Evaluation of Groundwater Recharge Dynamics using the Wetspass Model in the Usangu Plains, Tanzania

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Abstract

A comprehensive understanding of groundwater recharge dynamics is of great importance in enhancing the sustainable management of the groundwater resources and the sound planning of their utilization. This study aimed at evaluating the groundwater recharge dynamics in the Usangu Plains (20,810 km^2) by the help of a hydrological GIS-based model named WetSpass. The Water and Energy Transfer between Soil, Plants, and Atmosphere under quasi-Steady State (WetSpass) model used land use/landcover, soil texture, topography, slope, groundwater table and hydrometeorology data to simulate the temporal (yearly and seasonal) averages and spatial differences of groundwater recharge, surface runoff and actual evapotranspiration. The findings of this study showed that 17.8% of the mean annual rainfall contribute to the groundwater storage while 66.1% and 16.1% are lost through evapotranspiration and surface runoff, respectively. The high rates of evapotranspiration occurred in the wet season and in the seasonal/permanent wetlands and water body. Also, the maximum amount of surface runoff took place during the rainy season and in the built-up and in bare land vegetation types given the impervious state of their ground surfaces. About 25% (1.025km^3/year) of the annual recharge was found to be the groundwater that can be safely extracted for domestic and economic purposes. Compared to the water lost through evapotranspiration and surface runoff, the simulated portion of groundwater recharge is noticeably low. Consequently, it could be wise to initiate the rainwater harvesting technologies and artificial groundwater recharge strategies particularly in the zones with moderate and low recharge rates to boost the groundwater storage as its users cannot cease to increase.

Keywords: recharge dynamics, groundwater safe yield, WetSpass, Usangu Plains

Introduction

Groundwater is an important natural resource that forms components of the hydrologic cycle with contribution to the economic development and environmental sustainability (Bhanja *et al.,* 2018). It sustains the ecosystems through maintenance of rivers while stabilizing land in areas with soils that are easily compressed (Foster, 2016). Its quantification is the mainstay of the water resources management and utilization. Though the groundwater is mainly lost through evapotranspiration and surface water bodies, its storage is replenished by the hydrologic process called groundwater recharge (Nyagwambo, 2006). Groundwater can be recharged directly from precipitation, locally from depressions and rivulets, indirectly from rivers, irrigation losses (Vries and Simmers, 2002), urban recharge and intermediate recharge (Scanlon *et al.,* 2006). The indirect and intermediate groundwater recharges imply that some of runoff could end up with groundwater recharge before or after joining in surface water courses (Lei *et al.,* 2010).

For irrigation purpose, groundwater is readily available, more suitable in quantity and naturally sheltered from direct surface contamination by anthropogenic actions (Fenta *et al.,* 2014). However, a great number of farmers rely on surface water resources to meet their crop water requirements. While it is noted that surface water sources are prone to seasonal variations due to climate change and global warming and are disposed to contamination caused by human activities (Meresa and Taye, 2019), still the comparative advantages of groundwater over surface water are not adequately taped. Little understanding of groundwater dynamics may be among the reasons of its limited utilization. Scanlon *et al.* (2006) indicated that there is a gap of knowledge concerning temporal and spatial distribution of groundwater recharge across Africa. In Tanzania, the knowledge gap is partly caused by limited aquifer data as reported for major aquifers (Mahoo *et al.,* 2015). Thus, insufficient data and information for major aquifers in Tanzania has resulted to insufficient groundwater resources management (Mahoo *et al.,* 2015). Consequently, limited information is available on the estimates of recharge flux for diverse aquifers in Tanzania. The available information of estimates for underground water recharge flux are that of the Makutupora groundwater basin which provides ranges between 1 to 2% of annual rainfall (Rwebugisa, 2008). There is a need to conduct studies on groundwater recharge dynamics for different aquifers. The studies are essential for enriching the understanding of recharge dynamics of diverse aquifers for the purpose of enhancing the sustainable management of the groundwater resources.

Groundwater recharge dynamics are very essential for the water resources management strategies. The focus of this study is the Usangu Plains as the areas have great lack of understanding on groundwater recharge dynamics despite the area being rich in research activities (Rwebugisa, 2008). It is well established that, insufficient information of recharge dynamics leads to the unsuitable development of groundwater resource (Shah *et al.,* 2000), which is a key element to expand the water supply to satisfy the domestic use and irrigation requirements. Due to the increasing irrigation water demands in Usangu Plains and the anticipated shifts of water withdrawal towards groundwater, the assessment of groundwater recharge dynamics is recommended with its spatial and temporal distribution for its efficient use.

Diverse methods have been used for the groundwater recharge quantification (Scanlon *et al.,* 2002). They can be generally categorized into numerical modelling, physical techniques, water balance approaches, chemical tracing, streamflow analysis and many more (Huet *et al.,* 2016). For the spatial and temporal evaluation of groundwater recharge, the numerical modelling approaches have been appreciated by many researchers for the accurate, reliable, and rapid estimations (Arshad *et al.,* 2020; Batelaan and De Smedt, 2007; Hailu *et al.,* 2018; Kashaigili *et al.,* 2006; Maréchal et al., 2006; Meresa and Taye, 2019; Wahyuni *et al.,* 2008). Among numerical modeling approaches, the use of GIS (Geographical Information System)-based models is adequate in handling the spatial and temporal variability (Tilahun and Merkel, 2009). In particular, the Water and Energy Transfer between Soil, Plants, and Atmosphere under quasi-Steady State (WetSpass) model has been used to evaluate the temporal averages and spatial differences of groundwater recharge on a seasonal and annual basis. The GIS-based WetSpass model functions depending on groundwater levels, topography, land use, soil texture and hydrometeorological factors (Batelaan and De Smedt, 2007).

This study is designed to analyze the groundwater recharge dynamics for Usangu Plains aquifer using the GIS-based WetSpass model. Specifically, the study intends to (1) determine the water budget components, (2) investigate the groundwater recharge zones and (3) evaluate the quantity of groundwater that can be extracted safely from the Usangu Plains aquifer for economic and domestic use to enhance the sustainable management of the water sources.

Materials and methods

Description of the study area

The study was conducted in Usangu plains, Tanzania (Fig. 1). The area is located at an average elevation of 1,100 m above mean sea level (amsl). The area is encircled by the Kipengere, Poroto and Chunya mountains with an elevation reaching 3,000m amsl. Usangu Plains cover an area of approximately 20,810 km^2 (Kadigi *et al.,* 2004) and lie between latitudes 7°41' and 9°25' South and longitudes 33°40' and 35°40' East. Its climate is mostly influenced by the air mass movements together with inter-tropical convergence zone (Kashaigili *et al.,* 2009). The Usangu Plains' rainfall regime is unimodal, having one wet season from December to June, with some irregularities, the rainfall distribution varies spatially and is very localized depending on the altitude (Kashaigili *et al.,* 2009). The mean annual rainfall is between 1000 and 1600 mm within the highlands while the central plains, formed of dry fans and wetlands ecosystems, receives 500-700 mm from July to November (Malley *et al.,* 2009). The Usangu Plains' mean annual temperature is between 18°C and 28°C in the highlands and lower parts, respectively and its mean annual potential evapotranspiration goes up to 1,900mm (SMUWC, 2001). The land vegetational cover differs from the high to the low altitudes, where between 2,000m and 1,100m amsl are dominated by the miombo woodland and below 1,100m amsl are the fans, the wetland ecosystems, and agricultural lands (SMUWC, 2001). The high increase of population and the expansion of anthropogenic activities within and in the vicinity of the wetlands have caused the extreme water demand. In both dry and wet seasons, there are water demand for irrigation, domestic use, livestock, brickmaking, and hydropower which is the major water user though taking place a long way downstream (SMUWC, 2001).

Description of the WetSpass Model

The WetSpass model is used to evaluate the groundwater recharge dynamics in the Usangu plains. The model is meant to simulate the temporal average and spatial differences of groundwater recharge, surface runoff and actual evapotranspiration. WetSpass stands for Water and Energy Transfer between Soil, Plants and Atmosphere under quasi-Steady State (Batelaan and De Smedt, 2001). This model is fully integrated in the GIS ArcView (version 3.2) as raster model, coded in Avenue. WetSpass is a steady state spatially distributed and physically based water balance model. It simulates yearly and seasonal long-term average spatial patterns of the water budget components by employing physical and empirical relationships. Inputs for this model include grids of land use,

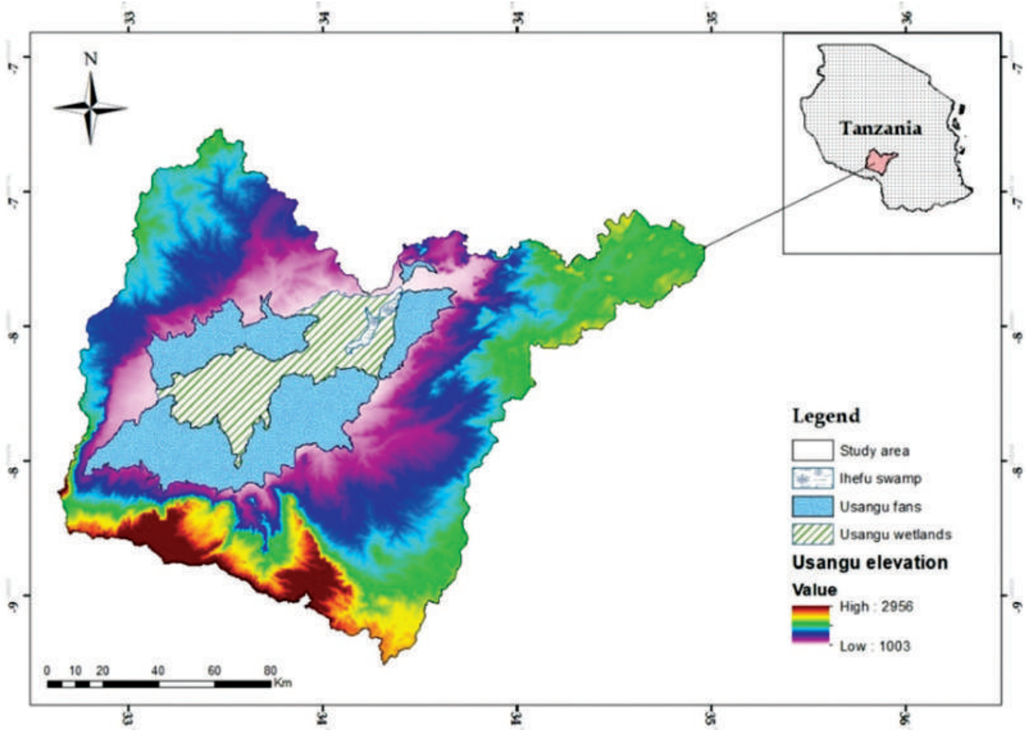

Figure 1: Map of Usangu Plains showing topography, fans, wetlands, and swamp

groundwater depth, precipitation, potential evapotranspiration, wind-speed, temperature, soil, and slope whereby parameters such as land-use and soil types are connected to the model as attribute tables of their respective grids.

Given that WetSpass is a distributed model, the water balance calculation is executed at a raster cell level. Individual raster water balance is obtained by summing up independent water balances for the vegetated, bare soil, open water, and impervious fraction of a raster cell (Fig. 2). The total water balance of a given area is thus calculated as the summation of the water balance of each raster cell (Batelaan and De Smedt, 2007).

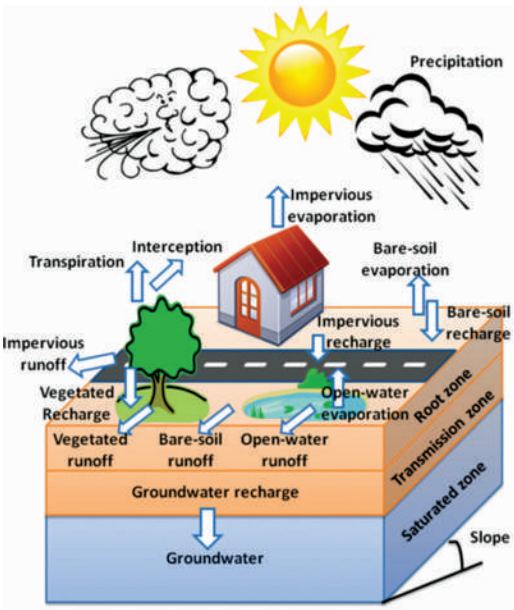

Figure 2: Schematic representation of water balance for a hypothetical landcover grid cell (Batelaan and De Smedt, 2007)

Concerning a vegetated area, the water balance depends on the average seasonal precipitation (P), interception fraction (I), surface runoff (S_v), actual transpiration (T_v), and groundwater recharge (R_v) all with the unit of [LT-1], referring to the equation given below:

$$P = I + S_v + T_v + R_v \qquad (1)$$

Using the water balance components of vegetated, bare soil, open water, and impervious areas, the total water balance of a raster cell is therefore calculated as illustrated in the following equations:

$$ET = a_v\,ET_v + a_s\,E_s + a_o\,E_o + a_i\,E_i \qquad (2)$$

$$S = a_v S_v + a_s S_s + a_o S_o + a_i S_i \qquad (3)$$

$$R = a_v R_v + a_s R_s + a_o R_o + a_i R_i \qquad (4)$$

Where ET, S and R are the total evapotranspiration, surface runoff, and groundwater recharge of a raster cell respectively, each having a vegetated, bare soil, open water and impervious area component denoted by a_v, a_s, a_o, and a_i, respectively.

Description of input data for WetSpass model

As the WetSpass model necessitates seasonal-based parameters, seven months (December, January, February, March, April, May, and June) are considered as wet (winter) season and the remaining five months (from July to November) as dry (summer) season for the case of Usangu Plains (Kashaigili *et al.,* 2009).The inputs data were prepared in the form of grid maps using ArcGIS software (ArcGIS Desktop version 10.8 Copyright © 1995-2019 Esri Inc., USA) and parameter tables were edited in Microsoft Excel 365 (Microsoft Corporation, Redmond, WA, USA) and converted to dbf format by Advanced XLS Converter. The grid maps were of land-use, soil texture, slope, topography, groundwater levels, precipitation, potential evapotranspiration, temperature, and wind speed. The cell size of grid maps was 30m by 30m and had 7646 columns and 6345 rows. The grid maps were prepared through the ArcGIS environment using universal linear kriging interpolation method. The nearest and bilinear resampling techniques were used to set, respectively, continuous (all weather parameters) and discrete (soil) grid maps to the same resolution (30m). The input files prepared as parameter tables were summer and winter land use, soil texture and runoff coefficient. The runoff parameter table contains runoff coefficients for land use, soil type and slope angles.

Hydrometeorological inputs

This study used global meteorological data provided by the NASA POWER version 1.0 last modified in 2019/12/19 (https://power.larc.nasa.gov/data-access-viewer/). The collected data from twelve global stations of the NASA

POWER within Usangu were precipitation, dew point, temperature (maximum and minimum), and wind speed at 2m of height from the soil surface. These daily data ranging from 01/01/2000 to 31/12/2017 were validated based on the observed meteorological information from Igawa, Kimani, Msembe and Matamba weather stations of the Usangu Plains. Solar radiation was derived from temperature using the Hargreaves' radiation formula. The daily extraterrestrial radiation values from Allen *et al.* (1998) were averaged to get monthly figures, given that Usangu plains are located in the southern atmosphere between 7 and 10 degrees of latitude. The actual evapotranspiration was computed through the Instat computer package which uses the FAO-Penman Monteith equation, as it is globally recommended for calculating the evapotranspiration (Rwebugisa, 2008). For the WetSpass requires meteorological inputs in the grid format on a seasonal basis, the universal linear Kriging interpolation method in the ArcGIS environment was used to prepare the grid maps of precipitation, temperature, wind speed and evapotranspiration; both for wet and dry seasons.

Groundwater (GW) level fluctuation data were obtained from the Rufiji Basin Water Board (RBWB). Six years, ranging from 2015-2020, daily groundwater level data of six boreholes were availed. The universal linear Kriging interpolation technique of the ArcGIS Desktop10.8 environment was used to generate the grid maps of the wet and dry seasons of GW depths. The adoption of mean GW depths does not influence the WetSpass simulation results if the GW depths in the study area are more than the root depths (Tilahun and Merkel, 2009). Since the water balance is regulated by some factors like precipitation, soil texture and land cover types (Nyagwambo, 2006), the combined method in ArcGIS environment was used to detect the influence of biophysical features on the water budget components.

Table 1: The summary of meteorological data used

Parameter	Season	Minimum	Average	Maximum
Precipitation (mm)	Wet	800	1001	1229
	Dry	80	105	132
	Annual	893	1106	1361
Temperature (C)	Wet	17.99	20	21.66
	Dry	18.04	20	23.09
	Annual	18.01	19.90	22.37
Wind speed (m/s)	Wet	0.70	1.00	1.88
	Dry	1.18	2.00	3.00
	Annual	0.94	1.69	2.44
Evapotranspiration (mm)	Wet	651.7	728	808.9
	Dry	582.7	710	850.6
	Annual	1234.4	1438.2	1659.5

Areal-based biophysical inputs

Topography and slope

For slope and topography data, digital elevation model (DEM) of the study area was extracted from the Shuttle Radar Topography Mission (SRTM) available on the United States geological survey (USGS) earth explorer website (https://earthexplorer.usgs.gov/) at a spatial resolution of 30m. The raster images were imported into ArcGIS 10.8 and merged to cover the whole study area. With the Usangu basin boundary, its raster was clipped from the combined satellite images. The clipped raster of Usangu was used to create elevation and slope grid maps of the Usangu Plains using spatial analyst tools of ArcGIS 10.8, considering the year 2017 for spatial data. The elevation ranges from 1003m to 2956m (Fig. 3(b)) above mean sea level with an average of 1429m and the slope varies from 0% to 74% (Fig. 3(a)).

Soil texture

Soil textural information is an important input of the WetSpass model for the recharge quantification. As far as this study is concerned, the soil data were obtained from the FAO-UNESCO (http://www.fao.org/geonetwork/srv/en/metadata.show%3Fid=14116) digitized (vector dataset) soil map of the world at a scale of 1:5,000,000. ArcGIS software was used to clip the soil textural map of the Usangu Plains from the digital soil map of the world. The attribute table of soil textures of Usangu was adjusted using the Soil Water Characteristics program developed by United States Department of Agriculture (USDA) Agricultural Research Service (http://hydrolab.arsusda.gov/soilwater/Index.htm). The textural classes were found to be clay (24%), clay loam (32%), sandy clay loam (13%), loamy sandy (3%) and sandy loam (28%) (Fig. 3(c)). The soil classes outputs of this program were validated based on the soil textural triangle.

LULC classification

Land use/land cover data were processed based on Landsat 8 images of the year 2017 extracted from the United States geological survey (USGS) earth explorer website at a spatial resolution of 30m. Usangu catchment covers three different paths and rows, the periods of the Landsat images used in the area of interest and their respective rows and paths are given in Table 2. Land use classification was made using Random Forest classifier in the R-Studio software after performing a supervised classification in ArcGIS environment to generate the spectral classes (regions of interest, ROI). The classification accuracy assessment was executed based on the Google Earth pro truths of

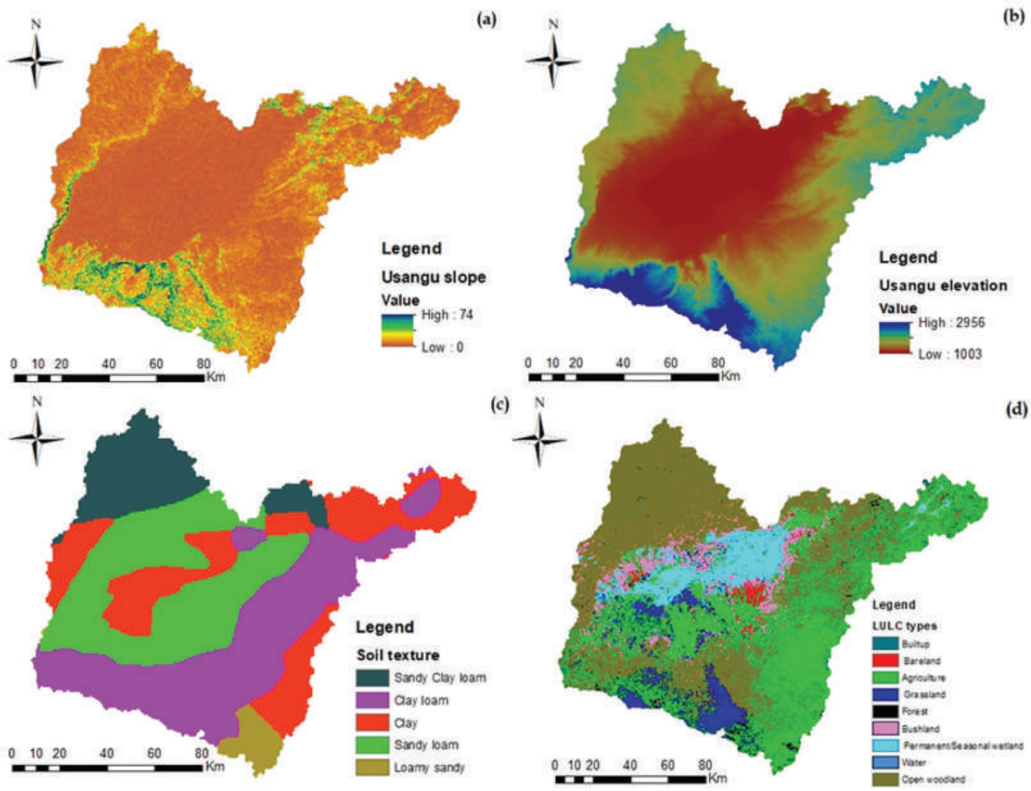

Figure 3: Slope map (a), topographic map (b), Soil textural map (c) and LULC map (d) of the Usangu Plains

the Usangu catchment boundaries. The overall classification accuracy was 82.5% while the overall Kappa statistics was 83.2%. Normally, the land use/ land cover classification accuracy assessment results (Fig. 3(d)) in this study are satisfactory, for the kappa statistics greater than 80% represent strong accuracy between the performed classification and ground truth information (Manandhar *et al.,* 2009).

Table 2: characteristics of the Landsat 8 images of the Usangu Plains

Period	Path	Row
2017-05-02 / 2017-05-15	168	066
2017-11-17 / 2017-11-22	169	066
2017-11-17 / 2017-11-22	169	065

Results

The water budget components of the Usangu plains

Surface runoff

The spatial mean annual surface runoff estimated by the model is presented in Figure 4(a). Seasonal and annual average values of surface runoff are illustrated Table 3 in comparison with the annual average rainfall and other features. The annual surface runoff simulated by the model varies from 1 to 1,005 mm with an average of 178mm which represents 16.1% of the annual mean rainfall (1106 mm). About 85.4% of the surface runoff occurred in the wet season while the remaining 14.6% happened during the dry season. The maximum amount of annual average surface runoff (813-1005mm) takes place in the built-up and in bare land vegetation types given the impervious state of their ground surfaces. On the other hand, the minimum runoff (1-95mm) occurred in sandy loam and loamy sandy soil types (Fig. 4(a) and 5(a)).

Evapotranspiration

The WetSpass model computed the total actual evapotranspiration (AET) as a sum of evaporation from the bare soil within land cover types, evaporation from rainwater intercepted by vegetation, evaporation from open water bodies, and transpiration from the vegetation canopy. The simulated spatial mean annual AET is presented in Figure 4(b) and compared to the mean annual precipitation in Table 3. The annual average AET is 731mm which represents 66.1% of the annual rainfall (table 3). 80.4% (588m) of the mean annual evapotranspiration occurred in the wet season whereas 19.6% (143mm) happened in the dry season. The maximum evapotranspiration took place in the seasonal/ permanent wetlands and water body (Fig. 5(b)). The next highest values of evapotranspiration occurred in the forest, this is because of the high transpiration and evaporation from the intercepted water. The lowest values are from built-up and bare land due to the impermeable surfaces which allow more surface runoff than transpiration and interception.

Groundwater recharge

The average long-term annual groundwater recharge in the Usangu plains simulated by the WetSpass model is presented in Figure 4(c) with comparison to the annual average precipitation in Table 3. The simulation results proved the spatial and temporal variations of the groundwater recharge process within the area. The recharge dynamics depend much on the hydrometeorological conditions, land use/ landcover composition and soil textures. The model results for the winter, summer and annual average recharge are 254mm, -29mm and 226mm, respectively. This temporal variation of recharge is caused by the reason that during dry season there is high evapotranspiration compared to the precipitation. The fact that the mean dry season recharge reached a negative value of -29mm indicated the absence of groundwater recharge and led to a decrease of 2.6% of annual average recharge.

Therefore, about 17.8% (197mm) of the annual average recharge represents the contribution of the rainfall to the groundwater storage. The highest annual values of recharge occurred in all soil classes covered by open woodland but specifically in loamy sandy and sandy loam soil types. The lowest recharge values appeared in clay soils covered by wetlands, bare land, and water body; and sandy clay loam soils covered by water body (Fig. 5(c)).

Table 3: Water budget components of Usangu Plains simulated by the WetSpass model

Parameter	Summer (mm)	Winter (mm)	Annual (mm)	Percentage (%)
Precipitation	105	1001	1106	100
AET	143	588	731	66.1
Surface runoff	26	152	178	16.1
Recharge	-29	254	226	17.8

Groundwater recharge zones of the Usangu Plains

Ensuing the total annual groundwater recharge, the potential recharge zones in the Usangu Plains are illustrated in Figure 4(d). The natural break slice method in the ArcGIS environment was used to investigate the recharge zones. There were three zones of recharge with different rates (0-138mm/year, 139-337mm/year and 338-767mm/year). The groundwater recharge zone with the highest recharge rates occupied 47% of the total Usangu area, the zone receiving the moderate recharge rates has 30% while the zone with the lowest rates occupied 23%.

On Figure 4(d), groundwater recharge is mostly happening in the southern part and in some zones of the north-eastern and north-western places. The moderate recharge rates occurred in the northern and some central zones of the area. The lowest rates are located majorly in the central and southwestern zones of the Usangu catchment.

Groundwater safe yield of Usangu Plains

The term safe yield of groundwater in a catchment is used when determining the amount of water that can be extracted from the catchment without depleting the storage (Meyland, 2011). Safe yield is considered as percentage of

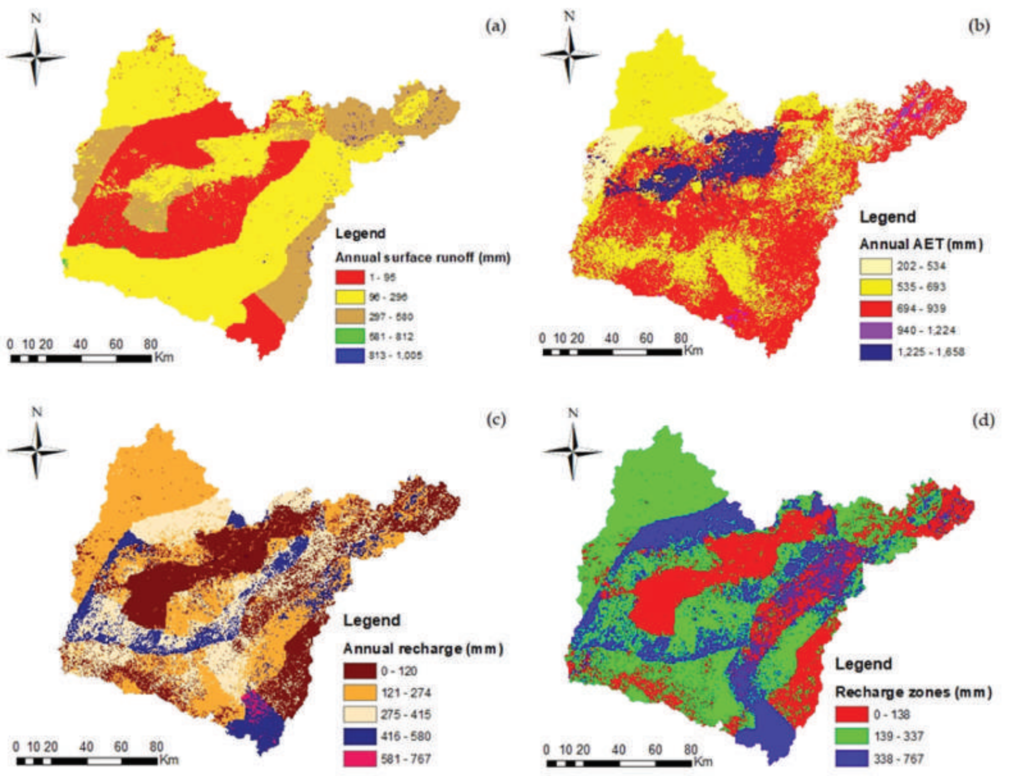

Figure 4: Map of annual average of surface runoff (a), annual average of AET (b), annual average of recharge (c) and recharge zones (d) of the Usangu Plains

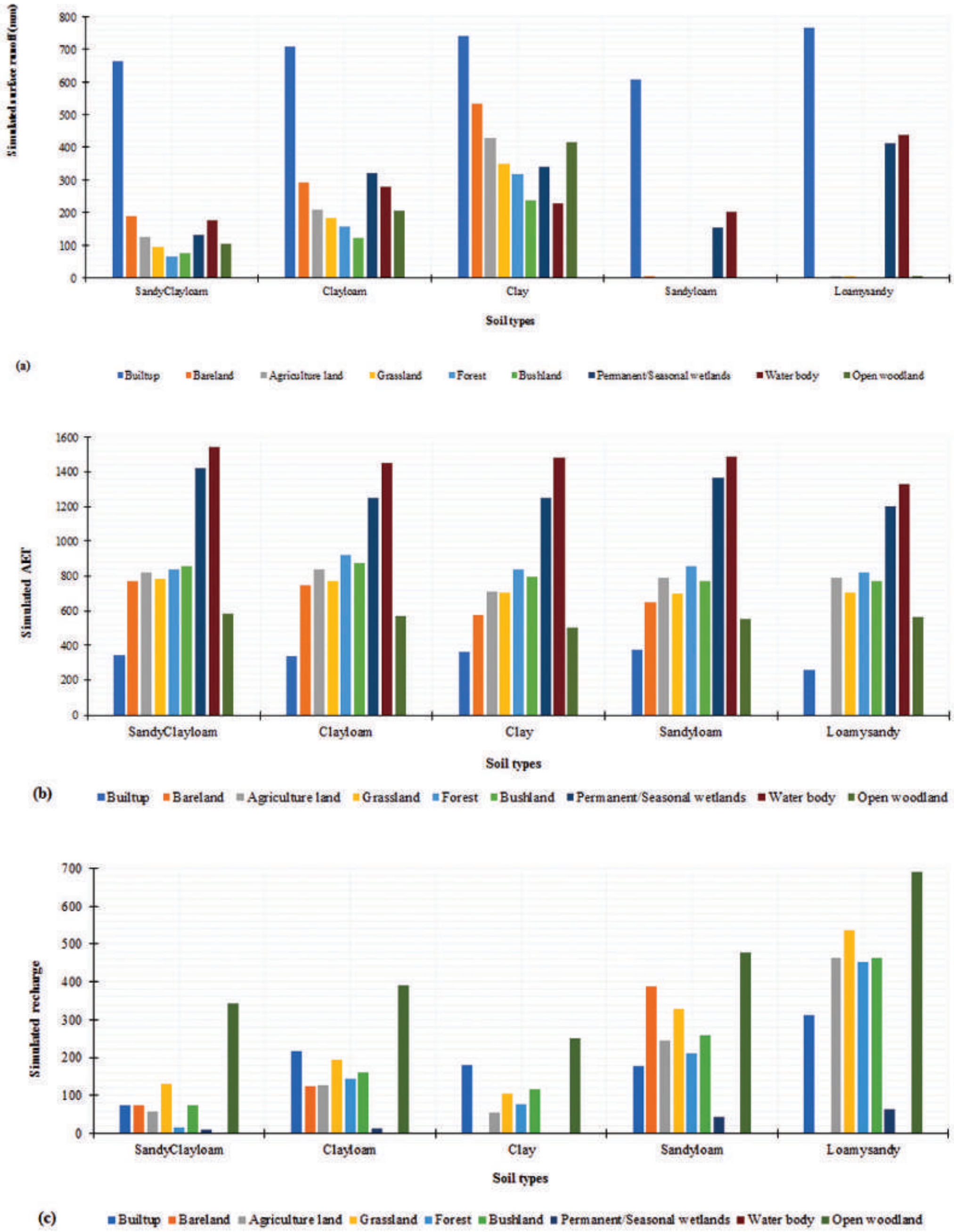

Figure 5: Simulated mean annual surface runoff for combinations of LULC and soil texture (a), simulated mean annual AET for combinations of LULC and soil texture (b), simulated mean annual recharge for combinations of LULC and soil texture (c).

groundwater recharge; moreover, a number of authors suggest different percentages of safe yield, from the least conservative (100%) to the reasonably conservative (10%) (Gebreyohannes *et al.,* 2013). This concept implies the sustainable groundwater management to the extent of not exceeding the annual recharge and remain within the safe level of groundwater

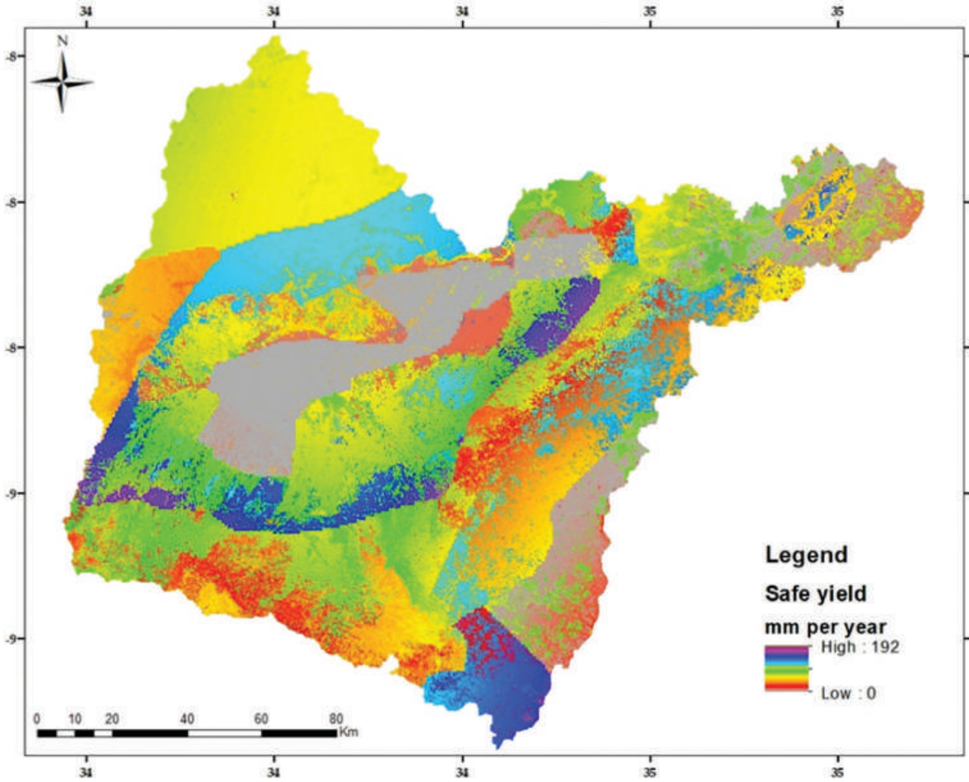

Figure 6: groundwater safe yield of the Usangu Plains

utilization (Russo *et al.,* 2014). Practically, the sustainable yield of groundwater of more than 10% of annual recharge requires to account for the groundwater-dependent ecosystems (Zeabraha *et al.,* 2020). Three studies done in Ethiopia (Gebreyohannes *et al.,* 2013; Meresa and Taye, 2019; Zeabraha *et al.,* 2020) adopted the safe yield of 25% of recharge. Consequently, the reasonably conservative estimate of safe yield of 25% of the mean annual recharge was adopted for the Usangu plains from the formula below:

$$SY = 0.25*R \quad (5)$$

where SY is safe yield (mm/year) and R the total mean annual groundwater recharge (mm/year). According to equation 12 and Figure 6, the groundwater safe yield ranges from 0 to 192mm/year with an average of 49.25 mm/year. Considering the area of Usangu (20810km^2), 1.025km^3/year of groundwater can be safely withdrawn for irrigation, domestic use and many more purposes. 3.996 km^3 being the maximum of groundwater to be extracted annually.

Discussion

The aim of this study was to evaluate the spatial and temporal (seasonal and annual) distribution of the groundwater recharge in Usangu Plains using the WetSpass model. The model simulated the water budget components (surface runoff, actual evapotranspiration, and groundwater recharge) of the Usangu Plains.

Surface runoff depends mainly on the availability of land use/landcover types, soil type, rainfall, topography and slope of the area (Batelaan and De Smedt, 2007). As Figure 5(a) illustrates, surface runoff was very high in the clay, clay loam and sandy clay loam soils covered with built-up and bare land because of the less infiltration capacities of the soil types similar to the findings of the study done by Zeabraha *et al.* (2020). Likewise, the highest values of surface runoff occurred in sandy loam and loamy sandy soils covered by built-up areas due to the imperviousness of this surface cover type. On the other hand, the minimum surface runoff happened in loamy sand and sandy loam soils covered by forest, open woodland, bushland, agricultural land, grassland, and uncovered soils as a result of the highest permeability of the soils and the high evapotranspiration rate of the land cover types. As SMUWC (2001) reported, a high proportion of vegetation in Usangu reduces the rate of runoff. There was less runoff amount in the lowland compared to the highland of Usangu (Fig. 3). Similar to the study done by Tilahun and Merkel (2009), this study showed that elevation and slope are major factors causing the high surface runoff rate.

The study of Helena (2016) showed a great increase of evapotranspiration in the Usangu catchment in both dry and wet seasons. This is proved by the fact that the evapotranspiration losses passed from about 700mm/year (SMUWC, 2001) to 731mm/year as per the findings of this study. The high rate of AET occurred in sandy clay loam soil covered by open water sources, then followed clay loam covered by forest. Uncovered loamy sandy soils present low rates (Fig. 5(b)). AET decreased in the highlands compared to the lowlands of the Usangu Plains because of the high altitudes and low temperature. This decrease of AET in highland can be a factor to enhance agricultural activities during dry season. In agreement with other studies conducted in Usangu catchment and worldwide (Kashaigili *et al.,* 2009; Rwebugisa, 2008; SMUWC, 2001; Helena, 2016 and Zeabraha *et al.*, 2020), the major factors influencing the actual evapotranspiration are soil texture, land use/landcover types and climate parameters.

SMUWC (2001) defined the lowlands in Usangu catchment as areas below about 1100m of elevation and the remaining areas above 1100m to be the highlands. The same report (SMUWC, 2001) considers the whole zone of highlands as groundwater recharge area. Similarly, this study found that the highest recharge rate occurred in the south-western highland and slightly above the lowland zones (Fig. 4(d)). The minimum recharge happened in the lowlands particularly the zones covered by the permanent and seasonal wetlands for they act as discharge zones of the catchment. Figure 5(c) shows the maximum occurrence of recharge in loamy sandy and sandy loam soils covered by open woodland, grassland, bushland, and agricultural land due to the fact that the soil types have good infiltration capacity and the land use/landcover types which reduce surface runoff rate. It is also due to the low rate of evapotranspiration caused by less temperature and high elevation (SMUWC, 2001). A study done in Ethiopia (Meresa and Taye, 2019) indicated that clay soils covered with wetlands, water bodies and clay-based bare lands had low recharge values similar to the findings of this study (Figure 4(d)). The comprehensive understanding of potential recharge zones in the Usangu Plains is of paramount benefit for locating areas of conservation.

The study conducted in Dodoma, Makutupora basin, indicated that recharge represents 1-2% of annual rainfall (Rwebugisa, 2008), this is because the area is arid and receives less amount of annual rainfall compared to Usangu Plains. In contrast, 17.8% of annual rainfall in Usangu Plains go to the groundwater reserve. The sustainable groundwater yield was adopted to be 25% of the annual groundwater recharge (Fig. 6) to account for other groundwater-dependent users as it has been stated by the study conducted in Ethiopia (Zeabraha *et al.,* 2020). The information on the safe yield plays a tremendous role in conserving the groundwater storage. This study agreed that topographic, soil types, land use and land management are driving factors of spatial and temporal recharge dynamics.

Conclusions and Recommendations

Groundwater usage covers many sectors such as irrigated agriculture, domestic use, industrialization, livestock, and many more. Sustainable management of the groundwater storage is vital; however, it requires a clear understanding of the groundwater recharge distribution whether spatially and/or temporally. This study aimed at evaluating the groundwater recharge dynamics in the Usangu plains using the hydrological WetSpass model to help water users and decision makers have a comprehensive understanding of the quantity of recharge that replenishes the groundwater storage. The model showed that 17.8% of the annual rainfall goes to groundwater storage while 16.1% and 66.1% go to surface runoff and actual evapotranspiration, respectively. Low slopes and a high proportion of vegetation were found to reduce the surface runoff, hence increase the groundwater recharge contribution. Open water sources and vegetated soils have high rates of actual evapotranspiration. The model reported the absence of groundwater recharge in the dry season; however, 47% of the total Usangu area receives the high rates (338-767mm/year) of groundwater recharge in southern zone and some zones of the north-eastern and north-western area. The northern and some central zones of the Usangu Plains are moderately recharged while the lowest recharge rates occurred mainly in the central and southwestern zones. The groundwater safe yield was 25% of the total annual recharge allowing 1.025km^3/year to be sustainably abstracted to mainly support all the water requirements in the Usangu plains without depleting the groundwater storage. The findings of this study are useful as a base for future groundwater recharge-oriented considerations. Further studies are needed to understand the interactions between groundwater recharge dynamics and groundwater withdrawal (pumping) actions in the Usangu Plains for the sound and efficient management. Moreover, there must be rigorous regulations for groundwater drilling/extracting entities to not deplete the water storing capacity which may lead to the water usage conflicts. Compared to the water lost through evapotranspiration, the simulated portion of groundwater recharge is obviously low. Consequently, it could be wise to initiate the rainwater harvesting technologies and artificial groundwater recharge strategies particularly in the zones with moderate and low recharge rates to boost the groundwater storage as its users cannot cease to increase.

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References

Allen, R.G., Pereira, L.S., Raes, D. and Smith, M. (1998). Guidelines for Computing Crop Water Requirements. Irrigation and Drainage Paper 56. FAO, Rome, Italy, 200pp.

Arshad, A., Zhang, Z., Zhang, W. and Dilawar, A. (2020). Mapping favorable groundwater potential recharge zones using a GIS-based analytical hierarchical process and probability frequency ratio model: A case study from an agro-urban region of Pakistan. Geoscience Frontiers 11(5): 1805–1819.

Batelaan, O. and De Smedt, F. (2007). GIS-based recharge estimation by coupling surface-subsurface water balances. *Journal of Hydrology,* 337(3–4): 337–355.

Batelaan, O. and Woldeamlak, S.T. (2003). ArcView Interface for WetSpass, User Manual, Version 1-1-2003. Department of Hydrology and Hydraulic Engineering, Vrije Universiteit Brussel, 50 pp. + app.

Bhanja, S.N., Zhang, X. and Wang, J. (2018). Estimating long-term groundwater storage and its controlling factors in Alberta, Canada. Hydrology and Earth System Sciences 22(12): 6241–6255.

Fenta, A.A., Kifle, A., Gebreyohannes, T. and Hailu, G. (2014) Spatial analysis of groundwater potential using remote sensing and GIS-based multi-criteria evaluation in Raya Valley, northern Ethiopia. Hydrogeology 23(1): 195–206.

Foster, P.S. (2016). Evaluation of the UNESCO Category 2 Centre. Final Report. International Groundwater Resources Assessment Centre, Netherlands. 77pp.

Gebreyohannes, T., De Smedt, F., Walraevens, K., Gebresilassie, S., Hussien, A., Hagos, M., Amare, K., Deckers, J. and Gebrehiwot, K. (2013). Application of a spatially distributed water balance model for assessing surface water and groundwater resources in the Geba basin, Tigray, Ethiopia. *Journal of Hydrology* 499: 110–123.

Hailu, G., Tesfamichael, K., Mewcha, G., Gebremedhin, A. and Gebrekirstos, A. (2018). Spatial groundwater recharge estimation in Raya basin, Northern Ethiopia: an approach using GIS based water balance model. Sustainable Water Resources Management.

Helena E.S. (2016). Estimating baseflow in the Usangu catchment, Tanzania : accounting for the influence of evapotranspiration. Dissertation for Award of MSc Degree at University College London, United Kingdom, 72pp.

Huet, M., Chesnaux, R., Boucher, M. and Poirier, C. (2016). Comparing various approaches for assessing groundwater recharge at a regional scale in the Canadian Shield. *Hydrological Sciences Journal,* 61(12): 2267–2283.

Kadigi, R.M.J., Kashaigili, J.J. and Mdoe, N.S. (2004). The economics of irrigated paddy in Usangu Basin in Tanzania: Water utilization, productivity, income, and livelihood implications. Physics and Chemistry of the Earth 29(15-18): 1091–1100.

Kashaigili, J.J., McCartney, M.P., Mahoo, H.F., Lankford, B.A., Mbilinyi, B.P., Yawson, D.K. and Tumbo, S.D. (2006). Use of a hydrological model for environmental management of the Usangu wetlands, Tanzania. Colombo, Sri Lanka: International Water Management Institute. 48p. (IWMI Research Report 104)

Kashaigili, J.J., Mbilinyi, B.P., Mccartney, M. and Mwanuzi, F.L. (2006). Dynamics of Usangu plains wetlands: Use of remote sensing and GIS as management decision tools. Physics and Chemistry of the Earth 31(15–16): 967–975.

Lei, W., Brighid, D. and David, M. (2010). A Literature Review of Recharge Estimation and Groundwater Resource Assessment in Africa. Report No. 51. British Geological Survey Internal, England. 31pp.

Mahoo, H, Simukanga L, K.R.A.L. (2015). Water Resources Management in Tanzania: Identifying Research Gaps and Needs and Recommendations for a Research Agenda. *Tanzania Journal of Agricultural Science* 14(1): 57–77.

Malley, Z.J.U., Taeb, M., Matsumoto, T. and Takeya, H. (2009). Environmental sustainability and water availability: Analyses of the scarcity and improvement opportunities in the Usangu plain, Tanzania. Physics and Chemistry of the Earth 34(1–2): 3–13.

Maréchal, J.C., Dewandel, B., Ahmed, S., Galeazzi, L. and Zaidi, F.K. (2006). Combined estimation of specific yield and natural recharge in a semi-arid groundwater basin with irrigated agriculture. *Journal of Hydrology* 329(1–2): 281–293.

Meresa, E. and Taye, G. (2019). Estimation of groundwater recharge using GIS-based WetSpass model for Birki watershed, the eastern zone of Tigray, Northern Ethiopia. Sustainable Water Resources Management 5(4): 1555–1566.

Meyland, S.J. (2011). Examining safe yield and sustainable yield for groundwater supplies and moving to managed yield as water resource limits become a reality. WIT Transactions on Ecology and the Environment 145: 813–823.

Nyagwambo, L.N. (2006). Groundwater Recharge Estimation and Water Resources Assessment in a Tropical Crystalline Basement Aquifer. Dissertation for Award of PhD Degree at Delft University of Technology International in Delft, The Netherlands, 182pp.

Ramita, M., Inakwu, O.A. and Tiho, A. (2009). Improving the Accuracy of Land Use and Land Cover Classification of Landsat Data Using Post-Classification Enhancement. Remote Sensing (1): 330-344.

Russo, T., Alfredo, K. and Fisher, J. (2014). Sustainable water management in urban, agricultural, and natural systems. Water (Switzerland) 6(12): 3934–3956.

Rwebugisa, R. A. (2008). Groundwater recharge assessment in the Makutupora basin, Dodoma, Tanzania. Dissertation for Award of MSc Degree at International Institute for Geo-Information Science and Earth Observation, Enschede, The Netherlands, 111pp.

Scanlon, B.R., Healy, R.W. and Cook, P.G. (2002). Choosing appropriate techniques for quantifying groundwater recharge. *Hydrogeology Journal,* 10(1): 18–39.

Scanlon, B.R., Keese, K.E., Flint, A.L., Flint, L.E., Gaye, C.B., Edmunds, W.M. and Simmers, I. (2006). Global synthesis of groundwater recharge in semiarid and arid regions. Hydrological Processes 20(15): 3335–3370.

Shah, T., Molden, D., Sakthivadivel, R. and Seckler, D. (2000). The global groundwater situation: Overview of opportunities and challenges. Colombo, Sri Lanka: International Water Management Institute.

SMUWC. 2001b. Final Report, Water Resources. Supporting report 7, Volume 3. Directorate of Water Resources Dar es Salaam, Tanzania. 203p

Tilahun, K., and Merkel, B.J. (2009). Estimation of groundwater recharge using a GIS-based distributed water balance model in Dire Dawa, Ethiopia. *Hydrogeology Journal* 17(6): 1443–1457.

Vries, J. J. and Simmers, I. (2002). Groundwater recharge: an overview of processes and challenges. *Hydrogeology Journal,* 10: 5 – 17.

Wahyuni, S., Oishi, S. and Sunada, K. (2008). the Estimation of the Groundwater Storage and Its Distribution in Uzbekistan. Proceedings of Hydraulic Engineering 52, 31–36.

Zeabraha, A., G/yohannes, T., W/Mariyam, F., Mulugeta, A. and Gebreyesus, Z. (2020). Application of a spatially distributed water balance model for assessing surface and groundwater resources: a case study of Adigrat area, Northern Ethiopia. Sustainable Water Resources Management 6(4): 1–19.