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# Water Balance Components Estimation using WetSpass Model: A Case study of Mekelle Area, Tigray, Ethiopia

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***Authors' contributions***

*This work was carried out in collaboration among all authors. Author KH designed the study, wrote the protocol, analyzed data, interpolated and interpreted the spatial data, and wrote the first draft of the manuscript. Author TG edit the protocol design and reviewed the manuscript. Authors AH and HB reviewed the manuscript. All authors read and approved the final manuscript.*

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## ABSTRACT

This research was aimed at estimating the spatially distributed Water balance components of the catchments in Mekelle area by using WetSpass hydrological model and verifying the model outputs with ground truth. Long term mean metrological data and physical characteristics of the catchments were used as an input to the model. The input data were manipulated using Arc- GIS tools. Results of this model depicted that about 73.13% and 19.96% of the precipitation in the study area was lost through evapotranspiration and surface runoff respectively. However, 7% of it replenished the groundwater. The annual runoff and groundwater recharge estimated in WetSpass model accumulated using Arc-GIS were verified using the annual runoff gauged records and base flow measurements. Accordingly the accumulated runoff and base flow derived from the WetSpass

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model using Arc-GIS software results were quite close to the observed runoff and base flow values measured in the gauging points. Therefore, WetSpass model is appropriate model in estimating water balance components in the study area.

*Keywords: Groundwater; recharge; runoff; evapotranspiration; WetSpass; Mekelle.*

## 1. INTRODUCTION

Water is the most vital and crucial element of human life needed to meet the ever-increasing demand for different purposes accompanied by its sufficient quantity and acceptable quality [1, 2, 3, 4, and 5]. However its availability and distributions are limited both in time and space in which 97.5% of the global water is saline and exists in the oceans and only 2.5% is considered to be fresh water. 68.7% is fresh water which is locked up in glaciers while 30.1% and 0.9% represent groundwater, surface water, and other fresh waters respectively [6]. The groundwater is the largest available source of fresh water sustaining both the human needs and the economic development [7, 8]. However, it should be managed properly as its contamination problem increase in alarming rate due to random urbanization with poor sewage system including wastewater disposal from industries, intensive use of fertilizers in agriculture [9, 8]. Sustainable use of groundwater is largely determined by groundwater recharge [10, 11, and 12]. Hence, knowledge of rates and locations of recharge is important for determining sustainable yields of groundwater systems [13, 14, and 15].

Different methods have been proposed to determine the groundwater recharge [11, 16, 17, and 12]. However, the largest classes of techniques are water-budget methods and models [12,18,19 and 20]. Hence, this study intends to investigate the groundwater recharge, runoff, and evapotranspiration using WetSpass hydrological model and verify the model out puts using ground truth data. The WetSpass is an acronym for Water and Energy Transfer in Soil, Plants, and Atmosphere under quasi Steady State. WetSpass model is a numerical model to simulate long-term average spatial distributions of hydrological parameters and processes on basin scale [21, 22] and results in partitions of the precipitation in to the surface runoff, evapotranspiration, and groundwater recharge.

Nowadays application of spatially distributed water balance models for assessing surface water and groundwater resources were common in the world. This model was also applied in our region by [23]. Groundwater Recharge, Evapotranspiration, and Surface Runoff Estimation Using WetSpass Modele were made in Illala Catchment by [24]. As groundwater recharge, the flux of water across the water table is arguably the most difficult component of the hydrologic cycle to measure [25] and need to be properly quantified using modern and reliable scientific techniques such as WetSpass model. Therefore, focus is given to the recent WetSpass model studies made in the study area. The study made by [24] covers only the Illala catchment and the study made by [23] is a large regional scale study covering the whole Geba basin. Hence in this study WetSpass hydrological model was applied to determine appropriate estimate of the water balance components in the catchments within 30 km radius of Mekelle city and determine the reasons for the controversies in the WetSpass outputs of the previous studies.

## 2. MATERIALS AND METHODS

### 2.1 Study Area Description

The study area is part of the Geba catchment and belongs to the Tekeze drainage system. It includes catchments within 30 km radius of Mekelle city, and covers an area of about 1,038 $km^2$. Geographically, the area is found between1465136 to 1512585 N and 531219 to 578803 E UTM with an altitude varies from 1,576 to 2,762 m a.s.l and has a slope range of 0° – 76° (Fig. 1).

A semi-arid climate characterizes the region with a mean annual precipitation ranging from 391 to 646 mm/year and the rainy season is confined to a short season called ‘kiremt‘, which extends from June to September. The rest of the Year (8 months) is generally dry with occasional light precipitation in some parts. The air temperature ranges from an average daily minimum of 13.97 ºC to an average daily maximum of 18.47 ºC.

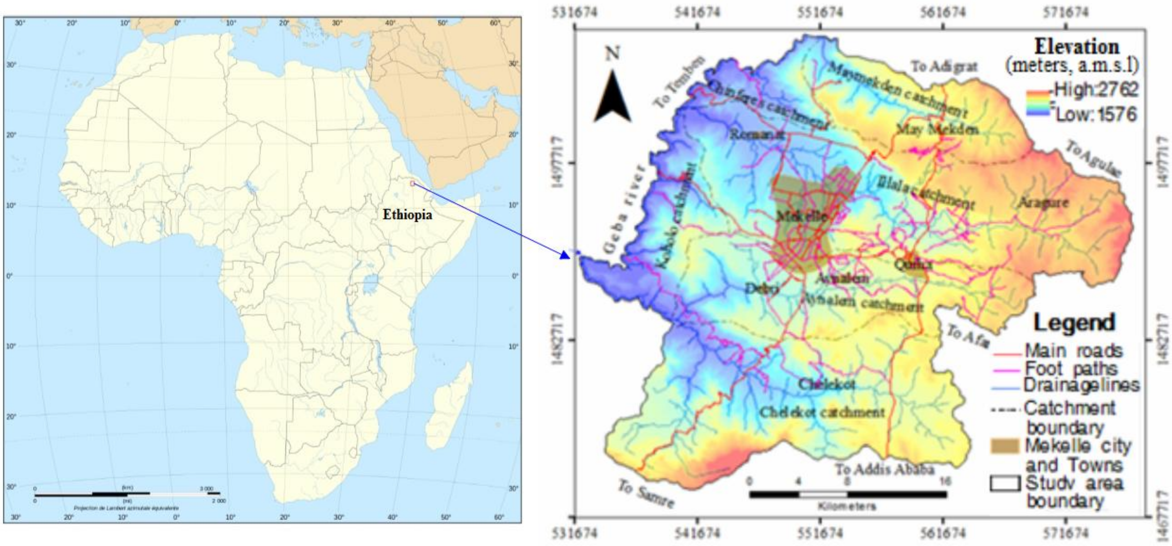


**Fig. 1. Location map of the study area.**
*(a.m.s.l. stands for above mean sea level)*

## 2.2 WetSpass Modeling and Input Data Preparation

All input grid maps for the WetSpass model are prepared by using ArcView GIS 3.2 and its spatial extensions and the potential evapotranspiration (PET) was estimated by using Modified Penman - Monthith method in the $ET_0$ calculator software version 3.2 [26] and regression equations derived from the relationship between elevation and the metrological parameters, an approach developed by [27]. The runoff and recharge components in the WetSpass model by the flow accumulation techniques in Arc GIS 10 software were verified with the observed runoff and base flow measurements on the gauging points. The runoff verification process was made in view of the impacts of the gross capacity of upstream micro dams as well as the discharge estimates of the upstream springs and wells within the study area.

The required inputs for WetSpass model such as grid maps and parameter tables were prepared with the help of ArcGIs and Arcview softwares. The boundary delineation in this study was done by using the Digital Elevation Model (DEM) of the Northern part of Ethiopia. The digital elevation model was downloaded from Advanced Land Observing Satellite (ALOS) Phased Array type L-band Synthetic Aperture Radar (PALSAR) with 12.5m spatial resolution and has been patched for missing data using 3DEM software. Generally the data for topography and geological structures were extracted from the DEM using ENVI 4.5 software and were exported in shape files to the ArcGIS v10 software.

On the other hand the mean potential evapotranspiration (PET) was calculated using $ET_0$ calculator software version 3.2 [26]. Reliability of the PET was testified with altitude correlation approach developed by [27].

The runoff verification was done by subtracting the observed runoff from the total accumulated simulated annual flows (Runoff plus Base flow) at the gauging points (Table 1). The gross capacities of the upstream micro dams and measured discharge values of the upstream wells are considered as extracted water before reaching the gauging stations. A water extraction by the upstream springs (Table 1) is assumed to be negligible and the majority of whatever is available joins the river flow and is accounted for in the gauging stations. Hence, comparisons between the observed discharge volumes (the run off, micro dams and wells) and the simulated annual flows (surface run off and base flow) have been made to visualize the deviations and verify the simulated annual runoff.

Assuming that groundwater flow paths are also following topography and river base flow can be determined by accumulating the groundwater recharge along topography, similar to what was done for surface runoff. The accumulated winter groundwater recharge was compared with the average of the base flow measurements.

**Table 1. Mean annual river flow at gauging stations, with corresponding number of recording years, summarized from [23] and base flow measurements taken on January 2017**

| **Runoff gauging records** | | | | | |
|---|---|---|---|---|---|
| **Gauging stations** | **UTM location (m)** | | | **Mean runoff flow (million m3/year)** | **Recording period (years)** |
| | **Easting** | **Northing** | **Elevation** | | |
| Illala (Mekelle) | 554628 | 1495279 | 2008 | 21 | 18 (1980 to 2002) |
| Metere (Aynalem) | 553310 | 1487163 | 2181 | 5.80 | 7 (1985 to 2001) |
| Dello (Upper Illala) | 560464 | 1492327 | 2155 | 5.98 | 10 (1976 to 1995) |
| **Base flow measurements** | | | | | |
| **Base flow measurement points** | **UTM location (m)** | | | **Mean measured annual base flow (million m$^3$/year)** | **Measurement time** |
| | **Easting** | **Northing** | **Elevation** | | |
| Illala WS Bridge | 551987 | 1495992 | 1975 | 0.18 | January, 2017 |
| Dello Bridge | 559475 | 1492182 | 2123 | 0.20 | January, 2017 |
| Aynalem kalamino Bridge | 549963 | 1486652 | 2113 | 0.19 | January, 2017 |
| Gabat Bridge | 545240 | 1479985 | 1900 | 1.00 | January, 2017 |
| Maymekden Bridge | 561420 | 1501680 | 2194 | 0.42 | January, 2017 |
| Koholo outlet | 538755 | 1496286 | 1702 | 0.34 | January, 2017 |

## 3. RESULTS AND DISCUSSION

### 3.1 WetSpass Model Results

The WetSpass model result includes several annual and seasonal hydrologic outputs. However, only the annual groundwater recharge, surface runoff, and actual evapotranspiration are important for the water balance analysis of the present study. These results are provided in the form of grid maps of 12.5 m resolution. Highest groundwater recharge values in the area were correlated with the intense geological structures, while the opposite is true for the actual evapotranspiration and surface runoff (see Figs. 2, 3 and 4). In general high values of groundwater recharge were observed in the cultivated land with sandy clay loam and clay loam soils. This could be due to good permeability of these soils. However, all types of soils with the residence and bare land-use areas resulted in low amounts of groundwater recharge. This might be due to the higher amounts of transpiration through the plant and grass leaf stomata respectively. Inline to this, the largest amount of evapotranspiration simulated for the study area, relative to the groundwater recharge and the surface runoff, indicated that much effort is needed to change the environmental conditions of the catchment by applying soil and water conservation practices.

#### 3.1.1 Evapotranspiration

Based on WetSpass model results, the annual actual minimum and maximum evapotranspiration values of the catchment were 259.45 mm and 1729.38 mm respectively. The mean and standard deviation of this distribution are 414.61 mm and 90.48 mm respectively. The average evapotranspiration became the largest portion of the mean annual rainfall which showed that evapotranspiration was the main processes by which water is lost in the study area. This might be attributed to the high rates of radiation and the persistence of strong dry Easterly winds coming from the Northern Afar depression. The evapotranspiration is largely determined by the solar radiation, which is fairly constant between years. As a result evapotranspiration varies little from year to year, especially in the dry season. However, the largest standard deviation in the actual evapotranspiration can probably be due to the very diverse nature of agricultural lands based on soil texture and slope.

The simulated evapotranspiration grid map is mainly a function of vegetation type and soil texture and showed that the areas covered with agriculture and forest in a clay loam soil texture were experienced high evapotranspiration while those with land cover of shrubs and grass lands in a sandy clay loam soil texture were low (experiencing high infiltration rate). The residence and bare land fall on to the medium evapotranspiration indicating that they have high evaporation rate.

### 3.1.2 Surface runoff

The WetSpass model uses the runoff coefficient method for the estimation of surface runoff. The surface runoff coefficient on the other hand is a function of vegetation type, soil texture, and slope. The simulated run off grid map showed that the surface runoff in Mekelle area vary spatially with topography, vegetation type, soil texture, and slope. Clay soil dominated agricultural lands gave the largest amount of runoff. This is due to the lesser infiltration capacity of clay soil. The simulated runoff varies from 0 mm to 265.48 mm with a mean and standard deviation of 113.17 mm and 29.64 mm respectively.

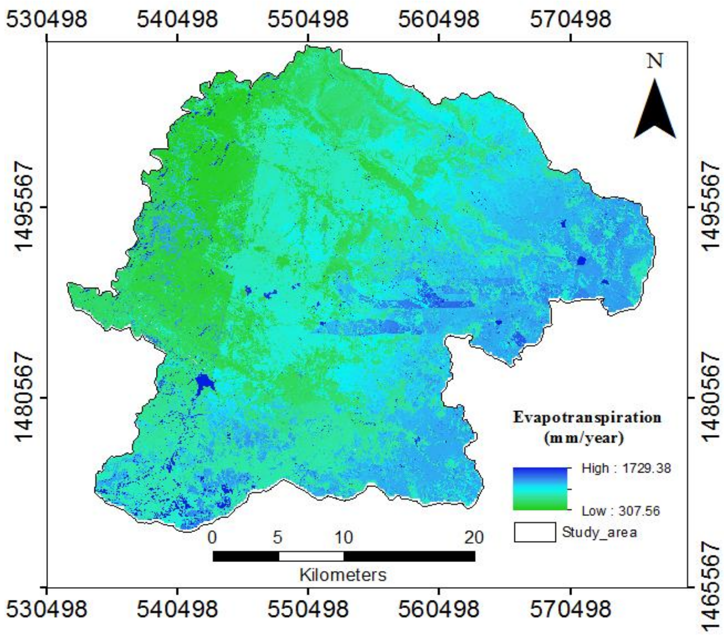


**Fig. 2. Annual actual evapotranspiration grid map of the study area**

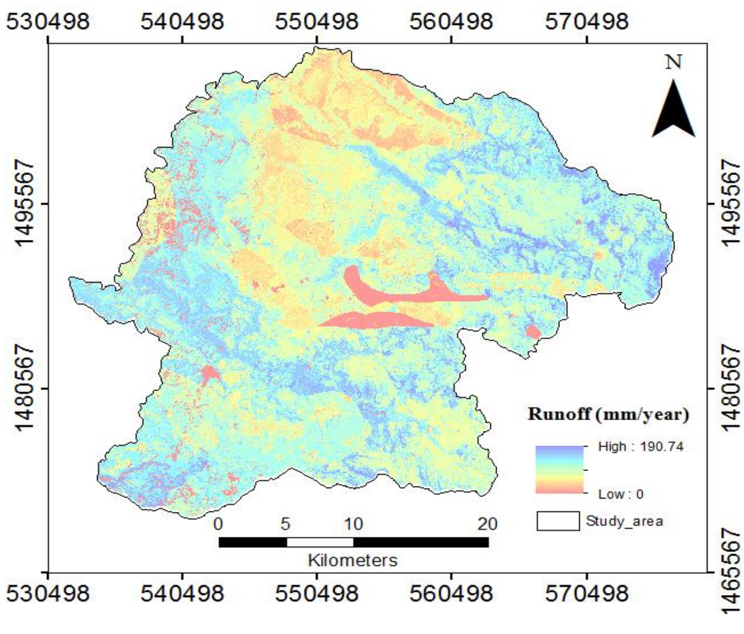


**Fig. 3. Annual surface runoff grid map of Mekelle area**

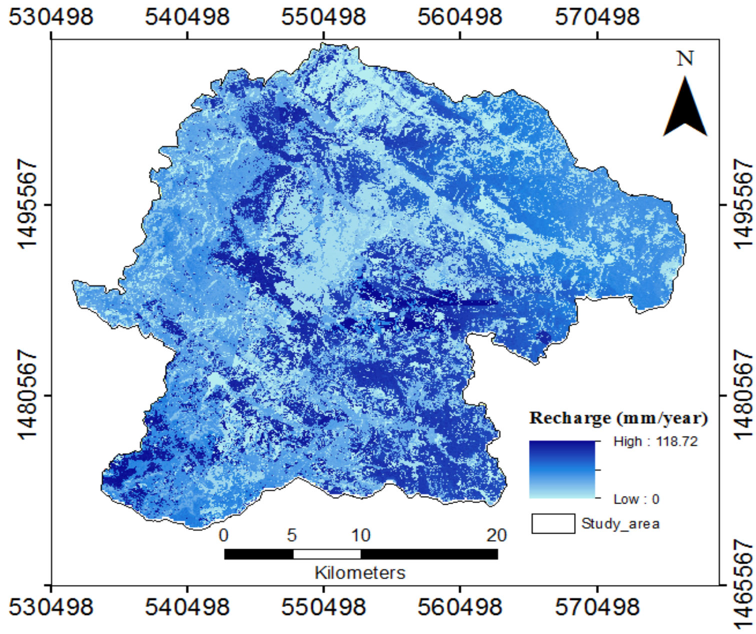


**Fig. 4. Annual groundwater recharge grid map of Mekelle area**

### 3.1.3 Groundwater recharge

According to the WetSpass model (grid map) the groundwater recharge for the catchment ranges from about 0 mm to 118.72 mm, with an average value of 39.68 mm and standard deviation of 29.22 mm.

## 3.2 Water Balance Results Analysis

The overall summery of water balance components of the study area based on WetSpass model is shown in Table 2. Based on this result, about 7% and 19.96% of the mean annual precipitation changed to groundwater recharge and surface runoff respectively, while the rest and the major part, 73.13%, and was lost as evapotranspiration The Annual groundwater recharge in this study (7% of the annual precipitation) is comparable with the 6% WetSpass recharge estimate of [23]. Hence, the WetSpass model in this study provided appropriate annual Evapotranspiration, surface run off and groundwater recharge outputs for the study area.

## 3.3 WetSpass Result Verification

Verification of the WetSpass model outputs was made against discharge measurements at six points in the study area by accumulating surface runoff and groundwater recharge. The respective accumulated flow values are zoomed out and read using the identify tab. The accumulated annual river flow and the accumulated annual and winter groundwater recharge grid maps in the study area are shown in Figs. 5, 6 and 7 respectively.

Comparison of simulated versus measured flows at the gauging stations should be made considering the impact of the surface water and groundwater abstraction structures. Accordingly, the runoff and groundwater recharge verification processes are made in view of the impacts of the gross capacity of upstream micro dams as well as the discharge estimates of the upstream springs and wells.

Six years annual groundwater discharge estimates from Aynalem and Illala catchments were made for this purpose on the wells owned by Mekelle Water Supply Office. The average groundwater abstraction of the wells in the area is 22 working hours per day. Numerous wells owned by private companies in the area were not included due to lack of data on daily pumping hours.

This comparison indicated that the respective deviations are feasible as compared with the gross capacities and catchment water potentials of the micro dams. However, the negative deviation (Observed minus simulated annual flows) in Metere gauging station probably indicates that either the water extracted by the wells includes seepage from the micro dams or due to additional recharge sources from adjacent catchments (Table 3).

The base flow measurements and the accumulated results of the simulated groundwater recharge are presented in Table 4. The comparison between the simulated and measured base flow values in the dry period showed slightly higher discrepancies in Illala Water supply Bridge (WS Bridge) and small discrepancies in Dello and May Mekden Bridges. The higheest simulated values in all the gauging points except Koholo outlet might bedue to the presence of a large number of upstream micro dams. The highest percentage deviations in Illala WS Bridge justified the abstraction of water by the micro dams upstream of the gauging stations (Table 4).

The reason for the relatively small discrepancies between simulated and measured base flow values in Dello Bridge and May Mekden Bridge (upstream sections of their respective catchments) could be due to drain of water from the upstream micro dams in Dello Bridge and implying the existence of undefined upstream groundwater recharge sources in May Mekden Bridge.

However, the measured values are slightly exceeded the simulated values in Koholo outlet, possibly due to the additional spring water seepages joining the base flow system further downstream. Over all the runoff and base flow verification results indicate that the WetSpass model results (Accumulated runoff and base flow) are quite close to the measured runoff and base flow discharge values. Hence, it is verified that the WetSpass model results are in reliable estimates of the water balance components.

**Table 2. Annual water balance of the Mekelle area (mm) based on the WetSpass results**

| | Min. | Max. | Mean | Std.dev |
|---|---|---|---|---|
| **Precipitation, P** | 391.00 | 646.00 | 566.97 | 63.11 |
| **Evapotranspiration, ET** | 259.45 | 1729.38 | 414.61 | 90.48 |
| **Surface runoff, Ro** | 0 | 265.48 | 113.17 | 29.64 |
| **Groundwater recharge, Re** | 0 | 118.72 | 39.68 | 29.22 |

*Water balance = P – ETP – Ro – Re = - 0.49*

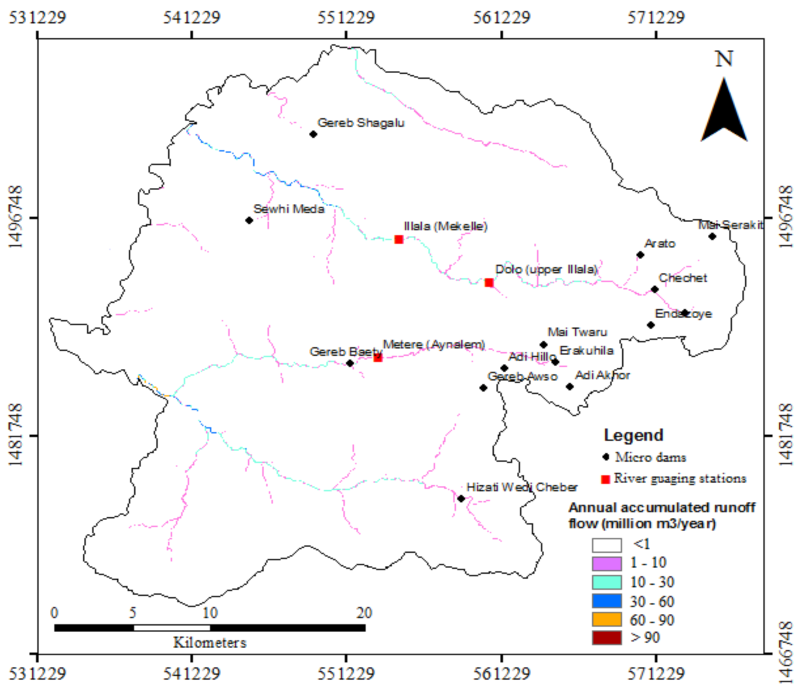


**Fig. 5. Accumulated annual flow (Surface runoff plus groundwater recharge) grid maps of the study area**

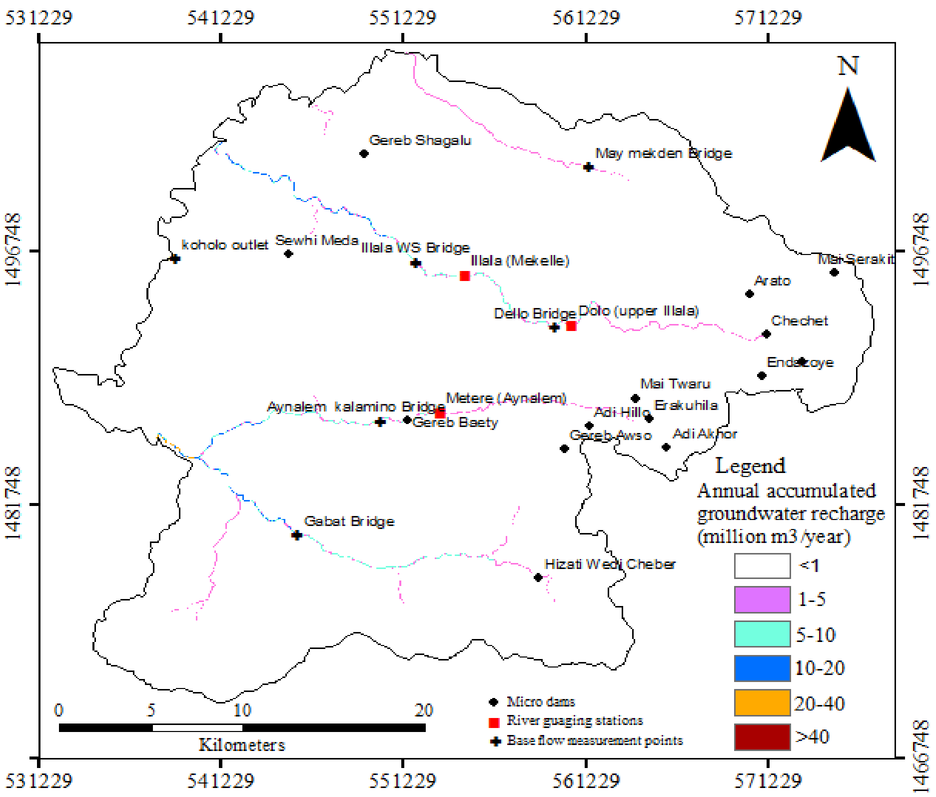


**Fig. 6. Accumulated annual groundwater recharge grid maps in the study area**

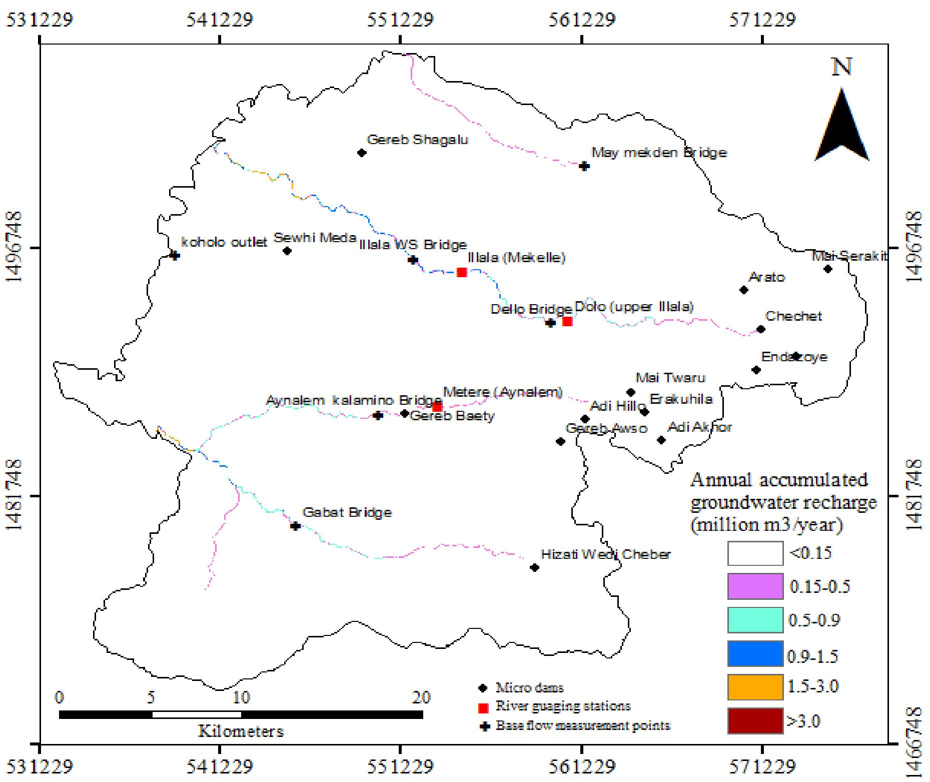


**Fig. 7. Accumulated winter groundwater recharge grid maps in the study area**

**Table 3. Comparison of simulated and measured runoff flow, base flow and estimated groundwater abstractions upstream of the gauging points in million $m^3$/ year**

| River gauging stations (period of measurement ) | Annual observed surface and groundwater abstractions | | | Micro dams ($Mm^3$) | | Annual simulated flows | | | Deviation (Simulated flow minus Measured flow) |
|---|---|---|---|---|---|---|---|---|---|
| | Measured surface runoff | Average groundwater abstraction | Average spring discharge | Gross capacity | Catchment water potential | Surface runoff | Base flow | Total flow | |
| Dello (1976 to 1995) | 5.98 | 0.64 | 0.13 | 6.54 | 4.82 | 9.46 | 0.13 | 9.59 | 2.97 |
| Illala (1980 to 2002) | 21 | 0.79 | 0.13 | 6.54 | 7.13 | 25.68 | 0.99 | 26.67 | 4.88 |
| Metere (1985 to 2001) | 5.80 | 5.27 | 0.39 | 2.06 | 6.02 | 9.06 | 0.34 | 9.40 | -1.67 |

**Table 4. Comparison of simulated and measured base flows in $m^3$/second**

| Base flow measurement points | Measured winter base flow ($m^3$/s) | Simulated winter base flow (***accumulated winter groundwater recharge***) ($m^3$/s) | Deviation (Simulated flow minus Measured flow in %) |
|---|---|---|---|
| Dello Bridge | 0.0057 | 0.010 | 0.004 |
| Illala WS Bridge | 0.0047 | 0.073 | 0.068 |
| Aynalem kalamino Bridge | 0.0052 | 0.030 | 0.025 |
| Gabat Birdge | 0.026 | 0.050 | 0.024 |
| May Mekden Bridge | 0.0116 | 0.014 | 0.002 |
| Koholo outlet | 0.0128 | 0.002 | -0.011 |

## 4. CONCLUSION

Investigation of the water balance components using WetSpass model and the verification technique in this study was successful in providing reliable estimates of the water balance components. Water balance analysis based on the WetSpass model showed that only about 7 % and 19.96 % of the mean annual precipitation was effective in producing groundwater recharge and surface runoff, respectively. While the rest and the major part (73.13 %) was lost as evapotranspiration. This showed that Evapotranspiration is the main process of water loss as a result of the prevailing high rate of radiation and persistence of strong dry wind in the area. The annual groundwater recharge simulated with this model was comparable with the ground truth base flow measurements and hence it can be concluded that WetSpass model is a suitable model to simulate groundwater recharge of the Mekelle area. The present study also showed that the WetSpass model outputs are very sensitive to the input grids and parameter tables where their miss use could be reasons for the controversies on the runoff and groundwater recharge estimations manifested in some of the previous studies. Ground truth verified land use land cover grids, respective groundwater level inputs for both the winter and summer seasons and precipitation data from numerous metrological stations are some of the sensitive input parameters identified in this study. Moreover, this study helps to visualize the significant impacts of the surface water and groundwater extraction structures (micro dams and wells) on the volume of the runoff and base flow components in the study area. Though, contributions of these structures were previously considered to be negligible in the verification analysis of the WetSpass model results, this study indicated that these structures had significant contributions in addressing the deviations between the simulated and observed annual flows (Surface runoff and base flow) in the gauging points.

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## COMPETING INTERESTS

Authors have declared that no competing interests exist.

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