GROUNDWATER RECHARG ESTIMATION: THE CASE OF HORMAT-GOLINA SUB-BASIN, NORTHERN ETHIOPIA

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GROUNDWATER RECHARGE ESTIMATION: THE CASE OF HORMAT-GOLINA SUB-BASIN, NORTHERN ETHIOPIA.

A Thesis Submitted to Ethiopian Institute of Water Resources, Addis Ababa University in Partial Fulfillment of the Requirement for the Degree of Master of Science in Water Resource Engineering and Management Specialization in Groundwater Management.

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Abstract

Water is one of the most essential commodities for mankind and the largest available source of fresh water is obtained from groundwater. The Hormat-Golina sub-basin is one of the groundwater-based irrigation areas located in north wollo zone of Amhara region. Due to the erratic nature of rainfall (both time and space) distribution in the area, people often fail to maintain the soil moisture requirement for growing crops. Thus, the need for agricultural development using groundwater resources in the area is growing continuously. However, the ambitious plans for expanding irrigation have not been adequately strengthened through the assessments of groundwater reserves and groundwater recharge estimations. Understanding the spatial variability of groundwater recharge in response to distributed Land-use, soil texture, topography, groundwater level, and hydrometeorological parameters is significant when considering the safety of groundwater resource development. Thus, this study was aimed at estimating the spatial groundwater recharge of Hormat-Golina sub-basin, in northern Ethiopia using a spatially distributed water balance model (WetSpass). Input data for the model were prepared in the form of grid maps using a 30 m grid size and the parameter attribute tables were adjusted to represent the Hormat-Golina sub-basin condition using expert knowledge and scientific literature. The model result shows there was a good agreement between the observed and simulated surface runoff with R^2*=0.90 and NSE= 0.85. The results of the model indicated that the long-term temporal and spatial average annual rainfall of 828.5 mm was partitioned as 156.4 mm (19%) of surface runoff, 616.7 mm (73%) of evapotranspiration, and 55.4 mm (8%) of recharge. The recharge corresponds to* $4.2*10^5$ *cubic meters (*m^3*) for the Hormat-Golina sub-basin (with an area of about 698.25* km^2*) from which 83% of the recharge takes place during the rainy /wet/ summer/*

season, while the remaining 17% takes place during the bega (dry) season. The highest recharge was observed in forest land with sandy soil. The analysis of the simulated result showed that WetSpass works well to simulate water balance components of the Hormat-Golina sub-basin and is especially suitable for studying the effects of Land-use changes on the water regime in the basin.

STATEMENT OF THE AUTHOR

By my signature below, I declare and affirm that this thesis entitled "Groundwater Recharge Estimation: The Case of Hormat-Golina Sub-Basin, Northern Ethiopia" is my work. I have followed all ethical and technical principles in the preparation, data collection, data analysis, and compilation of this thesis. Any scholarly matter that is included in the thesis has been given recognition through citation.

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Thesis Approval Sheet

This is to certify that the thesis presented by **Seyoum Bezabih Kidane** entitled "**Groundwater Recharge Estimation: The Case of Hormat-Golina Sub-Basin, Northern Ethiopia."** is submitted in partial fulfillment of the requirements for the degree of Master of Science in Water Resource Engineering and Management with specialization in Groundwater Management to the Graduate Program of Ethiopian Institute of Water Resources, Addis Ababa University complies with the regulations of the University and meets the accepted standards concerning originality and quality. Signed by the examining committee:

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ACRONYMS AND ABBREVIATIONS

ASF	Alaska Satellite Facility
AWWCE	Amhara Water Works Construction Enterprise
DEM	Digital Elevation Model
DHB	Distributed Hydrological Budget
EGI	Ethiopian Geospatial Institute
ET	Evapotranspiration
FAO	Food and Agriculture Organization
Fig	Figure
GIS	Geographical Information System
GPS	Global Positioning System
HB	Hydrological Budget
IDW	Inverse Distance Weighting
KGVDP	Kobo Girana Valley Development Project
LULC	Land use Land cover
MoA	Ministry of Agriculture
MWIE	Ministry of Water Irrigation and Energy
PCP	Precipitation
PET	Potential Evapotranspiration
Re	Recharge
RS	Remote Sensing
WTF	Water Table Fluctuation

1 INTRODUCTION

1.1 Back Ground

Water is one of the most essential commodities for mankind and the largest available source of fresh water is obtained from groundwater (Arkoprovo *et al.*, 2012). Groundwater is a very important and dependable source of water supply in all climatic regions due to its inherent qualities such as consistent temperature; widespread occurrence and continuous availability; excellent natural quality; low development cost, and draught reliability (Todd and Mays, 2005). However, groundwater is a finite and vulnerable resource that should be used properly and efficiently for present and future generations (Arkoprovo *et al*., 2013).

Therefore, knowledge of groundwater resource potential which is directly dependent on recharge is important for the sustainable use and management of groundwater resources (Tilahun and Merkel, 2009). Quantifying the rate of groundwater recharge is a prerequisite for efficient and sustainable groundwater resource management and is practically vital in arid regions where such resources are often the key to economic development (De Vries and Simmers, 2002). Techniques of recharge estimation vary based on the source and process of recharge mechanisms such as direct measurements, water balance methods, tracer techniques, and empirical methods (Simmers, 2017).

According to Scanlon *et al*., (2002), important considerations in choosing a technique include space or time scales, range, and reliability of recharge estimates based on different techniques. For this research, distributed water balance model (WetSpass) was adapted to estimate the long-term average groundwater recharge which is dependent on land use and land cover, soil type, topography, and hydrometeorological factors. This is because understanding the spatial variability of groundwater recharge in response to land use land cover, soil texture, topography, groundwater level, and hydrometeorological parameters is significant when considering the safety of groundwater resource development.

Despite the highly variable rainfall (raining in one or two rainy seasons, followed by a relatively long dry season), agriculture is mainly rain-fed in Ethiopia (Belete, 2007). The shortage and variability of rainfall during the growing season often lead to low production rates. The study area Hormat-Golina sub-basin, north Ethiopia, has a mean annual evapotranspiration rate ranging from 1900 to 2100 mm which is greater than the mean annual precipitation, which ranges from 300 to 800 mm (MoA, 1998). According to MoA (1998), the region has a growing period of about 60 days and annual air mean temperature ranges from 16 to 27 °C. Hence, supplementing rain-fed agriculture through irrigation practices is vital for the food security of the region.

The research area Hormat-Golina sub-basin, which is located south of Raya Valley in northern Ethiopia. The area's low-lying intermountain valleys are recognized for their significant groundwater potential and semi-arid climate. Because of the scarcity of surface water and low annual rainfall that varies seasonally, it is currently being investigated and used as a groundwater supply, mostly for agriculture. Earlier studies have focused on resource development to fulfill user needs and alleviate the recurring drought problem, with little emphasis paid to groundwater recharge, which is critical for good planning, future usage, and long-term water resource management.

1.2 Statement of the problem

Hormat-Golina sub-basin is one of the groundwater-based irrigation areas located in north wollo zone, Amhara region (Tadesse *et al*., 2015). Due to erratic nature of rainfall (both time and space) distribution in the area, people often fail to maintain soil moisture requirement for growing crops. Thus, the need for agricultural development using groundwater resources in the area is growing continuously. However, the ambitious plans for expanding irrigation have not been adequately strengthened through the assessments of groundwater reserves and groundwater recharge estimations.

Previous groundwater study efforts in the area (German Agency for Technical Cooperation LTD 1977; Belay, 2015, Ayenew *et al*., 2008) focused on delineation of potential sites to develop groundwater resources, by considering point estimates of recharge. However, groundwater recharge estimation needs a reliable method to quantify its spatial and temporal variability (Rwanga, 2013). Therefore, this research was proposed to estimate long-term seasonal/annual average groundwater recharge in the Hormat-Golina sub-basin, Northern Ethiopia by adapting the WetSpass model.

1.3 Objectives

1.3.1 General objective

The main objective of this study is to estimate the groundwater recharge of Hormat-Golina sub-basin in the Danakil basin, northern Ethiopia.

1.3.2 Specific objectives

- ✓ To estimate groundwater recharge, surface runoff, and Actual Evapotranspiration in the sub-basin;
- ✓ To map the spatial distribution of groundwater recharge.

1.4 Research Questions

- ❖ How much water is added /recharged/ to the ground water reserve?
- ❖ Is there a change in recharge spatially and temporally?

1.5 Scope of the Study

The goal of this study was to look at groundwater recharge, water balance components, and the spatial distribution of the water balance components. The study attempted to address the sub-basin hydrometeorological and biophysical properties, which are critical for hydrological processes. This has to do with determining the spatiotemporal characteristics that govern those components and this method does not deal with deep regional groundwater recharge; it takes into account the shallow groundwater recharge.

1.6 Significance of the Study

Estimating groundwater recharge is critical for long-term groundwater resource management. The sustainability assessment of groundwater recharge is critical in decision-making for irrigation and domestic usage, and it must give condensed crucial information concerning effect pathway linkages based on complicated scientific study.

As a result, this study was carried out with the above mentioned objectives for the Hormat-Golina sub-basin, integrating by using WetSpass hydrological models to gain a better understanding of the hydrological and biophysical elements of the sub-basin for proper management, wise utilization, future planning, and sustainable resource utilization in the context of sustainable development. Understanding the sub-basin hydrological characteristics is also critical for implementing an integrated water resource and watershed management strategy aimed at improving water resource utilization among upstream and downstream user communities for multipurpose benefits while minimizing conflicts of interest.

1.7 Limitations

The study was only conducted in the Hormat-Golina sub-basin, Denakil basin, in the northern region of the country. Obtaining a complete, dependable, and accurate set of meteorological and stream flow data was a major challenge. This study does not consider groundwater recharge resulting from irrigation practice in the area because the WetSpass model does not incorporate irrigation practice as input parameters.

2 LITERATURE REVIEW

2.1 Water Resources and Hydrologic Cycle

Globally there are 1.36 Billion km^3 of water from which 97.2% is salt water mainly in oceans and 2.8% is available as freshwater. Although the water available in water bodies, such as oceans and great lakes stores plenty of water in amount, it is not directly useful for human beings (Rwanga, 2013). The immediate use of water for human beings is stored as groundwater and the remaining water is found in land surfaces, lakes, and streams as fresh water.

Yazew, (2005), stated that Ethiopia is relatively rich in water resources, and its outflows are of great importance to its neighboring countries. It has twelve river basins with total annual water resources estimated at 111 Billion m^3 from which 75.5 Billion m^3 is stocked in the Nile basin. Furthermore, the country releases an annual runoff volume of 122 Billion m^3 of water (Awulachew *et al*., 2007). Water by nature is a renewable natural resource found in three phases liquid, solid, and vapor which are mostly explained by the hydrologic cycle (Blete., 2018).

The hydrologic cycle is the conceptual model which stats the storage and movements of water between the biosphere, atmosphere, lithosphere, and hydrosphere. Water on this planet can be stored in any of the following reservoirs: atmosphere, oceans, lakes, rivers, soils, glaciers, snowfields, and groundwater. Water moves from one reservoir to another by ways of processes like evaporation, condensation, precipitation, deposition, runoff, infiltration, sublimation, transpiration, melting, and groundwater flow (Blete., 2018).

The oceans supply most of the evaporated water found in the atmosphere. From this evaporated water, only 91% is returned to the oceans and basins by way of precipitation.

The remaining 9% is transported to areas over landmass where climatological factors induce the formation of precipitation (Karamouz *et al*., 2003). Water is a naturally circulating resource that is continuously recharged. Even if the stocks of water in natural and artificial reservoirs are helpful to increase the available water resources for human society, the flow of water would be the main focus in water resource valuations (Oki, 2005).

According to Raghunath, (2006), the hydrological cycle is also defined as a water transfer cycle that occurs continuously in nature; in which the phenomena of evapotranspiration, precipitation and runoff take place during the water transfer system. Precipitation and runoff are only the visible components of this process. Other components such as evaporation, infiltration, transpiration, percolation, groundwater recharge, discharge, etc. are other important mechanisms of this cycle.

The water exchange between the land surface and the atmosphere is based on the continuous evaporation of water from the Earth, the temporary storage of water in the form of water vapor in the atmosphere and the return of water to the land surface through several forms of precipitation such as rain, snow, sleet or hail. Even if these mechanisms are relatively simple to represent, the interaction between the land surface and underground and in particular ground water movement is not so easy to visualize (Karamouz *et al*., 2003).

2.2 Groundwater Recharge

Groundwater recharge can be defined as the entry of water into the saturated zone of water made available at the water table surface together with the associated flow away from the water table within the saturated zone (Pandian *et al*., 2014). Most natural groundwater recharge is derived directly from rainfall and snowmelt that infiltrate through the ground surface and migrate to the water table. To quantify recharge from precipitation, it is critical to understand rainfall-runoff relationships. The first step is to determine the fraction of precipitation available for groundwater recharge, after subtracting what is lost to overland flow (runoff) and evapotranspiration (ET) (Scanlon *et al*., 2002).

The vital to the rainfall-runoff relationship are the soil type, the antecedent moisture condition, and the land cover. Soils that are well drained generally have high effective porosities and high hydraulic conductivities, whereas soils that are poorly drained have higher total porosities and lower hydraulic conductivities. These physical properties combine with initial moisture content to determine the infiltration capacity of surficial soils (Graf and Przybyłek, 2014).

The land cover determines the fraction of precipitation available for infiltration. Impervious, paved surfaces prevent any water from entering the soil column, while open, well-vegetated fields are conducive to infiltration. Regardless of soil type, antecedent moisture, or land cover, the chain of events occurring during a storm event is the same (Xu, 2002). Since the main source of recharge for the groundwater system is rainfall, the groundwater recharge system is variable as rainfall varies in both space and time.

Recharge processes vary from one place to another, and there is no agreement that a method developed and used for one area will give reliable results when used in another. So, it is necessary to identify the probable flow mechanisms and the important features influencing the recharge in an area before deciding on the recharge method to use

(Nuramo, 2016). There are three types of recharge those are direct (diffuse) recharge, indirect recharge, and localized recharge.

Direct (diffuse) recharge: this can be the water superimposed to the groundwater system is far more than soil wetness deficits and evapotranspiration by direct infiltration of precipitation and percolation through the unsaturated (vadose) zone) (Sanford, 2002; Zdon *et al.*, 2019). This kind of recharge happens throughout the whole vadose zone (diffuse). Direct recharge forms the very best contribution to wet climates because the vadose zone has high water content and tiny extra storage capability because of regular precipitation. Indirect or non-diffuse recharge: this can be the flow of water to the groundwater system through the beds of surface water bodies (Scanlon *et al.*, 2002).

Indirect recharge:- this type of recharge forms the foremost in-depth and vital recharge in arid areas that spreads flood water over giant areas on each side of watercourses (Yunus *et al.*, 2014). As outlined by (Senanayake *et al.*, 2016; (Srinivasa Rao and Jugran, 2003), artificial recharge may be a form of controlled recharge wherever surfaces water is injected within the ground and afterward flows to the geological formation to reinforce the groundwater resources.

Localized recharge: an intermediate form of groundwater recharge resulting from the horizontal, near-surface concentration of water in the absence of well-defined channels such as small depressions, joints, and rivulets (Nuramo, 2016).

Those mechanisms listed above usually do not occur separately but rather in combination which makes the assessment complex. On the other hand, the recharge and discharge conditions of an area are controlled by several factors such as; climate (rainfall, temperature, etc.), topography, drainage, geologic framework, soil type, land use/land cover, etc. (Blete., 2018).

2.3 Estimation of groundwater recharge

Groundwater recharge estimation is extremely important for the efficient and sustainable management of groundwater systems. For estimating groundwater recharge a range of methods exists. Different scientists (Nakashima *et al*., 2001; Scanlon and Cook, 2002; Carrera-Hernández *et al*., 2012; Ahmadi *et al*., 2012) have used different methods to estimate groundwater recharge. Scanlon and Cook, (2002) classified groundwater recharge methods supported by hydrological zones from which the recharge data is obtained. These zones are surface water, the unsaturated zone, and the saturated zone.

The groundwater recharge estimation methods are further classified into physical techniques, tracers, and numerical modeling within each of the hydrologic zones. Kallioras *et al*., (2011) introduced a replacement approach for the investigation of the unsaturated zone through the combined use of laboratory and field techniques in arid environments. This method uses direct push techniques to induce undisturbed soil samples, extraction of pore water for isotope analyses, and application of Time Domain Reflectometry (TDR) to see soil moisture contents (Dahan *et al*., 2003).

The combination of those techniques resulted in a far better quantification of present and historic groundwater recharge. Similarly, Ahmadi *et al*., (2012) used the water balance principle (rainfall-groundwater level relationship) based approach to estimate groundwater recharge. These methods are WTF (Water Table Fluctuation), DHB (Distributed Hydrological Budget), and HB (Hydrological Budget).

Manghi *et al*., (2009) noted these methods were useful, easy to use, cost-effective, and simple, requiring few data like formations measurements, rainfall, aquifer properties, and groundwater extraction datasets. The use of those methods helps to supply irrigation return flow, percentage, and contribution of precipitation to natural groundwater recharge.

2.4 Hydrological models

Hydrologic models are among those methods frequently used for groundwater investigation. Hydrological modeling techniques can be used to estimate the groundwater recharge based on the biophysical characteristics of the watershed and climatic time-series data. The application of Hydrological modeling techniques is also important for forecasting water resources for the future time horizon (Al Kuisi and El-Naqa, 2013). According to Beven, (2001), Hydrological models are simplified systems to quantify the processes of the hydrological cycle in an entire river basin or parts of it. They are based on a set of interrelated equations that try to convert the physical laws, which govern extremely complex natural phenomena.

Moreover, different varieties of models can be used, depending upon the considered output, the existing database, input variables, and required analysis. Representation of physical processes described by rainfall-runoff models can either be based on a simple mathematical link between input and output variables of the basin or include the description of basic processes involved in the runoff generation. Various models have been developed for the past decades in different parts of the world. These models can be generally classified based on process description as physically based distributed models, conceptual models, and data-driven models (Beven, 2001).

Two types of modeling approaches have been proposed (Klemeš, 1983): a bottom-up and a top-down approach. Physically based distributed models are examples of a bottom-up modeling approach (Savenije, 2001), which were developed starting in the 1980s at the same time as the development of Remote Sensing Techniques and Geographical Information System tools and can provide the highest accuracy in the modeling of precipitation-runoff processes (Xu, 2002). These models are largely based on the principles of physical processes based on continuity and the conservation of energy, mass, and momentum.

In this modeling approach, hydrological processes are modeled by introducing a large number of model parameters that are supposed to be measurable at a plot or micro-catchment scale representing the different heterogeneities in the catchment. In top-down modeling approaches, the equations used to describe the physical processes often have indirect physical meaning but parameters are obtained through calibration. The modeling procedure usually starts with a very simple model and progressively increased complexity through the step-wise incorporation of process descriptions (Sivapalan, 2003; Montanari *et al*., 2006). In recent times, advances have been made in hydrological process understanding and modeling using topography-driven, flexible, conceptual, semi-distributed model structures (Gharari *et al*., 2014; Gao *et al*., 2014).

Data-driven models are based on extracting information that is implicitly contained in hydrological data. These models involve mathematical equations that do not rely on realistic principles such as mass, momentum, or energy balance equations (Peel and

Blöschl, 2011). The applications of such models depend on proper analysis of the input/output time series (Bowden *et al*., 2005). WetSpass was also used in the analysis of the hydrological characteristics of the sub-basin (Rwanga and Ndambuki, 2017).

WetSpass recharge outputs for the river basins were used as input for the groundwater model. Total discharge and surface runoff and base-flow were used for the calibration of the WetSpass water balance components. The associated groundwater model was also calibrated along with the WetSpass calibration. Lastly, the resulting groundwater discharge areas were verified by mapped areas. WetSpass was also used in the analysis of the hydrological characteristics of the sub-basin (Van Rossum *et al*., 2001 as cited in Blete., 2018).

The modified WetSpass model is a physically raster-based water balance model that for each grid cell, partitions precipitation into surface runoff, evapotranspiration, and recharge (Abdollahi *et al*., 2017) which stands for water and energy transfer between soil, plants, and atmosphere under quasi-steady-state conditions (Batelaan and De Smedt, 2001). The model conceptualizes a watershed hydrological system, based on physical and empirical relationships, being composed of the atmosphere, plant canopy, soil zone, root zone, and saturation groundwater zone divided into grid cells/raster to deal with the heterogeneity of the watershed (Batelaan *et al*., 2003).

The input data to the model are digital maps prepared with the help of GIS and remote sensing packages software and parameter files from spreadsheet tables with their specific extensions (De Smedt, *et al*., 2010). The digital maps are seasonal or monthly records of meteorological parameters such as precipitation, potential evapotranspiration, temperature and wind speed, groundwater level, land use, soil, slope, and topography of the study area.

The parameter tables are time series data that have attribute data for the model which contains vegetation height, leaf area index, and land-use type as rooting depth, soil parameter for each textural soil class as field capacity, wilting point, permeability and runoff for all combinations of land-uses, slope, and soil type (Batelaan and De Smedt, 2001). By using the WetSpass model of the actual hydrological situation in the sub-basin as a starting point, the sensitivity of the discharge coefficients of the sub-basin towards climate and land use changes was analyzed. Numerous climate and land use scenarios were used and the geographical input data of the present situation was adjusted for their simulations by WetSpass (Batelaan and Woldeamlak, 2004).

2.5 WetSpass model

WetSpass stands for water and energy transfer between soil, plants, and atmosphere under quasi-steady-state conditions (Batelaan and De Smedt, 2001). It is a physically based model for the estimation of long-term average spatial patterns of groundwater recharge, surface runoff, and evapotranspiration employing physical and empirical relationships. WetSpass is a quasi-steady state model developed as a regional groundwater model to simulate infiltration–discharge relations based on long-term average recharge input data. This model simulates water balance components, surface runoff, actual evapotranspiration, and groundwater recharge based on distributed data. The model was developed as a method to estimate long-term average, distributed water balance components (Batelaan and De Smedt, 2001).

This model was developed based on the time-dependent spatially distributed water balance model WetSpass (Batelaan and De Smedt, 2001). The model has been developed and applied to study the influence of the long-term effects of land cover changes on the water regime in a basin (Batelaan *et al*., 2003). By using long-term average standard hydro-meteorological parameters as inputs, the model simulates the temporal average and spatial information of surface runoff, actual evapotranspiration, and groundwater recharge have been simulated

The model estimates spatial groundwater recharge at seasonal and annual scales. Regional groundwater models used for analyzing recharge-discharge relations are often quasi-steady and need long-term average recharge input that accounts for the spatial variability of the recharge. Thus, they can use the recharge output from WetSpass for their computations. WetSpass is especially suited for studying the long-term effects of land-use changes on the water regime in a watershed and was founded on the time-dependent spatially distributed water balance model, called "WetSpa" (Batelaan *et al*., 2001 and 2003).

Inputs for this model include grids maps of land use, groundwater depth, precipitation, potential evapotranspiration, wind-speed, temperature, soil, and slope, and parameters tables such as land use and soil types are connected to the model as attribute tables of their respective grids. The model makes use of grid GIS technology and digital data to partition the precipitation into surface runoff, evapotranspiration, and groundwater recharge (Batelaan and De Smedt, 2007). Parameter tables such as land-use and soil types are connected to the model as attribute tables of land use and soil raster maps, which allow new definitions of climatic as well as land-use and soil types (Batelaan *et al*., 2003). WetSpass was originally developed for conditions in temperate regions, Europe in particular. WetSpass has been developed to be used worldwide (Rwanga, 2013). It has been successfully applied in different areas of the world.

The WetSpass model has first applied successfully in Belgium (Batelaan and De Smedt, 2001). In the WetSpass model total water balance for a raster, the cell is split into independent water balances for the vegetated, bare soil, open-water, and impervious parts of each cell. This accounts for the non-uniformity of the land-use per cell, which is dependent on the resolution of the raster cell. The processes in each part of a cell are set in a cascading way.

This means that an order of occurrence of the processes, after the precipitation event, is assumed. Defining such an order is a prerequisite for the seasonal timescale with which the processes will be quantified. A mixture of physical and empirical relationships is used to describe the processes. The quantity determined for each process is consequently limited by several constraints (Batelaan and De Smedt, 2007). WetSpass is developed as regional groundwater models are quasi-steady states used to simulate infiltration–discharge relations based on long-term average recharge input data. This model simulates water balance components, surface runoff, actual evapotranspiration, and groundwater recharge based on distributed data. The model estimates spatial groundwater recharge at seasonal and annual scales (Batelaan and Woldeamlak, 2004).

2.6 Previous Work on Groundwater Recharge Estimation Using WetSpass

There are Several techniques are used to assess groundwater recharge and water balance, including experimental methods, hydrological budget (HB), empirical methods, distributed hydrological budget (DHB), and water table fluctuation (WTF). Wang *et al*., (2008), used experimental methods through isotope tracers, to evaluate groundwater recharge. Moon *et al*., (2004), estimated groundwater recharge by applying a modified WTF and groundwater hydrographs for the basin of a river in South Korea. Martin, (2006), applied WTF to quantify the annual average groundwater recharge in West Africa.

He found that the recharge varies from 13 mm to 143 mm. El-Rawy *et al*., (2016), used the DHB approach to estimate the distribution of recharge rate over the Zarqa River Basin, Jordan. Manghi *et al*., (2009), utilized (HB) method to estimate the groundwater recharge in the Hemet sub-basin, United States. According to the reported results, the annual long-term average recharge was 12.5 million cubic meters, for the period between 1997 and 2005.

Empirical methods based on WTF and precipitation depths to assess the groundwater recharge in the Cún-Szaporca oxbow of Drava floodplain, Hungary. Recently, energy and water transfer among plants, soil, and the atmosphere under a quasi-steady state was used by (Ali Salem, 2019). The WetSpass model (Batelaan and De Smedt, 2001), has been used widely for groundwater recharge assessment. Abdollahi *et al*., (2017), developed a WetSpass-M model by downscaling the seasonal resolution to a monthly scale. Abu-Saleem *et al*., (2010), developed a modified WetSpass model WetSpass-Jor, for watersheds by adjusting the parameters for Jordanian conditions.

The WetSpass model has been shown to help better characterize recharge, including its variety over geographical areas in the world. It has been successfully used in Belgium (Batelaan and De Smedt, 2001) and different environments like Hasa and Jafr basin, Jordan (Abu-Saleem *et al*., 2010; Al Kuisi and El-Naqa, 2013), Birki watershed, Werii watershed, and Geba basin, Ethiopia (Meresa *et al*., 2019; Gebremeskel and Kebede, 2017; Gebreyohannes, *et al*., 2010), Mashhad basin, Iran (Zarei *et al*., 2016), Gaza Strip, Palestine (Aish *et al*., 2010), Drava Basin in Hungary (Ali Salem, 2019), Nile Delta aquifer, Egypt (Armanuos and Negm, 2016) and WetSpass-MODFLOW works well in the Takelsa multilayer aquifer in northeastern Tunisia (Ghouili *et al*., 2017)

3 MATERIALS AND METHODS

3.1 Description of the Study Area

3.1.1 Location of the study area

Hormat-Golina Sub-basin is located in northern part of Ethiopia between latitudes of 11°56′–12°13′N and longitudes of 39°25′–39°47′E (Figure 3.1). It is bordered on the west by Lasta Mountains, on the east by Zobel Mountains, on the north by Raya Valley, and on the south by volcanic ridges with a total area of 698.25 km^2. It is among the sub-basins on the western edge of the Danakil basin.

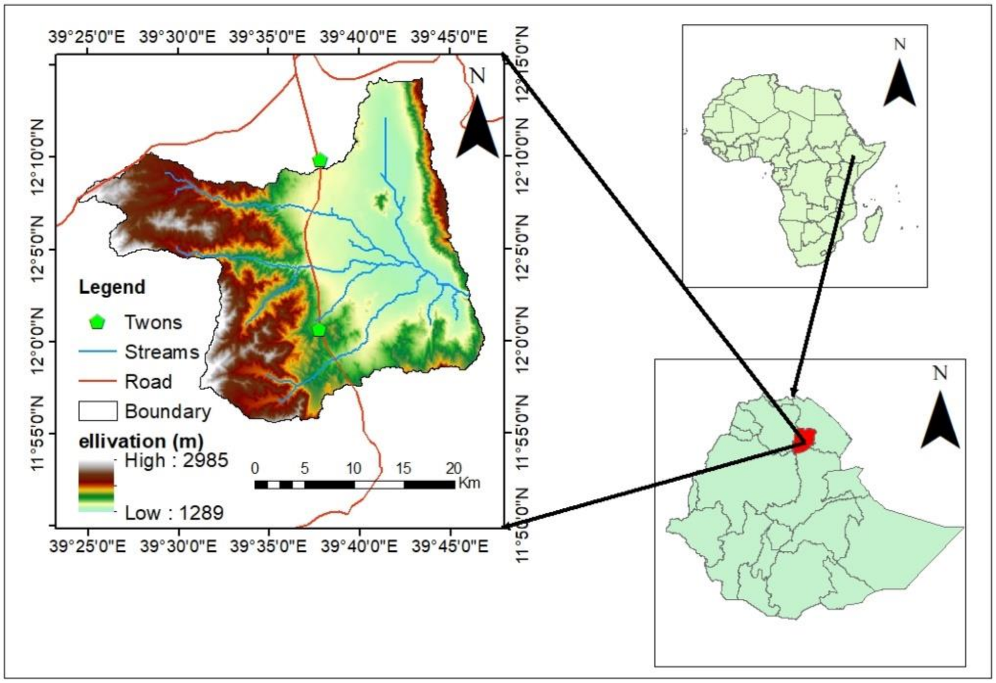


Figure 3-1: Location of the study area.

3.1.2 Topography

The main physiographic features prevailing in the area were north–south oriented mountains in the west, a steep fault scarp in the east, a major graben, and isolated hills within the graben. The study area is elongated inter-mountain graben filled with quaternary sediments, bordered to the east and west by rugged volcanic mountains with relatively high elevation. The average altitude of the area ranges from 1289 meters within the valley floors to 2985 meters above sea level in the western mountain ridges.

3.1.3 Drainage

The Hormat-Golina sub-basin features an open surface water drainage system that opens into the Afar region at the Golina outlet. It is located within the Danakil dry basin and bounded by the Raya valley to the north, the Alwuha basin to the south, the Golina dry basin to the east, and the Tekeze river basin to the west. The basin is drained by three major streams. These are Golina, Hormat, and Kelkelit. It collects all run-off water during the rainy season and discharges it into the Afar depression through a break in the valley's southeast corner (Figure 3.2). The western highlands have a high drainage density, while the valley bottom and eastern highlands have a low drainage density. During the rainy season, all streams and gullies carry significant volumes of sediments from the mountains and dump them on the valley plain.

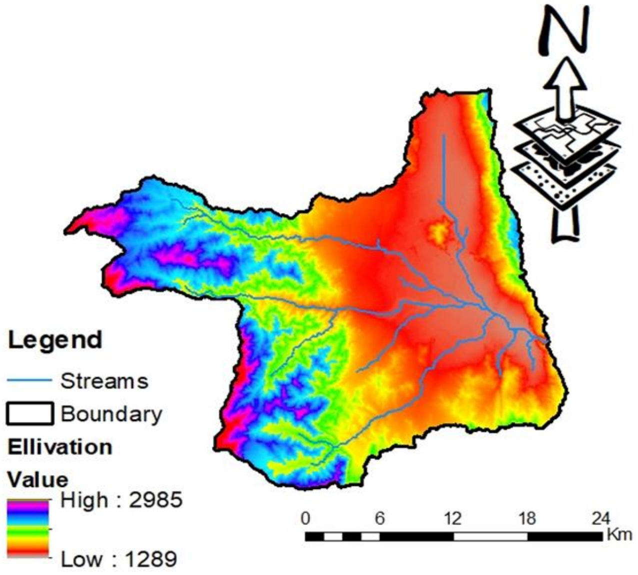


Figure 3-2: Drainage map of the area

3.1.4 Climate

The study area is characterized by an erratic, bimodal rainfall pattern with the main rainy season lasting from late June to early September. The highest rainfall record occurs in July and August, whereas the short spring rainy season extends from February to March. The average monthly temperature of the Hormat-Golina sub-basin varies from a minimum average of 4.7 °C in the Korem station to a maximum average of 35.5 °C in the Kobo lowlands. The highest temperature is recorded in June and the lowest value is in November.

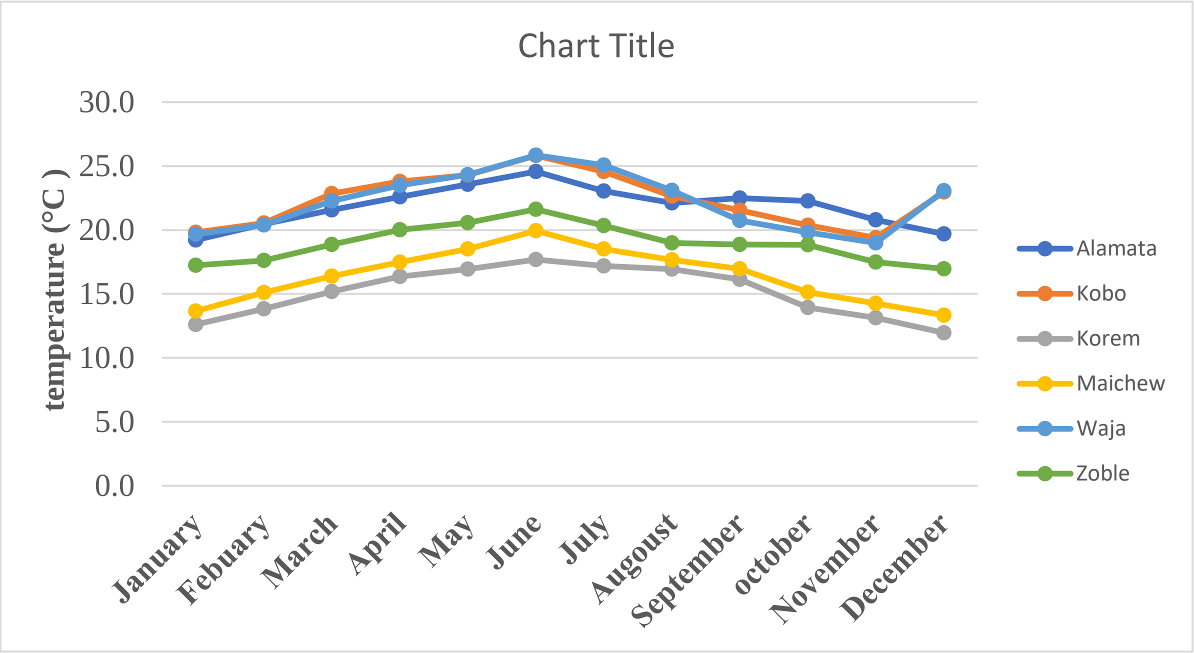


Figure 3-3: Mean monthly temperature of the area.

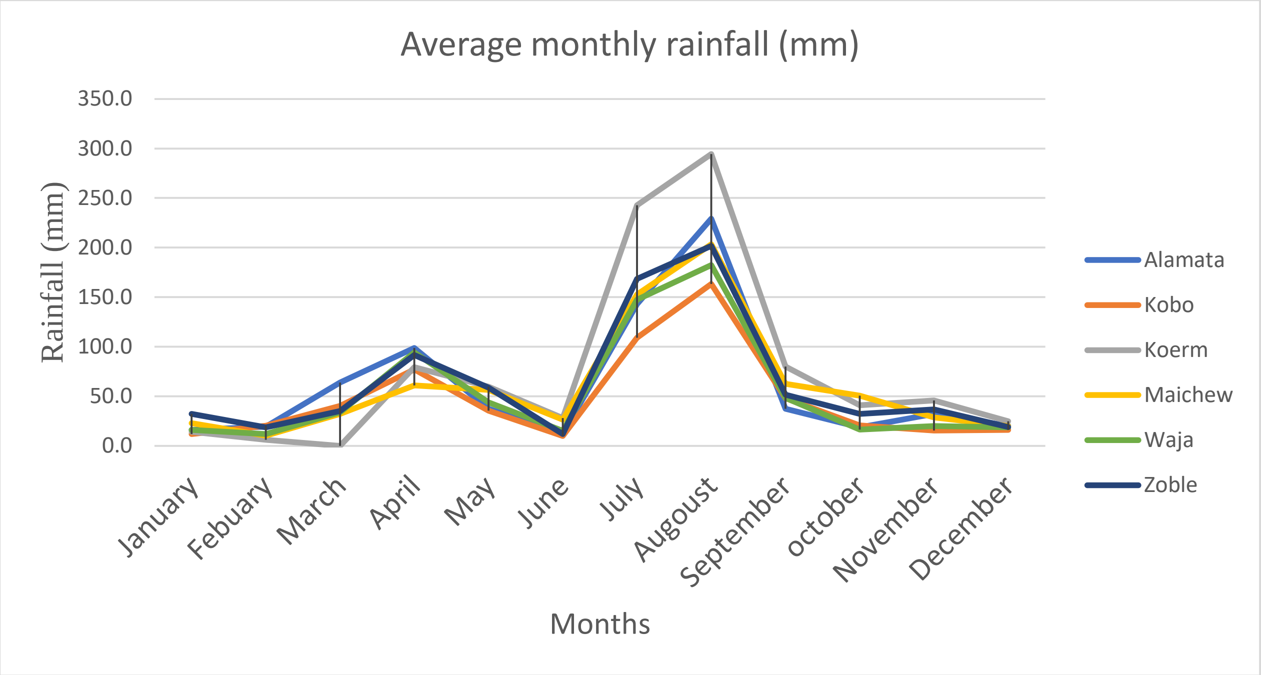


Figure 3-4: Mean monthly rainfall.

3.1.5 Geology and hydrogeology

The geology of north and central Ethiopia, which includes the current research area, is characterized by tertiary volcanic strata underlain by Mesozoic sedimentary rocks. The most prevalent outcrops on the mountains are fissured basalts with silica variations. The northern Ethiopia volcanic were classified into Ashange and Magdala groups (Adane, 2014). Between the Palaeocene and Miocene periods, two volcanic successions called the Ashangi and Magdala groups formed. Tectonic events that contributed to the creation of the Rift System have altered the geological structure of the area. Fissure volcanism resulted from tensional movements, which were followed by block-faulting and tilting to form the escarpment zone, which featured marginal grabens.

These marginal grabens are modest, elongated depressions on both sides with typical faults that face each other (Tadesse *et al*., 2015). A series of opposite dipping faults oriented parallel to the plateau escarpments characterize the Hormat-Golina eastern and western ridges, which surround the plain area. The eastern edge of this graben is a steep slope fault downthrown to the west around 800 meters from the foot of the hill to the summit on the Kobo-Zoble all-weather road (Adane, 2014).

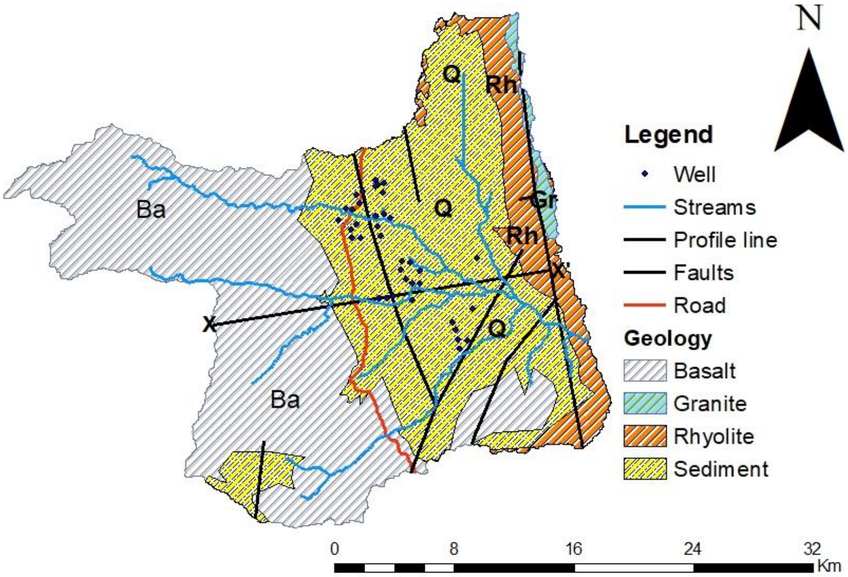


Figure 3-5: Geological map

The study area and its surroundings have a regional hydro-geological setup that can be described as a localized graben filled with unconsolidated material consisting of clay, silt, sand, gravel, boulders, and pebbles above the Ashangi group of volcanic rocks, which are underlain by Mesozoic sedimentary rocks. Faulting and displacements had a substantial impact on the Trepan volcanic and underlying formation before the deposition of quaternary sediments in the grabens and troughs. The Ashangi volcanic deposits are the most extensive above the sedimentary basin (Tadesse *et al*., 2015).

Groundwater movement and storage have a lot of potential in the unconsolidated sediments in the grabens and the sedimentary rock underneath the Ashangi Group volcano. Despite their limited presence, the unconsolidated sediments are relatively thick and have high hydraulic permeability, and they receive recharge from the weathered Ashangi volcanic surrounding the grabens. The aquifers in the study area were dominated by alluvial deposits, and cracked and worn basalts. The results of previous investigations, as well as pumping test data, were used to characterize subsurface groundwater flows in the study area. The sediment thickness has varied between 18 and 212 meters, with an average depth of 129 meters (Moges, 2012). The lateral and vertical changes in grain composition of the sediment found across the valley are due to the mixing of proximal and distal deposits following flood and depositional cycles. As a result, the unconsolidated sediment has a diversified aquifer both vertically and horizontally. As a result, unconsolidated sediment is recharged by subsurface input from the locally weathered and cracked zone of the volcanic rock of the mountains around the plain area. Groundwater outflow is mostly caused by the Golina streams, which drain into the Danakil depression in the Afar Region.

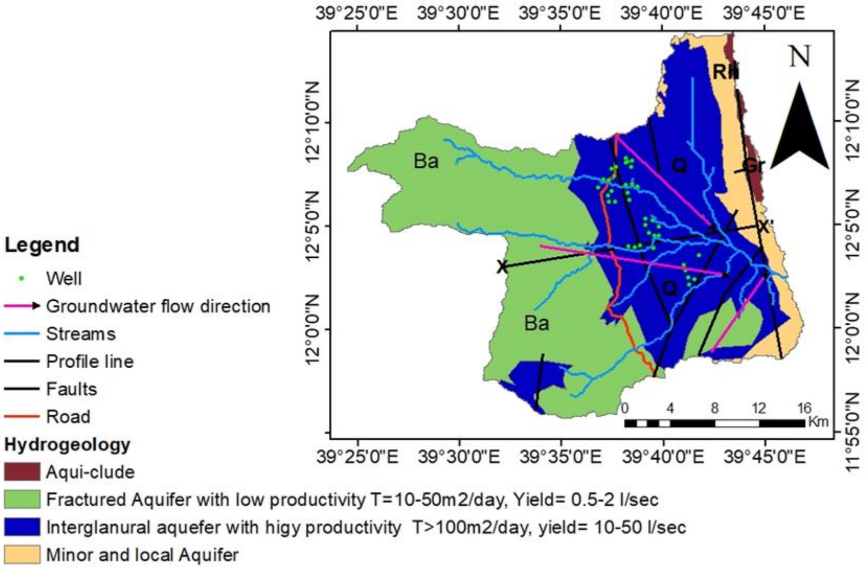


Figure 3-6: Hydro-Geological map

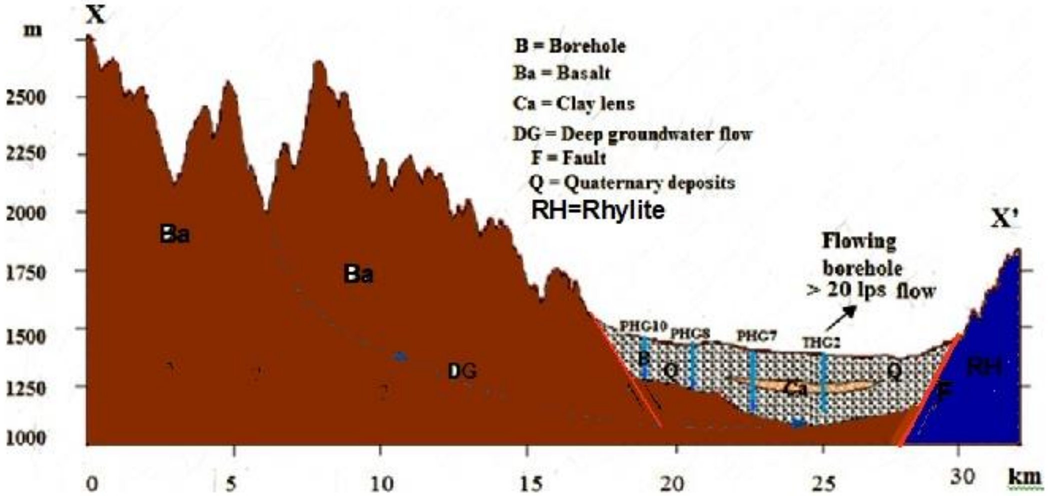


Figure 3-7: Hydrogeological cross-section (West – East).

3.2 Data collection

The main data used in this study were remote sensing data and ancillary data. The remote sensing data includes the Digital Elevation Model and groundwater level data. The ancillary/secondary data includes hydro-meteorological data such as rainfall, temperature, wind speed, potential evapotranspiration, and, bio-physical data such as soil texture and land use land cover were used to produce the required input data for the water balance model (WetSpass).

A. Meteorological data

22 years (2000–2021) mean monthly meteorological variables (rainfall, temperature, and wind speed) for seven stations from the National Meteorology Agency (NMA) of Ethiopia were collected. Potential evapotranspiration was determined by the Hargreaves equation. The Hargreaves equation (Hargreaves and Samani, 1982), is a straightforward evapotranspiration model that only requires a few easily accessible variables: minimum, maximum, and mean temperature, as well as extraterrestrial radiation. If there is inadequate meteorological data for the Penman-Monteith approach, the FAO

recommends the Hargreaves method (Allen *et al.*, 1998), as an alternate method for predicting PET. The PET was estimated using the Hargreaves method, which is available in the R-software SPI package. PET after Hargreaves is estimated using a strongly empirical approach. As input data, both radiation and temperature are employed. Because the model works using calculated extraterrestrial radiation, there is no need to monitor radiation.

$$\mathrm{PET} = 0.0135 * \mathrm{Rs} * \mathrm{conv} * (\mathrm{T} + 17.8) \tag{1}$$

Where: -

PET	Evapotranspiration	[mm day^{-1}]
T	Mean temperature of the day	[°C]
Rs	Solar radiation	[MJ m^{-2} day^{-1}]
Conv	Conversion to ET equivalent conv=4082 .0	[m^{2} mm MJ^{-1}]

B. Physical Data

Understanding groundwater recharge requires biophysical data such as soil texture and groundwater level data. The Hormat-Golina sub-basin soil texture map was collected from the Ministry of water irrigation and energy (MWIE) of Ethiopia. Initial groundwater depth was taken from 34 boreholes drilled in the study area (from 1999 to 2019), mainly by the Amhara water works construction enterprise (AWWCE) and Kobo-Girana Valley Development Project (KGVDP).

C. Remote Sensing data

The slope and Topographic map of the study area was processed from the Alaska satellite facility (ASF) website (https://asf.alaska.edu/). The ASF provides 12.5*12.5 m resolution Digital Elevation Model (DEM) processing by ArcGIS. Land use land cover (LULC) data was obtained from the Ethiopian Geospatial Institute (EGI) with a resolution of 30m. To extract the required input variables for the WetSpass model, remote sensing and ancillary/secondary data were processed using remote sensing and GIS software packages. GIS applications are the sole tools used to handle spatial and temporal variability (Tilahun and Merkel, 2009).

3.3 Materials and Software used

To conduct this study different software and materials were used. The following is the list of the various materials and software used throughout this research (Table 3.1).

Table 3-1: Materials and software used for this research.

Materials and software	Applications
GPS	Borehole, outlet point collection
ArcGIS	Grid data preparation, interpolation of point data, spatial data analysis, and interpretation of simulated results.
R-software	Evapotranspiration estimation
WetSpass	Groundwater recharge simulation
Google Earth	Ground truth collection and feature identification
Deep meter	Groundwater depth measurement

3.4 Data preparation and analysis

3.4.1 WetSpass model description

WetSpass is an acronym for Water and Energy Transfer between Soil, Plants, and Atmosphere under quasi Steady State (Batelaan and De Smedt, 2007). It is a physically based model for the estimation of the long-term average spatial patterns of groundwater recharge, surface runoff, and evapotranspiration from long-term average meteorological data together with Land-use, soil, and groundwater level grid maps by employing physical and empirical relationships (Batelaan and De Smedt, 2001). WetSpass gives the various hydrologic outputs on a yearly and seasonal (summer and winter) basis (Batelaan and De Smedt, 2001). The model is integrated within ArcView as a raster model and coded in Avenue and Visual Basic. Parameters such as land use and related soil type are connected to the model using attribute tables of the land use and soil raster maps. The attribute tables also allow defining new land cover or soil types easily, as well as changes in the parameter values, which permits analysis of future land and water management scenarios (Batelaan and De Smedt, 2007). The WetSpass model treats a basin or region as a regular pattern of raster cells (Batelaan and De Smedt, 2007). The total water balance for a raster cell is split into independent water balances for the vegetated, bare-soil, open-water, and impervious parts of each cell (Figure 3.6).

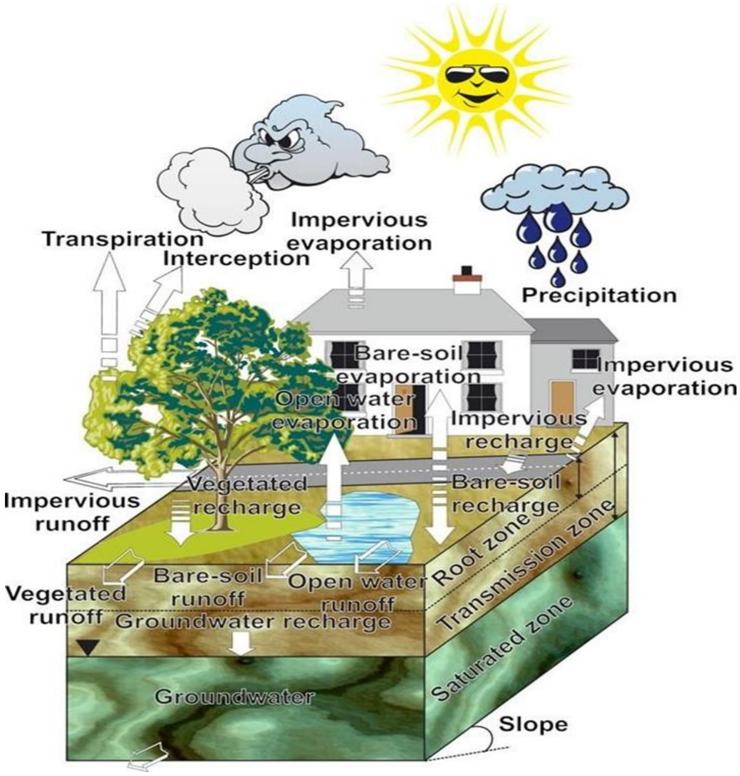


Figure 3-8: schematic water balance of hypothetical raster cell (Batelaan and De Smedt, 2001).

This allows one to account for the non-uniformity of the land use per cell, which is dependent on the resolution of the raster cell, and the processes in each part of a cell are set in a cascading way (Batelaan and De Smedt, 2001). Since the WetSpass model is a distributed water balance model, the water balance computation is performed at the raster cell level. As described by Batelaan and De Smedt (2001), individual raster water balance is obtained by summing up independent water balances for the vegetated, bare soil, open water, and impervious fractions of a raster cell as follows:

$$\mathrm{ET}a = avETv + asEs + aoE0 + aiEi \tag{2}$$

$$Sa = vSv + asSs + aoRo + aiRi \tag{3}$$

$$R\,a = vRv + asRs + aoRo + aiRi \tag{4}$$

where *ETa*, Sa, and Ra are the total evapotranspiration, surface runoff, and groundwater recharge of a raster cell respectively, each having vegetated, bare soil, open water, and impervious area fractions denoted by av, as, ao, and ai respectively, E is evaporation.

Precipitation was taken as starting point for the calculation of the water balance for each of the components of a raster cell. Other processes (interception, runoff, evapotranspiration, and recharge) followed in an orderly manner; which becomes a prerequisite for the seasonal time scale to compute the processes. Evapotranspiration is calculated as the sum of evaporation of the precipitation intercepted by the vegetation, transpiration by the vegetation, and evaporation from bare soil and open water bodies (Batelaan and De Smedt, 2001). For the simulation of surface runoff, the WetSpass model uses the runoff coefficient which on the other hand is a function of vegetation type, soil texture, and slope. As discussed by (Batelaan and De Smedt, 2007), in

WetSpass, the surface runoff (Sv) is simulated in two stages. First, the potential surface runoff (Sv−pot) is calculated as a coefficient times the precipitation minus the interception (Eq. 5).

$$S_{v-pot} = C_{SV}(P - I) \tag{5}$$

Where, Csv (as a function of vegetation type, soil type, and slope) is a surface runoff coefficient for vegetated infiltration areas based on the rational formula (Smedema *et al*., 2004; Pilgrim and Cordery, 1992; Chow *et al*., 1998). However, the potential surface runoff is conceptualized to occur only in groundwater-saturated areas (Batelaan and De Smedt, 2007). Rubin, (1966), indicated that, in the second stage, the potential surface runoff is actualized for recharge areas by considering differences in precipitation intensities to soil infiltration capacities (Eq. 6).

$$Sv = C_{HOR}S_{v-pot} \tag{6}$$

Where *CHor* is a coefficient that parameterizes the part of the seasonal precipitation which is contributing to the Hortonian surface runoff. As explained by Batelaan and De Smedt (2001), in groundwater discharge areas all intensities of precipitation contribute to surface runoff, i.e. CHor is 1. In infiltration areas, only high-intensity storms will generate surface runoff.

The most common way of estimating recharge by the water budget method is the indirect or residual approach, whereby all of the variables in the water budget equation except recharge are estimated, and recharge is set equal to the residual (Scanlon *et al*., 2002). In WetSpass, groundwater recharge is calculated as a residual term of the water balance (Eq. 7).

$$\mathrm{Rv} = \mathrm{P} - \mathrm{Sv} - \mathrm{ETV} - \mathrm{I} \quad (7)$$

Where P is the average seasonal precipitation [LT^{-1}], ETv is the actual evapotranspiration [LT^{-1}], Sv is the surface runoff [LT^{-1}], I is the interception by vegetation [LT^{-1}], and Rv is the groundwater recharge, all variables have the unit of [LT^{-1}].

3.4.2 Conceptual Framework

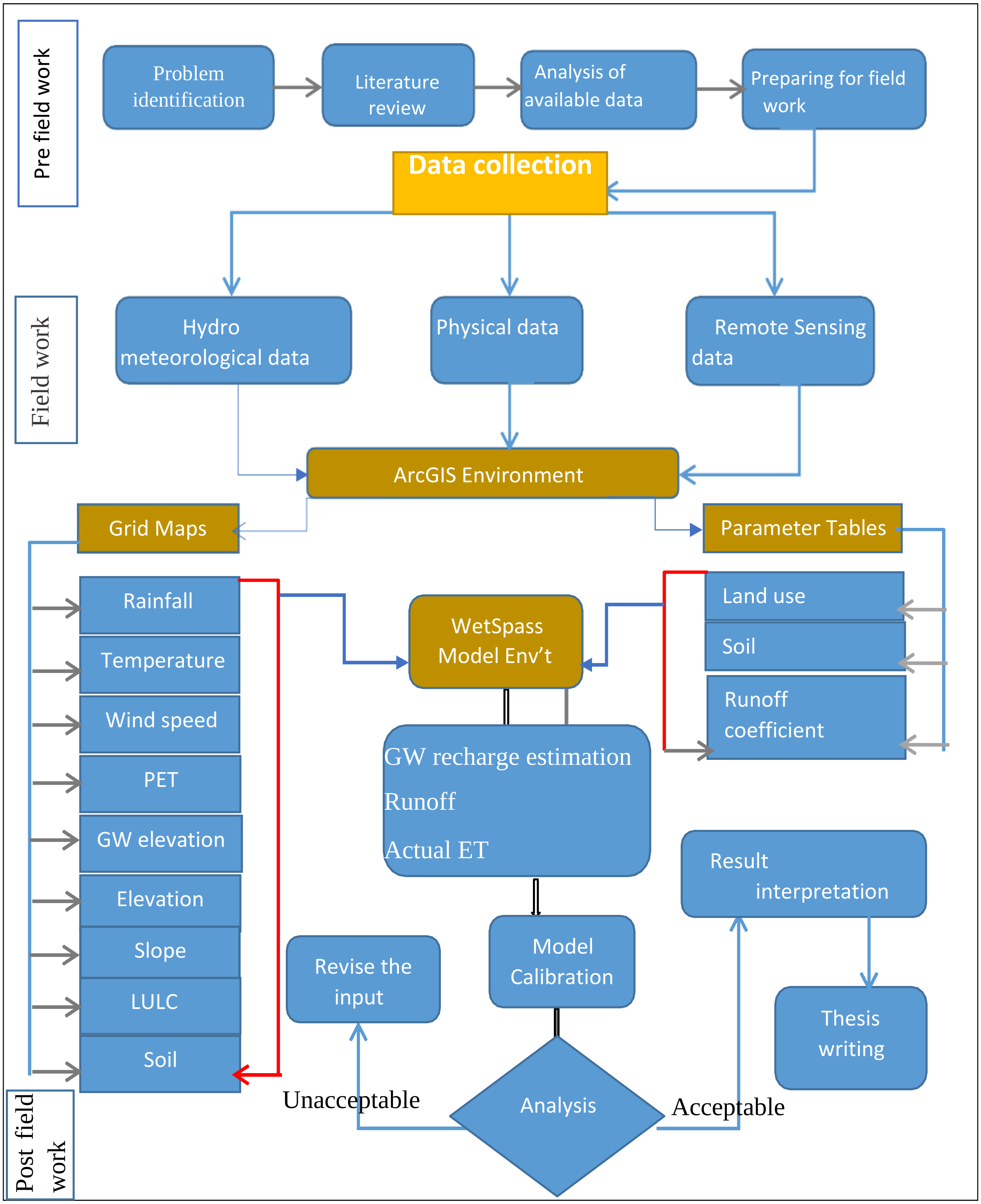


Figure 3-9: Conceptual flow diagram.

3.4.3 Preparation of input data

Preparation of input data involves digitizing existing maps, digital image processing of remote sensing data, and integration of field data for the extraction of relevant information. As described by Rwanga (2013), two types of inputs are required for the WetSpass model: arc Info grid maps and parameter dbf tables. De Vries and Simmers (2002), noted that the interaction of climate, geology, morphology, soil condition and vegetation determine the recharge process. As such, the input data were prepared in the form of grid maps of meteorological, hydrological, and geographical elements in the sub-basin. All input grid maps were prepared using a grid cell size of 30 m by 30 m resolution.

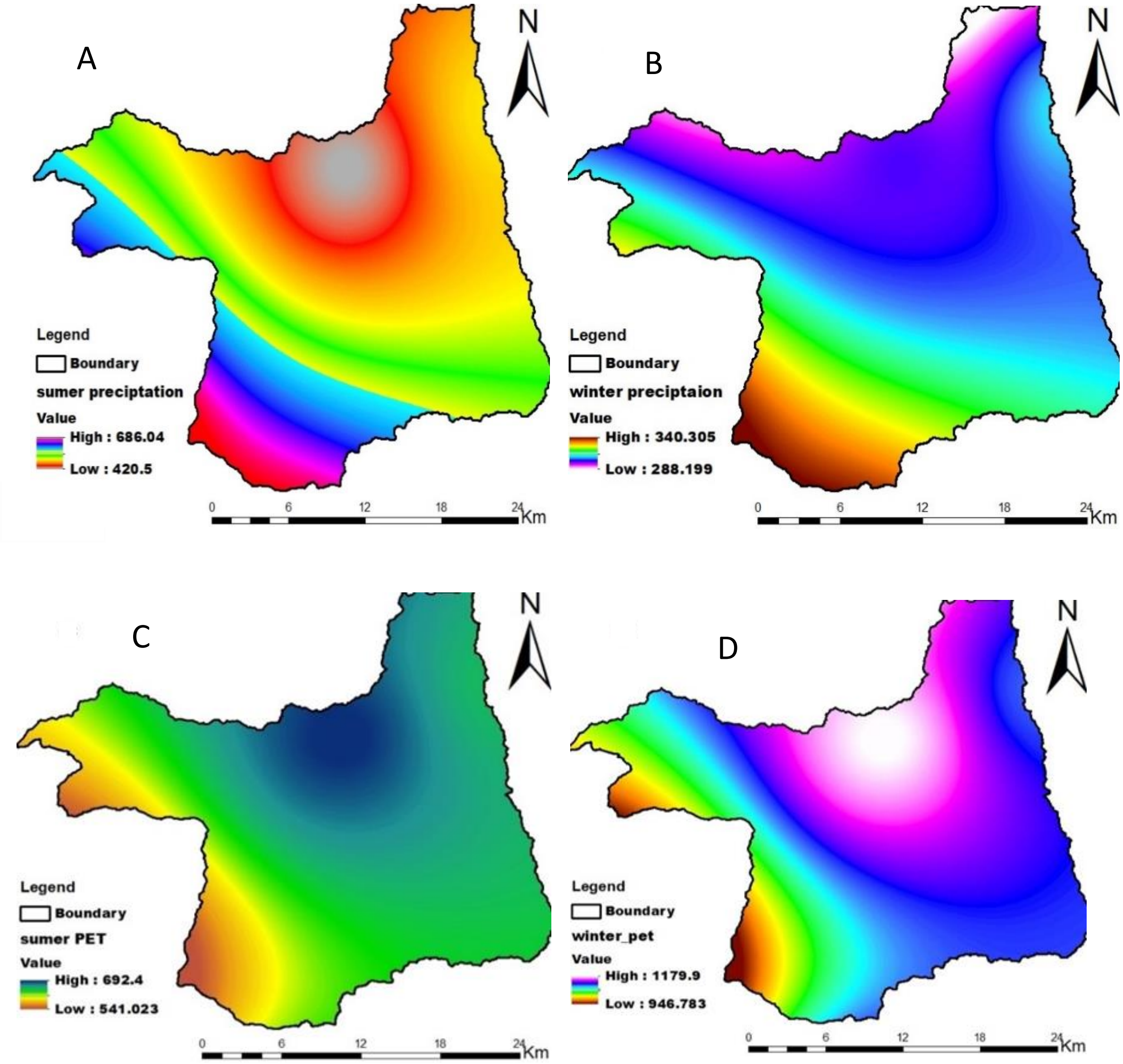
A. Meteorological data

Meteorological data obtained from seven stations of the Ethiopian national Meteorological Agency (EMA) were used for the preparation of metrological input data for the WetSpass model. Missing meteorological data records was a common problem in the stations of the study area. However, the selected stations for the 22 years (from 2000 to 2021) had relatively consistent data records. Each station's data was analyzed for the calculation of the seasonal and annual meteorological values. Precipitation and temperature data were available for all seven stations while wind speed was recorded only at Kobo, Maichew, and Chercher meteorological stations. The Hargreaves equation (Hargreaves and Samani, 1982) was used to calculate potential evapotranspiration at the seven stations.

The seasonal and annual grid maps of the climatic variables were developed using an interpolation method to predict values from a limited number of sample data points at unknown geographic point data. The inverse Distance Weighted (IDW) interpolation method was applied as it gives consistent results with known values. The WetSpass input grid maps of major meteorological parameters of the Hormat-Golina sub-basin (Figure. 3.9) indicate high spatial variation as a function of topography. For example, there was a significant spatial variation of rainfall in the sub-basin which is strongly influenced by the orographic effect where the Lasta highland receives high rainfall as compared to the valley bottoms.

The precipitation values of the wet /summer/ season range from 420.5 mm to 686.4 mm with a mean of 416.3 mm (Figure 3.9A) while in the dry /winter/ season precipitation values range from 288.2 mm to 340.3 mm with a mean of 312.2 mm (Figure 3.9B). High values are located mainly in the western highlands of the Hormat-Golina sub-basin. The mean annual precipitation of the Hormat-Golina sub-basin was 828.5 mm. The average monthly PET was calculated during the period 2000-2021 for seven (7) stations using monthly average temperature values. The highest value (1179.9 mm) is recorded during the dry season /winter/ season (October to May). 946.8 mm and 1179.9 mm were minimum and maximum values respectively with a mean value of 1112.6 mm for winter /dry/ season (Figure 3.9D) while for the summer /wet/ season the minimum and maximum values of potential evapotranspiration were 541.0 mm and 692.4 mm with a mean value of 646.5 mm (Figure 3.9C). The mean annual potential evapotranspiration of the sub-basin was 1759.1 mm.

The minimum and maximum temperature for the dry season /winter/ was 14.5°C to 22.6 °C (Figure 3.9F) with a mean value of 19.2 °C whereas the minimum and maximum temperature of the summer /wet/ season ranged from 16.5 °C to 24.6 °C (Figure 3.9E) with a mean value of 21.4 °C. The mean annual temperature of the Hormat-Golina sub-basin was 20.3°C. The average summer wind speed is 1.87 m/s with minimum and maximum values ranging from 1.8 m/s to 1.94 m/s (Figure 3.9H) while the average winter wind speed is approximately 2.25 m/s with minimum and maximum values ranging from 2.12 m/s and 2.38 m/s (Figure 3.9G) with an annual average wind speed of 2.06 m/sec.



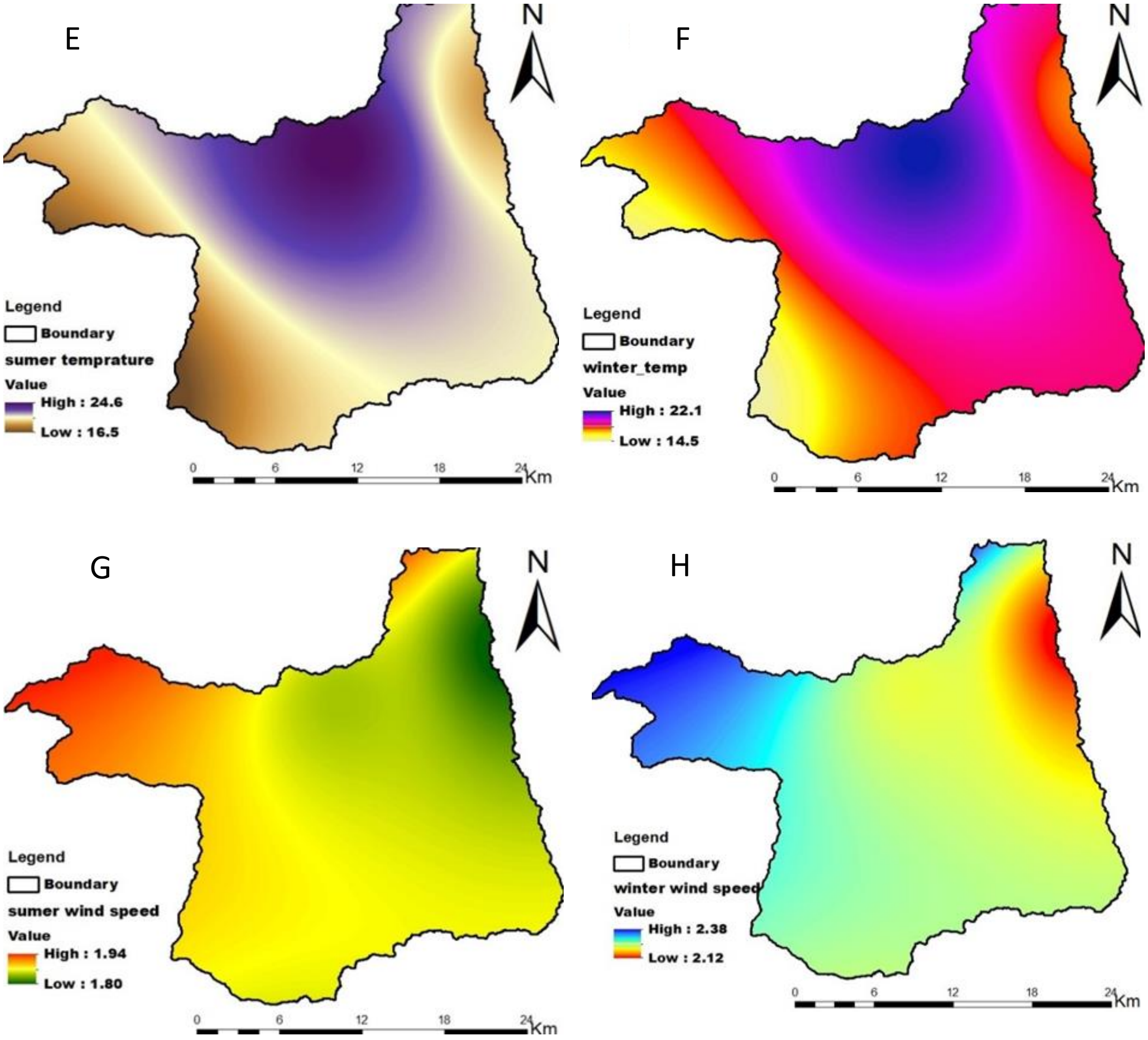


Figure 3-10: WetSpass input grid maps of major meteorological parameters in Hormat-Golina sub-basin.

A. Land use land cover

The land use/land cover map of Ethiopia was prepared by Ethiopian Geospatial Institute (GSI) for 2020. The Hormat-Golina sub-basin land use land cover was derived and modified from this map. Different land uses and vegetation cover were characterized in the Hormat-Golina sub-basin. Forests, Shrub-bush land, crop land, bare land, wetland, grass land, wood land and settlements are the most important land cover units in terms of area coverage.

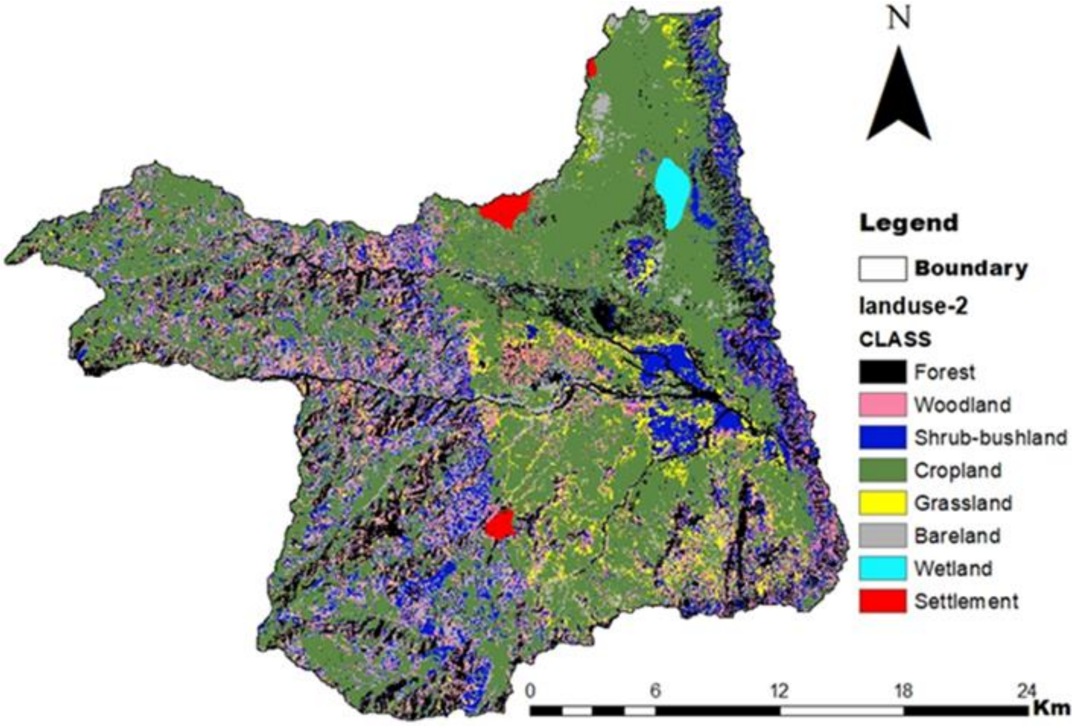


Figure 3-11: Land use map of the areas.

The land-use/land cover classification of the study area (Figure 3.10) resulted in eight classes comprising settlement (0.7%), bare land (10.5%), crop land (47.4%), grassland (4.4%), wetland (0.6%), woodland (11.2%), forest (12.6%) and shrub-bush land (12.6%) of the Hormat-Golina sub-basin (Table 3.2).

Table 3-2:- Land use classification

Land use Class	Area (Km^2)	Area (%)
Forest	88	12.6
Wood land	78	11.2
Shrub-bush land	88	12.6
Cropland	331	47.4
Grass land	31	4.4
Bare land	73.25	10.5
Wetlands	4	0.6
Settlements	5	0.7
Total	698.25	100.0

B. Soil texture

Soil texture and permeability are important in recharge estimation because coarse-grained soils generally result in higher recharge rates than fine-grained soils (Cook *et al*., 1992). The soil map of the Hormat-Golina sub-basin was derived from the Soil map of Ethiopia which is developed by the ministry of water irrigation and energy (MWIE) of Ethiopia. According to the soil map, the Hormat-Golina sub-basin was divided into four classes: sandy loam, silty clay loam, loam, and clay loam (Figure 3.11). Silty clay loam covers the majority of the catchment.

Table 3-3:- soil texture of Hormat-Golina sub-basin

Soil type	**Area KM2**	**Area (%)**
silty clay loam	278.65	39.91
clay loam	214.16	30.67
sandy loam	115.72	16.57
loam	89.70	12.85
Total	698.25	100.00

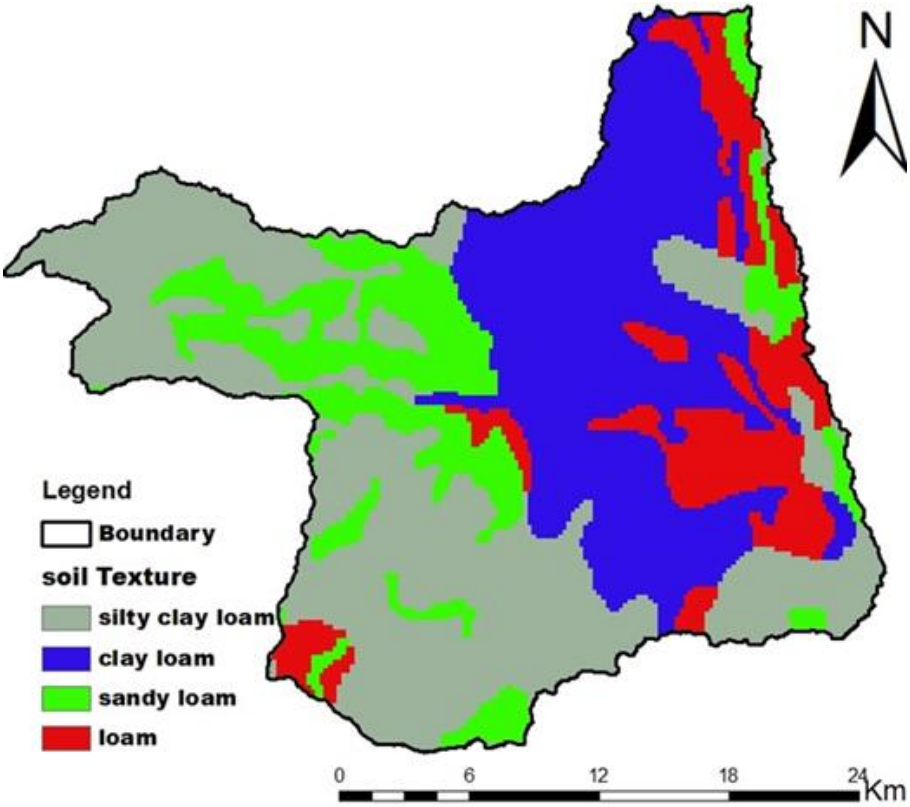


Figure 3-12: Soil map of the area

C. Groundwater depth

Groundwater depth data was produced from the elevation of static water level measurements in boreholes and springs. Overall 34 static water level measurements which were mostly concentrated in the valley area were used for interpolation to produce the groundwater depth grid map. The groundwater elevation map was calculated by subtracting static water level from ground elevation. The groundwater elevation of the Hormat-Golina sub-basin ranges from 1368 m to 1481 m in the summer /wet season/ while it ranges from 1359 m to 1489 m in the winter /dry/ season (Figure 3.11).

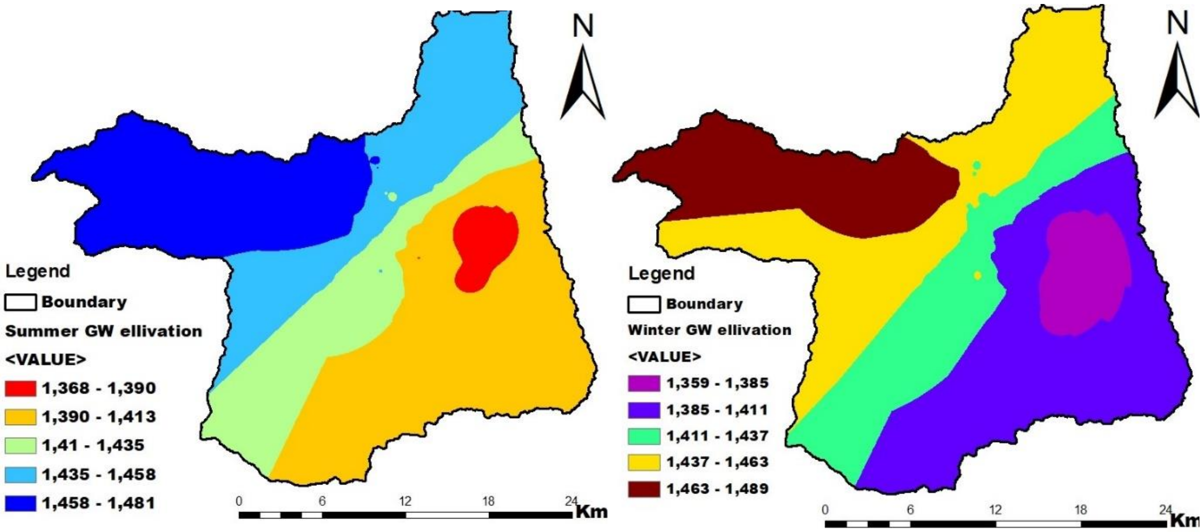


Figure 3-13: Groundwater Elevation map of Hormat-Golina sub-basin

D. Topography and slope

The Alaska satellite facility (ASF) data set was used to create an elevation and slope map of the study area. The ASF provides Digital Elevation Model with a resolution of 12.5*12.5m (DEM). The sub-basin's highest point, at 1319 meters, is found upstream on the Western escarpment, while the lowest point, at 1290 meters, is found in the eastern/downstream section (Figure 3.12a).

The slope is an important component for determining the watershed's hydrological features. The watershed's steep slopes serve as recharge zones, while the moderate slopes serve as discharge areas. It usually has a direct relationship with topography. The research area slope map was likewise created using ArcGIS and a 12.5m*12.5m DEM.

It is categorized according to the degree of steepness, which ranges from 0 to 43. The value 0 represents gentle/lowland, while value 43 represents steep/escarpment. The Hormat-Golina sub-basin comprises both a large region of high slope/steep escarpment, which is unsuitable for agricultural activities and a flat/gentle slope of lowland area/plane, which is suitable for agriculture. Around 41% of the study area is below 5^{o}, 4.85% of the study area is above 25^{o}, and the remaining 54.15 % is between 5 and 25^{o}, which is ideal for the recharge/discharge hydrological process (Figure 3.12b).

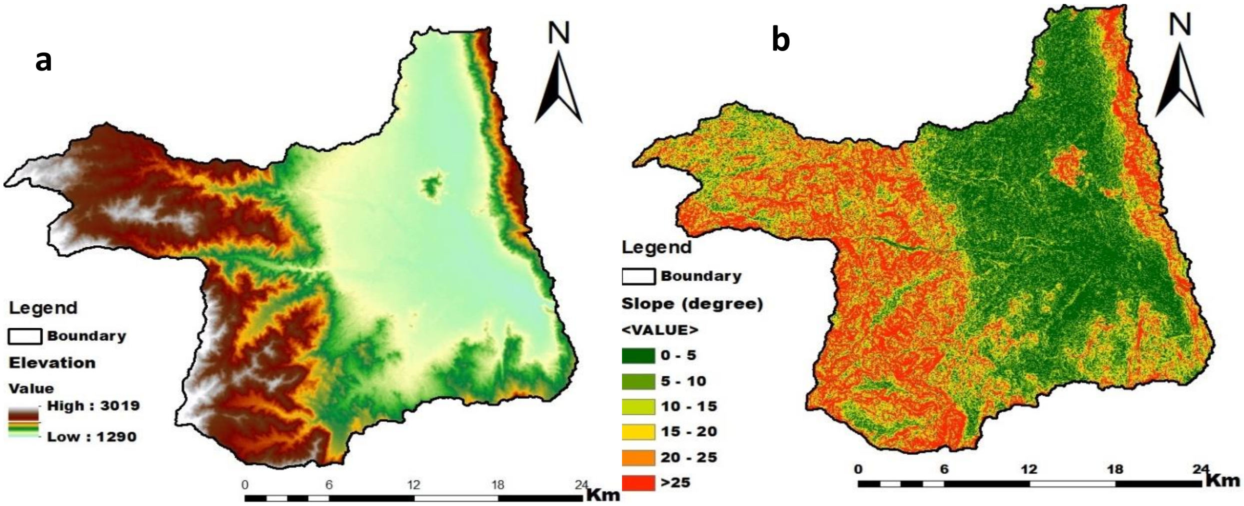


Figure 3-14: Elevation and slope of Hormat-Golina sub-basin

3.4.4 Parameter tables /lookup tables/ preparation

For a smooth functioning process, the WetSpass model requires multiple biophysical parameter tables in addition to grid maps. The parameter tables are runoff coefficient, land use/land cover, and soil parameters. Those parameter tables were created in a way that was both appropriate and essential (DBF). To adapt and develop the parameter values to Hormat-Golina sub-basin parameters, the WetSpass user guide, and some additional literature research was employed. The model was processed after both the needed grid map and parameter tables were prepared.

3.4.5 Adaptation of WetSpass to the case of Hormat-Golina sub-basin

WetSpass is originally developed for conditions in temperate regions in general and Europe in particular (Batelaan and De Smedt, 2001). Later the model was applied all over the world under different conditions by modifying its parameters (Aish *et al*., 2010; Teklebirhan *et al*., 2012; Pandian *et al*., 2014; Armanuos *et al*., 2016). The modified

WetSpass model was applied in the semi-arid region of Ethiopia to simulate the hydrological water balance of the Geba basin (Gebreyohannes *et al*., 2013) and long-term average recharge in Dire Dawa, (Tilahun and Merkel, 2009).

The land-use classes and textural composition and classification of soils for tropical countries like Ethiopia are different than the case in temperate regions. Even though some similar land-use classes exist in both temperate and tropical regions, they are not the same in characteristics. Furthermore, the summer and winter seasons of temperate regions are not the same as those of tropical regions. Taking the case of Ethiopia, winter is the dry season while summer is the main rainy season. Hence, before doing any watershed simulation modification of the model is required to adopt it for the Ethiopian condition.

Thus, a modified WetSpass model was developed for the Hormat-Golina sub-basin where the land-use parameter tables (summer and winter seasons) for the Hormat-Golina sub-basin were modified and adjusted to represent the condition of the Hormat-Golina sub-basin using expert knowledge and scientific literature. Land use (summer and winter), soil, and runoff coefficient are the parameter tables used by WetSpass. The land-use attribute table includes parameters such as land-use type, rooting depth, leaf area index, and vegetation height. The soil parameter table contains soil parameters such as textural soil class, plant available water contents, and others. Whereas, the runoff coefficient attribute table contains parameters for runoff classes of various land uses, slope, runoff coefficient, etc.

The necessary modification was done on the land-use parameters mainly for the leaf area index, crop height, and interception percentage, to fit the condition of the Hormat-Golina sub-basin. Moreover, the vegetative area, bare area, impervious area, and open water area proportions of each land-use class in the Hormat-Golina sub-basin have been modified (Table 3.3 and 3.4). The year was divided into two seasons’ summer (from June to September) and winter (from October to May) with their respective input data (land use, precipitation, potential evapotranspiration, temperature, wind speed, and groundwater depth).

Table 3-4: Summer land-use parameter table modified for the Hormat-Golina sub-basin

Number	Luse_type	Runoff_veg	Num_veg_ro	Num_imp_ro	Veg_area	Bare_area	Imp_area	Openw_area	Root_depth	Lai	Min_stom	Interc_per	Veg_height
2	Settlement	Grass	2	2	0.5	0.2	0.3	0.0	0.3	0.20	100.0	10.0	0.12
7	Bare	Bare soil	4	0	0.0	0.7	0.3	0.0	0.05	0.00	110.0	0.0	0.001
21	Agriculture	Crop	1	0	0.8	0.1	0.1	0.0	0.4	0.20	180.0	35.0	0.7
23	Grass	Grass	2	0	1.0	0.0	0.0	0.0	0.3	2.00	100.0	10.0	0.2
28	Wet land	Grass	2	0	1.0	0.0	0.0	0.0	0.3	2.00	100.0	10.0	0.3
31	Wood	Forest	3	0	0.8	0.0	0.2	0.0	2.0	5.00	250.0	25.0	15.0
33	Forest	Forest	3	0	0.80	0.0	0.20	0.0	2.50	3.50	310.0	50.0	10.00
36	Shrub	Grass	2	0	0.80	0.0	0.2	0.0	0.6	6.00	110.0	42.0	2.50

Table 3-5: Winter land-use parameter table modified for the Hormat-Golina sub-basin

Number	Luse_type	Runoff_veg	Num_veg_ro	Num_imp_ro	Veg_area	Bare_area	Imp_area	Openw_area	Root_depth	Lai	Min_stom	Interc_per	Veg_height
2	Settl	Grass	2	2	0.4	0.50	0.10	0.0	0.3	0.2	100.0	10.0	0.12
7	Barel	Bare soil	4	0	0.00	0.70	0.3	0.0	0.05	0.0	110.0	0.0	0.001
21	Agric	Crop	1	0	0.20	0.40	0.4	0.0	0.35	2.0	180.0	22.0	0.6
23	Grass	Grass	2	0	0.60	0.30	0.10	0.0	0.30	1.0	140.0	10.0	0.12
28	Wetl	Grass	2	0	0.60	0.30	0.10	0.0	0.30	1.0	140.0	10.0	0.2
31	Wood	Forest	3	0	0.20	0.80	0.0	0.0	2.00	4.0	250.0	10.0	15.0
33	Forest	Forest	3	0	0.80	0.10	0.10	0.0	2.00	4.0	340.0	42.0	10.0
36	Shrub	Grass	2	0	0.65	0.30	0.05	0.0	0.60	3.0	110.0	30.0	2.0

Luse_type land-use type, Runoff_veg runoff vegetation, Num_veg_Ro runoff class for vegetation type, Num_imp_Ro impervious runoff class for impervious area types, Veg_area vegetated area, Bare_area bare area, Imp_area impervious area, Openw_area open-water area, Root_depth Root Depth Lai Leaf Area Index, Min_stom minimum stomatal opening, Interc_per interception percentage, Veg_height vegetation height

3.4.6 Analysis and grid maps combination

WetSpass gives various hydrologic outputs on a yearly and seasonal (summer and winter) basis (Batelaan and De Smedt, 2001). The results from the WetSpass model can be analyzed in various ways (Al Kuisi and El-Naqa, 2013). The spatial variations of recharge and runoff can be obtained as a function of land use and soil type. As all output from the model are grid maps and not tabular values, it would be helpful to combine two or more grid maps. The Arc GIS function called 'combine' is used to combine different grids to produce database files for further analysis and graphical presentations. Accordingly, the land-use and soil maps were combined with surface runoff, recharge, and actual evapotranspiration maps to visualize the impact of different land covers and soil texture on evapotranspiration surface runoff and groundwater recharge.

3.5 Generating Hydrometric Data for the Outlet of the Sub-Basin

Getting adequate and accurate inputs such as precipitation and stream flow data are important for successful hydrological modeling (Guo *et a*l., 2021). Hence, hydrometric data is one of the important input data in any hydrological modeling to evaluate the performance of the hydrological model through calibrating the outputs of the simulated value with the observed one. However, in many developing countries including Ethiopia, high-resolution hydrological and meteorological stations cannot be installed in remote locations due to financial and technical constraints. In this region runoff simulations, and estimates in ungauged catchments are the most significant and challenging issues for hydrologists. In the Hormat-Golina sub-basin of northern Ethiopia, it is a difficult task to implement any hydrological model to predict the effects of human-induced and natural stress on surface and subsurface water resources and to produce appropriate water resources management strategies. This is because of the absence of stream flow measuring stations in the Hormat-Golina sub-basin. In order to solve such obstacles, researchers have been paid efforts through implementing multiple regionalization techniques worldwide. Therefore, regionalization is a technique to estimate the historic stream flow at the ungauged part of the watershed (Arsenault *et al*., 2019), through the process of transferring hydrometric information from gauged (Donors) to ungauged catchments. In the past several decades, some regionalization techniques have been developed by different investigators to estimate noticeable stream flow at an area with sparsely or limited hydrometric data, for example, Arithmetic Mean (AM) (Jin *et al.*, 2009; Merz and Blöschl, 2004; Oudin *et al*., 2008), Physical Similarity (PS), *(Narbondo et al*., 2020; Samaniego *et al*., 2010; Samuel *et al*., 2011), Spatial Proximity (SP) (Oudin et al., 2008; Li *et al*., 2009; Parajka *et al*., 2005), Regression (R) (Oudin *et al*., 2008; Parajka *et al*., 2005; Jillo *et al*., 2017; Ochoa-Tocachi *et al*., 201; Visessri and McIntyre, 2016; YOUNG *et al*., 2006), Catchment Runoff Response Similarity (CRRS), (Tegegne *et al.*, 2017) and Probabilistic Random Forests (PRF) (Prieto *et al*., 2019). According to a comprehensive review of Guo et al., (2021) in physical similarity regionalization, a variety of remotely sensed based evidence such as land use and vegetation cover, slope, topography and meteorological data such as rainfall, minimum and maximum temperature needs to be extracted from the catchment attributes for prediction of stream flow at ungauged catchments. The physical similarity approach consists of transferring hydrological information from donor (gaged) catchments that are similar to the ungagged catchments in terms of catchment descriptors.

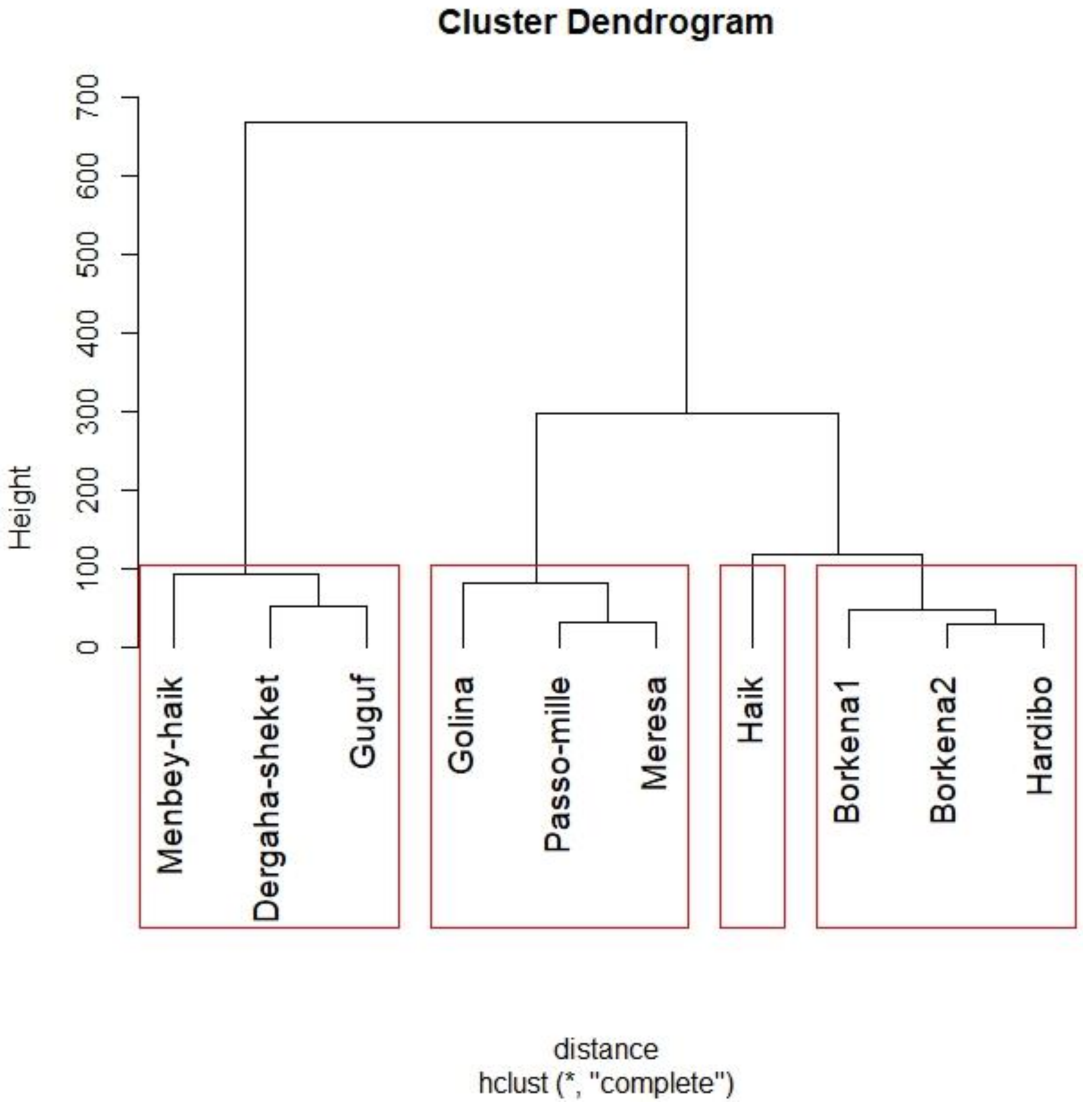


Figure 3-15: Watershed clustering with physical similarity.

Here, the selection of the donor catchments is based on the proximity of the ungagged catchments to the gaged ones in terms of catchment descriptors. The flow data for the ungagged catchment was produced by averaging the values of most similar catchments.

Table 3-6: Monthly generated flow using regression techniques.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Flow (MCM)	2.43	2.28	5.61	4.54	3.68	2.08	6.91	14.64	6.70	4.20	2.32	1.78

3.6 Validation of WetSpass Mode

The validation of the WetSpass model was performed by using generated flow data using physical similarity regionalization techniques to perform the hydrograph analysis. The automated Web-Based Hydrograph Analysis Application (WHAT) is applied to derive a base flow from stream flow data. WHAT has three separating filters: the Eckhardt recursive digital filter method (RDF) (Eckhardt, 2005), the one-parameter digital filter method (OPM) (Lyne and Hollick, 1979; Nathan and McMahon, 1990; Arnold and Allen, 1999; Arnold *et al*., 2000) and the local-minimum method (LMM) (Lim *et al*., 2005).

The Eckhardt recursive digital filter method (RDF) (Eckhardt, 2005) is applied in this study:

$$\mathrm{b_t} = \frac{1 - \mathrm{BFI_{max}} \mathrm{x} \alpha \mathrm{bt} - 1 + 1 - \alpha \mathrm{x} \mathrm{BFI_{max}} \mathrm{x} \mathrm{Q_t}}{1 - \alpha \mathrm{x} \mathrm{BFI_{max}}} \tag{9}$$

Where, bt represents base flow at time step t (m^3/s); *bt−1* represents the filtered base flow at time step t−1 (m^3/s); BFImax presents the maximum long-term ratio of base flow/total stream flow; *Qt* is the total stream flow at time step t (m^3/s) and α is the filter parameter. Eckhardt (Eckhardt, 2005), suggested BFImax values of 0.50 for ephemeral streams including porous aquifers, 0.25 for perennial streams containing hard rock aquifers, and 0.80 for perennial streams containing porous aquifers. The proposed values of 0.80 for BFImax and 0.98 for the filter parameter, which correlates to the hydrogeological characteristics of the watershed, were used in this case.

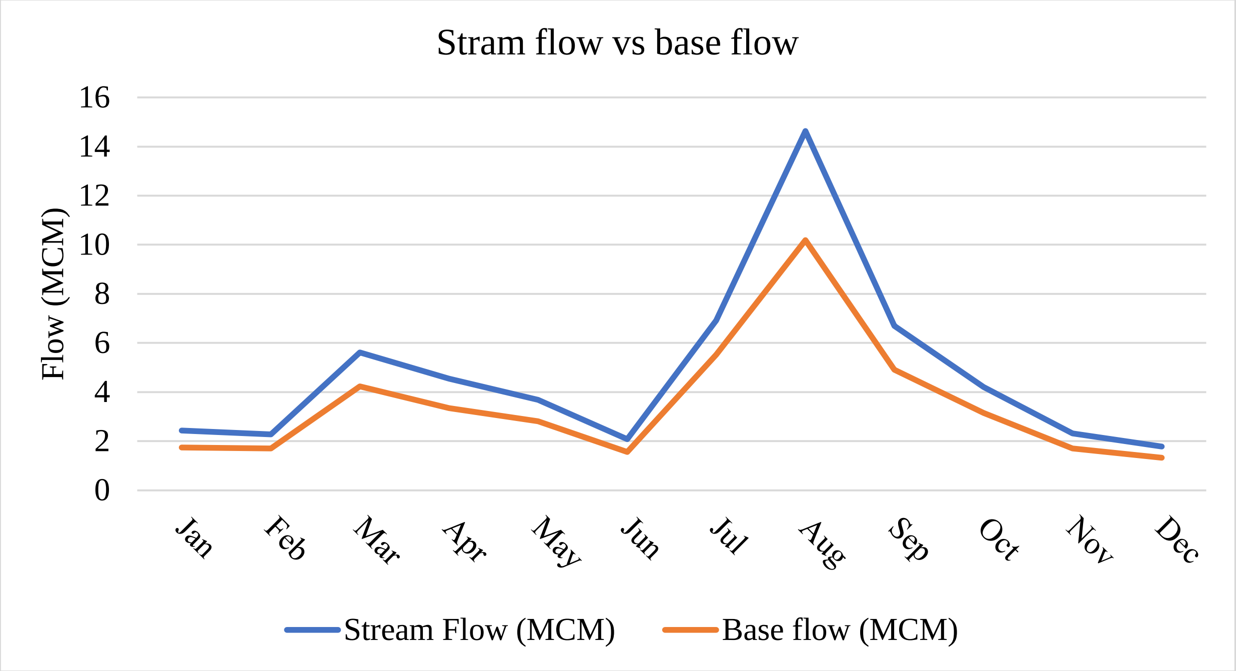


Figure 3-16: Comparison between stream flow and base flow

4 RESULTS AND DISCUSSIONS

4.1.Validation of WetSpass Model

Conventionally, the validation processes of the WetSpass distributed hydrologic water balance model were implemented through manual adjusting or modifying the model parameters existing in the WetSpass model within a given range of values. The objective function is typically the correlation of the coefficient of determination R^2 between the simulated surface runoff and observed discharge. The adjusted parameters include alfa coefficient, “a” interception, Lp coefficient, and runoff delay factor “x.” These parameters were held in reserve optimizing up to the attainment of a final agreement between the calculated against observed discharge recorded at Hormat-Golina river and base flow obtained from separating the observed discharge using base flow separator techniques. The total flow in a river from a basin is a function of surface runoff and subsurface flow that is equivalent to the long-term mean seasonal river discharge from the basin. The summation of subsurface flow and surface runoff simulated by the WetSpass model was implemented to calibrate the model with in situ observed stream flow data obtained from Hormat-Golina river. Figure 4.2 shows that the simulation analysis has attained excellently with a correlation coefficient of the “line of the goodness of fit” and Nash-Sutcliffe efficiency (NSE) of 0.90 and 0.85, respectively, with a standard error of 0.21. Evaluation of the WetSpass model showed representative results for the total discharge and good results for the base flows.

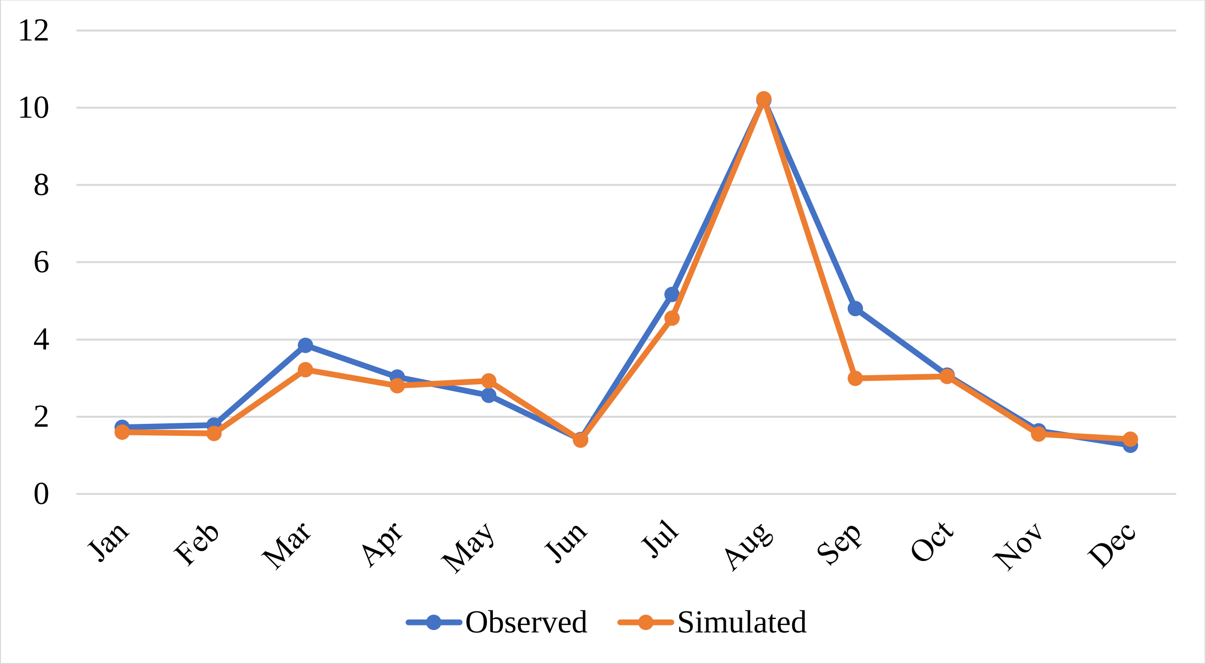


Figure 4-1: Compression between simulated and observed flow data

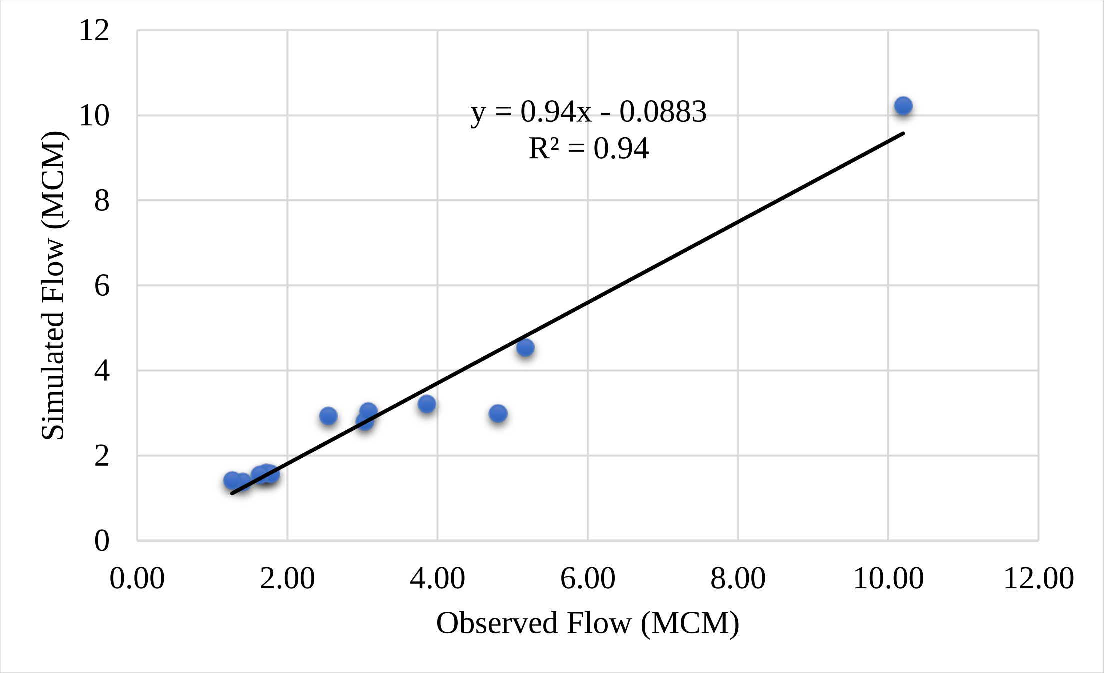


Figure 4-2: Model performance evaluation using coefficient of determination.

4.2. WetSpass Model Results

The results of the WetSpass model were comprised of digital images of the spatial distribution of annual and seasonal average values of actual evapotranspiration, surface runoff, and groundwater recharge for the 22 years from 2000 to 2021. These maps are in raster format in which every pixel represents the magnitude of the respective component of the water balance.

4.2.1. *Groundwater recharge*

The amount of infiltration to the groundwater depends on the vegetation cover, slope, and soil composition, depth to the water table, and the presence or absence of confining beds (Al Kuisi and El-Naqa, 2013). Natural vegetation cover, flat topography, permeable soils, a deep-water table, and the absence of confining beds favors recharge. The WetSpass model simulated the long-term average spatially distributed groundwater recharge depending on soil texture, land use, slope, and meteorological conditions. The annual summer and winter WetSpass simulated recharge to the Hormat-Golina sub-basin is presented in Figure 4.3 a–c respectively. The simulated annual groundwater recharge for the existing land use ranged from 0 to 196.8 mm, with an average value of 55.4 mm, and represented only 8% of the mean annual precipitation. About 83% of the annual groundwater recharge of the basin occurred during the wet /summer/ season, while the remaining 17% took place during the dry /winter/ season. The mean annual spatial groundwater recharge is highly variable depending on the factors that govern groundwater infiltration (Figure 4.3a). The southern and western highlands of the Hormat-Golina sub-basin had high annual groundwater recharge due to the presence of permeable soils, high precipitation, and vegetation cover. The western foothill side areas were also characterized by high groundwater recharge occurrence mainly due to the flat topography and coarse permeable soils. On the contrary, the lowlands and central southeastern of the area had low groundwater recharge due to their being discharge areas and the dominance of less permeable fine-textured soils.

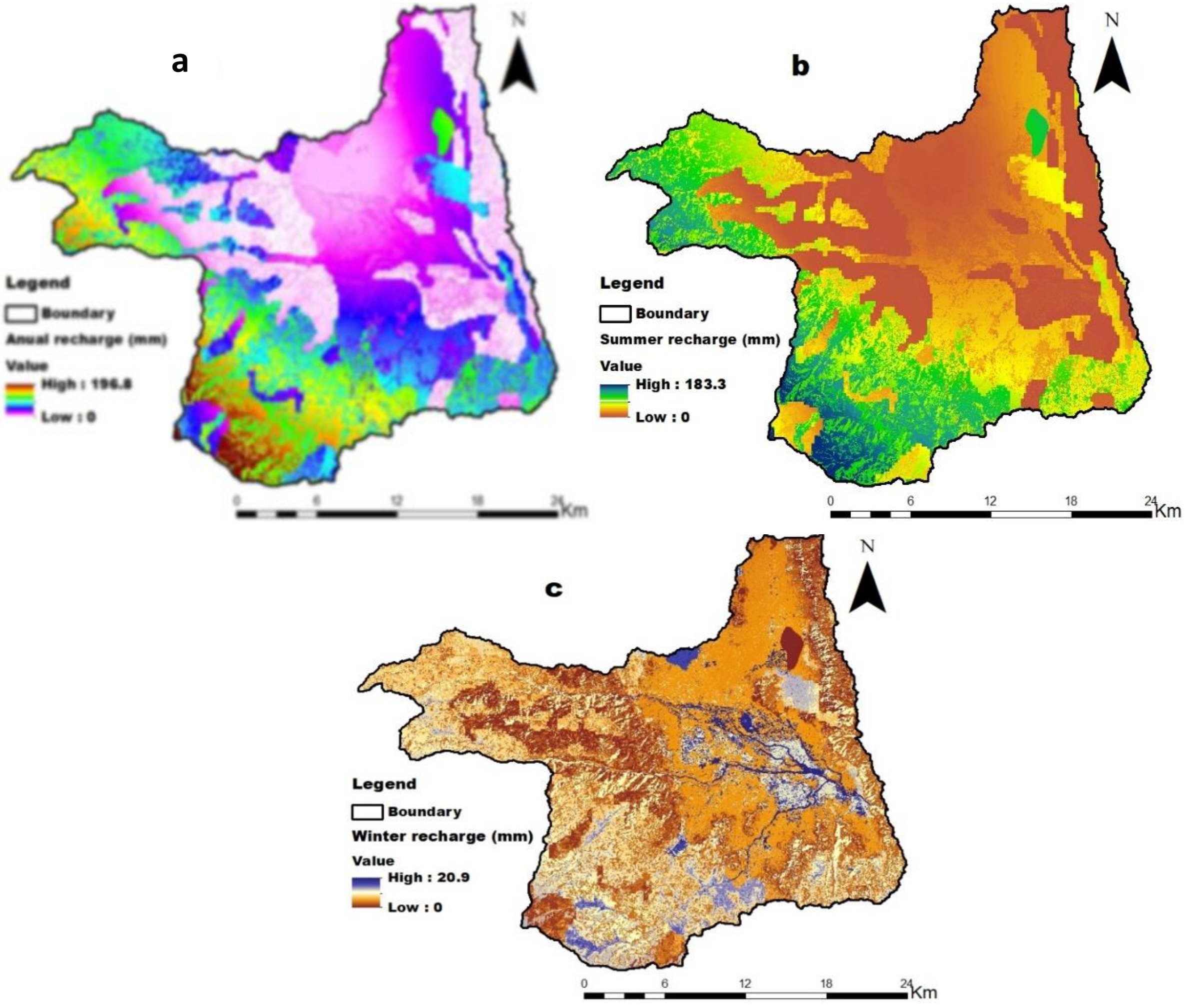


Figure 4-3: Spatial maps of simulated groundwater recharge: annual (a) summer (b) and winter (c).

In other research locations, similar studies have been undertaken to estimate average groundwater recharge using the WetSpass model. Accordingly, average recharge was found to be 28 mm (5 percent of annual precipitation); (Tilahun and Merkel, 2009), 37 mm (6 percent); (Teklebirhan *et al*., 2012), 24.9 mm (7.4 percent); (Meresa *et al*., 2019), 30.06 mm (4.2 percent); (Gebremeskel and Kebede, 2017), 116 mm (9.4%) ; (Dereje and Nedaw, 2019), and 66 mm (12 percent); (Teklebirhan *et al*., 2012). Considering the entire area of the sub-basin (698.25 km^2), the simulated mean annual recharge accounted for about 0.5 million cubic meters.

The highest groundwater recharge was observed in forest lands and sandy-textured soil class (Table 4.1). This is basically because of the high permeability of sandy soils, and less runoff on the relatively gentler slopes of forest lands. On the other hand, the lowest recharge was observed in bare land with silty clay loam and clay loam soils and this can be attributed to the shallow nature of the groundwater table and the less permeability of the soils, respectively.

Table 4-1: Simulated mean annual recharge (mm) for the combinations of land-use and soil texture

	Settlement	Bare land	Agriculture	Grassland	Wetland	Forest	Shrub land	Mean	Sd. dev.
Sandy loam	80	50	142	71	115	150	130	105	36
Silty loam	40	30	85	53	80	115	103	72	30
Silty clay loam	36	22	41	35	30	–	35	33	6
Clay loam	42	30	143	90	52	96	35	70	38
Mean	50	33	103	62	69	120	76		
Std. dev	18	10	43	20	32	22	42		

4.2.2. *Actual evapotranspiration*

The annual, summer, and winter actual evapotranspiration maps are presented in Figure 4.4a–c, respectively. The WetSpass simulated mean annual evapotranspiration of the basin was 616.7 mm constituting about 78% of the annual average precipitation of the area. This indicated that evapotranspiration was the main process of water loss in the basin mainly due to the high rate of radiation and the existence of strong dry winds. The higher evapotranspiration took place during the summer season (62%) while the remaining 38% took place during the winter season. The actual evapotranspiration during the summer season was only 24% higher than the simulated actual evapotranspiration that took place during the winter period which indicates the bimodal nature of the precipitation in the study area. The annual evapotranspiration map (Figure 4.4a) showed a high annual rate in the south and southwest part of the study area which is attributed to the higher precipitation and vegetation cover.

Similarly, Gebremeskel and Kebede, (2017), reported that actual evapotranspiration is 90.7% of the annual precipitation in the Werii watershed of the Tekeze River Basin, Ethiopia, Yenehun et al., (2017), reported 90.7% of the annual precipitation in Geba basin, Northern Ethiopia, Meresa et al., (2019), get 85.5% of annual precipitation in the Birki Watershed, Eastern Tigray, Northern Ethiopia, Dereje and Nedaw, (2019), also simulated 69.8% of annual precipitation in the Upper Bilate Catchment, Southern Ethiopia and Teklebirhan et al., (2012), reported that 81% of annual precipitation in the Illala Catchment, Northern Ethiopia. As a result, evapotranspiration removes the majority of annual precipitation (Haile, 2015; Teklebirhan et al., 2012; and Tilahun and Merkel, 2009).

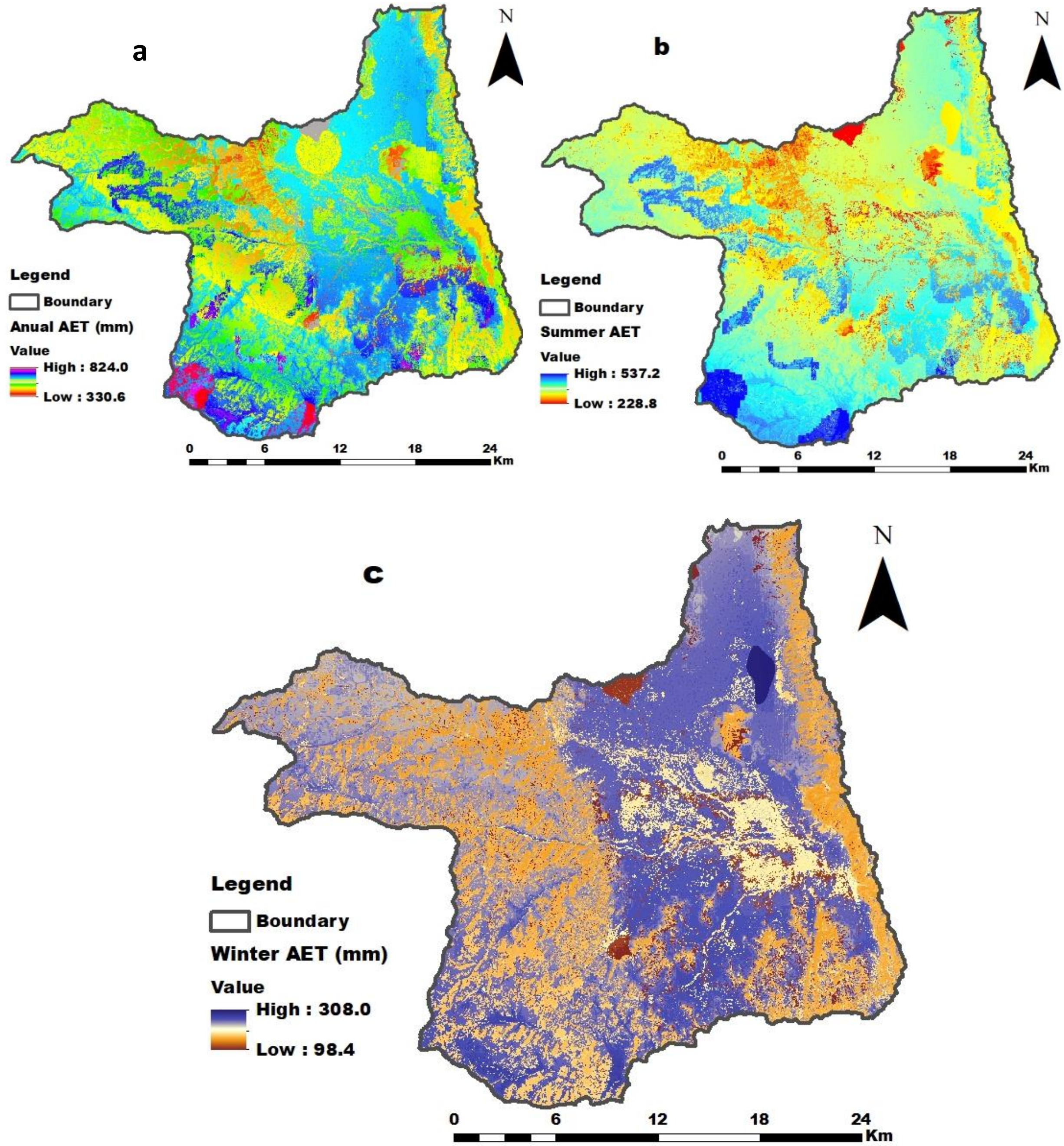


Figure 4-4: Spatial maps of simulated evapotranspiration: annual (a) summer (b) and winter (c).

The mean annual evapotranspiration was combined with different land-use and soil classes to analyze spatial variations of the evapotranspiration as a function of land use and soil types. High evapotranspiration was observed in the forest, grassland, wetland,

and woodland with clay loam soil texture which could be due to water availability in soil texture and high transpiration from the vegetation (Table 4.2).

Table 4-2: Simulated mean annual evapotranspiration for combinations of land-use and soil texture

	Settlement	Bare land	Agriculture	Grass land	Wet land	Forest	Shrubs	Mean	Sd. dev.
Silty clay loam	520	500	518	580	580	----	547	541	34
Sandy loam	605	642	590	695	710	671	712	661	50
clay loam	640	656	646	730	650	710	692	675	36
silty loam	569	590	539	639	674	654	619	612	48
Mean	584	597	573	661	654	678	643		
Std. dev	51	71	57	66	55	29	75		

4.2.3. *Surface runoff*

The annual, summer, and winter surface runoff of the Hormat-Golina sub-basin varied spatially with topography and other catchment characteristics (Figure 4.5a–c). The simulated annual surface runoff in the Hormat-Golina sub-basin ranges from 21.9 mm to a maximum of 448 mm with a mean of 156.4 mm. The mean value represented about 19% of the total mean annual precipitation of the area (about 1.2 million cubic meters for the whole basin). About 53% of the runoff occurred during the summer season while the remaining 47% occurred during the winter season.

similar results are reported in different watersheds in Ethiopia; 20.8% of precipitation, Upper Bilate Catchment, Southern Ethiopia (Dereje and Nedaw, 2019),7.1% of precipitation, Birki Watershed, Eastern Tigray, Northern Ethiopia (Meresa *et al*., 2019), 6% of annual precipitation, Werii watershed of the Tekeze River Basin, Ethiopia

(Gebremeskel and Kebede, 2017), 7.2% of annual precipitation, Geba basin, Northern Ethiopia (Yenehun *et al*., 2017) and 7% of precipitation, Illala Catchment, Northern Ethiopia (Teklebirhan *et al*., 2012b).

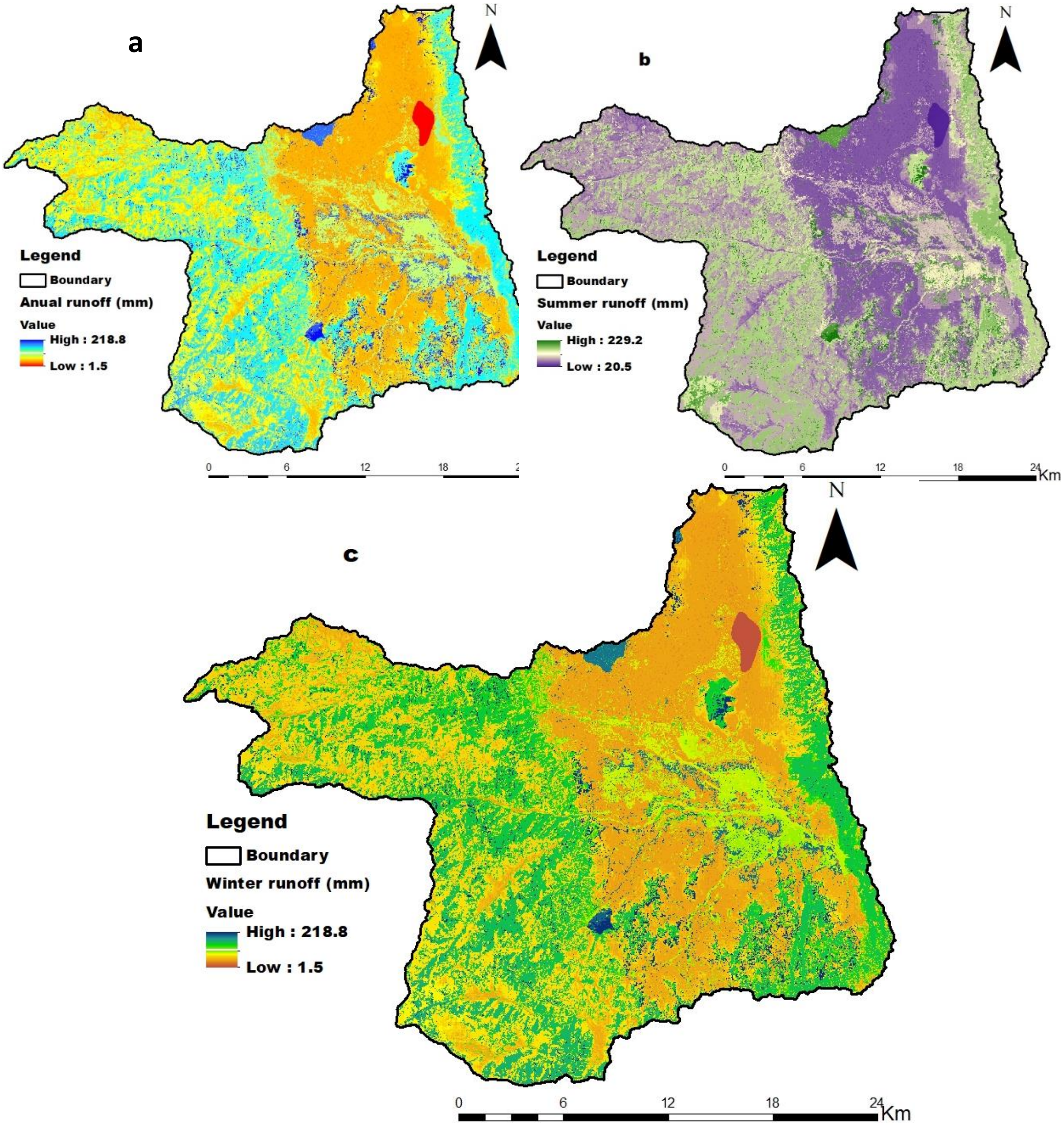


Figure 4-5: Spatial maps of simulated evapotranspiration: annual (a) summer (b) and winter (c).

The highest mean annual surface runoff occurred on silty clay soils with settlement, bare land, and grassland, while the lowest runoff occurred in sandy loam soils with forest and Shrub land (Table 4.3). The standard deviation of the runoff for the different soil types was higher than the standard deviation of the runoff for the different land-use classes and this indicated that surface runoff was more influenced by soil type than by land use. The influence of the precipitation was also noticeable by the fact that areas around Lasta and Zoble highlands, which have higher precipitation, had higher runoff than the valley floors.

Table 4-3: Mean annual surface runoff for different combinations of land use and soil texture

	Settlement	Bare land	Agriculture	Grassland	Wetland	Forest	Shrubs	Mean	Sd. dev.
Silty clay loam	142	130	133	120	136	–	131	132	7
Clay loam	210	205	201	179	220	175	185	196	17
sandy loam	37	20	29	19	13	14	22	22	8
Silty loam	58	38	34	33	30	31	31	36	10
Mean	112	98	99	88	100	73	92		
Std. dev	80	86	83	75	97	88	79		

4.3.Water balance components

Water balance is essentially a representation of the net result of the inflow and outflow of water. Precipitation is the most significant inflow component. The most important outflow components of water balance are surface runoff, evapotranspiration, and groundwater recharge. An area of the world would have a water surplus if it receives more rainfall than the amount that it loses mainly through the process of evapotranspiration. Similarly, regions with water deficits would get fewer spots of rain than the amount that they lost through evapotranspiration. Meanwhile, those who neither get surpluses nor deficits will experience some sort of water balance.

The overall water balance analysis of the Hormat-Golina sub-basin Table 4.4 indicated that only a small fraction of the annual precipitation remains to recharge the groundwater reservoir of the basin. While the rest leaves the basin mainly through evapotranspiration and to a lesser extent via surface runoff. The higher standard deviation value revealed in the water balance component is indicating high spatial variation of the water balance element within the basin. This is mainly in response to the uneven distributions of the climatic parameters associated with variations of Land-use/land cover, soil type, topography, and slope.

Table 4-4: Water balance components of Hormat-Golina sub-basin

Water balance components	Annual values (mm/year)			
	min	max	mean	Standard deviation
Precipitation (PCP)	726.5	1026.3	828.5	66.5
Evapotranspiration (ET)	330.6	824.0	616.7	66.8
Runoff (Ro)	21.9	448.0	156.4	73.3
Recharge (Re)	0.0	196.8	55.4	42.0
Water balance	PCP-ET-Ro-Re=0.0			

5. CONCLUSION AND RECOMMENDATION

5.1. Conclusion

Water is one of the most essential commodities for mankind and the largest available source of fresh water is obtained from groundwater. The Hormat-Golina sub-basin is one of the groundwater-based irrigation areas located in the north wollo zone of the Amhara region. Due to the erratic nature of the rainfall (both time and space) distribution in the area, people often fail to maintain the soil moisture requirement for growing crops. Thus, the need for agricultural development using groundwater resources in the area is growing continuously. However, the ambitious plans for expanding irrigation have not been adequately strengthened through the assessments of groundwater reserves and groundwater recharge estimations. The WetSpass model was used to assess the groundwater recharge of the Hormat-Golina sub-basin. The WetSpass model considers all of the area's meteorological, hydrological, and biophysical aspects. To examine groundwater recharge and other water balance components, researchers looked into the watershed's hydrometeorology, land use, soil texture, terrain, and slope.

The distributed WetSpass model was used to simulate the seasonal and annual water balance components of the Hormat-Golina sub-basin successfully. Changes in the water balance components within the watershed are caused by the extremely diverse distribution of climatic inputs (parameters) coupled with variations in land use/land cover, soil texture, elevation, and slope. The validation of the WetSpass model was performed by using generated flow data using physical similarity regionalization techniques to perform the hydrograph analysis. WetSpass model performance is evaluated by statistical parameters namely; Nash-Sutcliffe efficiency (NSE) and coefficient of determination (R^2). The overall performances of the WetSpass models were good, (R^2=0.90 and NSE = 0.85). From the model simulation result, Hormat-Golina, annual groundwater recharge was 6.0 and 196.8 mm, respectively, with a mean value of 55.4 mm, or 8% of total annual rainfall. The winter season (October to May) accounts for 17 percent of groundwater recharge, while the summer season (June to September) accounts for 83 %. The highest recharge was observed in forest land with sandy soil texture while the lowest recharge was observed in bare land with silt clay loam and clay loam soils. The minimum and maximum values of annual Actual evapotranspiration of the Hormat-Golina sub-basin are 330.6 mm and 824 mm with a mean value of 616.7 mm which accounts for 62% of total rainfall. 62% was found in the wet and the rest 38% occurred in the dry season. The annual runoff from the model was 21.9 to 448 mm with a mean of 156.4 mm which represents 19% of annual precipitation. 53% of runoff occurred in the wet season and the remaining 47% occurred in the dry season. The highest surface runoff was observed in settlements with clay loam and silt clay loam while the lowest surface runoff was observed in sandy loam soil with shrub land use type.

5.2. Recommendation

The following recommendation was made based on the aforementioned conclusion: The groundwater recharge modeling results of this study can be used as a starting point for water resource assessment initiatives in the Hormat-Golina sub-basin.

This research will be used:

- As a starting point for subsequent research, as well as for water resource planning, design, and development;

  - To plan for the availability of water resources in the watershed based on resident’s demand for irrigation water and water supply;
  - To build and improve future groundwater resources based on the water balance results derived from this modeling;
- Additional meteorological stations should be established in the highland because there are only two stations available in the sub-basin.
- To preserve the resource's long-term viability, the balance between groundwater recharge and projected abstraction rates for agriculture and domestic water supply must be considered in future groundwater resource development plans in the valley. It was also crucial to think about the distance between the boreholes.
- The WetSpass model was suitable to study the relationship between recharge and land use land cover change in the basin.

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APPENDIX

Appendix I: Monthly average PET (mm) value of different stations around Hormat-Golina sub-basin

Months	Alamata	Kobo	Korem	Waja	Maichew	Zoble
January	107.3	113.5	93.3	121.8	90.9	111.6
February	113.6	115.7	99.9	130.3	101.1	116.5
March	139.8	144.7	125.1	164.2	119.8	141.3
April	141.5	147.9	127.2	163.7	118.6	146.4
May	154.3	172.6	138.7	178.1	134.4	155.6
June	155.5	173.2	136.8	181.8	126.1	156.0
July	149.5	164.7	126.2	171.3	112.3	153.6
August	144.4	161.7	120.8	158.7	110.2	147.5
September	137.2	151.8	114.5	157.5	115.0	144.0
October	133.1	140.2	107.9	148.5	109.2	138.3
November	112.0	118.9	95.1	126.9	94.1	114.2
December	107.3	123.3	85.4	122.4	88.5	111.6

Appendix II: Monthly average rainfall (mm) value of different stations around Hormat-Golina sub-basin

Months	Alemata	Kobo	Korem	Waja	Maichew	Zoble
January	16.08	11.9	14.2	16.0	22.97	34.1
February	19.14	20.1	6.1	11.9	10.26	18.5
March	63.79	40.1	15.0	33.7	34.19	35.2
April	98.70	77.1	79.5	94.1	60.83	91.7
May	37.39	35.4	59.7	43.9	56.29	58.8
June	12.20	10.0	28.0	15.0	26.48	11.9
July	143.07	109.2	242.6	147.4	152.68	168.3
August	229.09	163.4	294.4	182.2	203.24	201.7
September	37.46	48.0	80.0	48.5	62.70	51.7
October	18.72	20.7	40.8	16.5	50.47	34.3
November	34.15	15.3	45.9	20.0	28.79	36.7
December	20.29	16.1	24.9	18.7	20.08	18.8

Appendix III: Monthly average temperature (ºC) value of different stations around Hormat-Golina sub-basin

Months	Alemata	Kobo	Korem	Waja	Maichew	Zoble
January	19.2	19.81	12.6	19.66	13.65	17.24
February	20.5	20.55	13.8	20.38	15.12	17.62
March	21.6	22.85	15.2	22.28	16.38	18.87
April	22.6	23.80	16.4	23.48	17.49	20.01
May	23.6	24.30	16.9	24.31	18.50	20.57
June	24.6	25.83	17.7	25.84	19.93	21.62
July	23.0	24.56	17.2	25.07	18.50	20.34
August	22.1	22.64	16.9	23.10	17.67	18.98
September	22.5	21.54	16.1	20.74	16.96	18.86
October	22.3	20.37	13.9	19.82	15.14	18.85
November	20.8	19.38	13.1	18.98	14.27	17.48
December	19.7	22.97	12.0	23.06	13.33	16.96

Appendix IV: Monthly average wind speed (m/s) value of different stations around Hormat-Golina sub-basin

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Kobo	1.64	1.83	1.94	2.29	1.74	1.76	1.85	1.65	1.41	1.14	1.13	1.34
Maichew	0.96	1.10	1.16	1.15	1.22	2.02	2.85	2.09	1.08	1.00	0.97	0.95
Chercher	1.32	1.40	1.52	1.45	1.63	1.91	1.98	1.72	1.12	1.30	1.22	1.25

Appendix V: Groundwater level /Elevation/ data

Well Id	X	Y	Z	Static water level	GWD
PHG1	567688	1338578	1487	25	1462
PHG2	567801	1337977	1477	19	1458
PHG3	568356	1337982	1472	17	1455
PHG4	566854	1339244	1510	29	1481
PHG5	571398	1335248	1432	29	1403
PHG6	571821	1334963	1426	29	1397
PHG7	572289	1334951	1419	29	1390
PHG8	570553	1334124	1447	29	1418
PHG9	570089	1333952	1456	29	1427
PHG10	569560	1334010	1462	25	1437
THG1	576123	1336656	1384	16	1368
THG3	575801	1333260	1385	2.7	1382.3
THG4	575471	1331124	1408	5.8	1402.2
Pk2	568476	1341101	1487	24	1463
Pk6	569299	1341890	1481	18	1463
Pk7	569892	1341651	1473	21	1452
Pk8	569814	1341065	1466	19	1447
Pk9	569485	1341610	1476	25	1451
Tk7	569334	1341467	1474	15	1459
HG1	568082	1338941	1480	21	1459
HG2	569450	1338823	1461	15	1446
HG3	569659	1338130	1455	15	1440
HG4	569354	1339493	1465	17	1448
HG5	571782	1333845	1429	20	1409
HG6	567804	1339909	1495	25	1470
HG7	568283	1340339	1487	21	1466
HG8	567346	1340010	1502	27	1475
HG9	569905	1339618	1461	26	1435
HG10	570348	1339366	1455	24	1431
HG11	571055	1335915	1437	14	1423
HG12	572295	1335804	1416	16	1400
HG13	571683	1336365	1424	16	1408
HG14	571067	1336466	1436	17	1419
HG15	574997	1330600	1412	8	1404
HG16	574865	1331232	1412	8.5	1403.5
HG17	574673	1331879	1405	10	1395
HG18	574474	1332360	1399	9.3	1389.7

Appendix VI: Runoff coefficient parameters for vegetated, bare soil, and open water raster cells

LAND USE	LAND USENUM	SLOPE [%]	SLOPE NUM	SOIL TYPE	SOIL NUM	RUNOFF COEF	UNIQUE _ _NUM	BARE ROCOEF	UNIQUE IMP
Crop	1	<0.5	1	silty-loam	4	0.4300	411	0.0000	0.00
Crop	1	0.5-5	2	silty-loam	4	0.4800	412	0.0000	0.00
Crop	1	5-10	3	silty-loam	4	0.5300	413	0.0000	0.00
Crop	1	>10	4	silty-loam	4	0.5800	414	0.0000	0.00
Grass	2	<0.5	1	silty-loam	4	0.2300	421	0.0000	0.00
Grass	2	0.5-5	2	silty-loam	4	0.2800	422	0.0000	0.00
Grass	2	5-10	3	silty-loam	4	0.3300	423	0.0000	0.00
Grass	2	>10	4	silty-loam	4	0.3800	424	0.0000	0.00
Forest	3	<0.5	1	silty-loam	4	0.1300	431	0.0000	0.00
Forest	3	0.5-5	2	silty-loam	4	0.1800	434	0.0000	0.00
Forest	3	5-10	3	silty-loam	4	0.2300	433	0.0000	0.00
Forest	3	>10	4	silty-loam	4	0.2800	434	0.0000	0.00
bare soil	4	<0.5	1	silty-loam	4	0.5300	441	0.0000	0.00
bare soil	4	0.5-5	2	silty-loam	4	0.5800	442	0.0000	0.00
bare soil	4	5-10	3	silty-loam	4	0.6300	443	0.0000	0.00
bare soil	4	>10	4	silty-loam	4	0.6800	444	0.0000	0.00
open water	5	<0.5	1	silty-loam	4	1.0000	451	0.0000	0.00
open water	5	0.5-5	2	silty-loam	4	1.0000	452	0.0000	0.00
open water	5	5-10	3	silty-loam	4	1.0000	453	0.0000	0.00
open water	5	>10	4	silty-loam	4	1.0000	454	0.0000	0.00
Crop	1	<0.5	1	loam	5	0.4000	511		0.00
Crop	1	0.5-5	2	loam	5	0.4500	512		0.00
Crop	1	5-10	3	loam	5	0.5000	513		0.00
Crop	1	>10	4	loam	5	0.5500	514		0.00
Grass	2	<0.5	1	loam	5	0.2000	521		0.00
Grass	2	0.5-5	2	loam	5	0.2500	522		0.00
Grass	2	5-10	3	loam	5	0.3000	523		0.00
Grass	2	>10	4	loam	5	0.3500	524		0.00

Forest	3	<0.5	1	loam	5	0.1000	531		0.00
Forest	3	0.5-5	2	loam	5	0.1500	534		0.00
Forest	3	5-10	3	loam	5	0.2000	533		0.00
Forest	3	>10	4	loam	5	0.2500	534		0.00
bare soil	4	<0.5	1	loam	5	0.5000	541		0.00
bare soil	4	0.5-5	2	loam	5	0.5500	542		0.00
bare soil	4	5-10	3	loam	5	0.6000	543		0.00
bare soil	4	>10	4	loam	5	0.6500	544		0.00
open water	5	<0.5	1	loam	5	1.0000	551		0.00
open water	5	0.5-5	2	loam	5	1.0000	552		0.00
open water	5	5-10	3	loam	5	1.0000	553		0.00
open water	5	>10	4	loam	5	1.0000	554		0.00
Crop	1	<0.5	1	silty clay	8	0.4500	811		0.00
Crop	1	0.5-5	2	silty clay	8	0.5000	812		0.00
Crop	1	5-10	3	silty clay	8	0.5500	813		0.00
Crop	1	>10	4	silty clay	8	0.6000	814		0.00
Grass	2	<0.5	1	silty clay	8	0.2500	821		0.00
Grass	2	0.5-5	2	silty clay	8	0.3000	822		0.00
Grass	2	5-10	3	silty clay	8	0.3500	823		0.00
Grass	2	>10	4	silty clay	8	0.4000	824		0.00
Forest	3	<0.5	1	silty clay	8	0.1500	831		0.00
Forest	3	0.5-5	2	silty clay	8	0.2000	834		0.00
Forest	3	5-10	3	silty clay	8	0.2500	833		0.00
Forest	3	>10	4	silty clay	8	0.3000	834		0.00
bare soil	4	<0.5	1	silty clay	8	0.5500	841		0.00
bare soil	4	0.5-5	2	silty clay	8	0.5800	842		0.00
bare soil	4	5-10	3	silty clay	8	0.6300	843		0.00
bare soil	4	>10	4	silty clay	8	0.6800	844		0.00
open water	5	<0.5	1	silty clay	8	1.0000	851		0.00
open water	5	0.5-5	2	silty clay	8	1.0000	852		0.00

open water	5	5-10	3	silty clay	8	1.0000	853		0.00
open water	5	>10	4	silty clay	8	1.0000	854		0.00
Crop	1	<0.5	1	clay loam	9	0.4800	911		0.00
Crop	1	0.5-5	2	clay loam	9	0.5300	912		0.00
Crop	1	5-10	3	clay loam	9	0.5800	913		0.00
Crop	1	>10	4	clay loam	9	0.6300	914		0.00
Grass	2	<0.5	1	clay loam	9	0.2800	921		0.00
Grass	2	0.5-5	2	clay loam	9	0.3300	922		0.00
Grass	2	5-10	3	clay loam	9	0.3800	923		0.00
Grass	2	>10	4	clay loam	9	0.4300	924		0.00
Forest	3	<0.5	1	clay loam	9	0.1800	931		0.00
Forest	3	0.5-5	2	clay loam	9	0.2300	934		0.00
Forest	3	5-10	3	clay loam	9	0.2800	933		0.00
Forest	3	>10	4	clay loam	9	0.3300	934		0.00
bare soil	4	<0.5	1	clay loam	9	0.5800	941		0.00
bare soil	4	0.5-5	2	clay loam	9	0.6300	942		0.00
bare soil	4	5-10	3	clay loam	9	0.6800	943		0.00
bare soil	4	>10	4	clay loam	9	0.7300	944		0.00
open water	5	<0.5	1	clay loam	9	1.0000	951		0.00
open water	5	0.5-5	2	clay loam	9	1.0000	952		0.00
open water	5	5-10	3	clay loam	9	1.0000	953		0.00
open water	5	>10	4	clay loam	9	1.0000	954		0.00
Crop	1	<0.5	1	sandy clay	10	0.5000	1011		0.00
Crop	1	0.5-5	2	sandy clay	10	0.5500	1012		0.00
Crop	1	5-10	3	sandy clay	10	0.6000	1013		0.00
Crop	1	>10	4	sandy clay	10	0.6500	1014		0.00

Grass	2	<0.5	1	sandy clay	10	0.3000	1021		0.00
Grass	2	0.5-5	2	sandy clay	10	0.3500	1022		0.00
Grass	2	5-10	3	sandy clay	10	0.4000	1023		0.00
Grass	2	>10	4	sandy clay	10	0.4500	1024		0.00
Forest	3	<0.5	1	sandy clay	10	0.2000	1031		0.00
Forest	3	0.5-5	2	sandy clay	10	0.2500	1034		0.00
Forest	3	5-10	3	sandy clay	10	0.3000	1033		0.00
Forest	3	>10	4	sandy clay	10	0.3500	1034		0.00
bare soil	4	<0.5	1	sandy clay	10	0.6000	1041		0.00
bare soil	4	0.5-5	2	sandy clay	10	0.6500	1042		0.00
bare soil	4	5-10	3	sandy clay	10	0.7000	1043		0.00
bare soil	4	>10	4	sandy clay	10	0.7500	1044		0.00
open water	5	0.5-5	2	sandy clay	10	1.0000	1052		0.00
open water	5	5-10	3	sandy clay	10	1.0000	1053		0.00
open water	5	>10	4	sandy clay	10	1.0000	1054		0.00

open water	5	0.5-5	2	sandy clay	10	1.0000	1052		0.00
Crop	1	<0.5	1	Silty clay	11	0.5300	1111		0.00
Crop	1	0.5-5	2	Silty clay	11	0.5800	1112		0.00
Crop	1	5-10	3	Silty clay	11	0.6300	1113		0.00
Crop	1	>10	4	Silty clay	11	0.6800	1114		0.00
Grass	2	<0.5	1	Silty clay	11	0.3300	1121		0.00
Grass	2	0.5-5	2	Silty clay	11	0.3800	1122		0.00
Grass	2	5-10	3	Silty clay	11	0.4300	1123		0.00
Grass	2	>10	4	Silty clay	11	0.4800	1124		0.00
Forest	3	<0.5	1	Silty clay	11	0.2300	1131		0.00
Forest	3	0.5-5	2	Silty clay	11	0.2800	1134		0.00
Forest	3	5-10	3	Silty clay	11	0.3300	1133		0.00
Forest	3	>10	4	Silty clay	11	0.3800	1134		0.00
bare soil	4	<0.5	1	Silty clay	11	0.6300	1141		0.00
bare soil	4	0.5-5	2	Silty clay	11	0.6800	1142		0.00
bare soil	4	5-10	3	Silty clay	11	0.7300	1143		0.00
bare soil	4	>10	4	Silty clay	11	0.7800	1144		0.00
open water	5	<0.5	1	Silty clay	11	1.0000	1151		0.00
open water	5	0.5-5	2	silty clay	11	1.0000	1152		0.00
open water	5	5-10	3	silty clay	11	1.0000	1153		0.00
open water	5	>10	4	silty clay	11	1.0000	1154		0.00