Estimation of Water Balance Components Using J2000 Model in a Semi-Arid Region, The Case of Upper Illala Catchment, Tigray

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Abstract
Upper Illala catchment, located northeast of Mekelle city, is one of the most water-stressed areas in Tigray region, with a short rainy period from mid-June to mid-September. The main objective of this research was to estimate the spatially distributed groundwater recharge, surface runoff and evapotranspiration, using J2000 hydrological model. Long term temporal metrological data series, runoff discharge gauging data, land use/cover and soil depth profiles in the study area were the inputs for the model. These input data were prepared in the form of digital maps using remote sensing images, GIS tools, and the PSpad text editor. Results of the J2000 model, for the upper Illala Bridge runoff gauging station appeared to be correct in its periodicity and its magnitude. However the simulated and observed hydrographs revealed model errors and uncertainties due to parameter; data and model structure uncertainties. Accordingly, about 70.28% of the precipitation in the study area is lost through evapotranspiration (58.64%) and canopy interception (11.63%), about 14.92% is surface runoff, 8.0% is groundwater recharge and 5.7% is soil moisture. These outputs were obtained after the model was validated through KGE_{mod} approach. In addition, these outputs were verified using other independent approaches— namely the WetSpass hydrological model and geochemical methods. Eventually, the J2000 model has produced reasonably acceptable results with a better fit KGE values and quite similar results with the outputs of the independent approaches.
Keywords: Water balance, J2000 hydrological model, Mekelle
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1. Introduction

In arid and semi-arid environments, the amount of recharge received by aquifers is far more critical to the sustainable use of water than it is in humid regions. Despite this fact, little remains known about the quantities of water that are required to sustainably recharge aquifers in such regions. Due to low rainfall and high evaporation, the recharge rate estimations in semi-arid regions like the Illala catchment involve a large degree of uncertainties. Groundwater recharge, the flux of water across the water table is arguably the most difficult component of the hydrologic cycle to measure (Hogan et al. 2004) and is quantified using modern and reliable scientific techniques appropriate to the research areas.

In the study area, the rate of increment in water demand and the capacity of the well fields to satisfy the need are not congruent. It has been reported that there is a continuous decline in groundwater levels and drying-up of production wells due to over pumping and recurrent droughts in many parts of the study area (WWDSE/Federal Water Works Design and Supervision Enterprise 2007 and Teklay 2007). For the sustainable management of groundwater resources, the amount of recharge is by far the most important figure required and usually it is the least well-known quantity in hydrogeology, especially in arid and semi-arid environments. Many methods have been proposed to determine the groundwater recharge as described for instance by (Lerner et al. 1990; Simmers 1997; Kinzelbach et al. 2002 and Healy 2010). While the largest class of techniques is water-budget methods and models (Healy 2010). The annual groundwater recharge for the study area and its vicinity has been estimated by different researchers (Abdelwassie 2000; Samuel 2003; Gebrerufael 2008 and Tesfamichael 2009) using different techniques (Water balance method, Chloride mass balance method and WetSpass model). However, the water balance method is conventional and the WetSpass model has limitations to incorporate the soil depth profiles, type of geological formations, Recession constants of different geological formations and surface water harvesting structures such as micro dams. Hence, estimation of the water balance components using techniques that incorporate these limitations is crucial for sustainable utilization of the groundwater resource as well as its protection against depletion. Therefore, the J2000 hydrological model is used in this study to simulate the vertical and lateral water transport processes and to quantify the water balance components in general; and the spatial and temporal variability of the groundwater recharge in particular.

1.1. Study Area description

The study area, Upper Illala catchment is found in the northeastern part of the Ethiopian central plateau northeast of Mekelle City. It is part of the Geba catchment and belongs to the Tekeze drainage system and covers an area of about 199.49 km^2. Geographically, it is bounded by latitudes 1486662 to 1500190 North and longitudes 553538 to 577612 East UTM (Figure 1). The roads Quiha - Aragure and Quiha – May Mekden cross in the northeast and south to east directions (Figure 1). Small gravel roads which connect villages and quarries branch from the main roads and improve accessibility.

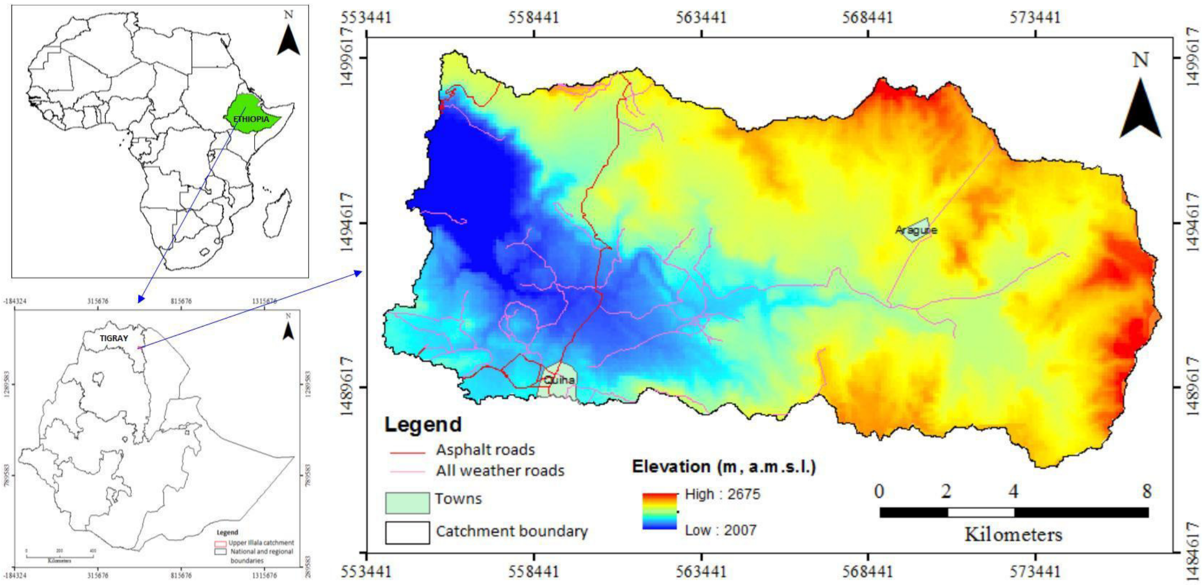

Figure 1.Location map of the study area. (a.m.s.l stands for above mean sea level).

The topography of the study area is highly controlled by erosional features and geological structures. The altitude of the area varies from 2,007 m a.s.l in the western part to 2,675 m a.s.l in the eastern part. The area is characterized by chain of dolerite ridges, which has intruded as sills and dykes. The slope ranges 0° – 41°. It is drained by Illala river that flow towards the west. Most of the seasonal tributaries that feed the main stream both from north and south which have substantial runoff during the rainy season (Figure 2). A semi-arid climate characterizes the region with a mean annual precipitation ranging from 434 to 822 mm/year and the rainy season is confined to a short season, 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. The Land-use/land cover of the study area is categorized in to seven classes which include: cultivated agricultural land with scattered trees, shrub land, bare land, grass land, water body, settlement of rural community and urban areas and forest. Four soil textural classes have been identified in the area, which are Sandy clay loam, Silty loam, Clay loam and Silty clay loam.

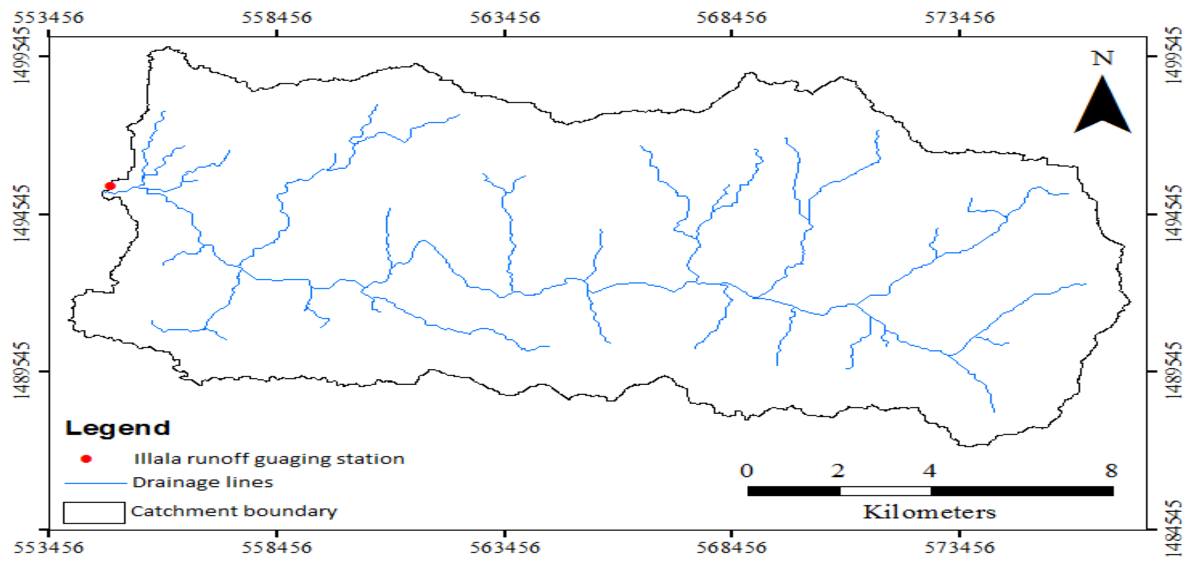

Figure 2.Drainage lines and the runoff gauging station

Geologic setting of the area chronologically consists of the Doleritic rocks, Agulae Shale Formation, Antalo Limestone and their intercalations. The alluvial sediments are exposed in the river banks of the Illala River and are composed of fluvial sediments ranging from well-sorted, well-rounded pebbles and boulders, to poorly sorted mixtures of clay, silt, sand, and pebbles. The intensity of major and minor fractures varies from one lithology to another and that may be due to the geological properties of the various units. Strong fracturing is observed in the Antalo limestone whereas in the Mekelle dolerite, the intensity of fracturing is very low as compared to the other adjacent units. Local hydrogeological studies in the vicinity of the study area indicate that the main aquifers in the area are the limestone unit and weathered and fractured dolerite (Abdelwassie 2000 and Samuel 2003). The limestone is commonly outcropped with inter-beds of shale-marl intercalation with rare thin gypsum layers recorded in the borehole logs. The highly jointed parts of the limestone bed favor groundwater storage and movement. Figure 3 shows geological structures and the geological formations comprising the study area where Limestone-marl represents for the intercalation of limestone layer with marl and Marly-limestone for the intercalation of marl with marly limestone.

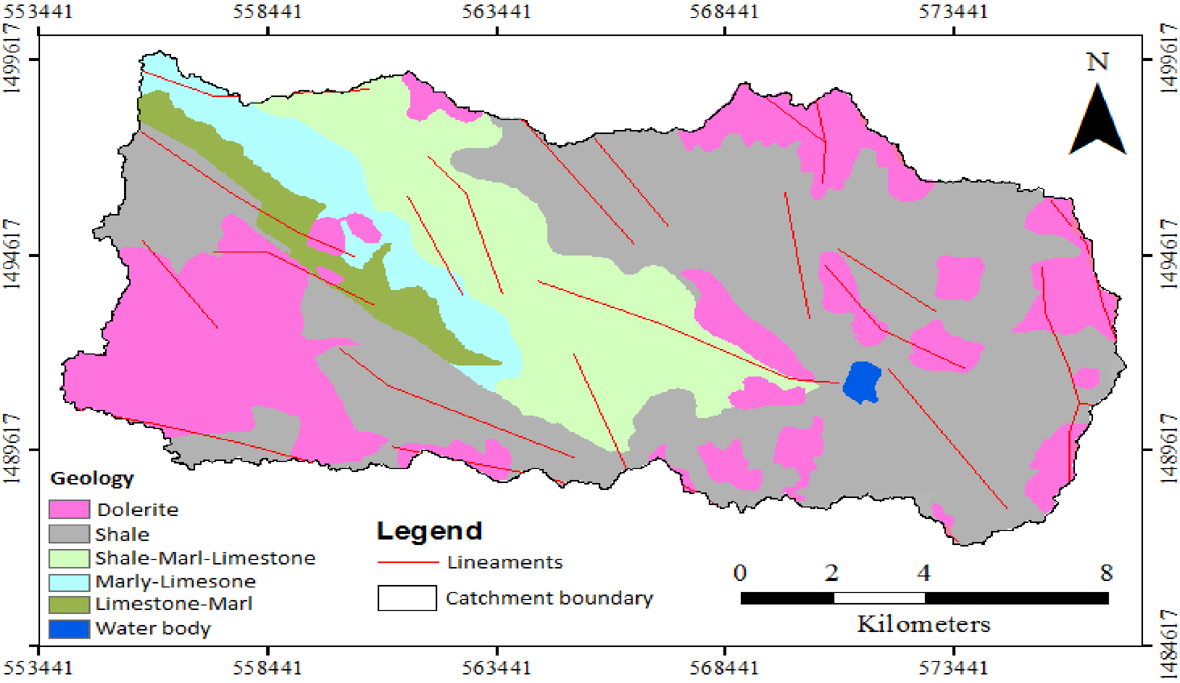

Figure 3.Geology and geological structures (Extracted from Tesfamichael 2009).

2. Methodology

2.1. JAMS/J2000 Modeling

The J2000 model is a distributed and process oriented hydrological model for hydrological simulations of meso- and macro-scale catchments. It is implemented in the Jena Adaptable Modelling system (JAMS), a software framework for component-based development and application of environmental models (Kralisch and Krause 2006; Kralisch et.al. 2007). The simulation of different hydrological processes is carried out in encapsulated process modules which are to a great extent independent of each other. This allows changing, substituting or adding single modules or processes without having to restructure the model once again from the start.

The modelling application represents important hydrological processes of a river catchment. The principal layout of the J2000 hydrological model is provided in Figure 4. The modelling system differentiates among four different runoff components according to their specific origin. The component with the highest temporal dynamics is the fast direct runoff (RD1) (overland flow). It consists of the runoff of sealed areas and surface runoff originating due to saturated access and infiltration access runoff. The slow direct runoff component (RD2) (also known as Interflow 1), which corresponds to the lateral hypodermic runoff within soil zone, reacts slightly more slow. This process reacts slightly more slowly than RD1. Two further baseflow runoff components can be distinguished. The relatively 'fast baseflow runoff (RG1) (also known as Interflow 2) simulates the runoff from the upper part of an aquifer, which is more permeable due to weathering, compared to the lower zone of the aquifer. The slow baseflow runoff component (RG2), which can be seen as a flow within fractures of solid rocks or matrix in homogeneous unconsolidated aquifers. The detailed description of the modelling systems is provided in many publications. Some of the important publications are: (Krause 2001; Krause 2002; Krause 2010; Nepal 2012; Kralisch and Krause 2006; Kralisch et.al. 2007). A list of publications can be also accessed from the link: http://jams.uni-jena.de/documentation.

Hence, in this study, it was possible to setup J2000 for specific requirements, implementing modules for interception (reducing precipitation via interception by the canopy), soil water (describing infiltration, evapotranspiration and storage of water in the soil matrix) and groundwater (describing storage and runoff characteristics of the groundwater reservoir) stated by (Krause 2001). Runoff modelling for each time step and each model unit (the hydrological response unit— HRU) results from the interaction of these modules (Figure 4). According to the lateral routing, the runoff components (surface runoff, interflow and baseflow) are transferred within a flow cascade into the corresponding storages of the next HRU or river segment (Krause 2001).

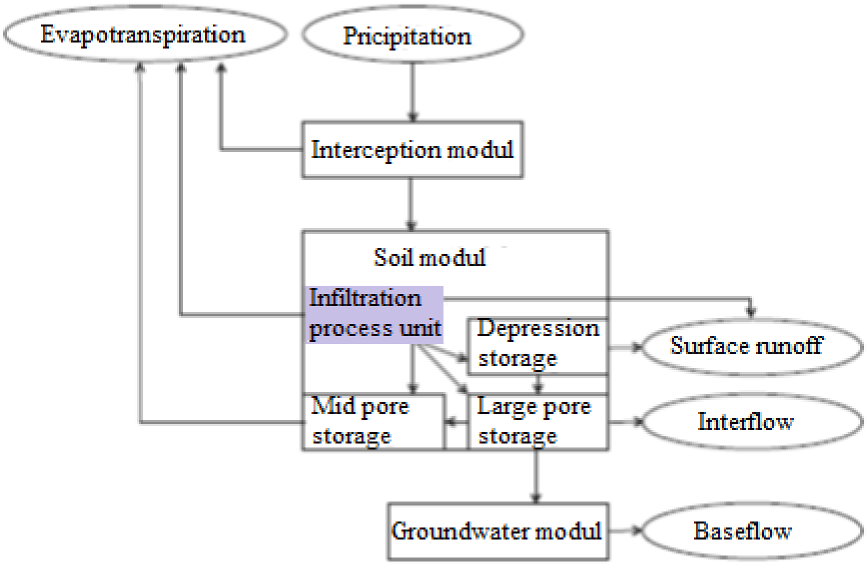

Figure 4.Schematic diagram of the J2000 model concept for the runoff generation of each HRU (after Krause 2001)

2.2. JAMS/J2000 Modeling Process

The J2000 model assumes that a fraction of the total precipitation is intercepted (Interception) as precipitation (effective rainfall) reaches the soil. A significant part goes through surface runoff (RD1) and the rest infiltrates. Here also some of the infiltrated rainfall is either consumed by vegetation and transpired or directly evaporated from the soil surface (ET) and returns to the atmosphere. When the infiltrated water exceeds the middle pore storage (MPS) and large pore storage (LPS) capacity of the soil, the remaining flow can either percolate or recharge aquifers (Groundwater) or drain as interflow (RD2) or fast groundwater flow (RG1) and baseflow (RG2) that reach the closest rivers or surface water bodies and contributes to the total runoff. Figure 4, illustrates the different pathways of water movement simulated by J2000. To reflect the hydrological differences across a catchment, J2000 computes all water balance components for each HRU based on the HRU parameter file generated after the model entities delineation process in GRASS-HRU which is a GIS based program working under Quantum GIS (QGIS).

The J2000 model is composed of four modules, namely interception, soil-water, groundwater and routing.

INTERCEPTION

$$Int_{max}\,(mm) = \alpha.LAI \qquad (1)$$

In J2000 model, the amount of rainfall intercepted by a vegetation cover is generated using Equation (1). Intmax is the maximum interception capacity of each HUR; α is the interception coefficient of the leaf area index (LAI) for the vegetation type in each HRU. Leaf area index (LAI) of individual vegetation type is provided in the land-use parameter file throughout the year. Because LAI changes according to seasons, four different LAI types, based on the phenology period of each vegetation type, are proposed in land-use parameter file. In this study, LAI values for the study area were taken from literatures (Fang et al. 2013; Jarlan et al. 2008; Jin and Zhang 2002) previously done in similar semi-arid regions. Since the J2000 hydrological model allows to use available land-use and land-cover parameters including the LAI ranges derived from literatures of similar regions. Alternatively, such information can be estimated by using remote sensing images and subsequent classification, though such data was not available in the study area. The model also requires major classification of land-use and land-cover which affects the hydrological dynamics (Nepal 2012) and http://ilms.unijena.de/J2000.

2.2.1. SOIL WATER

Soil water is the principal module in the J2000 modelling system. It indicates the essential position of soil, acting as a regulation and distribution system, influencing nearly all processes of the hydrological cycle (Krause 2002). Effective rainfall constitutes the inputs for soil water module. In J2000 model, an empirical approach is used to calculate infiltration by taking into account the actual soil moisture. If infiltration rate is less than the rainfall rate, water is stored as depression storage (DPS) at the soil surface; the excess is treated as surface runoff (RD1) and routed to the next HRU. The soil zone of each HRU is considered as two storage areas according to the specific soil pore volumes. Thus, infiltrated water is distributed between MPS and LPS according to the actual MPS' water saturation. The first one represents the pores with a diameter of 0.2–50 mm where water is held against gravity but can be consumed through plant transpiration. When water reaches the MPS capacity, it is considered as soil field capacity. LPS represents the macro pores (>50 mm), which cannot hold water against gravity. Equations 2 and 3 are used to compute the amount of water entering the middle pores and large pores.

$$MPS_{in}(mm) = Inf_{act} \cdot \left[1 - \exp\left(\frac{-1 \cdot \text{soilDistMP SLPS}}{\text{satMPS}}\right)\right] \quad (2)$$

$$LPS_{in}(mm) = Inf_{act} - MPS_{in} \quad (3)$$

Where: MPSin and LPSin represent, respectively the middle and large pores' inflows, infact is actual infiltration, satMPS is actual water saturation in MPS and soilDistMPSLPS is a calibration parameter. LPS' water is separated into lateral flow considered as Interflow 1 (RD2) which is routed to the next HRU or connected to a stream (Equation 4) and vertical flow (percolation) depending on the slope (Equation 5). Percolation is treated as input of groundwater module.

$$Inflow\ (mm) = Slope_{weight} - Q_{LPS} \quad (4)$$

$$Percolation\ (mm) = (1 - Slope_{weight}) \cdot Q_{LPS} \quad (5)$$

All soil properties, regarding soil water-holding capacity, are provided in a soil-parameter file. Detail information on different equations of soil module are available in (Nepal, 2012) and http://ilms.unijena.de/J2000.

2.2.2. GROUNDWATER

Two geological units are identified in J2000 model for each HRU: the upper groundwater storage (RG1) in the loose material with high permeability and short retention time, and the lower groundwater storage (RG2) in the matrix, fissures and ravines of bedrock with low permeability and long retention time. Therefore, two basic runoff components are generated depending on the slope of the response unit, the fast one from the upper groundwater storage and the slow one from the lower groundwater storage. Groundwater contribution to the total runoff is carried out in the form of a linear-outflow function using storage retention coefficients for the storage. These coefficients (kRG1, kRG2) are a factor of the current storage volume (actRG1 and actRG2) used for the calculation of the groundwater outflow (outRG1 and outRG2) that contribute to the total runoff (Equation 6 and 7). Also, a certain amount of upper groundwater storage is conveyed into capillary rise in J2000 model.

$$outRG1(mm) = \frac{1}{gwRG1Fact \cdot kRG1} \cdot actRG1 \quad (6)$$

$$outRG2(mm) = \frac{1}{gwRG2Fact \cdot kRG2} \cdot actRG2 \quad (7)$$

Where: outRG1 and outRG2 are groundwater outflow that contribute to total runoff; gwRG1Fact and gwRG2Fact are calibration parameters; kRG1and kRG2 storage retention coefficients of upper and lower groundwater respectively; actRG1 and actRG2 are the actual groundwater storage in upper and lower zones in the geological unit of each HRU.

2.2.3. ROUTING

HRU Routing and Reach Routing constitute the two routing components considered in J2000 model. The first one concerns water transfer between HRU from the upper areas until the receiving stream, according to the topological connectivity. The second routing component (most important one) describes flow processes in the reach network by using the commonly applied kinematic wave approach and the computation of velocity according to Manning and Strickler (Krause 2002; Nepal et al. 2012). Here, the individual reaches receive water from neighboring HRU and upstream reaches and the user has to estimate a routing coefficient.

2.3. JAMS/J2000 Modeling Procedure

The modeling period (1985 to 2001) was limited to the availability of the respective metrological and runoff flow data measurements in Mekelle Airport metrological station, and Illala Bridge runoff gauging station at the outlet of the upper Illala catchment. The modeling procedure applied in this study was mainly model setup, model calibration and validation, water balance elements quantification and analysis. The model setup has considered the input of the hydro-climatic data and the different parameter files into J2000 model as it is recommended. Five different parameter files such as HRU, reach, hydrogeology, land use and soil parameter files are required to run the model.

The first two parameter files (HRU and reach) are automatically generated during the HRU delineation process in GRASS-HRU. The Hydrologic Response units (HRUs) were delineated using GRASS-HRU which is a GIS based program working under Quantum GIS (QGIS). The modeling entities delineation is based on the overlaying of the spatial data using the process developed by Pfennig and (Wolf 2007). In this process, two concepts are combined namely topological connectivity (for the water and mass transport modelling in a specific surface area) and the process oriented regionalization concept in which a single HRU is an area of homogeneous topographic and physiographic environment. This HRU delineation approach aims to delineate the modelling entities based on a geomorphological method. The real advantage of this HRU concept is the reduction of modeling entity's size without losing information. The model is run for each HRU and thereby produces the average value for the particular area (Nepal et al. 2012). Accordingly, the water balance components can be assessed in a small area as possible. This will contribute to a good application of the integrated watershed management approach. The spatial data of elevation, soil, LULC and geology maps are used for HRU delineation. The HRUs for this study were therefore derived using the GRASS-HRU software package, (Schwartze 2008). The complete process chain for the HRU derivation was implemented according to a service-oriented application in GRASS-GIS. The execution environment is strictly separated from the operating environment by using a preconfigured, virtual machine which is in charge of data preparation and the calculation of HRUs in GRASS-GIS. A plug-in developed for QGIS creates an intuitive, wizard-driven and transparent environment for the execution of the process chain. Thus, based on the spatial data, the HRU parameter file contains information on the elevation, coordinates, area, slope, aspect, drainage type, flow-length, land-use type, hydrogeology, soil type and topological connectivity for each HRU. In the reach parameter file the length (m), slope (percent), mean width (m), connectivity between reach and reach roughness according to Manning-Strickler (Krause 2002; Nepal et al. 2012) are stored. Based on the geological information, the maximum storage capacities of RG1 and RG2 are estimated and the storage coefficient values (RG1_k and RG2_k) are used as a general recession co-efficients of two storages. These parameters are stored in the hydrogeology parameter file. The land use parameter file stores information about the land surface albedo, surface resistance for water saturated soil of each month, leaf area index for the four quarters of the vegetation periods, effective vegetation height for the four quarters of the vegetation periods, the maximum root depth and the sealed grade to check infiltration. In this study, these information were taken from literature (Fang et al. 2013; Jarlan et al. 2008; Jin and Zhang 2002) in semi-arid regions for the different land use classes due to similar reasons with LAI as described in the modeling process section— interception sub section. Finally, the soil parameter file stores information on soil thickness; maximum and minimum permeability coefficient of the soil; the depth of the horizon, above the horizon with the smallest permeability coefficient; air capacity representing excess water in a LPS; useable field capacity representing a MPS and; useable field capacity per decimeter of profile depth. These parameters were obtained from soil investigations to parameterize the soil map. The soil parameters measured through the soil investigation are the saturated hydraulic conductivity, texture and organic matter. The texture information gathered from the soil survey was used to depict the characteristics of the soil water retention curve and it was provided as an input data to the software component Rosetta inside 'HYDRUS 1D' to understand the soil pedotransfer function in three different hypothetical pressure scenarios (0 mbar, 60 mbar and 15,000 mbar) which help to estimate the LPS and MPS of each soil type.

After the model was set up, it was manually and automatically calibrated for the period 1992 – 1996, and validated for the period 1997 – 2001 using a curve fitting approach between the simulated and observed discharge as indicated in the result and discussion section.

2.4. JAMS/J2000 Model Input Data Preparation

The data requirements to run the J2000 hydrological model are two types: i) meteorological and ii) model parameter files. The J2000 modelling system uses Inverse Distance Weightings (IDW), with elevation correction method, for the regionalization of the input climate data. All the meteorological input data (first group of inputs) might not be available in some catchments. Normally, temperature and precipitation data are commonly available. If there are only few stations (less than 3) for some parameters, the IDW does not work properly. In that case, the same input value is applied for the entire catchment. For some particular variables, for example, temperature, this approach would bring large amounts of errors/uncertainties. In such cases, the regionalization approach based on a lapse rate is suggested for temperature. The details of this approach and its data set preparation are provided in the Tutorials Data Himalaya (http://ilms.uni-jena.de/ilmswiki/index.php/Applying_the_J2000_model). The relative humidity (rhum), wind and sunshine hours (sunh) are also not frequently available in some catchments. These values are used for the estimation of evapotranspiration while using the Penman-Monteith approach. The sunshine hours and wind speed can be assumed to be enough from one station, in case no other station data is available. In such cases, the same station value is applied for a whole catchment. The one station value for relative humidity also brings certain errors while calculating relative humidity using absolute humidity and temperature. In the J2000 modelling system, a direct regionalization of the relative humidity values is not recommended. The details are provided in the calculation of evapotranspiration sub-tutorial. In case these data (rhum, sunh, wind) are not available the Pennmann-Monteith approach cannot be used. Rather a more empirical approach based on temperature such as Hargreaves (insert citation here), can be used. All the grid input data (i.e. soil, land use/cover, geology, DEM) are in raster format with certain resolution. While delineating HRUs, all the input data have to be provided in the same resolution. The resolution of the dataset mainly controls the number of HRUs to be formed without losing the heterogeneity of a catchment.

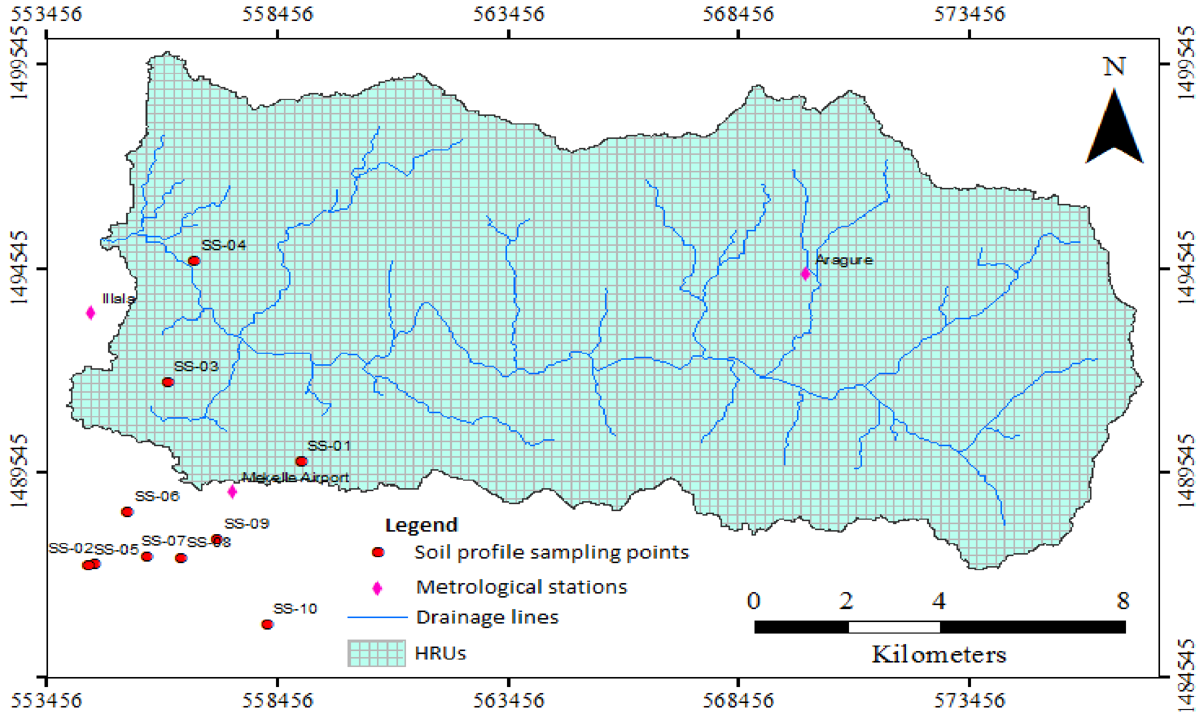

Figure 5.Metrological stations, drainage lines, available soil profile sampling points and the developed HRUs in upper Illala catchment. HRUs Stands for Hydrological Response Units

Accordingly, the meteorological elements (such as precipitation, temperature, relative humidity, sunshine hours and wind speed) in this study were available from the Mekelle Airport metrological station. The potential evapotranspiration is estimated using the Penman-Monteith approach. All these metrological inputs are summarized in suitable formats to be used as an input to the J2000 hydrological model. Besides, the grid input data (i.e. soil, land use/cover, geology, DEM) in this study were prepared in raster format with a 30 meter resolution. The J2000 model was used with input data of 46 years temporal metrological data series, for the time period of 1961 to 2000 from Mekelle Airport station and 18 years (1980 to 2002) runoff discharge gauging data from the Illala gauging stations. The runoff gauging records were taken from WWDSE (2007). These all input data were prepared through updating of the J2000 model test (.dat) files by editing them in the PSpad text editor software. Moreover 10 soil depth profile samples with a depth of up to 90 cm by (Abayneh et al. 2005) were used for the soil parameterization of 38 soil horizons in the study area and its vicinity. The soil parameterization was made using the 'Hydrus 1D' software. The soil parameterization is used to obtain the water holding capacity of the specific texture combination and to prepare the input soil parameter table as soil physical properties, such as field capacity and percolation rate, influence hydrological processes. The HRUs and location maps of the, metrological stations, the gauging station and the soil depth profile sampling points are presented in Figure 5.

On the other hand, spatial data such as elevation, aspect, slope, land use, soil and hydrogeology have been incorporated into this modelling. Elevation, aspect and slope are extracted from Advanced Land Observing Satellite Phase Array type L-band Synthetic Aperture Radar (ALOS PALSAR) dataset of the National Aeronautics and Space Administration (NASA) in 2016.

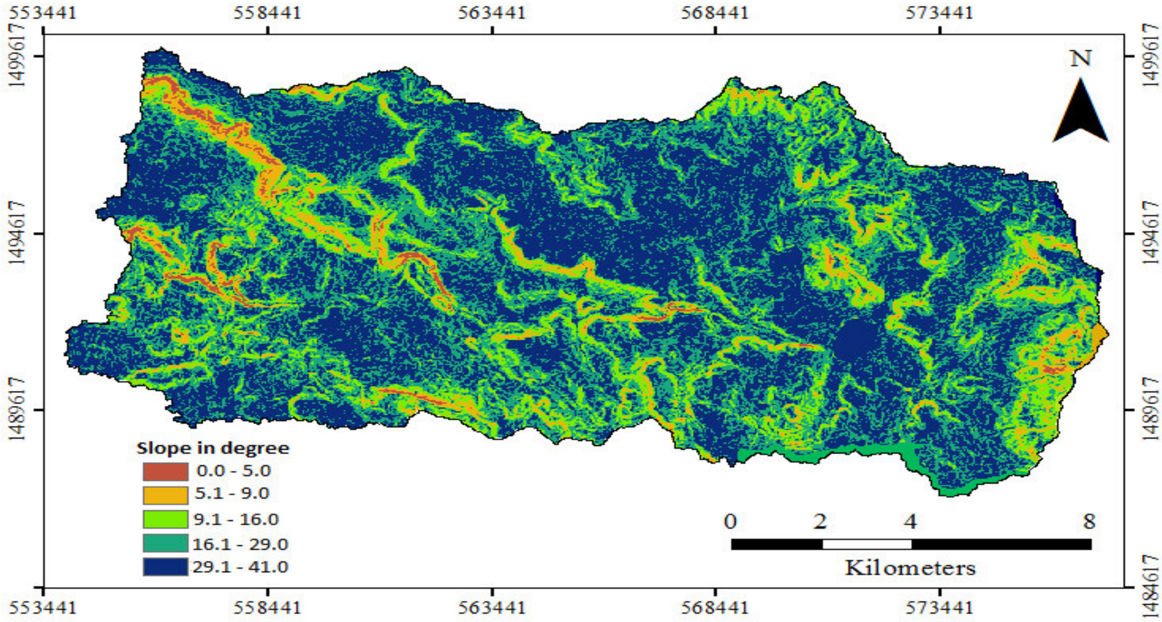

Figure 6. Slope map of Upper Illala catchment.

The slope map of the catchments in the study area is directly derived from the topography map using the 'derive slope' module in Arc GIS 10. The slope angle ranges from 0° – 41°and is classified into five slope classes: as 0 to 5.0 degrees (flat plain), 5.1 to 9.0 degrees (gentle slope), 9.1 to 16.0 degrees (intermediate), 16.1 to 29.0 degrees (steep) and 29.1 to 41.0 degrees (highly steep) (Figure 6).

Landsat 8 OLI imagery was downloaded from the Earth Explorer, U.S. Geological Survey website (www.earthexplorer.usgs.gov) and the satellite digital images of (row number 51) and (path numbers 168 and 169) captured on February 14 to 22, 2018. The two images for each path number have been mosaicked using raster management and extraction tools in ArcGIS 10. Training samples were assigned using different (RGB) band combinations for Land sat 8 and the interactive supervised classification in ArcGIS 10 was also used to develop the LULC map. This LULC map was verified using 458 ground truth points collected using Garmin GPS with a fit of 82.97 % and masked to smaller size, fitting the study area boundary. The developed LULC map consists of seven LULC classes namely: cultivated agricultural land with scattered trees, shrub land, bare land, grass land, water body, settlement of rural community and urban areas and forest (Figure 7).

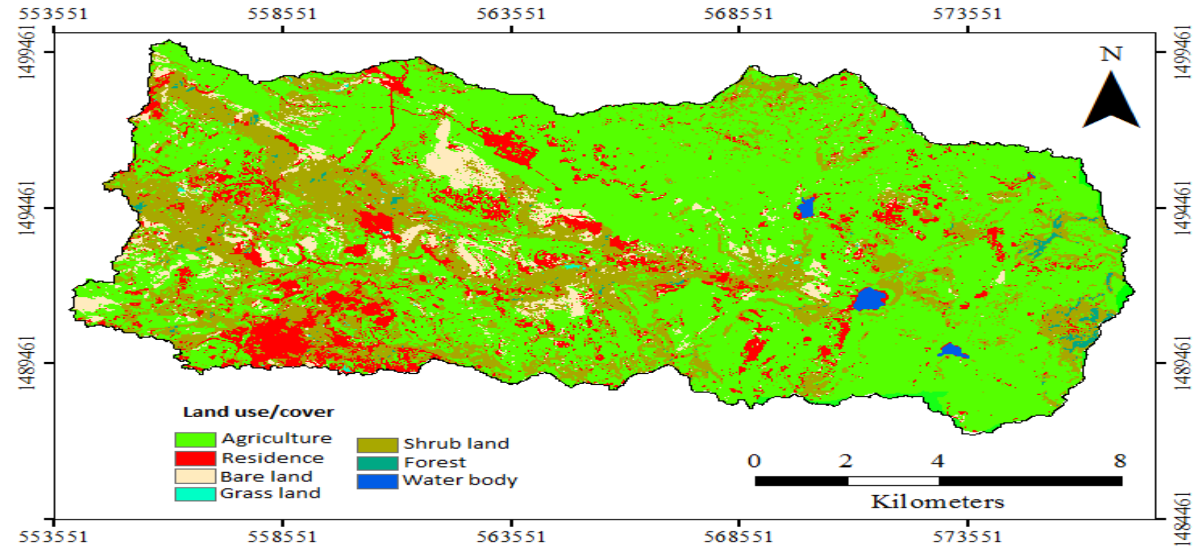

Figure 7. Land use map of Upper Illala catchment.

Soil map of the area was developed by compilation of previous works of Tesfamichael (2009) on the Geba basin and that of Gebremedhin (2015) for the Illala-Aynalem sub basins. Moreover, about 16 primary soil samples were collected during the field work in 2016 and analyzed for the physical textural parameters in Mekelle University, department of civil engineering to verify some mismatch among the previous works. The developed soil map (Figure 8) shows that the major soil textures of the study area are classified in to four: Sandy clay loam, Silty loam, Clay loam and Silty clay loam.

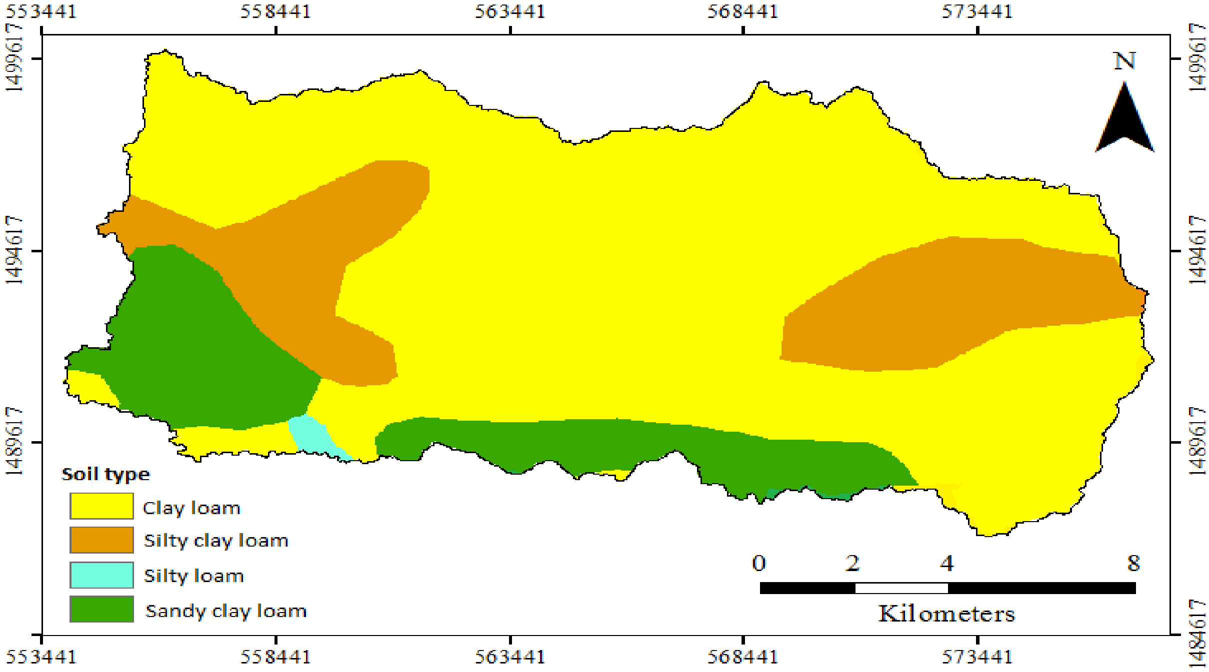

Figure 8. Soil map of Upper Illala catchment.

The second groups of input files (parameter tables) are prepared and quantified inside the GIS environment and known as model parameter files. The parameter files and their values are static in the modelling application. The detailed descriptions to derive the parameter files are provided in the tutorial of the J2000 model (http://www.geoinf.uni-jena.de/5580.0.html). The hydrogeology parameter table is assumed that the storage capacity and storage coefficient of the upper ground water storage are lower than the lower one. This is so due to the fact that the storage in the lower zone represents the saturated groundwater aquifer with longer residential time. These values are difficult to acquire as they cannot be directly measured. Recession constants and volumes of the lower ground water storage for different types of hydrogeological formations are provided in the link: http://ilms.uni-jena.de/ilmswiki/index.php/Applying_the_J2000_model. These recession constants (CG2) for the slow groundwater runoff component (RG2) of the selected hydrogeological classes are derived based on the data of more than 100 catchments. Hence, the hydrogeology parameter for this study was prepared using the values of CG2 and RG2 of similar rock formations.

3. Results and Discussion

3.1. Hydro Mmeteorological Cconditions

The hydrological model J2000 has been able to simulate the annual variations of the hydro meteorological parameters through the inverse distance weighting (IDW) and vertical (regression) variation, as regionalization approach. Figure 9 and Figure 10 show the average monthly rainfall, discharge, actual (AcET) and potential (PET) evapotranspiration simulated by J2000 model over the investigated period (1985 to 2001). Figure 9 indicates that the climate in upper Illala catchment is characterized by only one rainy season with simulated rainfall and runoff discharge peaks in July and August. In addition, Figure 10 shows the variations of AcET and PET within a year, where May and September represent the moment of high evapotranspiration. Moreover, the water demand from the atmosphere is very important from February to May. Even though, the maximum of the rain falls in July and September, the atmosphere water demand is not satisfied, which indicates the semi-aridity of the region. This result shows that the IDW method in the J2000 model for the simulation and reproduction of the hydro meteorological parameters is quite good and fairly accurate at the upper Illala catchment.

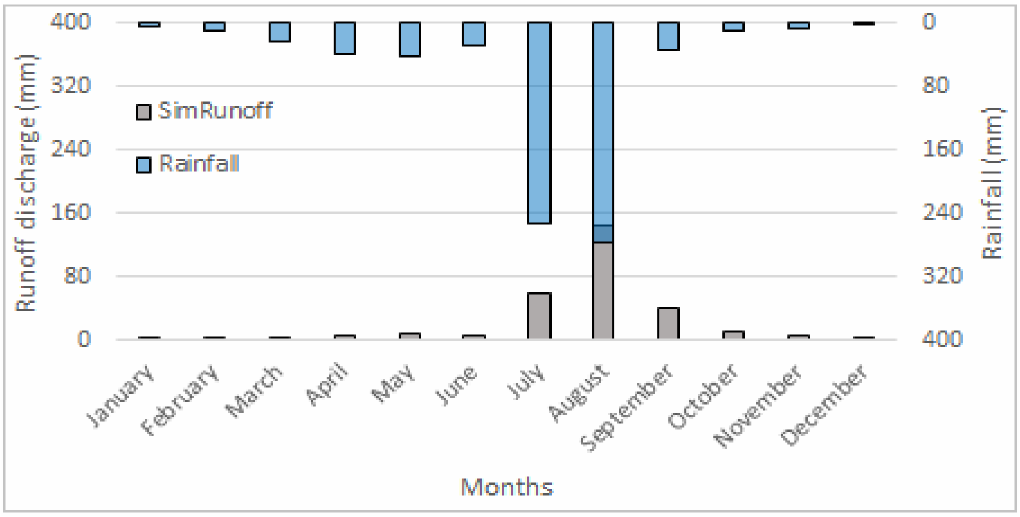

Figure 9.Average monthly simulated rainfall and runoff discharges.

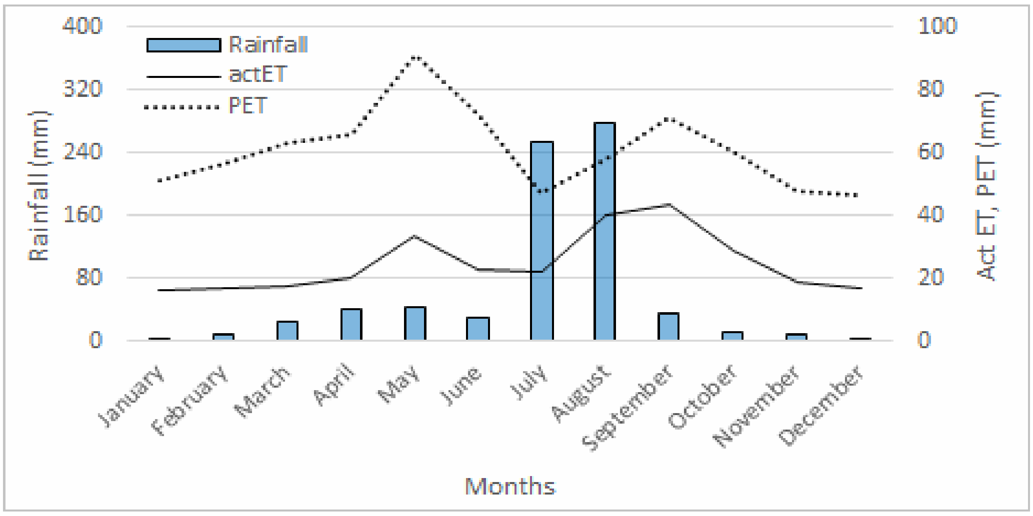

Figure 10.Average monthly simulated rainfall, ActET and PET.

3.2. JAMS/J2000 Model Results and Model Calibration Strategy
To realize the J2000 distribution concept, the upper Illala catchment was subdivided into HRUs. These units are areas of which physical characteristics are regarded as hydrologically homogenous, which are delineated by intersecting a 21 km mesh. As a result, 5,217 HRUs and the subdivision of the river network into 184 reaches were derived (Figure 5). Spatial data such as elevation, slope, aspect, land use, soil, and hydrogeology are projected on these HRUs. Since J2000 comprises lateral routing and reach routing (flow in the channel), it was essential to provide the model with additional data such as flow length and drainage for each potentially draining HRU, and roughness, width, length, slope and drainage for each channel segment, respectively. Land use, soil, reach, HRUs and hydrogeology parameter tables and the metrological inputs have been incorporated into the J2000 modelling as per the requirement of the model. The J2000 model was run for the upper Illala catchment as shown in Figure 5. The J2000 model calibration was carried out by matching the simulated and observed discharges on the Illala gauging station. Five years modelling period (01/01/1992 to 31/12/1996) were used for calibration. The direct runoff and baseflow were calibrated against the groundwater discharge by curve fitting calibration method. A satisfying curve fitting of simulated and observed runoff does not guarantee a good estimation of the water balance components. To achieve this, the J2000 model results are cross validated with the WetSpass model results in the area and its vicinity.

For the gauging station in Illala, the J2000 model was able to simulate the runoff correctly in its periodicity. A visual analysis of the simulated and observed hydrograph revealed significant model errors. Particularly, conspicuous errors occur in the rainy seasons of 1985 to 2001.

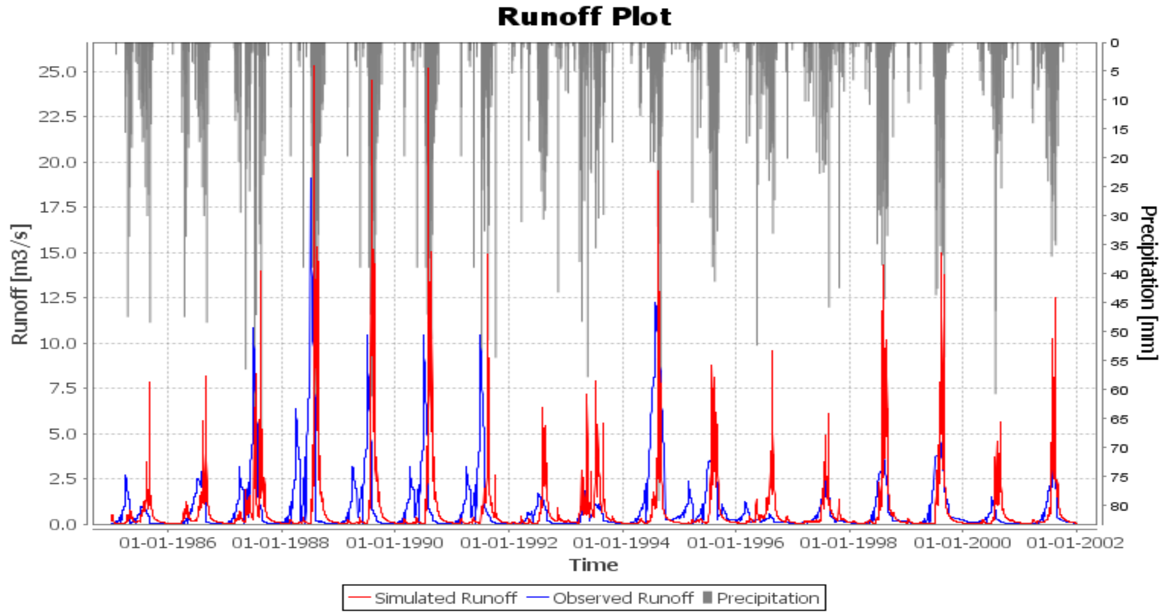

Figure 11.Simulated and observed runoff discharge versus Precipitation model results.

A general analysis of the hydrographs shows that the occasional light precipitation in the dry season (March and April) and the rainy season (June to September) in the study area leads into a rather unimodal runoff distribution. That indicates retention of surface runoff during the dry season in March and April because this event is hardly depicted by the hydrographs. The catchment's soils seem to infiltrate the first rain events after the dry season quite well. Obviously, the former rain events in the wet season contribute to subsurface storage to a high degree, while for the later rain events, the soil is already more or less saturated and less water can infiltrate. The unimodal hydrographs are typical for the seasonal tropics (Schultz 2005). However, the height and slope of the runoff peaks are outstanding and characterized as flush floods or similar, because they are not single-event based. Accordingly, the peak discrepancies between the observed and simulated discharges were calibrated and validated in reasonably acceptable results using 24 calibration parameters as shown in Table 1.

Besides performing an evaluation under different efficiency criteria, a visual analysis of the simulated and observed hydrograph revealed model errors and uncertainties. Figure 11 indicates occurrence of conspicuous errors in the rainy seasons of 1985/86, 1987 to 1991 and 1995/96. Here, part of the observed flash floods could not be reproduced by the model. The opposite scenario is the case for the rainy season of 1986/87, 1991 to 1993 and 1995 to 2001: simulated runoff exceeds observed runoff. We assume that these errors are caused by data uncertainties, that inhomogeneous small scale rainfall patterns could not be captured by the monitoring network. Generally, modelling results can be affected by various errors and uncertainties. Here, it is possible to distinguish between three sources of uncertainty: (i) parameter uncertainty; (ii) data uncertainty and (iii) model structure uncertainty. The main sources of uncertainty for this work can therefore be described as:

(i) Parameter uncertainty: the parameterization of the soil map was based on the analysis of only 10 soil depth profile samples, with no infiltration tests, were used for the soil parameterization of 38 soil horizons and land use parameters were extracted from the literature and were not measured under specific conditions in the investigated area.

(ii) Data uncertainty: only one metrological station was used for this study and hence small scale rainfall patterns could not be captured by the monitoring network, uncertainties occurring due to regionalization of point data (climate and rainfall) and baseflow had to be corrected. Moreover, the daily runoff records were interpolated from the monthly runoff records, which was one source of uncertainty.

(iii) Model uncertainty: problem of equifinality - different parameter settings in the model led to the same simulated runoff, but not to exactly the same groundwater recharge.

As a consequence of the aforementioned uncertainties, the model results have to be calibrated and validated under different parameters. Selection of the calibration and validation periods, depended on the availability of continuous runoff gauging records at the upper Illala Bridge.

3.3. JAMS/J2000 Model Calibration Results

Model calibration was carried out by matching the simulated discharge for the catchment above the Illala River gauging station, with the observed discharge at the gauging station (Figure 12). The direct runoff and groundwater discharge were calibrated by curve fitting and the calibration settings were applied to the entire area of the upper Illala River catchment. During the calibration process, the simulated runoff is fitted to the observed runoff at the Illala Bridge gauging station (Figure 2). The obtained model calibration results are summarized in Figure 10 and the simplified water balance equation is presented in Table 1.

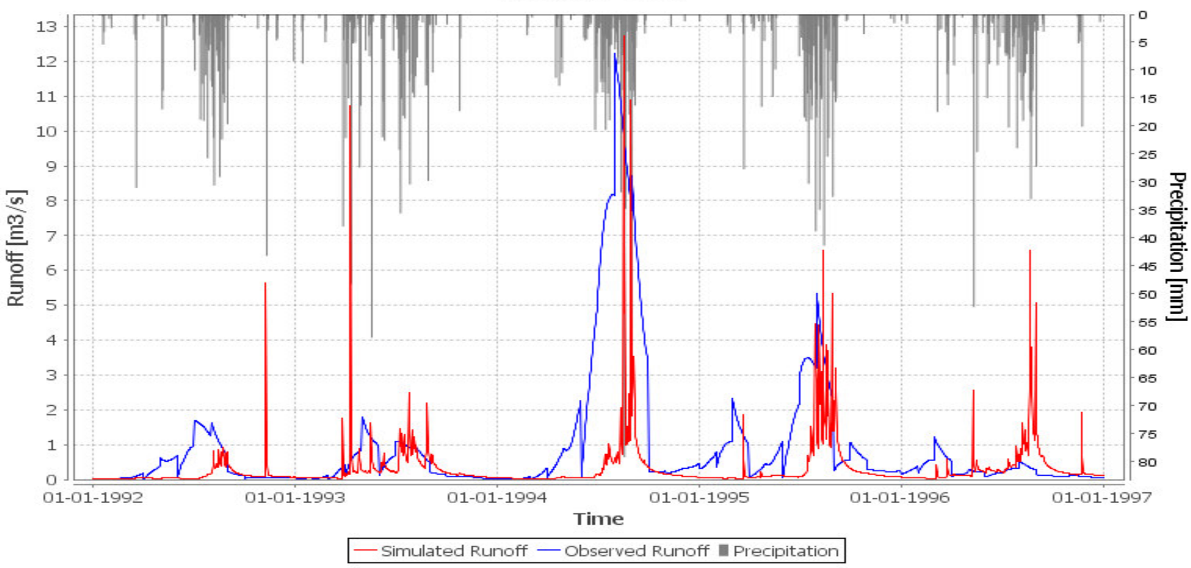

Figure 12.Simulated and observed runoff discharge versus Precipitation model calibration results.

Comparison between daily observed and simulated discharge for the calibration period (01/01/1992 to 12/31/1996) indicated that J2000 was able to capture and reproduce the average flows and seasonal variations in the upper Illala catchment. The prediction on daily discharge was accurate with corresponding values of r^2, NSE, RMSE and pbias of 0.863, 0.2395, 1.79 and 0.856 %, respectively, where RMSE: Root mean square error (range = −∞/+∞, optimum 0); pbias: percent bias (< 10 %: very good; 10 to 15 %: good; 15 to 25 %: Faire); NSE: Nash-Sutcliffe efficiency (range = −∞/1, optimum 1); regression coefficient (r^2) (range = 0–1, optimum 1).

Table 1 Calibrated parameters for upper Illala catchment.

Parameters	Description	Final value	Range
Initializing module			
FCAdaptation	Multiplier for field capacity	2.8	0 - 5
ACAdaptation	Multiplier for air capacity	5	0 - 5
initRG1	Initial storage relative to maximum storage for groundwater component RG1	0.05	0 - 1
initRG2	Initial storage relative to maximum storage for groundwater component RG2	0.0005	0 - 1
Interception module			
a_rain	Maximum storage capacity per LAI for rain (mm)	0.5	0 - 10
Soil water module			
SoilMaxDPS	Maximum depression storage capacity (mm)	3.6	0 – 10
SoilPolRed	Potential reduction coefficient for actual Evapotranspiration computation	6.0	0 – 10
SoilLinRed	Linear reduction coefficient for actual Evapotranspiration computation	0.35	0 – 10
SoilMaxInfSummer	Maximum infiltration in summer (mm)	122	0 – 200
SoilMaxInfWinter	Maximum infiltration in winter (mm)	39	0 – 200
SoilImpGT80	Relative infiltration for impervious area	0.25	0 – 1
SoilImpLT80	Relative infiltration for impervious area	0.6	0 - 5
SoilDistMPSLPS	Middle pore storage & large pore storage distribution coefficient	0.4	0 – 10
SoilDiffMPSLPS	Middle pore storage & large pore storage diffusion coefficient	0.7	0 – 10
SoilOutLPS	Outflow coefficient for large pore storage	0.5	0 - 10
SoilLatVertLPS	Lateral-vertical distribution coefficient	1.04	0 – 100
SoilMaxPerc	Maximum percolation rate (mm)	1.04	0 – 10
SoilConcRD1	Recession coefficient for overland flow	0.3	0 – 10
SoilConcRD2	Recession coefficient for interflow	9.9	0 – 10

Parameters	Description	Final value	Range
Groundwater module			
gwRG1RG2dist	RG1-RG2 distribution coefficient	0.75	0 – 1
gwRG1Fact	Adaptation for RG1 outflow	0.57	0 – 10
gwRG2Fact	Adaptation for RG2 outflow	1.5	0 – 10
gwCapRise	Capillarity rise coefficient	0.2	0 - 1
Reach routing module			
flowRouteAT	Flood routing coefficient	3	0 - 100

3.4. JAMS/J2000 Model Validation Results

Different efficiency criteria can be applied to evaluate the simulation results. Commonly used criteria, in the field of hydrological modelling, are the coefficient of determination (r^2) and the Nash–Sutcliffe efficiency (NSE) criteria. Due to the fact that both criteria are insufficient for appropriate model evaluation (e.g. they are not very sensitive to systematic over- or under-prediction), Gupta et al. (2009) introduced the Kling-Gupta efficiency (KGE) criteria. The respective r^2, NSE, RMSE and bias values for the validation period are 0.698, 0.3719, 0.8814 and 0.496 as the runoff hydrographs indicate in Figure 13. The J2000 model validation was carried out using the KGE_{mod} criterion to evaluate best-fit values in the curve fitting of the simulated and observed run off components. The Kiling Gupta efficiency (KGE) accounts for the linear correlation (r), the variability error (α) and bias error (b) and incorporates them into a single multi-objective criterion to describe and evaluate the fit of simulated and observed heads as indicated in equation (8 to 11). For this purpose, each model run is evaluated by the Euclidian distance (ED) to an ideal point in the three-dimensional criteria space (Gupta et al. 2009) as indicated in equation (8). The KGE ranges from -∞ to 1, with higher values indicating a better fit (Gupta et al. 2009).

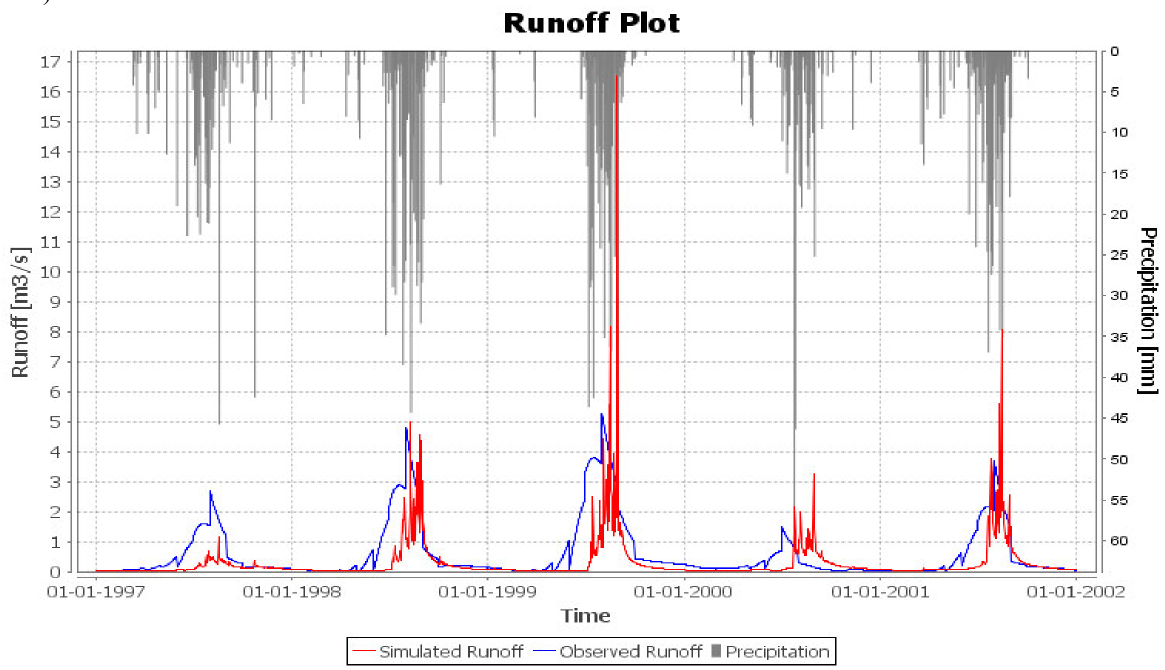

Figure 13.Simulated and observed runoff discharge versus Precipitation model validation results.

The runoff and baseflow outputs of the J2000 model were validated by a split-sample-validation in the validation period (1997 to 2001), using the Kling-Gupta efficiency (KGE) approach. The respective (r), (α), (b), ED and KGE values are computed to be 0.549, 0.781, 0.496, 0.711 and 0.289 for the runoff hydrograph outputs. And the values of (r), (α), (b), ED and KGE_b for the baseflow hydrographs are 0.00001, 0.952, 0.493, 1.122 and -0.122, respectively. The KGE_{mod} based on equation (13) was computed to be 0.0834, indicating a better fit for both the observed and simulated runoff and baseflow hydrographs.

KGE = 1- ED, With

$$ED = \sqrt{(r-1)^2 + (\alpha - 1)^2 + (b-1)^2} \tag{8}$$

And

$$r = \frac{Cov_{sim,obs}}{\delta_{sim} . \delta_{obs}} \tag{9}$$

$$\alpha = \frac{\delta_{sim}}{\delta_{obs}} \tag{10}$$

$$b = \frac{\mu_{sim}}{\mu\delta_{obs}} \tag{11}$$

Where $Cov_{sim, obs}$ is the covariance between the simulated and observed heads, δ_{sim} is the standard deviation of the simulated heads, δ_{obs} is the standard deviation of the observed heads, μ_{sim} is the arithmetic mean of the simulated heads and μ_{obs} is the arithmetic mean of the observed heads.

Different efficiency criteria were compared and highlighted the problem of squared differences, which was subject to high sensitivity for extreme values (Krause et al. 2005). The correlation coefficient, as it is used in the KGE, is affected by this disadvantage too. However, for groundwater recharge estimation, the fit of low values (baseflow) is of great importance. To overcome this problem, the baseflow of simulated and observed discharge was separated and analyzed individually. For baseflow separation, a filter that was developed by (Hollick and Lyne 1979) was applied. Nathan and McMahon (1990) suggested a forward–backward–forward filtering method and a filter coefficient range (β) between 0.90 and 0.95 as indicated in equation (12). Figure 12 shows the runoff and baseflow hydrographs according to this filtering method.

$$Q_B(i) = \beta . Q_B(i-1) + \frac{1-\beta}{2} . Q(i) + Q(i-1) \tag{12}$$

Where; QB(i) is the baseflow at time step i, and Q(i) is the total runoff at time step i.
Taking this into consideration, curve fitting was evaluated by the KGE of the total runoff and KGE of the baseflow (KGE_b). Both criteria are incorporated in the modified KGE (KGE_{mod}) as shown in equation (13) below:

$$KGE_{mod} = \frac{KGE_b + KGE}{2} \tag{13}$$

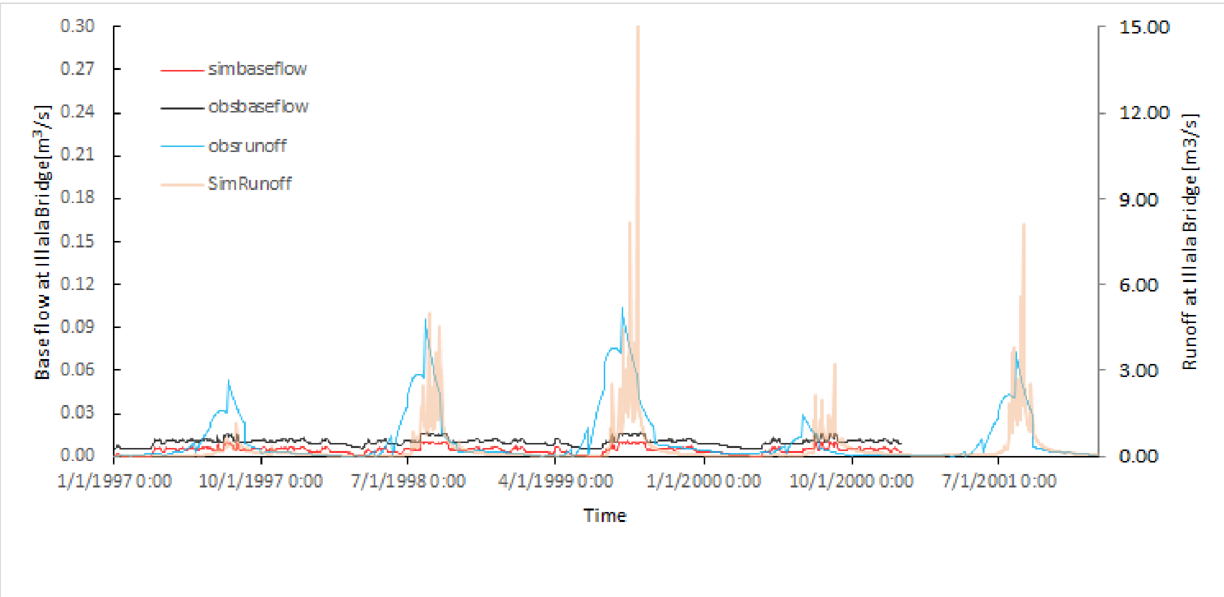

Figure 12.Observed and simulated runoff during the calibration period (01/01/1997 to 12/31/ 2000) at Illala Bridge runoff gauging station.

3.5. Computation of Water Balance Components in Upper Illala Catchment

The water balance components are accessed from the TimeLoop.dat output data of the JAMS Data Explorer, immediately after the run of each target model.

Table 2 Annual water balance components (mm) based on the J2000 model at Upper Illala catchment.

Water balance components	Calibration	Validation	Average mean annual (mm/year)	Rainfall partition (%)
Precipitation (Rainfall) , P	682.19 (1.869)	673.43 (1.845)	677.81	100
Total actual Evapotranspiration, ETP (Interception + actET)	467.57 (0.218 + 1.063)	485.09 (0.214 + 1.115)	476.33 (78.84) (397.49)	70.28 (11.63) (58.64)
Surface runoff, Ro	116.80	105.85	111.33	16.42
Groundwater recharge, Re	61.03	47.09	54.2	8.0
Soil moisture, Sm	33.58	43.62	38.60	5.70
Water balance (average stock) = P – ETP – Ro – Re – Sm	3.92	- 8.22	- 2.65	- 0.37

Table 2 shows the annual summary of the daily outputs provided by J2000 model. The largest fraction of annual rainfall (70.28%) returns to the atmosphere through canopy interception (11.63%) and evapotranspiration (58.64%). This is the amount of the evapotranspired water. The fraction of rainfall, which does not regain the atmosphere is composed of soil moisture (5.7%), surface runoff (14.92%) and groundwater recharge (8.0%). The model results, under both calibration and validation periods, confirm the reliability of J2000 model to estimate the water balance components in the upper Illala river catchment.

3.6. Verification of the JAMS/J2000 Model Outputs

Although baseflow reflects groundwater discharge, a satisfying curve fitting of simulated and observed runoff does not guarantee a good estimation of groundwater recharge. Hence, two independent approaches i.e WetSpass hydrological model and geochemical methods using groundwater samples were applied in this study. The model verification process for the recharge estimation was therefore carried out using independent water balance model (WetSpass) for all the water balance components and geochemical approaches (Chloride mass balance and stable Isotope compositions). Results of these independent approaches were compared with the J2000 modelled water balance components as indicated in Tables 3 and 4.

The first J2000 model validation strategy is verification of the J2000 model outputs using the results of the WetSpass model water balance components in the study area (Kahsay 2021). The WetSpass is an acronym for Water and Energy Transfer in Soil, Plants and Atmosphere under quasi Steady State. It is a numerical model to simulate long-term average spatial distributions of hydrological parameters and processes on basin scale (Batelaan and De Smedt 2001; 2007) and results in partitions of the precipitation in to the surface runoff, evapotranspiration and groundwater recharge components (http://www.vub.ac.be/WetSpa/introduction_wetspass.htm). Long term metrological records over the period of 1961 to 2017 in Mekelle Airport, Illala research center and Mekelle observational station were used for the WetSpass model. The WetSpass model result includes several annual and seasonal hydrologic outputs. However, only the annual groundwater recharge, surface runoff, and actual evapotranspiration were important for the verification of the water balance components simulated by the J2000 hydrological model in the study area.

Table 3 Mean annual water balance components (mm/year) using J2000 and WetSpass models.

Water balance components	J2000 model results	Rainfall partitio (%)	WetSpass model result (Kahsay, 2021)	Rainfall partition (%)
Precipitation, P	677.81	100	566.97	100
Evapotranspiration, ET	476.33	70.28	414.61	73.13
Surface runoff, Ro	111.33	16.42	113.17	19.96
Groundwater recharge, Re	54.2	8.0	39.68	7
Soil moisture, Sm	38.60	5.70	---	---
Water balance = P – ETP – Ro – Re – Sm	- 2.65	- 0.37	-0.49	- 0.086

The estimated annual precipitation percentages of the mean annual water balance components using both the J2000 and the WetSpass models are quite similar to each other (Table 3). The slight discrepancy between the water balance components of both models can probably be that the WetSpass model does not incorporate the soil depth profile, type of geological formations and recession constants of the geological formations and the soil moisture component output. On the other hand, the J2000 model had limitations to have continuous daily runoff gauging records which can be source of the discrepancy in the water balance component outputs. Moreover, the mean annual precipitation input for the area is different in the models as it represents different time series.

The second J2000 model verification strategy was verification of the groundwater recharge estimation of the model using geochemical methods (CMB and stable isotopes) applied in the study area (Kahsay 2021). The chloride mass balance (CMB) method was applied in arid and semi-arid regions in many regions such as in western Saudi Arabia by Bazuhair et al (1996) and in West Bank, Palestine by Marei et al (2010), and locally by Gebrerufael (2008) in Aynalem catchment. The groundwater recharge in CMB method was estimated using the CMB equation applied in Marei et.al (2010). Groundwater recharge estimations in different parts of the globe for various geological formations were made using empirical relationships with the stable isotope compositions, such as Allison et al. (1984) made the empirical relationships for groundwater recharge in mm/year through thick sands and (Lihe et al. 2010) applied in vadose zone with a small thickness (the depth of the water table is less than 2 m in 20% of the area) in the Ordos Plateau.

The estimated annual precipitation percentages of the mean annual groundwater recharge, using both the J2000 and the geochemical methods are quite similar to each other (Table 4). The small percentage discrepancies of the groundwater recharge signifies that the J2000 model and the geochemical methods are appropriate for the groundwater recharge in the area.

Table 4.Groundwater recharge estimations (mm/year) using different methods for verification purpose.

Applied method	Annual groundwater recharge	Rainfall partition (%)
J2000 model	54.20	8.00
WetSpass model (Kahsay, 2021)	39.68	7.00
CMB (Kahsay, 2021)	38.73	6.83
Stable isotope compositions (Kahsay, 2021)		
δ^2H_{Shift} (‰)	38.73	6.83
$\delta^{18}O_{Shift}$ (‰)	38.55	6.80

4. Conclusion

Estimation of the water balance components using the J2000 hydrological model and their verification techniques in this study was successful. The optimized estimates of the water balance components in this study indicate that about 70.28% of the precipitation in the study area is lost through evapotranspiration (58.64%) and canopy interception (11.63%), about 14.92% is surface runoff, 8.0% is groundwater recharge and 5.7% is soil moisture. The model validation results show that the J2000 model is applicable for the study area having quite similar outputs with the WetSpass model and the geochemical methods. Moreover, the J2000 model has advantages in considering the soil depth profiles, type of geological formations and incorporates the soil moisture component output in the water balance equation. Hence the J2000 hydrological model is an appropriate alternative to the study area and its vicinity having a semi-arid climate and fractured geological formations. However, it needs recent long term runoff gauging records and soil depth profile samples which are hardly found in previous studies. Therefore, it is recommended to motivate governmental and none governmental projects in the region on the installation of runoff gauging stations and soil depth investigations. Finally, this study contributes for future investigations on groundwater recharge and sustainability of the groundwater resources.

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