulation was simulated using the Soil moisture method that requires land use and climate data. WEAP was calibrated and validated based on observed and simulated stream flow data of Katar station near Abura. The performance evaluation coefficients result shows a very good model performance between observed and simulated flow that is used to simulate the catchment. After simulating the model, the total annual stream flow of the Katar sub-basin was 445.95 MCM.

The water demand analysis result shows that the current water demand for Domestic, Livestock, Industries, and Irrigation was 45.13 MCM. This shows that the current utilization of the water resources was very limited around 10.12% of the total available river flow. To predict future water demand under existing and planned water resources development fully implemented for the year 2050 three scenarios were conducted. Comparing Short-term scenario with base year water demand has not much effect on the water demand. Under medium and long-term scenario, the water shortage will happen for both Industrial and irrigation.

5.2. Recommendations

From the results obtained the following recommendations are derived.

- The accuracy of the model is highly dependent on the quality of input data. Hence, more detailed measurement data and more principal meteorological stations should be established in the Katar catchment for future catchment simulation.
- A water demand analysis of the Katar sub-basin up to the year 2050 was conducted and it is recommended that the results be used to assist in water resource decision making and planning by the decision-makers in the future.
- Water allocation planning should be applied on the basis of water resource availability and demand priorities. For optimal water allocation in the Katar catchment, in addition to the considerations taken in this study, the integration of additional data on groundwater, reservoirs, and catchment characteristics is also required. Further research on these topics is thus recommended.
- The irrigation system in this area is furrow/surface irrigation which demands a high amount of water. So, I suggest to the high efficiency of irrigation systems like drip, sprinkler irrigation system which leads to increase irrigation area coverage and reduce the probability of water loss through evaporation.

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APPENDIX

Appendix Tables

Appendix Table 1: Monthly rainfall at Kulumsa

Year	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
1994	0.09	13.12	34.51	66.71	42.82	161.34	120.19	133.64	105.65	1.18	32.91	15.44
1995	0.07	34.12	164.23	140.35	64.81	79.36	120.55	142.15	74.33	2.28	0.09	45.81
1996	42.01	4.33	133.33	58.91	182.52	134.64	130.44	98.54	87.77	1.33	3.51	0.08
1997	6.45	0.00	218.21	112.71	35.35	115.55	134.56	108.68	61.22	93.55	25.72	0.09
1998	27.81	62.12	51.82	69.15	91.71	84.14	78.22	186.61	119.81	106.12	35.08	0.95
1999	5.43	1.11	73.45	25.23	61.55	103.55	111.81	110.33	71.08	184.55	0.19	0.96
2000	0.00	0.07	0.45	74.61	146.61	158.38	150.91	82.91	120.15	34.81	27.32	1.61
2001	0.52	22.44	186.11	12.22	189.55	147.55	98.33	179.26	86.91	10.91	6.26	0.77
2002	102.19	68.45	50.21	70.81	49.44	68.21	44.64	168.44	46.55	1.66	0.55	38.55
2003	16.22	42.61	94.22	128.19	19.65	116.62	121.71	97.27	83.22	17.84	0.44	21.41
2004	56.01	1.54	25.65	83.91	24.51	102.51	106.35	97.54	156.14	70.91	0.91	2.81
2005	48.33	44.91	108.91	128.55	69.68	63.91	62.76	86.54	84.72	19.22	25.81	0.35
2006	5.22	16.03	82.71	131.44	61.91	80.65	161.64	99.72	81.33	77.08	2.84	6.55
2007	27.21	59.61	49.44	89.91	155.34	120.66	130.91	96.44	79.81	20.28	6.62	0.78
2008	0.55	2.35	0.22	41.55	81.28	100.77	158.72	232.81	101.61	78.92	65.65	0.85
2009	20.32	10.81	35.54	50.21	61.72	57.54	158.54	202.45	95.88	68.31	0.99	28.31
2010	4.54	127.43	101.17	107.21	94.71	115.91	147.51	85.71	123.55	3.31	3.55	3.51
2011	8.45	25.61	133.33	58.35	120.52	64.71	113.92	153.65	167.42	0.09	4.84	0.96
2012	1.41	2.52	28.31	101.34	72.71	75.75	198.21	187.91	272.12	3.89	4.92	13.31
2013	7.55	0.00	82.77	36.15	130.33	56.18	203.55	76.42	114.91	36.02	6.32	0.55
2014	2.61	29.71	75.34	65.55	110.71	40.81	40.81	128.11	158.77	214.72	1.52	0.99
2015	0.07	2.25	28.11	17.91	136.87	140.28	59.44	72.84	115.22	12.71	28.44	0.38
2016	20.91	1.91	38.22	250.15	127.01	118.84	136.33	63.35	96.91	26.44	12.26	0.08
2017	0.00	29.15	87.21	25.34	164.55	64.25	124.34	115.18	131.25	12.65	0.09	0.09
2018	4.21	27.34	71.83	82.71	119.71	124.64	120.61	184.91	72.33	45.71	12.65	0.67
2019	0.08	14.81	68.18	79.71	131.35	85.91	130.32	127.08	134.71	42.34	7.36	5.18

Appendix Table 2: Monthly rainfall at Arata

Year	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
1994	0.99	0.85	37.88	17.74	56.47	177.68	120.91	98.81	120.01	0.29	9.39	0.19
1995	0.85	40.61	182.21	221.66	55.91	186.51	94.55	137.45	113.72	16.54	0.96	16.54
1996	26.61	0.85	77.72	48.19	152.38	234.84	122.71	129.36	113.71	14.65	2.65	0.65
1997	0.77	5.75	109.55	183.91	60.76	91.16	153.45	57.84	80.70	108.05	31.12	0.85
1998	56.25	63.62	83.86	53.55	66.44	106.22	111.22	126.26	140.02	105.91	16.02	0.78
1999	0.18	0.97	46.16	12.87	24.71	98.28	115.17	67.45	73.50	213.56	17.84	0.98
2000	0.89	0.88	2.78	89.81	115.45	79.19	152.18	127.19	143.01	18.44	78.41	0.09
2001	0.00	28.45	110.16	20.39	127.88	128.18	67.18	189.34	163.91	1.55	0.87	0.88
2002	3.25	74.53	85.68	29.77	89.65	38.84	46.29	136.15	49.71	1.39	0.66	20.55
2003	0.88	51.44	39.58	107.55	58.64	121.68	150.19	79.19	107.63	7.16	20.42	28.71
2004	12.17	3.28	28.19	91.48	13.99	73.81	102.19	65.71	149.41	62.31	0.55	1.55
2005	53.25	6.55	46.91	121.19	136.41	77.55	111.28	88.87	109.23	16.15	19.26	0.55
2006	4.56	19.43	64.75	130.77	20.18	119.44	155.58	113.54	83.61	12.71	0.44	3.25
2007	11.71	10.25	36.16	72.68	122.77	129.88	178.64	117.49	87.13	21.36	4.33	0.85
2008	1.65	0.65	0.97	36.88	96.99	112.22	230.65	154.88	82.91	59.35	75.55	0.99
2009	32.81	4.32	72.61	52.28	46.88	44.61	102.28	145.14	38.28	97.02	1.94	41.65
2010	0.55	83.84	90.15	120.81	154.25	95.19	210.19	90.99	103.91	7.28	0.89	4.58
2011	0.91	18.71	56.25	45.33	133.15	82.18	152.85	155.71	88.33	0.99	24.41	0.65
2012	0.78	0.66	12.36	72.65	30.78	90.55	221.58	184.28	163.81	7.56	0.98	23.35
2013	17.81	0.86	122.19	16.57	96.28	61.48	193.39	104.42	70.61	105.81	0.85	0.99
2014	0.00	7.55	76.76	28.77	77.77	32.55	175.88	124.33	165.35	103.02	15.81	0.78
2015	0.99	0.54	11.46	10.65	63.55	134.91	87.81	51.27	79.71	0.66	0.56	0.98
2016	15.51	3.55	31.54	169.54	95.71	156.77	140.39	67.48	83.15	7.25	14.15	0.88
2017	16.81	28.21	75.56	25.58	117.85	64.22	139.38	145.71	123.71	7.55	0.99	0.99
2018	11.66	0.85	34.46	133.75	64.85	100.91	102.91	122.78	85.74	23.71	58.66	2.65
2019	0.87	0.98	42.18	67.58	80.94	95.18	133.91	94.61	72.71	19.55	10.23	0.55

Appendix Table 3: Monthly rainfall at Asela

Year	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
1994	0.00	0.00	138.91	44.51	83.88	205.81	249.71	164.55	178.19	5.55	23.95	3.55
1995	0.00	23.25	122.44	153.81	96.71	118.91	212.01	164.21	97.68	22.01	0.00	69.51
1996	69.81	16.55	171.71	155.90	156.55	193.91	163.33	142.71	133.91	31.55	1.98	4.32
1997	18.71	36.81	91.91	214.55	49.81	160.01	196.61	98.25	99.24	130.21	57.71	1.32
1998	27.34	60.61	48.22	94.99	72.61	109.02	192.45	266.56	135.55	131.33	3.55	0.33
1999	0.25	0.00	49.81	33.42	45.18	83.51	189.44	120.55	104.26	218.55	11.71	0.99
2000	0.00	0.00	1.18	178.32	127.81	138.32	150.81	153.62	173.91	101.61	36.08	0.44
2001	0.00	90.12	267.33	53.91	258.71	179.41	139.88	273.43	127.27	39.25	8.77	1.11
2002	7.18	53.91	85.81	62.83	35.81	120.45	68.91	204.91	76.28	9.21	0.09	55.33
2003	10.19	13.91	173.51	185.61	36.66	102.21	148.52	155.73	110.91	6.16	2.08	33.69
2004	60.91	0.12	38.33	118.22	44.91	103.52	149.77	171.31	161.55	158.11	21.12	49.61
2005	90.81	22.45	117.71	129.71	182.23	76.33	132.11	151.91	122.81	14.55	41.41	1.09
2006	2.77	21.05	57.01	121.55	92.61	141.61	209.43	178.29	120.09	45.68	0.00	11.66
2007	23.86	78.15	26.18	123.44	175.01	131.15	230.17	205.91	138.28	48.81	13.61	0.09
2008	5.81	1.47	0.00	32.71	127.31	93.41	203.74	238.33	144.61	56.09	56.91	0.08
2009	49.15	15.45	76.48	73.77	73.81	113.61	194.25	225.21	55.18	161.21	0.00	53.71
2010	6.16	127.51	102.91	191.62	125.65	88.91	143.71	137.91	193.71	1.09	17.31	2.91
2011	9.95	26.89	100.81	70.58	148.11	80.19	178.22	185.55	199.35	0.00	34.81	0.00
2012	0.00	0.15	32.27	110.71	33.33	93.33	224.91	181.81	136.66	4.25	3.65	34.51
2013	13.55	0.33	159.86	52.55	162.42	53.71	280.11	130.71	127.71	98.91	28.21	0.00
2014	4.13	34.55	156.34	76.71	132.11	49.15	180.01	172.35	185.62	194.15	11.81	0.00
2015	0.12	1.08	19.29	27.81	106.91	196.33	120.19	166.81	175.54	9.85	4.68	0.01
2016	15.52	27.35	96.36	318.21	151.01	99.01	112.42	144.18	150.61	42.91	13.81	0.51
2017	0.00	8.49	39.91	50.91	187.81	111.91	121.91	269.28	117.71	13.28	1.33	0.05
2018	0.00	19.25	34.48	61.21	114.22	255.33	196.44	187.19	147.61	35.37	52.91	7.12
2019	0.00	80.66	96.71	184.41	125.44	115.91	184.22	186.45	145.51	54.71	19.55	9.28

Appendix Table 4: Monthly rainfall at Bokoji

Year	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
1994	0.82	0.00	37.61	128.21	50.00	168.03	246.52	274.71	95.77	6.37	38.64	5.05
1995	0.00	41.42	94.23	151.82	73.43	50.12	181.71	230.03	157.21	17.55	1.25	32.47
1996	58.71	12.32	140.22	55.55	154.31	214.42	229.23	158.33	86.11	35.04	3.14	5.95
1997	8.62	14.23	139.92	170.41	48.62	122.21	161.53	88.24	80.41	110.62	38.22	0.44
1998	37.13	62.14	61.32	72.31	76.91	99.72	127.22	193.14	131.82	114.44	18.22	0.11
1999	1.91	0.44	56.31	23.71	43.62	95.15	138.82	99.33	82.92	205.54	9.81	0.33
2000	0.00	0.00	1.42	114.01	129.92	125.24	151.31	121.22	145.73	51.61	47.21	0.71
2001	0.23	47.00	188.01	28.81	191.81	151.71	101.61	214.03	126.01	17.22	5.02	0.44
2002	37.74	65.62	73.54	54.41	58.32	75.84	53.22	169.71	57.55	4.05	0.00	37.91
2003	8.84	35.83	102.44	140.41	38.34	113.53	140.13	110.72	100.64	10.35	7.55	27.94
2004	43.00	1.63	30.73	97.81	27.82	93.02	119.44	111.32	155.75	97.14	7.34	17.84
2005	64.00	24.62	91.21	126.42	129.41	72.43	102.03	109.11	105.65	16.63	28.82	0.45
2006	4.13	18.82	68.12	127.71	58.22	113.92	175.54	130.33	95.02	45.13	0.74	7.14
2007	20.92	49.31	37.23	95.31	151.00	127.25	179.91	139.91	101.74	30.12	8.22	0.00
2008	2.63	1.22	0.14	36.72	101.52	102.12	197.75	208.64	109.73	64.71	66.02	0.00
2009	41.01	9.91	74.52	66.22	64.64	61.62	159.23	254.65	97.12	52.43	11.62	42.74
2010	3.75	125.17	190.53	153.41	223.92	89.74	269.41	250.93	100.55	7.54	6.00	49.21
2011	18.36	56.02	36.81	60.35	118.23	187.42	190.02	239.55	111.55	16.82	29.61	0.00
2012	0.00	0.12	35.00	119.73	29.03	143.33	230.04	183.02	150.23	0.00	11.91	10.22
2013	8.32	7.00	85.91	110.62	78.92	111.25	236.72	177.33	43.54	97.82	20.55	0.00
2014	0.00	72.91	68.04	51.03	155.01	40.84	281.81	269.82	116.54	124.52	0.00	0.00
2015	0.00	0.00	51.32	64.52	103.52	147.52	123.61	207.00	127.44	0.00	2.63	0.00
2016	6.13	52.23	77.92	99.84	118.12	62.32	209.02	233.22	93.83	90.37	9.75	31.15
2017	6.52	37.62	59.24	95.55	79.81	165.41	394.34	229.62	93.23	48.11	10.44	25.14
2018	4.23	33.91	62.92	90.22	94.02	116.12	74.11	226.14	91.71	25.52	10.42	25.12
2019	0.00	48.12	74.22	98.13	111.21	122.51	221.52	229.23	93.01	45.66	9.91	29.11

Appendix Table 5: Monthly maximum temperature at Arata station

Year	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
1994	22.93	24.05	24.33	24.54	23.62	26.31	24.55	24.55	25.32	28.12	26.82	26.12
1995	27.43	28.31	27.81	26.44	27.71	28.31	25.01	25.11	25.81	27.91	27.84	26.91
1996	26.10	29.02	28.72	27.81	27.31	25.21	24.92	25.12	25.62	26.93	27.21	26.90
1997	26.92	26.91	29.51	27.32	29.21	27.64	26.11	26.44	27.55	26.81	26.52	26.72
1998	26.82	28.73	29.30	30.81	29.92	28.42	25.64	25.41	25.81	26.32	26.81	27.13
1999	24.15	26.55	29.00	30.74	29.31	27.81	24.62	25.62	26.92	25.43	26.50	27.11
2000	28.10	29.91	31.11	30.32	28.84	27.71	25.51	25.11	25.44	26.30	27.33	27.62
2001	28.22	29.91	28.12	29.72	28.25	26.62	26.23	24.94	26.52	28.33	27.91	28.01
2002	27.33	29.91	29.32	30.33	30.51	28.11	27.71	26.12	26.71	29.22	29.22	27.41
2003	28.21	30.54	29.64	29.42	31.22	27.42	24.44	25.91	26.11	28.71	28.65	26.62
2004	28.71	29.15	30.10	28.03	30.92	27.71	25.87	26.55	26.42	26.44	30.21	28.40
2005	28.62	29.32	29.82	30.71	27.32	27.23	25.75	26.81	27.22	29.02	28.41	28.21
2006	28.91	30.21	28.88	28.12	29.85	27.81	25.54	25.31	25.51	28.55	28.90	27.81
2007	28.42	29.54	31.06	29.51	29.73	26.35	25.23	24.62	25.50	27.51	28.22	28.02
2008	29.32	28.62	32.12	30.31	28.11	27.01	24.52	24.64	26.21	27.87	26.11	27.91
2009	28.14	29.62	31.63	29.92	30.61	29.63	26.14	25.81	27.74	27.45	28.44	27.65
2010	28.55	28.21	27.62	28.63	27.92	27.61	25.13	26.33	25.90	28.58	28.25	27.71
2011	28.54	30.33	29.55	31.62	28.55	27.61	25.61	25.42	25.14	27.95	27.34	27.24
2012	29.15	30.01	31.62	29.74	31.33	28.52	24.32	24.91	25.11	27.35	28.33	27.73
2013	28.12	30.61	30.05	28.91	27.74	27.61	24.41	24.43	25.92	26.54	27.15	27.31
2014	28.83	29.54	29.33	30.22	28.22	28.64	25.55	24.71	25.04	26.16	27.11	26.82
2015	27.71	30.41	31.43	31.71	29.54	27.81	26.62	27.12	26.72	29.90	28.87	27.71
2016	28.44	30.32	32.68	28.31	27.32	26.42	25.21	25.45	26.53	28.81	27.90	27.95
2017	28.11	31.11	33.39	33.23	29.90	31.01	27.90	27.61	27.55	30.33	30.31	27.43
2018	28.44	30.00	30.74	30.22	29.02	25.72	24.02	25.11	26.21	27.82	27.22	27.32
2019	28.91	30.33	29.72	30.07	30.11	27.01	24.41	25.61	26.08	28.11	28.02	27.44

Appendix Table 6: Monthly minimum temperature at Arata station

Year	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
1994	7.81	10.77	11.21	12.02	11.33	14.60	14.51	13.84	13.88	11.35	10.18	7.82
1995	8.93	11.64	13.86	14.33	14.15	13.91	14.65	14.32	12.13	11.41	9.41	9.90
1996	10.42	10.44	13.41	14.10	14.22	14.22	13.91	13.55	12.90	10.32	9.25	8.22
1997	10.91	8.63	12.92	13.87	13.81	14.09	14.03	13.61	12.74	13.45	12.41	9.81
1998	12.33	13.83	13.91	15.22	15.78	14.77	14.91	14.44	13.71	12.91	8.41	7.56
1999	8.02	8.71	13.41	14.11	14.02	13.81	14.77	13.32	12.65	11.90	8.82	7.72
2000	7.33	8.62	11.19	14.33	14.21	13.55	13.94	13.74	12.61	12.11	9.83	7.81
2001	9.22	9.75	13.16	13.87	14.33	13.75	14.12	14.42	12.54	12.23	9.75	9.34
2002	11.02	10.84	13.35	14.72	14.81	14.92	14.81	14.44	13.42	12.64	10.90	12.51
2003	10.65	12.31	13.32	14.92	14.45	14.61	14.42	14.23	12.61	11.15	11.24	8.90
2004	11.92	10.52	12.74	14.24	13.81	14.22	14.55	13.77	12.72	11.34	11.61	9.87
2005	10.44	10.11	13.63	13.92	14.44	13.89	14.15	13.71	13.31	11.81	10.29	7.33
2006	10.33	11.61	13.62	14.13	13.94	13.74	14.52	13.92	13.25	13.33	11.25	11.51
2007	11.32	13.23	12.55	14.55	14.77	14.62	14.52	14.02	13.52	10.90	10.71	8.02
2008	9.13	11.88	11.62	14.71	14.82	14.21	14.66	13.61	13.41	12.35	10.20	7.81
2009	9.95	10.90	13.11	14.92	14.81	14.62	14.66	14.62	13.82	11.61	10.11	12.02
2010	10.71	14.44	13.78	14.41	15.42	14.44	14.31	14.85	13.61	11.87	9.42	9.21
2011	10.55	11.21	13.45	14.33	15.21	14.71	14.62	14.71	13.15	10.65	12.31	8.11
2012	8.52	9.03	12.02	15.34	14.74	14.62	14.68	14.11	13.33	10.81	10.11	9.78
2013	10.02	10.92	15.25	14.81	14.95	14.83	14.44	14.55	12.81	12.66	10.71	8.62
2014	10.45	13.64	13.23	13.74	13.84	14.71	15.13	14.14	13.48	12.42	11.58	9.21
2015	9.03	11.55	13.55	14.62	15.31	15.22	15.14	14.42	13.94	14.61	13.21	12.71
2016	13.72	13.10	15.41	16.20	15.02	14.15	14.91	14.63	14.05	12.82	11.87	10.80
2017	9.23	12.22	13.44	14.31	15.81	15.33	15.25	14.51	14.34	13.32	11.24	12.41
2018	10.22	11.91	13.41	14.76	14.95	15.05	14.28	14.22	13.65	12.71	12.51	12.32
2019	9.33	12.52	13.85	14.87	15.32	15.43	14.33	14.44	13.61	12.21	11.12	10.31

Appendix Table 7: Monthly maximum temperature at Asala station

Year	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
1994	23.32	24.33	25.02	25.91	24.42	22.24	19.62	19.71	19.17	22.19	23.65	21.91
1995	24.02	25.24	24.44	23.16	24.11	24.45	22.51	21.72	21.92	21.91	21.14	22.84
1996	22.31	23.42	25.15	24.25	22.82	21.33	21.58	21.88	22.78	22.86	24.42	23.21
1997	23.95	23.16	24.53	25.88	24.41	22.54	21.15	21.53	22.72	22.44	22.25	23.55
1998	24.62	26.24	25.22	27.41	26.87	26.26	21.78	20.51	20.71	22.34	24.69	24.16
1999	25.30	27.41	26.09	27.96	27.55	25.55	21.81	22.15	23.23	21.86	22.71	24.45
2000	25.31	25.36	26.75	26.81	24.61	23.16	20.86	20.82	21.18	22.81	22.08	21.81
2001	23.13	25.64	24.28	24.33	22.55	20.44	19.61	19.44	20.09	21.26	20.84	21.87
2002	20.52	23.23	23.09	23.12	24.33	22.08	21.32	20.03	20.31	21.91	22.26	20.90
2003	21.44	22.55	22.55	22.07	24.11	21.81	19.16	19.92	20.33	21.64	20.91	20.21
2004	21.82	21.62	23.66	21.55	23.62	20.55	19.35	19.91	19.55	19.67	20.52	20.22
2005	21.02	23.17	22.21	22.92	20.91	20.65	19.53	20.22	20.54	21.18	20.51	20.53
2006	26.55	28.19	26.73	25.71	22.83	21.09	19.52	19.33	19.31	20.69	21.08	19.91
2007	21.53	22.48	28.58	22.38	22.52	20.71	19.24	18.44	19.13	20.66	20.54	20.34
2008	21.81	22.26	24.71	23.55	21.55	20.81	19.48	18.72	20.25	21.08	19.71	20.55
2009	20.81	21.91	24.02	23.33	23.71	23.32	20.31	19.71	20.81	20.84	21.88	20.61
2010	21.83	21.27	20.86	22.67	21.77	21.57	20.66	20.81	20.35	21.75	21.54	21.88
2011	21.93	23.33	22.19	24.28	23.15	22.61	21.33	20.66	19.54	21.71	20.36	20.55
2012	22.32	23.24	24.13	22.68	23.61	22.48	20.17	22.91	23.15	25.25	22.64	21.54
2013	22.23	24.42	23.95	22.81	22.12	21.36	20.22	19.77	20.45	20.69	20.63	21.64
2014	22.31	23.24	23.25	22.42	22.81	22.91	20.77	19.61	19.78	20.34	21.74	21.08
2015	21.82	24.63	24.64	25.21	23.33	22.12	21.72	21.88	21.15	23.12	24.81	25.42
2016	22.41	23.11	25.65	22.55	22.44	22.44	21.63	21.35	21.54	22.38	22.77	21.84
2017	14.71	23.42	25.84	24.13	23.71	26.66	26.64	20.22	21.38	22.17	21.63	20.34
2018	21.22	23.05	23.95	23.32	22.79	22.59	21.19	20.22	20.44	21.67	21.74	22.33
2019	20.81	23.17	23.44	23.45	22.87	22.53	20.9	20.0	20.28	21.54	21.26	20.19

Appendix Table 8: Monthly minimum temperature at Asala station

Year	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
1994	6.71	10.28	11.51	12.48	11.74	11.22	11.48	11.84	10.59	10.83	8.47	6.21
1995	6.74	9.55	11.55	11.57	10.91	11.25	11.71	11.65	10.74	11.22	8.34	7.94
1996	8.82	7.54	10.84	10.69	11.88	11.11	11.23	11.88	10.42	8.96	6.91	6.81
1997	8.44	7.48	9.92	10.68	10.62	11.18	11.60	11.44	10.87	10.61	9.58	7.73
1998	8.81	10.33	10.90	11.67	11.94	11.44	11.64	11.35	10.55	9.52	6.81	5.88
1999	8.08	8.71	10.86	11.58	11.45	11.52	11.67	11.33	10.91	10.18	8.01	6.41
2000	6.63	7.55	8.91	11.46	10.84	11.18	11.22	11.54	10.74	9.91	8.02	5.31
2001	7.09	10.09	11.18	11.44	11.91	10.77	10.51	10.82	9.25	9.35	6.65	6.18
2002	6.92	7.18	9.82	10.28	10.45	10.82	10.64	10.24	9.93	10.51	8.81	9.44
2003	8.84	9.44	10.33	11.55	10.96	10.41	10.77	10.41	10.44	10.64	10.93	12.15
2004	10.71	10.71	10.61	10.67	10.55	10.17	9.35	9.98	10.25	10.15	10.50	11.61
2005	11.55	11.55	9.54	9.66	8.61	9.18	9.22	9.22	9.12	9.51	11.71	6.71
2006	8.25	9.72	11.57	11.92	11.35	10.63	11.14	10.71	10.77	9.66	8.28	7.61
2007	7.81	9.71	9.93	11.66	11.54	11.51	11.15	10.54	10.35	9.55	7.36	5.88
2008	6.43	7.23	8.54	10.71	11.45	10.80	11.25	10.98	10.70	10.82	7.91	5.91
2009	7.45	8.42	9.55	10.85	10.51	10.54	10.94	10.84	10.95	9.70	8.52	8.88
2010	8.55	10.01	9.90	11.17	11.22	10.62	11.45	11.81	10.21	10.81	7.50	6.51
2011	7.61	8.35	9.81	10.71	11.44	11.58	11.55	10.91	10.35	10.45	8.74	7.22
2012	6.77	6.88	8.18	10.95	9.85	10.57	10.48	10.54	9.60	12.54	11.73	11.33
2013	11.65	11.91	14.33	11.21	11.41	10.55	11.11	11.35	10.71	10.69	8.60	5.81
2014	7.13	9.33	10.77	10.61	11.22	11.14	11.35	10.74	10.73	10.36	8.09	6.55
2015	5.64	8.44	9.82	10.64	11.14	11.35	10.96	11.24	10.65	10.41	12.71	12.11
2016	10.71	8.61	11.74	12.15	11.77	10.61	9.88	12.88	11.71	10.68	9.23	7.88
2017	5.68	7.85	8.65	10.55	11.25	11.61	11.55	9.85	11.88	10.64	8.91	7.51
2018	8.08	8.81	9.71	10.92	10.98	10.75	10.84	10.74	10.47	10.55	10.44	9.57
2019	8.09	8.88	9.74	10.81	10.94	10.17	10.84	10.17	10.46	10.23	8.95	7.74

Appendix Table 9: Monthly maximum temperature at Bokoji station

Year	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
1994	22.18	23.19	22.78	21.91	21.33	19.38	17.16	17.09	18.49	19.71	20.65	21.09
1995	22.15	22.51	21.19	20.18	21.91	21.25	17.58	17.94	18.91	19.38	21.25	20.69
1996	19.91	22.58	21.55	21.49	20.90	19.33	18.09	18.09	19.36	19.62	20.71	20.88
1997	24.65	24.61	26.45	25.18	26.05	24.44	22.82	23.09	24.22	23.64	23.43	24.09
1998	24.55	26.31	26.55	28.17	27.25	26.38	22.91	22.22	22.46	23.54	24.31	24.38
1999	24.25	26.62	26.45	28.28	27.22	25.44	22.33	22.84	23.90	22.61	23.45	24.37
2000	25.55	26.58	27.91	27.44	25.84	24.62	22.32	22.18	22.66	23.61	23.77	23.71
2001	24.55	26.61	25.09	26.22	24.71	22.91	22.44	21.81	22.81	24.38	23.88	24.09
2002	23.18	25.92	25.74	26.24	27.08	24.81	24.33	22.65	23.28	25.17	25.25	23.68
2003	24.37	26.21	25.61	25.28	27.34	24.17	21.44	22.33	22.48	24.55	24.19	22.71
2004	24.84	24.91	26.25	24.51	27.08	24.08	22.22	22.71	22.55	22.55	24.59	23.55
2005	24.38	26.09	25.72	26.44	23.81	23.71	22.13	23.09	23.26	24.45	24.08	23.88
2006	26.56	28.18	26.71	25.71	25.80	24.23	22.19	21.91	22.05	23.84	24.16	23.19
2007	24.35	25.44	28.64	25.67	25.91	23.26	21.91	21.25	22.18	23.61	23.69	23.59
2008	24.91	24.91	27.91	26.61	24.66	36.05	21.66	21.34	22.82	24.09	22.47	22.86
2009	23.91	25.35	23.90	21.77	27.04	23.87	20.33	19.18	18.81	19.09	20.69	19.55
2010	21.28	20.41	21.08	21.71	20.77	20.19	18.55	17.69	19.55	21.48	21.14	20.55
2011	21.09	23.65	23.91	28.55	22.22	20.57	19.81	20.49	21.86	23.91	22.09	25.41
2012	23.71	24.94	26.45	24.91	25.81	24.55	21.03	20.91	21.25	23.23	23.91	23.25
2013	24.08	25.91	26.32	40.71	24.16	23.84	21.33	20.91	21.87	22.71	23.26	22.84
2014	24.25	25.87	25.91	25.71	24.36	25.81	23.19	22.25	23.29	24.44	19.59	13.46
2015	13.91	26.28	27.39	27.15	25.74	24.45	23.71	23.44	22.85	24.91	23.71	23.15
2016	23.25	25.37	25.81	26.54	25.18	24.55	21.77	21.44	22.09	23.48	23.09	22.21
2017	23.27	25.27	25.81	26.54	24.91	24.55	21.55	21.35	21.91	23.35	22.81	22.17
2018	23.19	25.18	25.81	26.61	24.81	24.55	21.52	21.24	21.81	23.28	22.71	22.17
2019	22.91	25.27	25.87	26.17	24.60	24.55	21.44	21.18	21.82	23.28	22.61	22.09

Appendix Table 10: Monthly minimum temperature at Bokoji station

Year	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
1994	8.64	9.55	10.25	10.45	10.11	8.96	9.15	8.67	9.09	8.08	7.38	7.77
1995	7.75	9.54	9.89	10.48	9.81	9.25	9.15	9.28	8.55	8.78	7.91	9.09
1996	9.17	9.90	9.25	10.36	10.08	9.17	8.81	8.48	8.91	7.55	7.95	7.88
1997	9.71	8.44	11.33	12.16	12.22	12.19	12.33	12.04	11.45	11.85	10.71	8.91
1998	10.22	11.55	12.18	12.94	13.07	12.38	12.55	12.18	11.54	11.04	7.88	7.08
1999	8.01	8.71	12.01	12.82	12.55	12.55	12.55	12.16	11.66	11.25	9.32	7.71
2000	7.55	8.63	10.25	13.18	12.45	12.33	12.65	12.54	11.65	11.41	9.51	7.45
2001	8.77	10.01	11.22	11.82	11.91	11.17	12.36	11.65	10.16	10.15	7.94	7.15
2002	8.65	8.25	10.61	11.84	11.66	11.77	11.61	11.35	10.65	10.74	9.33	10.15
2003	8.91	10.01	10.84	11.91	11.65	11.45	11.44	11.33	10.55	10.45	9.91	9.15
2004	10.19	9.55	10.70	11.85	11.17	11.18	10.75	10.91	10.65	9.84	10.15	9.55
2005	9.71	9.51	10.84	11.23	11.17	10.71	10.88	10.64	10.55	10.24	10.08	6.21
2006	8.38	9.72	11.41	11.94	11.65	11.27	11.76	11.38	10.65	10.64	9.39	9.09
2007	8.81	10.63	10.38	11.92	12.09	11.95	11.74	11.08	10.76	9.71	8.58	6.48
2008	7.25	8.37	9.37	11.81	11.91	11.39	11.36	11.17	10.91	10.81	8.38	6.18
2009	7.71	8.38	6.08	5.78	11.81	6.85	9.28	10.74	12.44	12.54	13.65	12.44
2010	13.71	13.35	13.90	14.22	13.82	13.64	11.28	11.17	12.75	14.44	14.44	13.54
2011	14.01	13.71	14.08	11.91	13.73	13.82	13.67	13.17	13.75	14.17	10.19	7.28
2012	7.88	8.28	15.91	14.19	16.08	14.18	13.08	12.35	11.38	14.44	14.09	14.61
2013	15.01	14.52	15.25	14.90	14.66	13.81	11.69	13.35	15.16	14.27	14.54	7.24
2014	15.17	14.61	14.91	15.25	15.65	12.71	14.18	13.88	14.66	14.71	15.81	7.95
2015	16.55	15.26	12.65	9.23	9.44	9.65	8.68	7.88	12.33	7.35	12.71	12.15
2016	10.21	10.54	11.61	12.07	12.44	11.77	11.67	11.45	11.68	11.35	10.75	8.91
2017	10.34	10.62	11.72	12.15	12.52	11.81	11.77	11.65	11.79	11.55	10.81	8.91
2018	10.32	10.70	11.81	12.18	12.55	11.88	11.75	11.55	11.74	11.55	10.81	8.91
2019	10.33	10.64	11.77	12.14	12.55	11.71	11.68	11.55	11.77	11.67	11.09	9.09

Appendix Table 11: Monthly maximum temperature at Kulumsa station

Year	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
1994	23.45	24.61	25.28	25.78	25.18	22.91	20.54	20.45	21.13	17.77	23.65	16.87
1995	16.55	24.78	24.46	23.28	24.61	24.63	21.70	21.64	22.24	23.77	23.41	22.18
1996	21.82	25.44	24.14	23.69	22.90	21.44	21.21	20.41	21.88	22.61	22.55	22.32
1997	22.91	23.74	25.15	22.95	24.51	23.25	21.32	21.18	22.55	21.55	21.44	21.71
1998	22.18	24.55	25.88	26.88	24.91	24.24	21.44	20.81	20.81	21.81	21.65	21.74
1999	23.77	25.75	24.18	25.95	25.35	23.55	20.55	20.75	21.58	20.72	21.11	21.55
2000	23.18	24.32	25.91	25.15	24.77	23.16	20.64	20.45	21.27	21.64	21.82	21.81
2001	22.24	24.37	22.66	24.58	23.81	21.88	21.30	21.14	22.09	23.45	22.71	22.90
2002	21.64	24.64	24.85	25.48	26.36	24.32	23.97	21.81	22.62	24.27	24.10	22.65
2003	23.28	25.72	24.87	24.33	26.51	23.24	20.70	21.88	21.28	23.33	22.91	21.36
2004	23.91	23.90	25.42	23.94	26.55	23.77	21.51	21.71	21.61	21.58	22.81	22.77
2005	23.47	25.71	25.15	25.63	23.35	23.43	21.21	22.18	22.18	23.29	23.88	22.81
2006	24.15	26.22	24.54	23.22	24.81	23.74	21.34	21.52	21.33	22.81	22.55	21.65
2007	23.02	24.41	26.27	25.88	25.44	22.62	21.30	20.77	21.62	22.62	22.23	22.16
2008	23.54	24.88	27.88	25.91	24.33	23.57	20.91	20.60	22.14	23.27	21.38	22.71
2009	22.86	24.44	26.55	25.62	26.61	25.69	22.02	21.44	22.85	22.79	23.72	22.44
2010	23.71	23.81	23.21	24.58	24.55	23.61	21.45	21.55	21.44	23.84	23.61	23.19
2011	23.84	25.35	24.33	26.46	24.26	24.77	22.21	21.88	21.41	23.33	22.90	22.55
2012	23.72	24.91	26.44	24.98	25.81	24.58	21.77	20.91	21.28	23.25	23.91	23.26
2013	24.88	25.91	26.32	40.71	24.11	23.81	21.35	20.91	21.81	22.72	23.27	22.81
2014	24.22	25.82	25.91	25.75	24.39	25.75	23.17	22.15	23.28	24.47	19.45	13.45
2015	13.90	26.22	27.33	27.18	25.74	24.48	23.72	23.44	22.81	24.91	23.71	23.19
2016	24.71	26.55	29.23	24.79	23.95	23.58	22.27	21.92	22.58	24.44	23.55	22.65
2017	24.14	24.77	27.22	27.24	24.38	24.87	22.54	21.81	21.44	23.68	23.44	22.51
2018	23.81	25.23	26.35	25.86	24.72	22.72	21.45	23.18	22.48	24.19	23.65	24.22
2019	24.91	25.32	26.23	25.71	26.81	24.44	22.01	21.6	22.09	23.45	23.12	22.71

Appendix Table 12: Monthly minimum temperature at Kulumsa station

Year	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
1994	8.12	10.35	11.81	13.23	12.33	12.03	11.72	11.41	11.09	10.55	8.77	7.23
1995	7.77	10.24	11.53	12.12	11.65	11.44	11.81	11.71	10.45	10.41	11.33	8.91
1996	10.34	9.83	11.15	12.38	12.44	12.22	12.02	11.72	11.18	10.97	9.21	8.23
1997	9.81	9.21	11.22	11.93	12.27	11.21	11.41	11.17	10.71	11.52	10.34	9.25
1998	9.52	10.51	11.45	11.84	11.32	10.91	10.93	10.71	10.29	10.51	8.15	8.44
1999	8.33	8.74	11.81	12.72	12.11	12.21	11.88	11.82	11.43	11.62	11.12	9.12
2000	8.55	9.71	10.62	13.55	12.22	12.22	12.61	12.22	11.61	12.21	10.74	9.13
2001	10.33	10.46	9.53	10.12	9.51	8.82	12.41	9.71	8.51	8.93	7.41	6.05
2002	7.94	6.71	8.71	10.44	9.63	9.52	9.33	9.22	8.55	9.13	8.29	8.33
2003	7.32	8.46	8.72	9.42	9.61	9.21	9.22	9.41	8.49	9.68	7.65	6.41
2004	7.81	7.37	8.71	10.54	9.44	8.93	8.81	9.22	8.93	8.19	8.23	7.08
2005	7.22	7.06	9.33	10.13	10.48	9.10	9.22	9.09	9.21	9.32	8.11	5.08
2006	6.22	7.84	9.18	9.72	9.55	9.33	9.55	9.23	8.78	8.91	8.55	8.55
2007	7.43	8.84	8.42	9.55	9.81	9.63	9.41	8.55	8.22	8.72	7.58	6.16
2008	6.11	6.86	7.71	10.14	9.62	8.81	8.99	8.77	8.77	9.21	6.81	4.62
2009	5.88	6.14	8.42	10.13	10.33	9.09	9.62	9.23	9.22	7.78	7.09	7.42
2010	6.24	9.48	9.09	9.99	9.91	9.11	9.44	9.51	8.28	9.31	6.23	5.85
2011	5.98	7.36	8.65	9.41	10.02	9.35	9.12	9.12	8.12	9.09	9.21	6.41
2012	8.31	9.55	11.33	13.66	12.62	12.22	12.41	12.22	11.19	12.44	11.09	9.73
2013	9.70	10.44	12.64	12.44	9.41	9.41	9.31	10.77	10.91	12.23	11.22	7.28
2014	9.23	12.66	12.22	13.63	12.54	12.33	12.33	12.23	11.71	12.81	11.31	7.85
2015	9.81	10.25	12.21	13.41	13.63	13.45	12.81	12.77	12.33	13.69	12.18	11.44
2016	11.97	11.31	14.29	13.54	12.81	12.04	12.81	12.62	11.88	11.03	11.24	10.42
2017	9.12	10.74	11.83	13.51	13.34	12.55	13.15	12.71	12.22	12.61	8.91	7.45
2018	7.92	9.05	10.41	11.42	11.09	12.81	11.71	13.66	12.07	12.29	9.09	10.43
2019	9.13	9.12	10.55	11.55	12.81	10.71	10.18	10.81	10.22	10.62	9.41	8.01

Appendix Table 13: Monthly relative humidity at Kulumsa station

Year	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
1994	49.62	50.71	59.72	57.71	64.33	73.11	82.33	80.22	78.45	76.63	74.81	72.91
1995	71.13	69.34	67.54	65.74	63.95	62.18	60.32	58.41	56.63	54.81	53.02	65.37
1996	72.01	59.63	69.36	71.72	78.22	79.70	83.11	85.35	83.33	64.74	58.75	56.31
1997	63.66	50.44	61.03	74.74	69.74	70.31	79.07	79.36	73.70	75.34	79.77	71.33
1998	77.55	71.12	71.35	67.31	68.66	69.88	80.75	84.73	82.21	70.99	55.32	50.74
1999	56.01	44.85	66.10	55.66	63.05	71.34	81.25	81.71	78.08	75.33	55.11	58.11
2000	52.66	43.66	46.56	56.71	68.69	70.71	79.72	82.32	81.73	73.08	66.30	62.74
2001	61.79	55.15	71.73	61.55	73.65	78.72	81.73	83.04	77.71	63.33	55.31	58.71
2002	71.09	54.12	65.34	58.02	63.32	70.71	72.22	80.22	75.35	53.33	47.74	70.33
2003	61.55	52.33	62.03	67.38	55.22	75.33	82.71	84.33	80.08	54.09	59.07	63.72
2004	67.77	55.05	49.55	70.71	54.31	69.33	78.33	80.42	78.07	65.02	59.35	64.30
2005	60.73	50.55	65.22	60.33	74.32	73.74	79.31	80.77	79.34	57.71	54.09	49.71
2006	60.12	57.69	61.11	70.72	65.11	72.31	83.31	83.09	81.55	68.31	60.71	69.37
2007	69.44	65.22	54.36	65.05	67.02	77.32	81.03	85.55	80.44	59.88	59.22	52.71
2008	53.03	53.34	53.61	53.91	54.21	54.55	54.74	55.01	55.33	55.63	55.91	56.22
2009	56.55	56.82	57.12	57.42	57.74	58.01	58.25	58.55	58.81	59.11	59.44	59.71
2010	60.09	67.74	67.05	75.34	77.04	77.08	80.02	81.71	82.02	59.04	58.05	56.04
2011	58.36	50.01	55.34	56.71	62.15	67.51	72.91	78.32	83.74	54.09	55.51	57.08
2012	55.04	47.35	45.01	67.33	59.73	68.75	83.36	80.21	77.15	74.08	70.92	67.86
2013	64.71	60.34	61.02	61.08	60.94	60.91	60.91	60.83	60.83	60.81	60.71	60.71
2014	60.77	63.09	63.14	63.33	63.42	63.65	63.72	63.91	64.09	64.24	64.33	64.48
2015	64.65	64.74	64.96	65.02	65.24	65.32	65.55	65.64	65.81	65.91	66.02	66.21
2016	66.33	54.71	52.71	75.72	76.05	75.33	81.04	80.02	73.52	53.52	57.61	57.34
2017	49.01	50.72	59.74	57.70	64.01	73.04	82.01	80.24	78.44	76.61	74.87	72.92
2018	71.12	69.34	67.55	65.74	63.91	62.11	60.33	58.41	56.63	54.81	53.09	65.33
2019	72.88	59.22	69.33	71.71	78.00	79.77	83.88	85.34	83.88	64.74	58.74	56.32

Appendix Table 14: Flow Data

Year	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
1994	2.13	1.91	1.64	1.63	2.54	4.32	22.92	68.99	49.12	7.02	2.82	2.02
1995	1.66	1.62	7.92	7.21	5.43	2.52	12.61	48.43	59.32	4.63	2.33	2.11
1996	2.52	1.71	2.93	3.90	6.73	17.91	21.55	64.12	24.44	8.55	2.43	2.24
1997	2.91	1.72	1.64	6.02	2.62	2.77	13.62	21.01	11.14	5.64	7.01	2.95
1998	2.22	3.53	5.01	2.43	6.01	3.78	13.44	69.25	49.62	28.15	6.82	2.42
1999	2.01	0.41	1.73	1.62	1.72	3.23	17.03	33.95	21.23	44.52	7.55	2.32
2000	1.62	1.63	1.63	1.55	4.73	2.72	9.73	49.32	28.73	25.32	8.73	2.53
2001	1.83	1.55	2.22	2.63	7.62	13.84	34.32	80.12	37.91	10.42	2.41	1.82
2002	1.82	1.91	2.82	2.12	2.82	3.41	7.33	26.62	13.44	3.33	1.51	1.92
2003	2.42	1.45	1.65	3.93	3.87	2.48	16.63	51.92	29.01	7.54	1.82	1.93
2004	1.55	1.32	1.37	8.73	3.51	3.35	20.05	38.05	26.83	13.61	2.23	1.45
2005	1.54	1.43	2.33	2.77	13.93	6.05	25.92	59.33	38.90	10.44	2.34	1.52
2006	0.82	0.82	2.21	11.65	7.55	4.72	38.21	79.91	41.44	8.32	3.03	1.82
2007	1.22	1.91	1.01	3.66	3.82	11.81	28.87	67.23	58.42	12.22	2.32	1.11
2008	1.60	1.60	0.91	2.70	2.52	6.44	24.33	60.55	46.95	13.33	3.23	1.55
2009	1.94	1.33	0.84	1.85	1.15	1.18	19.82	53.82	35.44	14.42	4.22	2.01
2010	1.95	3.55	9.23	14.44	39.15	10.45	19.62	52.91	33.21	15.35	4.13	2.02
2011	2.03	1.63	2.65	3.82	7.81	6.11	19.82	53.44	33.44	15.12	4.53	2.02
2012	1.92	1.64	3.12	4.21	7.21	5.51	19.71	51.21	33.91	16.62	4.11	2.01
2013	1.72	1.64	2.54	4.52	7.62	6.12	21.43	55.72	33.91	16.42	4.12	1.83
2014	1.71	1.62	2.33	4.91	7.82	6.01	21.95	55.24	34.34	12.04	3.04	1.72
2015	1.63	1.64	2.63	4.72	8.01	6.02	20.33	56.92	35.11	10.44	2.32	1.65

Appendix Table 15: Kc coefficient of Katar catchment

Land Use	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
Cultivated land	1.20	1.20	1.10	1.00	0.80	0.40	0.60	1.00	1.00	0.70	1.20	1.20
Forest Land	0.80	0.80	0.80	0.80	0.80	1.15	1.15	1.15	0.85	0.85	0.85	0.85
Shrub Land	0.66	0.70	0.76	0.76	0.78	0.78	0.78	0.78	0.78	0.78	0.77	0.70
Grass Land	0.87	0.87	0.87	0.87	0.87	0.86	0.85	0.85	0.85	0.85	0.85	0.87
Bare Land	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Built up Area	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50

Appendix Table 16: Woreda level Katar watershed population distribution

Woreda	Urban Population	Rural Population
Tiyyo	6,525.00	80,236.00
Asala City	230,000.00	
Digaluna tiyyo	14,080.00	126,386.00
Zuway Dugda	4,506.00	116,356.00

Appendix Table 17: Water demand (l/c/d) (Source: GIRDC, 2020)

Year	2020	2030	2040	2050
Urban	70.00	85.00	95.00	105.00
Rural	25.00	35.00	45.00	55.00

Appendix Table 18: Domestic annual water consumption

Residents	Number of Population	Average daily demand (l/c/d)	Annual water use rate(m^3/person)
Urban	248586.00	70.00	25.55
Rural	242742.00	25.00	9.12

Appendix Table 19: Woreda level Livestock distribution over the Katar watershed

Woreda	Cattle	Sheep	Goat	Equine
Asalla	17895.00	4925.00	489.00	1206.00
D/ tiyyo	228112.00	121,98.00	10112.00	17296.00
Tiyyo	92160.00	58422.00	36952.00	24092.00
Zuway Dugda	20627.00	4221.00	6993.00	2216.00
Total	358794.00	67568.00	54546.00	44810.00

Appendix Table 20: Livestock water consumption rate

Livestock	Consumption rate (L/TLU/d)	Annual water requirement (M^3/TLU/yr.)
Cattle	50.00	18.25
Sheep	7.00	2.60
Goat	7.00	2.60
Equine	40.00	14.60

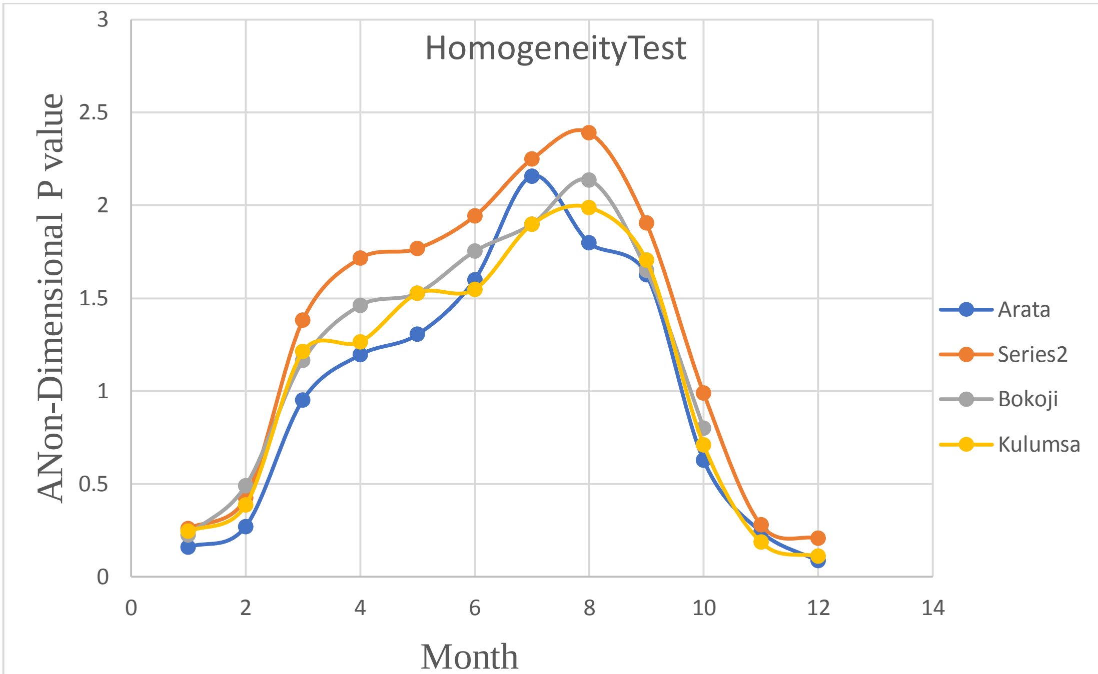
Appendix Table 21: Crop water requirement

Irrigation	Area(ha)	Dominant Crop type	Annual CWR (M^3/ha)
Katar1 (Abosera Alko)	110.00	Tomato	4698.00
Katar2 (katar genat)	200.00	Cabbage	6543.00
Katar3 (Hamsa asha)	122.00	Wheat	6832.00
Sheled	75.00	Potato	5468.00
Arata Chufa	256.00	Cabbage	6543.00
Laga ilu	177.00	Wheat	6832.00
Bosha	360.00	Tomato	4698.00

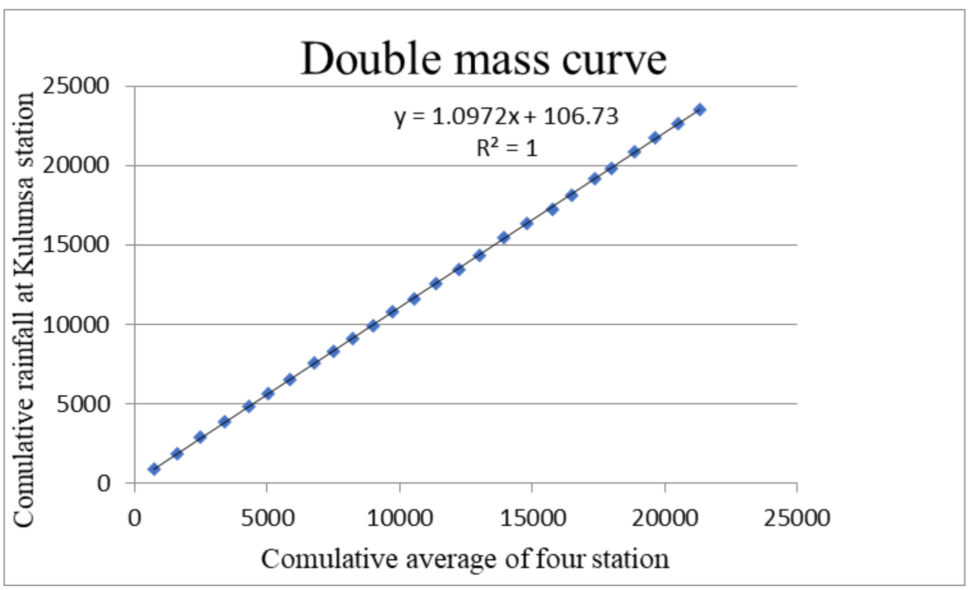
Appendix Table 22: Monthly hydrologic components in the Katar sub-basin (MCM)

Month	Surface Runoff	Interflow	Base Flow	ET actual	Precipitation
Jan	0.17	1.36	6.53	40.77	48.83
Feb	0.20	1.14	6.47	72.43	80.23
Mar	1.61	2.14	6.41	224.51	234.67
Apr	5.00	3.53	6.36	267.26	282.15
May	9.82	4.69	6.34	314.00	334.84
Jun	15.31	6.64	6.33	291.04	319.33
Jul	49.16	10.31	6.35	399.03	464.85
Aug	108.72	14.42	6.42	524.53	654.10
Sep	75.93	15.01	6.53	328.65	426.12
Oct	21.73	11.37	6.62	129.69	169.41
Nov	1.85	5.80	6.64	33.03	47.32
Dec	0.09	2.33	6.60	24.79	33.82

Appendix Figures



Appendix Figure 1: Homogeneity test of the stations



Appendix Figure 2: Consistency test of the stations

Station: Kulumsa | Eff. rain method: FAO/AGLW formula

	Rain	Eff rain
	mm	mm
January	15.7	0.0
February	24.8	4.9
March	77.8	38.2
April	81.1	40.9
May	97.9	54.3
June	99.3	55.4
July	121.7	73.4
August	127.6	78.1
September	109.3	63.4
October	45.6	17.4
November	12.0	0.0
December	7.0	0.0
Total	819.8	426.0

Appendix Figure 3: Rainfall and effective rainfall of the watershed

Crop Water Requirements

ETo station: Kulumsa | Crop: CABBAGE Crucifers

Rain station: Kulumsa | Planting date: 05/11

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Nov	1	Init	0.70	2.49	14.9	0.1	14.9
Nov	2	Init	0.70	2.39	23.9	0.0	23.9
Nov	3	Init	0.70	2.31	23.1	0.0	23.1
Dec	1	Init	0.70	2.22	22.2	0.0	22.2
Dec	2	Deve	0.71	2.19	21.9	0.0	21.9
Dec	3	Deve	0.78	2.43	26.7	0.0	26.7
Jan	1	Deve	0.84	2.69	26.9	0.0	26.9
Jan	2	Deve	0.91	2.95	29.5	0.0	29.5
Jan	3	Deve	0.98	3.36	36.9	0.1	36.8
Feb	1	Deve	1.04	3.79	37.9	0.2	37.7
Feb	2	Mid	1.08	4.15	41.5	0.3	41.2
Feb	3	Mid	1.08	4.33	34.6	4.5	30.2
Mar	1	Mid	1.08	4.51	45.1	10.0	35.1
Mar	2	Mid	1.08	4.69	46.9	14.1	32.7
Mar	3	Mid	1.08	4.91	54.1	14.0	40.1
Apr	1	Mid	1.08	5.14	51.4	13.0	38.3
Apr	2	Mid	1.08	5.36	53.6	13.2	40.5
Apr	3	Mid	1.08	5.41	54.1	14.8	39.3
May	1	Mid	1.08	5.45	54.5	17.0	37.6
May	2	Late	1.06	5.39	53.9	18.7	35.3
May	3	Late	1.00	4.90	39.2	13.5	20.6
					792.8	133.5	654.3

Appendix Figure 4: Irrigation water requirement of Cabbage

Crop Water Requirements

ETo station: Kulumsa | Crop: Potato
Rain station: Kulumsa | Planting date: 05/11

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Nov	1	Init	0.50	1.78	10.7	0.1	10.6
Nov	2	Init	0.50	1.70	17.0	0.0	17.0
Nov	3	Init	0.50	1.65	16.5	0.0	16.5
Dec	1	Deve	0.55	1.75	17.5	0.0	17.5
Dec	2	Deve	0.67	2.05	20.5	0.0	20.5
Dec	3	Deve	0.79	2.47	27.1	0.0	27.1
Jan	1	Deve	0.91	2.90	29.0	0.0	29.0
Jan	2	Deve	1.03	3.34	33.4	0.0	33.4
Jan	3	Mid	1.15	3.95	43.5	0.1	43.3
Feb	1	Mid	1.20	4.34	43.4	0.2	43.2
Feb	2	Mid	1.20	4.57	45.7	0.3	45.4
Feb	3	Mid	1.20	4.77	38.2	4.5	33.7
Mar	1	Mid	1.20	4.97	49.7	10.0	39.7
Mar	2	Mid	1.20	5.17	51.7	14.1	37.5
Mar	3	Late	1.19	5.38	59.2	14.0	45.2
Apr	1	Late	1.09	5.15	51.5	13.0	38.5
Apr	2	Late	0.96	4.75	47.5	13.2	34.3
Apr	3	Late	0.87	4.31	21.6	7.4	14.2
					623.7	**76.9**	**546.8**

Appendix Figure 5: Irrigation water requirement of Potato

Crop Water Requirements

ETo station: Kulumsa | Crop: Tomato
Rain station: Kulumsa | Planting date: 20/12

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Dec	2	Init	0.60	1.84	1.8	0.0	1.8
Dec	3	Init	0.60	1.87	20.6	0.0	20.6
Jan	1	Init	0.60	1.91	19.1	0.0	19.1
Jan	2	Deve	0.60	1.96	19.6	0.0	19.6
Jan	3	Deve	0.72	2.47	27.2	0.1	27.0
Feb	1	Deve	0.87	3.17	31.7	0.2	31.5
Feb	2	Deve	1.02	3.90	39.0	0.3	38.7
Feb	3	Mid	1.15	4.59	36.7	4.5	32.3
Mar	1	Mid	1.19	4.94	49.4	10.0	39.4
Mar	2	Mid	1.19	5.14	51.4	14.1	37.2
Mar	3	Mid	1.19	5.38	59.2	14.0	45.3
Apr	1	Mid	1.19	5.63	56.3	13.0	43.3
Apr	2	Late	1.16	5.71	57.1	13.2	44.0
Apr	3	Late	1.04	5.19	51.9	14.8	37.1
May	1	Late	0.92	4.64	46.4	17.0	29.4
May	2	Late	0.85	4.29	12.9	5.6	3.5
					580.4	**106.9**	**469.8**

Appendix Figure 6: Irrigation water requirement of Tomat

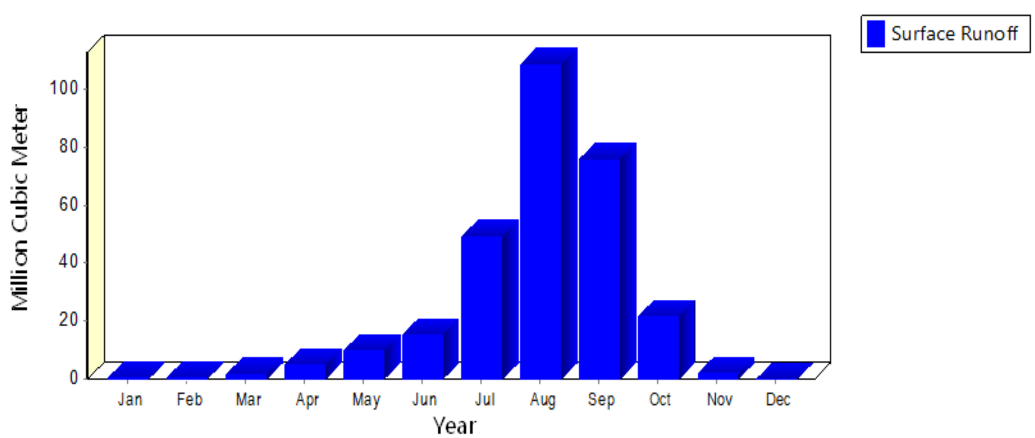
Crop Water Requirements

ETo station: Kulumsa | Crop: Winter Wheat f.f.

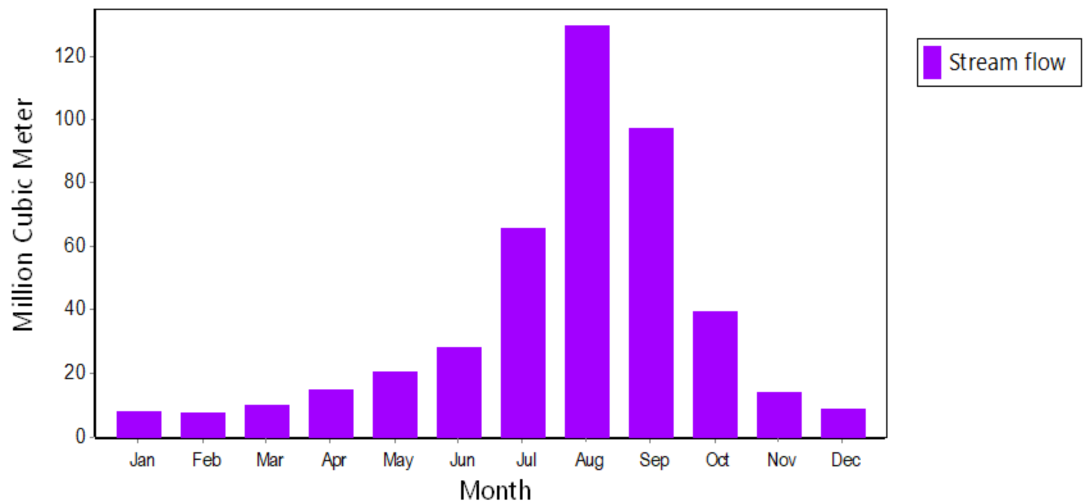
Rain station: Kulumsa | Planting date: 02/12

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Jan	1	Deve	0.72	2.29	22.9	0.0	22.9
Jan	2	Deve	0.75	2.44	24.4	0.0	24.4
Jan	3	Deve	0.79	2.71	29.8	0.1	29.7
Feb	1	Deve	0.82	2.99	29.9	0.2	29.7
Feb	2	Deve	0.86	3.28	32.8	0.3	32.4
Feb	3	Deve	0.89	3.54	28.3	4.5	23.8
Mar	1	Deve	0.92	3.81	38.1	10.0	28.1
Mar	2	Deve	0.95	4.11	41.1	14.1	26.9
Mar	3	Deve	0.99	4.46	49.1	14.0	35.1
Apr	1	Deve	1.02	4.83	48.3	13.0	35.3
Apr	2	Deve	1.05	5.21	52.1	13.2	38.9
Apr	3	Deve	1.09	5.42	54.2	14.8	39.4
May	1	Deve	1.12	5.64	56.4	17.0	39.4
May	2	Deve	1.15	5.85	58.5	18.7	39.9
May	3	Mid	1.17	5.74	63.1	18.6	44.5
Jun	1	Mid	1.17	5.54	55.4	17.9	37.6
Jun	2	Mid	1.17	5.35	53.5	17.7	35.8
Jun	3	Late	1.17	5.19	51.9	20.0	31.9
Jul	1	Late	0.97	4.20	42.0	22.9	19.1
Jul	2	Late	0.66	2.79	27.9	25.1	2.8
Jul	3	Late	0.37	1.54	13.9	20.8	0.0
					939.0	262.7	683.2

Appendix Figure 7: Irrigation water requirement of Wheat



Appendix Figure 8: Surface runoff of the Katar sub-watershed



Appendix Figure 9: Stream flow of the Katar sub-watershed