ASSESSING THE SPATIAL AND TEMPORAL CHARACTERISTICS OF GROUNDWATER RECHARGE IN ZANZIBAR: TOWARDS THE OPTIMAL MANAGEMENT OF GROUNDWATER RESOURCES

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March 2011

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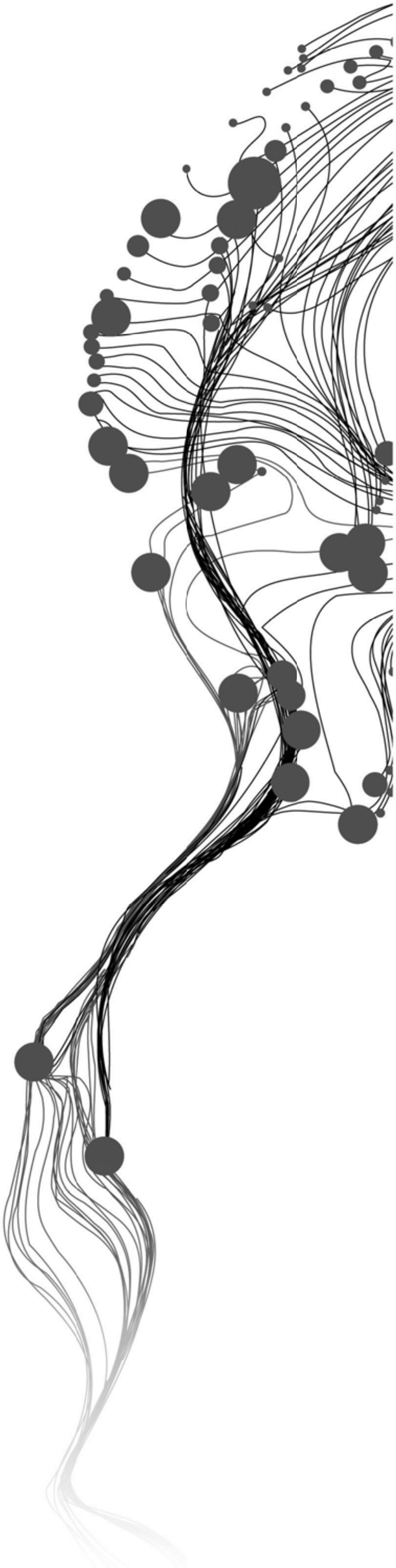

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Enschede, The Netherlands, March, 2011

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ABSTRACT

A recharge model for the Island of Zanzibar was simulated for the years 2007-2009 using SWAT. It shows that there are spatial and temporal variations in the distribution of recharge because of the variations in soil, land use and precipitation. Temporally, the highest recharge occurs during April to June and November to January, deviation of one month each from the regular rainy seasons which occur from March to May (Masika season) and October to December (Vuli season). The mean recharge contributed by Masika and Vuli rains was estimated to be 28% of the average yearly rain. This recharge does not include that which is contributed by sinking streams. The simulated average mean monthly flows for all the sinking streams total 5.7 cum/s. The spatial distribution of recharge show that most land cover over clayey soils with slowly permeable layer has marked low recharge compared to other land cover. The soils of significant recharge are the loamy soil products of the coralline limestone. Bushes overlying these soils show higher recharge than other land cover. Because of the distribution of precipitation, the northern portion of the Island has higher recharge than the southern portion.

The limited current and historical stream flow data and the distribution of real streams, as well as NDVI, were used to guide the parameterization of inputs to the model. The results of SWAT were validated using independent remote sensing derived ET_{act} and stable isotopes. ET_{act} derived from MODIS for two dates (Jan 8 2009 & Mar 6 2009) using SEBS was compared with SWAT ET_{act} for the same dates. Although SEBS ET_{act} and SWAT ET_{act} have different value ranges there are some similarities in the distribution of the high and low ET_{act} values. The reason for the difference in ET_{act} values in SWAT and SEBS is because of the following: instantaneous solar radiation in SEBS is higher than the average daily values required in SWAT; the crop calendar in SWAT does not mirror the events recorded in remote sensing data; the actual canopy characteristics are not reflected in SEBS. For this reason, there is a need to refine the crop calendar and land use map. Stable isotope results (δD and δ^{18}O) from rain and groundwater samples of Zanzibar were also used to verify the temporal variation in recharge. While better comparison can be done when using monthly average values of rainfall, it is still interesting to see that the rain sampled is heavier in δD and δ^{18}O than the groundwater sampled. The deuterium-excess values of groundwater and rain are also markedly different. These results suggest that the light rains during the time of sampling are not the recharge source for the groundwater sampled. The monthly sampling of rain and groundwater is a better and more complete method to establish the differences in isotope characteristics which may reveal seasonal recharge.

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1. INTRODUCTION

Groundwater is of prime importance in Island nations. In the main Island of Zanzibar, groundwater is the only reliable water resource available to supply the growing population and meet the requirements of its major economic sectors of agriculture and tourism.

1.1. Background

The water supply in Zanzibar is sourced mainly from sandy and limestone aquifers (Halcrow, 1994). These aquifers are intersected by more than two hundred wells of the official water supplier of the Island, the Zanzibar Water Authority (ZAWA), as well as by several other small, private, domestic and local dug wells. There are several studies made in the late 80's and early 90's concerning water resources, either for the whole of the Islands, in general, or for the development of specific irrigation, urban and rural water supply schemes for selected areas, in particular. The reports showed that the Island is receiving high amounts of rainfall that eventually replenish the aquifers. ZAWA-AfDB-UNHabitat (2008) indicated that some of the results of these early studies may no longer hold true at the present time and that an update on water resources accounting is imperative. The study by Halcrow (1994)showed that the water supply is enough, until 2015, for a design population for Zanzibar Town of 483,000. Based on the demand, it would appear that supply may no longer be adequate if we consider that the population of Zanzibar Town is already 390,074 by 2002 (TNBS, 2010), according to the national statistics bureau of Tanzania and is estimated at 460,000 in 2008 (TNBS-MFEA, 2009). Estimating the limits of the resource is important in managing the levels of groundwater withdrawals. As the population increase, so is the demand for water supply. But if the limit of the resource is not known, considering the present climate and land uses, groundwater will be poorly managed and more of the population will be inadequately supplied.

A new and promising supply may come from coastal aquifers that are much more productive than they were described in the early studies. This is one of the significant information resulting from the drilling of production boreholes in Zanzibar during the past decade. While this gives a positive insight to the resource, still, a well-established knowledge of the availability and distribution of the groundwater resource is needed. Without this knowledge, there will be insufficient management of the resource resulting in: abstractions that are heavier in certain areas than in others; and a perceived imbalance of water resource distribution. In the east coast, tourism-related abstractions through private wells, caves and piped water, are significant (Gössling, 2001). The tourism industry is and even competing with the local population in the use of water supplied by the government. Additionally, these coastal abstractions will make the problem of saline water intrusion even more significant and which will practically reduce the quantity of the supply.

1.2. Problem Statement

It has been more than a decade since the last assessment of groundwater recharge in Zanzibar. According to Sophocleous (1991), a fundamental component in the competent management of groundwater resources is the quantification of its recharge. The spatial and temporal aspects of recharge are likewise important for the protection of the groundwater resource. The temporal and spatial distribution of recharge is shaped by several factors including the spatial distribution of precipitation, land use, vegetation, soil and lithology.

A reliable assessment of groundwater recharge in Zanzibar will be significantly encumbered by inadequate availability of hydrogeological, hydrological and meteorological data. While there were groundwater studies in Zanzibar in the early 80s and 90s which were supplemented by hydrological, hydrogeological and meteorological monitoring specifically setup for these studies, only a few of these monitoring networks have survived and been maintained to this day.

An important thing to consider in quantifying recharge in Zanzibar is the presence of sinkholes in the karst landscape and the absence of streams in several parts of the Island. Because of the hydrogeological characteristic of the limestone, especially karstic limestone, there will be preferential flow of water into the ground and flow of groundwater through solution channels within the limestone. Previous groundwater recharge computations slightly consider this karstic limestone character, which provides for the localized concentrated recharge into the aquifers, and possibly, if not managed and protected, the direct contamination to these aquifers.

The study of natural recharge is a first step in the proper management of groundwater resources in Zanzibar. Encroachment of land use and economic development into recharge areas will impact the quantity and quality of groundwater in the aquifers. Knowing the spatial and temporal aspect of recharge is important for the protection of the groundwater resources such that informed decisions can be made as to which areas should be protected and which areas should be explored further for supply.

1.3. Research objectives and questions

The main research objective of this study is:

To characterize the spatial and temporal distribution of recharge in Zanzibar Island by using available historical and field information as well as remote sensing products, isotope chemistry, and water budget methods.

The specific objectives and corresponding research questions are shown in the following table:

Specific Objective	*Research Question*
To determine the spatial and temporal distribution of recharge in Zanzibar	-How diverse is the spatial and temporal distribution of recharge in Zanzibar?
To use available remote sensing products to enhance the assessment of recharge	-How can single-time remote sensing products be used to validate and/or enhance estimation of recharge?
To characterize recharge in Zanzibar using isotopes	-How can isotopes be used as significant characterization of recharge in Zanzibar?

Table 1. Specific objectives and questions

2. THE STUDY AREA

The landscape of Zanzibar and its hydrology are shaped by the processes and events that occurred in the geologic past. A better understanding of the environment and processes that shape the water resources of Zanzibar is achieved by a quick look into the past together with a depiction of its present climate and physiography.

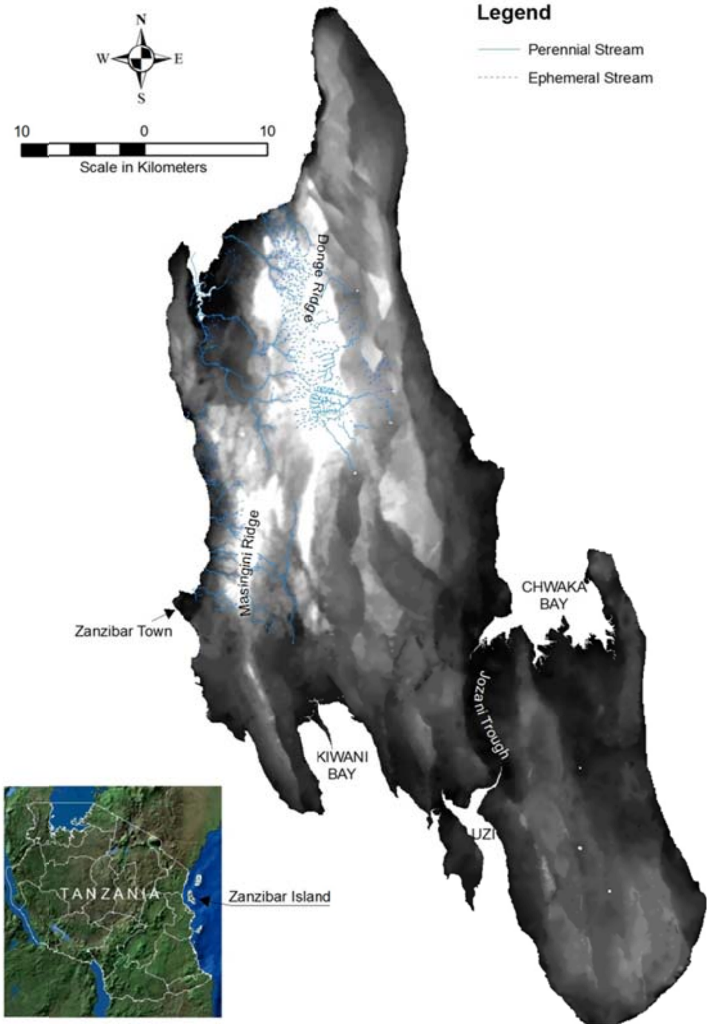


Figure 1. Location of Zanzibar Island

2.1. Physiography

Zanzibar Island (1600 km^2) is located 40 kms off the eastern coast of Tanzania, Africa (Figure 1). The Island lies between 4° 30’ and 6° 30’ South latitudes and between 39° and 40° East longitudes. It is an elongated north-south trending Island which is mostly flat. The highest point, about 120 meters above sea level, is at the north-south trending Masingini Ridge in the north-west. The two types of perennial stream system in Zanzibar, as described by Halcrow (1994), flow from the slopes of Masingini and Donge Ridges and these are: (a) those that physically drain into the sea, and (b) those that disappear inland and are captured by sinkholes, locally known as "pokaisi". These streams define watersheds with definite stream systems (Figure 1). The rest of the Island is generally a broad expanse of "coral rags" with no streams.

2.2. Geology and hydrogeologic setting

Zanzibar is underlain mainly with Lower Miocene rocks consisting of deltaic sandstones associated with marls and minor reef limestones. This is evidenced from the deep borehole drilled by the British Petroleum Company Ltd in the 50's located north of Zanzibar City which encountered about 4300 m of sediments, the upper 2500 m of which consisted of Miocene rocks (Kent, Hunt, & Johnstone, 1971). Fringing the Island and covering mostly the east and south-eastern parts of the Island are raised Quaternary coral reef terraces (Figure 2). The Island was once a part of the ancient delta of Ruvu-Rufiji Rivers of Mainland Tanzania Johnson (1984). Kent, et al.(1971) consider this delta as the largest Tertiary delta in East Africa that was detached from the mainland by drift faulting of the Tanzanian eastern coastal areas. The physiography of the Island was a product of the ancient delta-making process. The Miocene main channel diverged, within the delta, into a characteristic crow's foot pattern of meandering streams with shoe string sand channels which characteristically have thick beds of sands. Johnson (1984) called their surface expressions as corridors. Following rift faulting and uplift, in Pleistocene times, Zanzibar was raised from the sea and cut-off from the mainland, with a submerged portion of the delta becoming a shallow intervening channel in between.

The main deltaic sediments are the dense, tough and resistant materials that now comprise the Masingini and the parallel Donge Ridge. In between these ridges and along depressions and valleys lie the so-called corridors.

Subsequent submergence and exposure to tidal erosion have removed much of the corridor sediments and exposed the original Miocene channels. The reefs and coralline limestones were deposited along the corridor zones during the Quaternary. Following the subsequent and continued falling of sea levels, the growth of these reefal limestones continued much farther away from the Miocene ridges, in the shallow but sunlit portions of the sea along the wide coastal coral rag platform towards the east. Elsewhere in the elevated center of the Island, during these times, erosion of the surrounding Miocene ridges occurred filling the corridors with colluvial deposits of sand and clay and covering the Quaternary limestones.

The geology of Zanzibar (Figure 2 and Table 2) is based on the works of Johnson (1984), Johnson (1987) and Kent, et al. (1971). The schematic cross-section is based on the several lithologic logs of wells taken from the ZAWA archive and the stratigraphic sequence defined by Johnson (1984). The stratigraphic sequence is presented in Table 2, showing also a column on hydrogeologic significance.

At present we can observe all these formations on the surface of Zanzibar (Figure 2), except for the Miocene Marls which serve as the base of the thick aquifers in the corridor zones. From these formations the main aquifers are the Quaternary Limestone and Quaternary Sands/Miocene Sands.

The corridor zones in Figure 2 are considered by Johnson (1984) as the most promising areas for the exploration and development of groundwater, in contrast to the Quaternary Limestone (coral rag areas) in the eastern and southern portions of the Island. However the current information from wells drilled in the coral rags point to a productive aquifer underlying these areas (ZAWA-AfDB-UNHabitat, 2008). The wells and caves in these areas intersect the thin Quaternary Limestone and underlying Miocene Limestone, with the latter providing the major source of water.

The wells in Johnson (1984) have reported transmissivities from 200 to 20,000 m^2/day and with yields of 108 - 600 m^3/h but only a few have survived today and are still being used for irrigation in the corridor zones. One surviving well has a reported reduced capacity of 54 m^3/h from the original 600 m^3/h, according to Engr. H. Zahran of Irrigation Department (personal communication). Most of the high capacity wells at present are used for irrigation.

Wells of ZAWA within the corridor zones have discharge capacities between 21 – 92 m^3/h. These wells are used to supply water to Zanzibar Town. In contrast, a cave or hole developed as a shallow well by ZAWA for domestic water purposes (Paje well in Figure 2) in the southern portion of Zanzibar has a current discharge of 184 m^3/h and with a barely measurable drawdown (measured in October 2010). Initial data points to a transmissivity of more than 70,000 m^2/day and hydraulic conductivity of 1600 m/day. However, further testing has to be made to firmly establish the aquifer characteristics in the coral rag area.

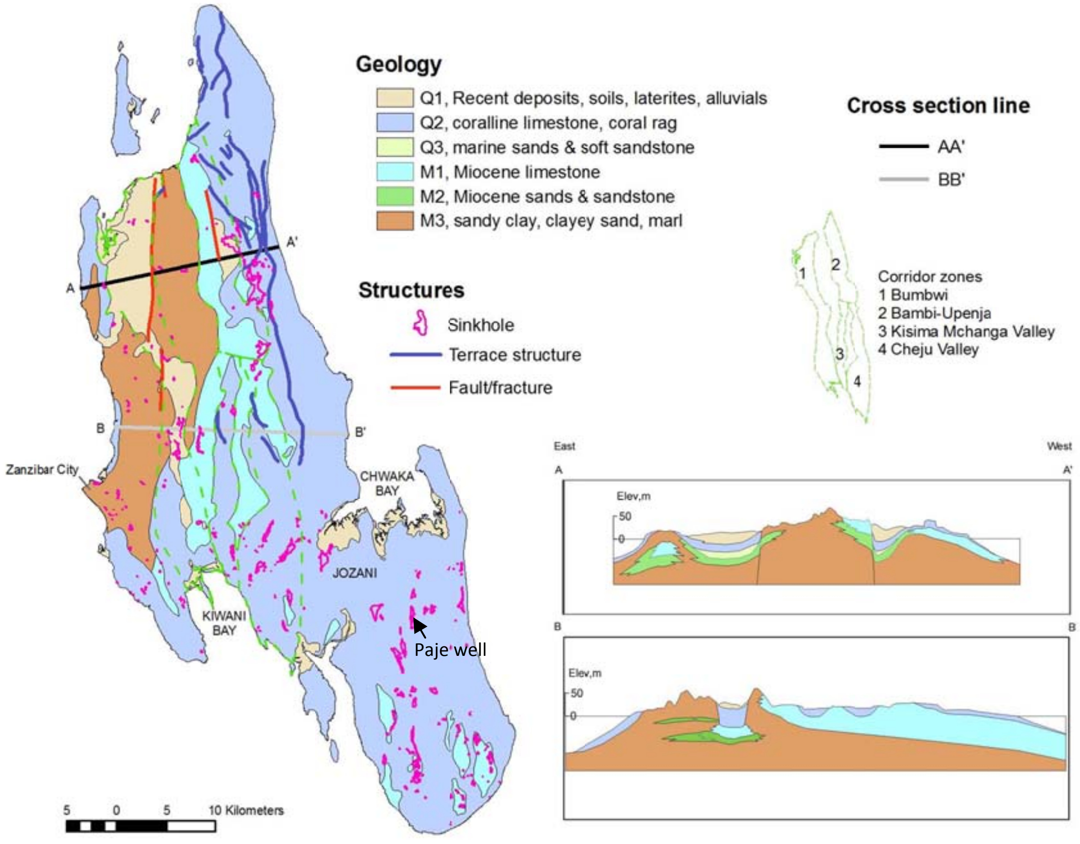


Figure 2. Geology of Zanzibar: Distribution of lithology and schematic cross-section.
Adapted from Johnson (1987). Sinkholes are mapped from Zanzibar 1:10,000 topographic maps.

Age	Geology	Lithology/Description	Hydrogeologic significance
Quaternary	Q1 – Recent Sediments	Soils, laterites, beach sands and gravel	Laterites are minor aquifers. Clays sometimes form an aquitard
Quaternary	Q2 – Coralline Reef Limestone (Coral Rag)	Limestones	Main aquifer material in corridor zones
Quaternary	Q3 – Quaternary Sands	Sands	Main aquifer material in corridor zones
Miocene	M1 – Miocene Limestone	3 kinds: crystalline; sandy limestones and reef limestones; detrital limestones	Aquifer in the coral rag areas, underlying the thin Q2
Miocene	M2 - Miocene Sands and Sandstones		This most often underlie the Q3 sands and together they form an aquifer
Miocene	M3 – Miocene Clayey Sands, Marls and Clays		Aquitard, the base of the aquifers in the corridor zones

Table 2. Stratigraphic sequence

2.3. Soils

A veneer of different soils lies on top of the solid rocks described in the preceding section. These soils have developed initially through the weathering and erosion of the rocks following emergence of the land due to falling seas. The characteristic of these soils partly dictates whether the ground will be easily replenished or not. The soils of Zanzibar were initially grouped into three by Calton, Tidbury, & Walker (1955) namely loamy soils (Kinongo); sandy soils (Mchanga); and clayey soils (Kinamo). However this grouping is misleading in terms of reflecting the hydrologic properties of the soils. Hettige (1990) in his evaluation of the suitability of Zanzibar soils for crop production described further subdivisions of the soils. The distribution of these soils is shown in Figure 3.

The Mchanga group are derived from non-calcareous sediments, mostly the Miocene sands, marls, and clays, and thus, have different textures and drainage characteristics that according to Hettige (1990) cannot be lumped together. The Reddish Mchanga is sandy loam while Sandy Mchanga is pure sand. Reddish Mchanga is well-leached and is well to moderately well-drained deep soil. Greyish Mchanga are sandy clay loam soils with permanent high water table. The relatively thick clayey soils of the Kinamo are characteristically cracking soils that provide direct conduits for water to infiltrate to the ground. The most mature soils of the Island are the red heavy loams of the Kinongo. The high humic shallow loamy soils of Uwanda overlie shelly limestone that is very porous. Maweni soils are mostly found in the eastern and southern portions of the Island and consist of black humic material that usually occupies crevices of the limestone (Hettige, 1990). Swampy Wanda mostly occupy the swamps and marshes of the Island and is similar to Uwanda but with a very high organic content.

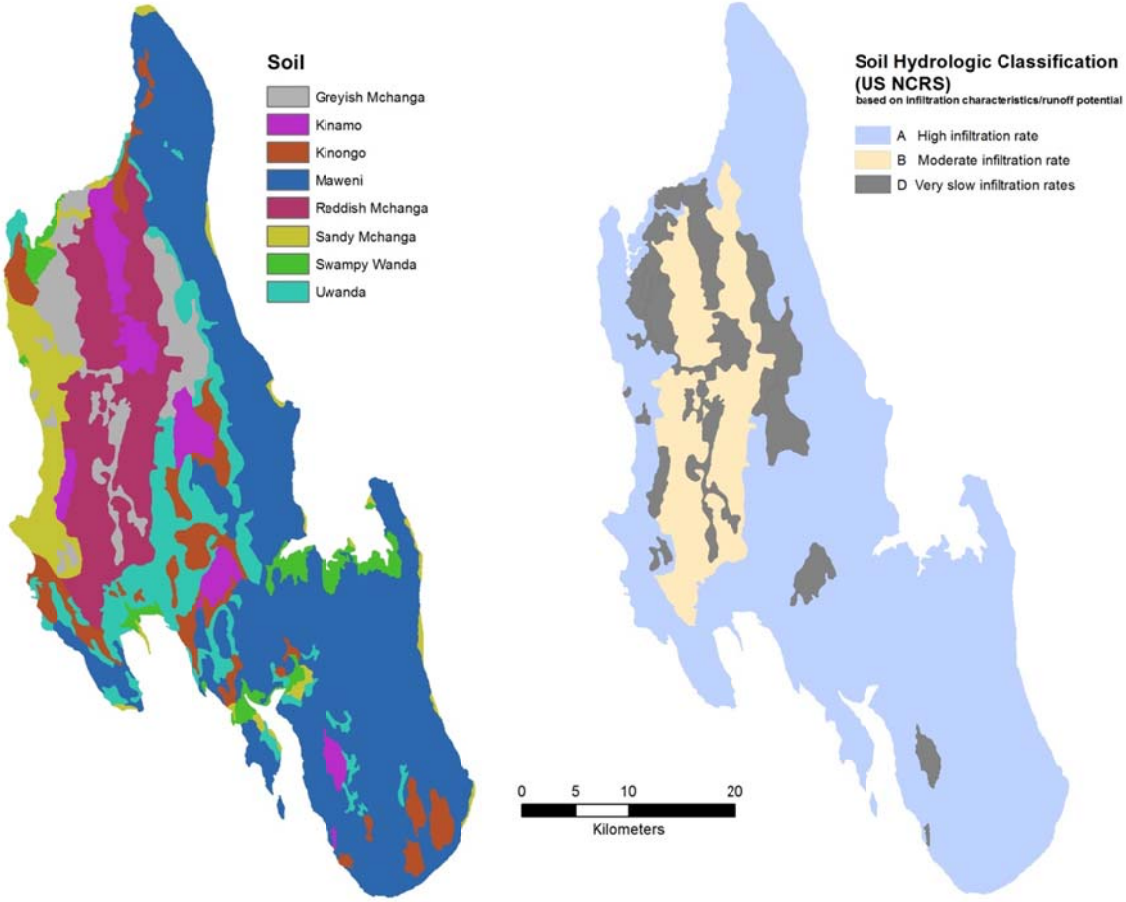


Figure 3. Soils of Zanzibar. a. Distribution of soils; b. Soil hydrologic group

Class	Infiltration Rate	Soil texture/ other characteristics
A (Low runoff potential)	High, even when thoroughly wetted	Deep, well to excessively drained sands and gravels
B	Moderate, even when thoroughly wetted	Moderately deep to deep, moderately to well drained, moderately fine to moderately coarse grained (e.g. sandy loam)
C	Slow, when thoroughly wetted	Have a slowly permeable layer that prevents downward movement of water or they are moderately fine or fine-textured soils.
D (High runoff potential)	Very slow, when thoroughly wetted	with high swelling potential, with permanent high water table, with clay near the surface, or shallow soils over impervious bedrock.

Table 3. Soil hydrologic classification
Based on Neitsch, Arnold, Kiniry, & Williams (2005)

The hydrologic significance of these soils lies in their infiltration and hydraulic conductivity characteristics as well the presence or absence of a very slowly permeable layer. These characteristics influence the runoff potential or conversely the potential for infiltration. In Figure 3b, the Zanzibar soils are classified into hydrologic groups (Table 3) based on their infiltration characteristics according to the classification of Neitsch, et al.(2005). This was done to give an idea of the potential distribution of recharge based on the soil characteristics. Most of the streams occur within the Mchanga soils, which have variable infiltration rates and runoff potential. While in the eastern and southern soils consisting mostly of Maweni soils, streams are naturally non-existent. These areas belong to class A, with high infiltration rates.

2.4. Climate

The climate of Zanzibar is characteristically bimodal. It has two rain seasons which are separated in between by dry seasons. The climate is influenced by the monsoon air flow coming in from Asia which constitutes the trade winds over east Africa. The trade winds during the months of January to February, which constitute the northeast monsoon, are hot and dry (FINNIDA, 1991). From June to September, the winds become cooler (southwest monsoon).

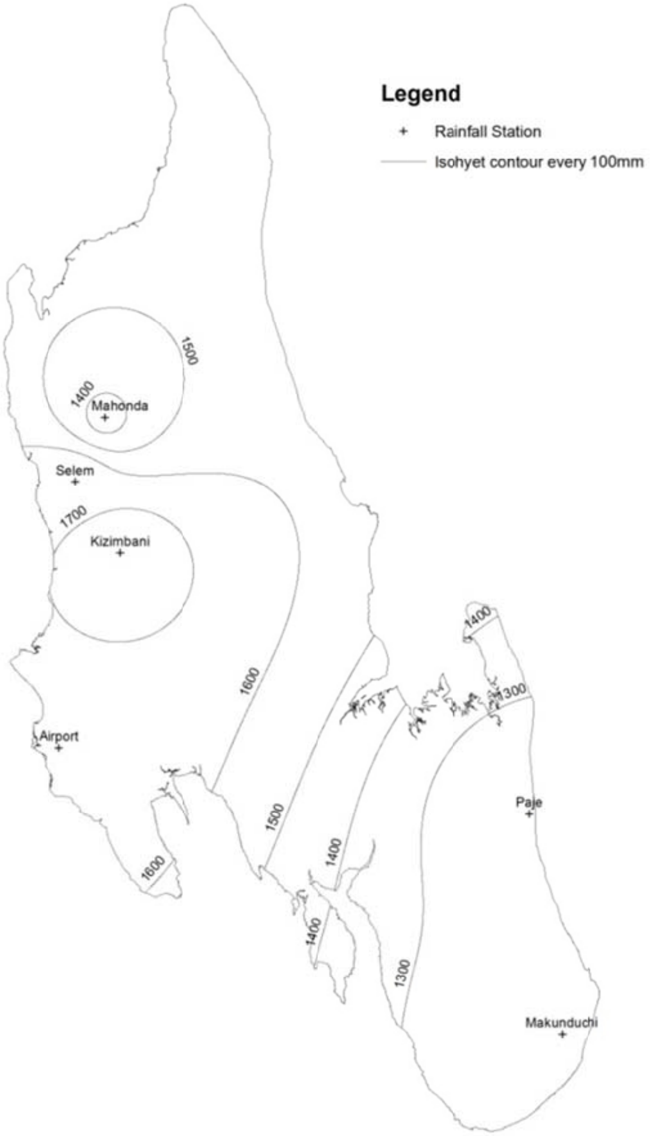


Figure 4. Rainfall isohyetal map based on years 1996 - 2006

The long rains called "Masika," fall from March to May. Peak rains occur in April and then start to diminish in May. The second rain season is characterized by shorter rains, called Vuli, occurring in the period from October to December. Table 4 shows the average monthly rainfall for each rain gauge station shown in Figure 4. As can be seen from the table, Masika rains comprise an average 52% of the total rains, while Vuli rains comprise a mean of 24% of the total. The station at Kizimbani is at a higher elevation (79m) than the rest of the stations. The isohyetal map in Figure 4 is created from the average yearly values from 1996 to 2006, the period common to all the stations. The isohyets show that from the highest rainfall value in Kizimbani precipitation values become lower both going north and south of the Island. Meanwhile in terms of temperature, the June to September dry period is relatively cooler while from January to February higher temperatures are the usual. Daily mean temperatures vary from a high 28.75°C in February to 24°C in September (Figure 5a).

Figure 5 shows the average daily monthly meteorological variables for each month: temperature, solar radiation , wind speed, potential evaporation, rainfall and relative humidity. The monthly solar radiation (theoretical and measured) is shown in Figure 5a. The theoretical solar radiation is computed from the hourly solar radiation excel sheet program developed by Mr. Gabriel Parodi of ITC. Solar radiation is the primary energy source used in photosynthesis by plants. It also determines the energy that drives evapotranspiration, which in turn provides moisture for subsequent rain forming processes. A comparison of the solar radiation measured from the meteorological station and the theoretical radiation (with 75% transmissivity applied) reaching the earth's surface shows that the energy reaching Zanzibar is half of the theoretical possible radiation. Zanzibar is an area with frequent cloud-cover as can be observed from the images of the area in the MODIS and Landsat product websites. Even Johnson (1984) observed that there is rarely a cloudless day in Zanzibar. The perennial occurrence of clouds explains the reduced radiation reaching the Island.

Rain Gauge	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	SUM	Year	Masika %	Vuli %
*Airport	79	67	145	396	255	62	43	42	45	95	207	163	1599	1965-2005	50	29
Kizimbani	92	57	192	370	288	91	68	59	72	127	195	183	1794	1963-2008	47	28
Mahonda	77	35	144	326	235	66	53	41	60	124	179	136	1474	1981-2006	47	29
Paje	71	32	139	274	235	98	26	15	16	91	86	143	1226	1996-2006	54	24
Selem	65	51	150	305	242	66	48	56	58	124	178	139	1482	1963-2006	47	30
*Makunduchi	48	29	144	314	267	98	30	41	46	90	54	48	1209	1996-2006	60	16

Table 4. Monthly average precipitation in Zanzibar.
Values from Tanzania Meteorological station – Zanzibar.
Masika season is from March to May; Vuli season is from October to December.
*monthly values adapted from (Klein, 2008).

The two peak temperatures in the Airport station coincide with theoretical solar radiation highs, but not with the measured solar radiation. However, the graph of the latter coincides more with that of the potential evaporation (Figure 5b). A comparison of wind speed for the two stations, Airport (elevation: 18m) and Kizimbani, shows that the wind speed in Kizimbani is almost constant throughout the year and greatly reduced compared to that of the Airport. Meanwhile, the peak in rainy and humid months coincides in both stations.

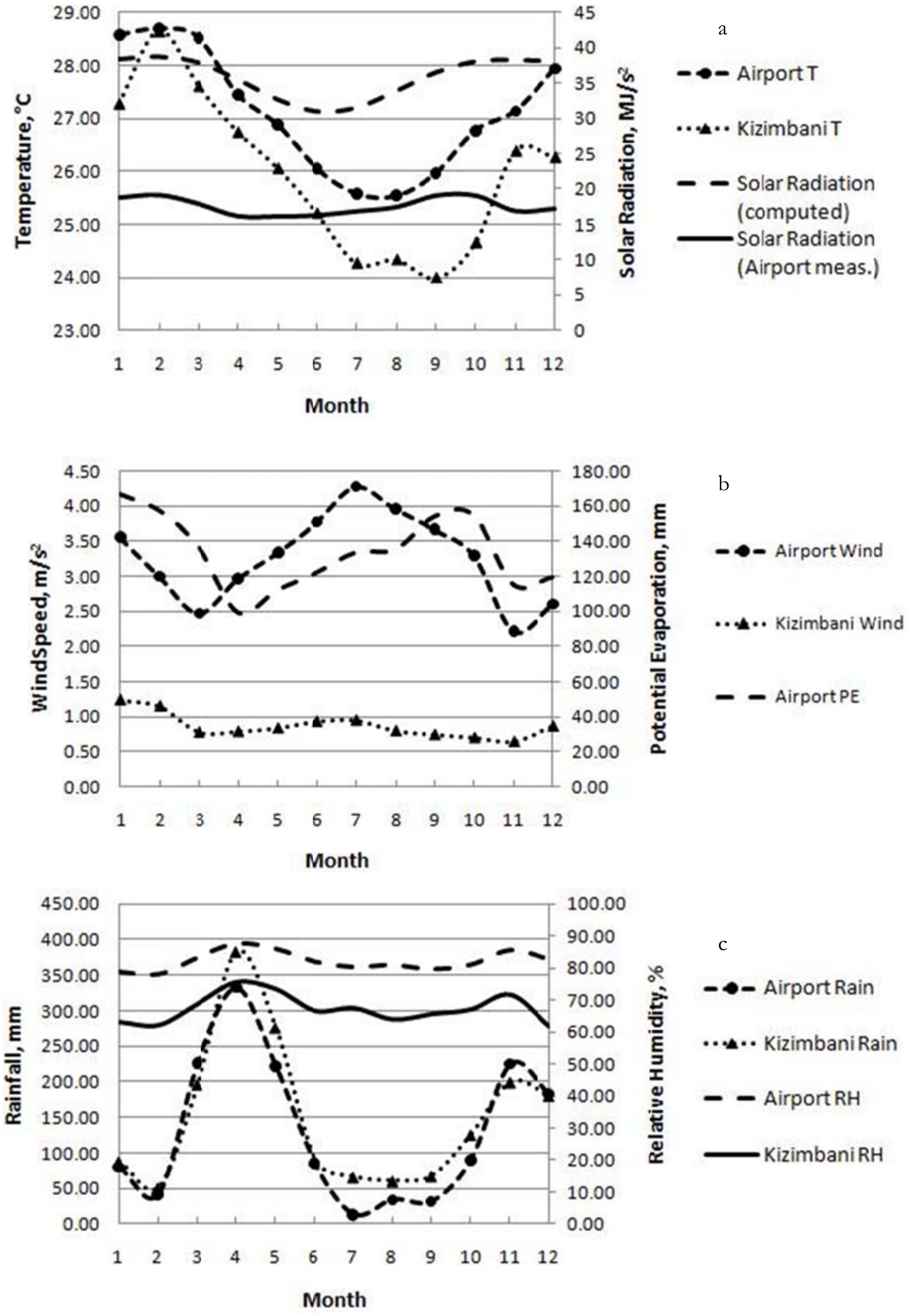


Figure 5. Average daily meteorological variables for each month.
a.)temperature and solar radiation b. wind speed and potential evaporation. c.)rainfall and relative humidity

2.5. Land use / land cover

Sixty-five percent (65%) of the Island is covered by tropical forest, and bush and scrub. The forest areas are mixed and include wooded areas, plantations of coconut interspersed with clove and several other tree species. The major forests are within the Jozani-Chwaka Bay National Park (JCBNP) and Masingini (Figure 6). The Jozani forest lies within a shallow trough in the coral bed (Finnie, 2003) and is bounded by the mangrove filled bays of Chwaka and Uzi, in the north and south, respectively. This area has a very high water table, unlike the areas to the east and west of Jozani that are situated on higher and dry coral ground and covered with forest and thickets (Finnie, 2003). Another forest area, the Masingini, is situated just north of Zanzibar Town and is being threatened by urbanization. The major urban area is Zanzibar Town and this covers less than 3% of the total area. The mangrove areas make up only 2% of Zanzibar Island.

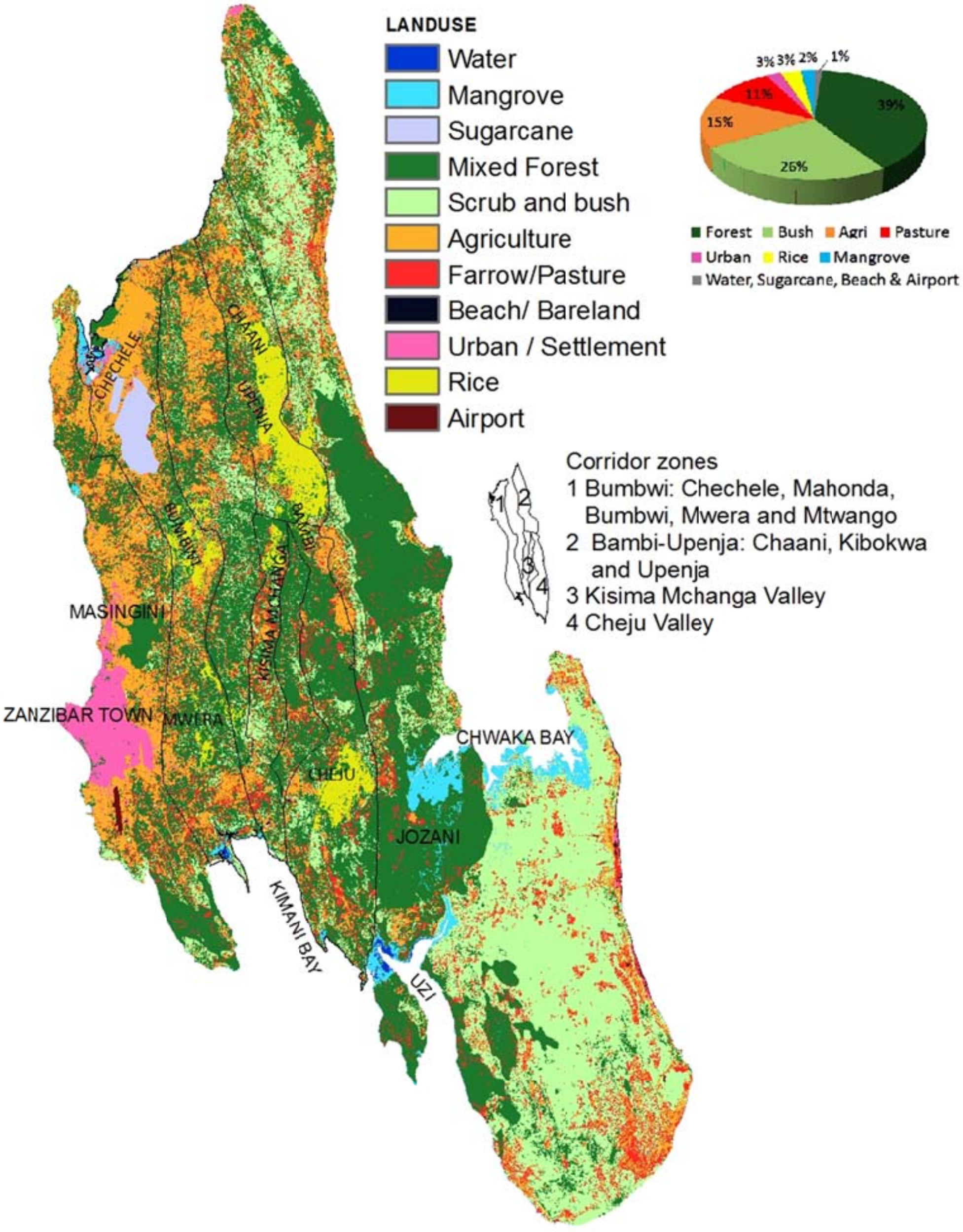


Figure 6. Land cover distribution in Zanzibar

Scrubs, shrubs and thickets are mostly found in the eastern and southern portions of the Island. These areas, according to Hettige (1990), undergo shifting cultivation. Sometimes these are utilized for agricultural purposes, but when the fertility of the soil diminishes these lands are left to revert back to the natural vegetation. That is why there are areas with bare soil or grass growing in between the scrub areas and these are referred to as farrow land or pasture. These areas encompass 11% of Zanzibar during the time of satellite overpass (Landsat 5: July 1, 2009).

The agricultural areas, which are undifferentiated, cover 15% of the Island and they comprise the areas cultivated for root crops, vegetables and some rain-fed rice. These areas, together with the sugarcane and major rice areas, are mostly found within the groundwater-rich corridor zones of Johnson (1984). But the major rice areas are only 3% of the total area of Zanzibar. Rice is primarily grown during the Masika rain season. According to Engineer Mchenga (personal communication) of the Irrigation Department, the potential rice areas comprise 2160 ha of land in Bumbwi Sudhi, Cheju and Kibokwa (Figure 6). However, only 17% of these lands is developed with irrigation infrastructures either using stream or boreholes. The Mwera River, which is a sinking stream, is a major source of irrigation during the Masika period. Boreholes drilled in the three areas mentioned above provide for irrigation water during the Vuli period and the dry season. Another source of irrigation is the Zingwe-zingwe stream. This is mostly used in irrigating the sugarcane areas, which comprise less than 1% of the Island, and some agricultural areas in Chechele.

3. CONCEPTUAL FRAMEWORK

3.1. Recharge concepts

Water that reaches an aquifer from any direction is usually referred to as recharge. Several terms referring to water movement beneath the root zone are often used and correlated to recharge (Scanlon, Healy, & Cook, 2002). These are: net infiltration, drainage and percolation. Studies based on surface water and unsaturated zone techniques give estimates of potential recharge. This is recharge water that may or may not reach the zone of saturation because of inability of the zone to accept recharge or due to processes in the overlying vadose zone. Rushton (1997) differentiates potential recharge from actual recharge, the latter being estimated from groundwater studies and which reaches the water table.

3.2. Recharge estimation methods

A comprehensive review of methods of estimating recharge was made by Scanlon, Healy and Cook (2002). They state that different techniques have variable reliability in estimating recharge. For this reason it is important to apply multiple techniques to enhance accurate results and limit uncertainties. Some of the techniques discussed, among several others, are based on: water budget; use of tracers such as stable isotopes of oxygen and hydrogen; surface water; unsaturated zone and saturated zone techniques. Only the first two are relevant to the present work and will be discussed below.

Groundwater recharge sources can be identified using stable isotopes of oxygen and hydrogen, combined with a correlation of the average isotopic data of precipitation (Terwey, 1984). Deuterium (D) and Oxygen-18 (^{18}O) are the major heavy stable isotopes in water. The use of the natural stable isotope abundance in water as a way to characterize recharge to groundwater is possible because of the fact that the stable isotope composition of the original water is naturally conserved when it enters the ground and percolate into the aquifer. The stable isotopic composition is retained in the aquifer over long periods of time. Deuterium and ^{18}O stable isotopes of groundwater mirror the characteristics or mechanism of recharge for the water. Jones, Banner, & Humphrey (2000) established the temporal and spatial variations of recharge in Barbados using the oxygen isotope content of groundwater and rainwater. They have shown that there is seasonality in recharge and it takes place only at the wettest 1-3 months of each year, wherein precipitation is more than 195 mm.

One of the methods based on the soil water balance concept is the physically-based model Soil and Water Assessment Tool (SWAT) developed by the USDA. It is based on daily computations of the soil water budget. SWAT is a semi-distributed model originally intended by Arnold, Srinivasan, Muttiah, and Williams (1998) for ungauged basins to estimate the impact of land management operations to watershed hydrology. The model does not require calibration simply because ungauged basins have limited stream flow data. While several studies using SWAT have emphasized on the calibration methods, Srinivasan, Zhang, & Arnold (2010) applied SWAT focusing more on the hydrologic balance of the watershed, which is the basis of nutrient and sediment predictions. Limitations of the input data are an important concern in the use of physically-based hydrological models because of the large amount of parameters to be satisfied and spatially variable input data. The emphasis of Srinivasan, et al. (2010) was on creating a structure for developing input data, such as, hydrography, terrain, land use, soil, tile, weather, and management practices, for Upper River Mississippi Basin. Their uncalibrated model provided satisfactory predictions of the hydrologic budget and crop yield comparable to previously calibrated SWAT models of the same area.

Combining SWAT with remote sensing to improve the input of parameters or calibration has been done by a few authors (Immerzeel & Droogers, 2008; Immerzeel, Gaur, & Zwart, 2008) because of the limitation of hydrologic data. They used remote sensing derived evapotranspiration in calibrating the SWAT model of a catchment in India. Cloud-free MODIS images from October 2004 to May 2005 (two images per month) were used to derive the actual evapotranspiration (ET_{act}) using Surface Energy Balance Algorithm for Land (SEBAL). The SWAT model was calibrated against the ET_{act} of SEBAL using a non-linear parameter estimation package (PEST).

3.3. Soil and Water Assessment Tool (SWAT)

In the SWAT model, the processes in the watershed are simulated in a daily time step using the water balance equation (Arnold, et al., 1998):

$$SW_t = SW_i + \sum_{i-1}^{t} (R_i - Q_i - ET_i - P_i - QR_i) \qquad \text{Equation 1}$$

Where SW_t and SW_i are the final and initial soil water content (mm H2O), respectively. t is the time in days; R, Q and ET are the amounts of precipitation, surface runoff and evapotranspiration; P is the percolation or the amount of water entering the phreatic zone from the soil profile, and QR is the amount of return flow. Recharge is the water that has passed through the lowest depth of the soil profile, through the unsaturated zone, through infiltration and percolation, and finally reached the aquifer. According to Neitsch, Arnold, Kiniry, Srinivasan, and Williams (2010) percolation in SWAT is considered groundwater recharge, when taken over long periods of time.

3.3.1. Summary of processes

SWAT performs daily water balance in each soil layer according to the saturated conductivity and moisture content in each layer. The details and equations are thoroughly explained in Neitsch, et al. (2005). During a precipitation event, the canopy interception is determined first before any water is allowed to fall to the ground. The runoff for the remaining water (rainfall less canopy interception) is estimated using the USDA curve number. Water infiltrates to fill the soil to field capacity. Soil is considered saturated when moisture exceeds field capacity. Water then exits the soil profile to become shallow or deep aquifer recharge in two ways: percolation and bypass flow. Water only percolates if there is excess of saturation in all soil layers. Water that passes through cracks in vertisols and directly infiltrates into the ground and bypassing all the soil layers is called bypass flow. The potential evapotranspiration is computed in SWAT using Penman-Monteith. The actual evapotranspiration is a function of potential evapotranspiration together with, canopy and soil evaporation and plant water uptake. Figure 7 shows the pathways of the movement of water in SWAT, from precipitation to the aquifer.

The hydrological processes within the SWAT model are summarized above. For the two major processes of concern in this work, recharge and evapotranspiration, they will be discussed further below. The equations used are based on Neitsch, et al. (2005).

3.3.2. Recharge

As stated in the previous section, percolation and bypass flow constitute the water passing through the lowest layers of the soil and recharging the aquifer. Recharge ($W_{rchrg,i}$) on day *i* is computed as:

$$W_{rchrg,i} = \left(1 - \exp\left[-\frac{1}{\delta_{gw}}\right]\right) \cdot W_{seep} + \exp\left[\frac{-1}{\delta_{gw}}\right] \cdot W_{rchrg,i-1} \qquad \text{Equation 2}$$

Where, δ_{gw} is the delay time or drainage time to account for the delay in recharge once the water exits the soil profile (days), and $W_{rchrg,\,i-1}$ is the amount of recharge on day *i-1* and W_{seep} is the total percolation (W_{perc}) and bypass flow (W_{crk})on day *i*, (mmH_2O).

$$W_{seep} = W_{perc} + W_{crk} \qquad \text{Equation 3}$$

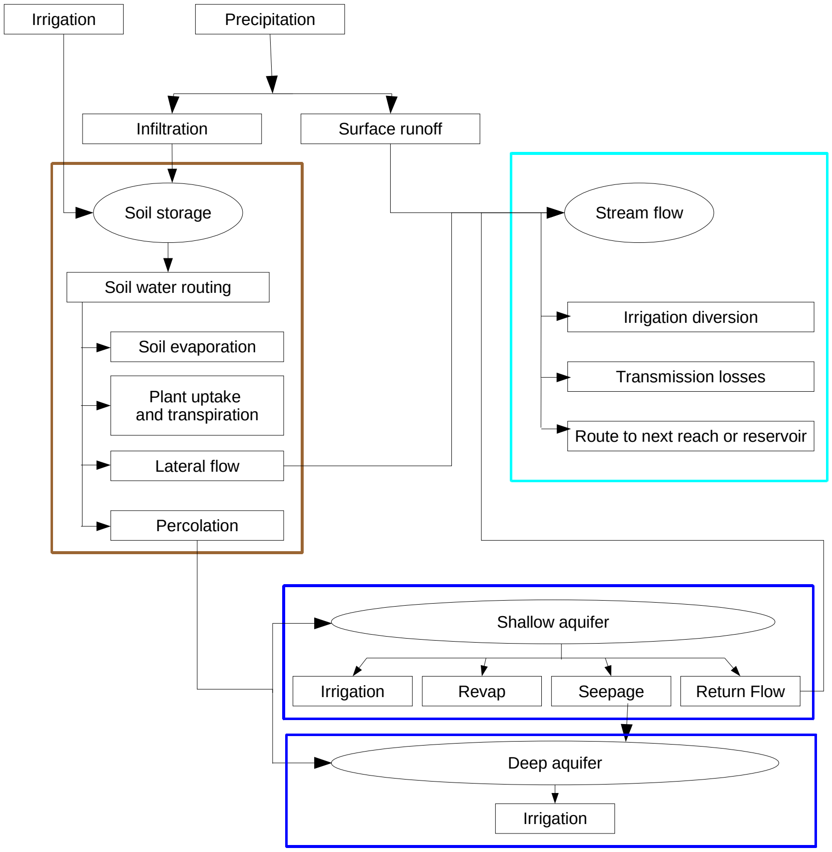


Figure 7. Schematic diagram of pathways available for water movement in SWAT
Adapted from Neitsch, et al. (2005)

3.3.3. Evapotranspiration

The primary mechanism for moisture removal from the watershed is the process of evapotranspiration. Thus the water available for human use and management is the difference between precipitation and evapotranspiration (Neitsch, et al., 2005). In computing for actual evapotranspiration, the potential evapotranspiration is first determined in SWAT.

The concept of potential evapotranspiration was first introduced by Thorthwaite (1948) and it is defined as "...the rate at which evapotranspiration would occur from a large area uniformly covered with growing vegetation that has access to an unlimited supply of soil and water ..." (Neitsch, et al., 2005).

A modified Penman-Monteith equation is used in SWAT to compute for potential evapotranspiration:

$$\lambda E_t = \frac{\Delta \cdot (R_{net} - G) + \gamma \cdot K_1 \cdot \left(0.622 \cdot \lambda \cdot \frac{\rho_{air}}{P}\right) \cdot (e^{\circ} - e)/ra}{\Delta + \gamma \cdot (1 + \frac{rc}{ra})} \qquad \textit{Equation 4}$$

Where λ is the latent heat of vaporization (MJ/kg), E_t is the maximum transpiration rate (mm/d); K_1 is a correction factor to make sure the units in the numerator are the same (K_1 = 8.64 x 10^4); and P is the atmospheric pressure in kPa; ρair, is the density of air (kg/m^3); R_{net} is the net radiation; G is the soil heat flux; Δ is the slope of the saturation vapour pressure-temperature curve; γ is the psychrometric constant; e° and e are the saturation and actual vapour pressures, respectively; ra and rc are the aerodynamic and canopy resistances, respectively.

The aerodynamic resistance is a function of the wind speed, the roughness length for vapour transfer and the zero plane displacement of the wind profile. The canopy characteristics of the crops/trees are important in determining both the aerodynamic resistance and canopy resistance. These characteristics are modelled to change as the plant/trees grow or become dormant and until the time it becomes mature.

SWAT uses alfalfa (40 cm height) as a reference crop to compute for the potential evapotranspiration using Equation 4. After this, the calculation for the amounts of actual evaporation and actual plant water uptake, which is the actual transpiration, is done.

The actual plant transpiration is a function of the potential plant water uptake, which is defined by:

$$w_{up,z} = \frac{E_t}{[1-\exp(-\beta_w)]} \cdot \left[1-\exp\left(-\beta_w \cdot \frac{z}{z_{root}}\right)\right] \qquad Equation\ 5$$

where $w_{up,z}$ is the potential water uptake from the soil surface to a specified depth, z, on a given day (mmH_2O); E_t is the maximum plant transpiration on a given day (mmH_2O); β_w, water use distribution parameter ; z_{root} is the depth of root development in the soil (mm).

3.4. Deriving ET from satellite data

The method of Immerzeel and Droogers (2008) involved the use of SWAT and SEBAL – derived ET_{act} to characterize the processes in the watershed. While the combined method is adapted in this work, the method: surface energy balance system (SEBS) of Su (2002) is used instead of SEBAL. Facility of SEBS routines incorporated in ILWIS makes it more attractive to use. The SEBS model is based on the energy equation:

$$Rn = G + H + LE \qquad Equation\ \ 6$$

Where, Rn is the net radiation (W/m^2);G is the soil heat flux (W/m^2); H is the sensible heat flux (W/m^2); and LE is the latent heat flux (W/m^2). ET_{act} is estimated from LE. The detailed description of SEBS can be seen in Su (2002).

3.5. Combining methods

While a distributed recharge model for the Island of Zanzibar can be simulated in SWAT, calibration will be difficult or is not possible because of limited stream flow data. And even if stream flow data is available, this can only be used on the sub-basin it represents. Sub-basins with streams exist only in the northwestern portion of the Island.

An alternative, which is the use of remote sensing-derived evapotranspiration for calibration based on Immerzeel and Droogers (2008) was intended. However, there are insufficient cloud-free MODIS satellite images that can be used because Zanzibar is rarely cloud free. Thus with the available data, the best that can be done are: adapt parameters to reflect sub-basin characteristics with stream flow and without, use satellite derived – NDVI and land use to determine different areas of vegetation where ET_{act} will be significant, and finally, use satellite derived ET_{act} and isotope data for validation and further characterization of recharge. However, instead of SEBAL, the method SEBS is used for the derivation of ET_{act}.

4. METHODOLOGY

The methods used in the assessment of recharge are grouped into three: SWAT recharge estimation, Validation of recharge through Satellite-derived ET_{act} and initial characterization of recharge by isotopes. The following is the description of the steps. Figure 8 shows the process flow of the methodology.

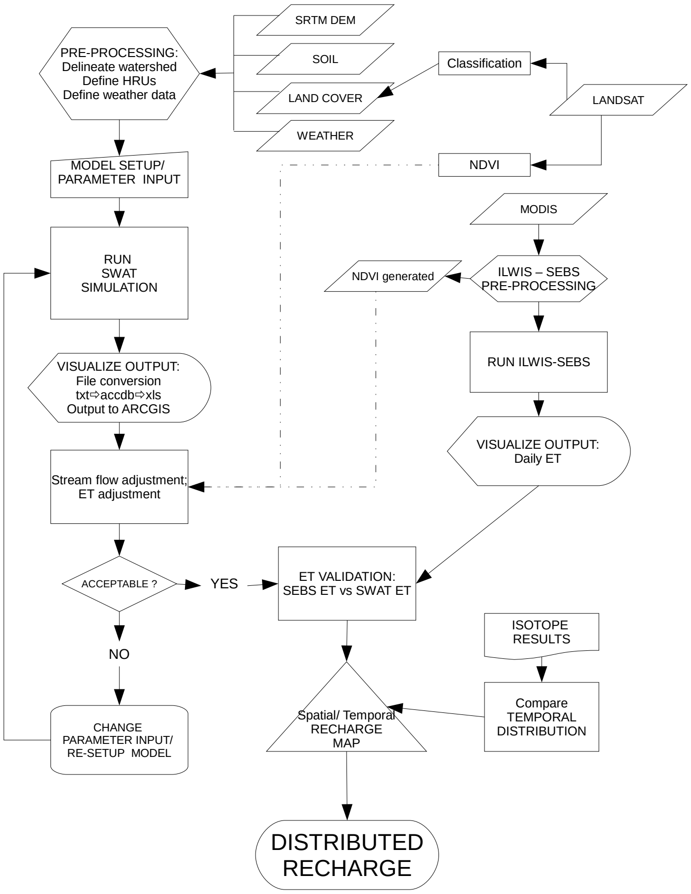


Figure 8. Recharge estimation process flow chart

Note: Dashed lines indicate comparing of data not as input map

4.1. SWAT recharge estimation

Recharge assessment using SWAT model starts with pre-processing and setting-up of the model components.

4.1.1. SWAT model set-up

The Zanzibar watershed simulation model is set-up starting with a Digital Elevation Model (DEM) which is the basis of the topographic information and the delineation of watersheds. This is then followed by definition of the hydrologic response unit (HRU), the basic unit of analysis in SWAT.

4.1.1.1. Watershed delineation

The DEM was created from a combination of Shuttle Radar Topography Mission (SRTM) data and topographic map information. The SRTM, which has a resolution of 90 m, was downloaded from the website (http://srtm.csi.cgiar.org). There are also several topographic maps with a scale of 1:10,000 and a 5 meter contour interval available as digital image from the ITC Zanzibar archive. When comparing the original SRTM of Zanzibar with that of the topographic maps there is a difference in elevation between 5 to about 20 meters in several parts of the Island. The following pre-processing steps were implemented to the SRTM DEM so that elevation values will be at least closer to that of the topographic map and surface generated will be smoother: 1.) subtraction of 5m; 2) low-pass filter, using weighted mean; Finally, the image was densified to 30m and contour lines were generated. The contour lines in the southern portion of the topographic map of Zanzibar, which is mostly flat, were digitized and these were combined with the SRTM contour lines in the northern portion of Zanzibar. The combined contour lines, with some modification along the coastal boundary, were then used to create a final DEM. An initial fill sink operation was done and the sink areas were isolated to compare with the sinkholes digitized from the topographic maps (see Figure 2). The sinkholes that coincide with the sinks were masked out and this mask was used in the Final DEM creation. The coordinate system used is shown in Table 4. All maps used in the pre-processing follow the same coordinate system to ensure that they all match spatially.

PROJECTION	Universal Transverse Mercator
SPHEROID	Clarke 1880
DATUM	Arc 1960
ZONE	37
CENTRAL MERIDIAN	39
REFERENCE LATITUDE	0
NORTHING	10,000,000
EASTING	500,000
SCALE FACTOR	0.9996

Table 5. Zanzibar coordinate system

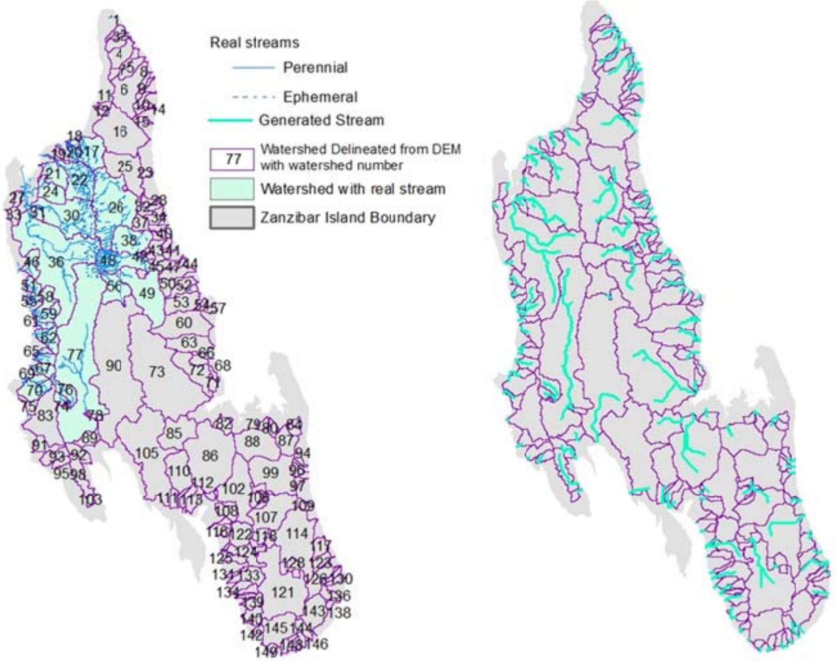


Figure 9. Delineated watersheds using ArcGIS/ArcSWAT. a Streams digitized from topographic map.; b. Generated stream network

Watershed delineation was done in ArcGIS/ArcSWAT. To ensure that the real streams are followed during stream delineation, the stream shapefile data (Figure 9a) was burned-in. Since the final DEM has masked out holes, the sinking streams were forced to stop into the sinkholes. If this is not done, the streams generated will drain into the eastern coast. Aside from the real streams, other virtual streams were generated within the eastern and southern portions of the Island (Figure 9b). Information gathered from field observation, topographic maps, aerial photographs, literature and interviews, show that the east and south portions of the Island don't have streams or gullies.

A total of 150 watersheds were created with a total area of 1200 km^2, which represents about 75% of Zanzibar Island. Two zones can be distinguished: real watersheds, which are found in the west, and virtual watersheds, which are found in the east and south. A major requirement of SWAT is that at least one stream is found in a sub-basin. This would allow SWAT to model the watershed processes within these sub-basins, but to fit the reality that there is no stream flow along these areas, parameter values have to be adjusted. The zoning is a visual guide for the modeller in adjusting parameter values to reflect the real situations in the field.

4.1.2. HRU definition

The basic unit of SWAT simulation is the hydrologic response unit (HRU). SWAT divides the sub-basins into HRUs comprising of unique land cover, soil and slope combinations. Using the ArcSWAT interface, the land use, soil and slope layers were overlaid generating 1703 possible unique combinations. The minor land cover comprising less than 5% of each sub-basin area was not included, thus generating 1296 total HRUs that were used later in the model simulation. The following describes the elements of HRU.

4.1.2.1. Slope

Slope in Zanzibar is from 0 – 39%. However, 73 % of the land is less than 2% slope, while only 2% of the land is on slopes greater than 8%. Thus it is best to use only one range of slope since the Island is mostly flat.

4.1.2.2. Land cover

Landsat 5 TM for July 9, 2009 was used for the derivation of land use/land cover. This is the only clear and cloud-free satellite image, so far, for Zanzibar Island. An unsupervised classification based on spectral characteristics was done creating 45 classes. Then, this was recoded to 11 classes, with supplemental information from the physiographic map of (Hettige, 1990) and land cover information from the ZAWA GIS and aerial photographs. The final land use / land cover map input is shown in Figure 6. However, since during the HRU definition, some minor land cover having less than 5% coverage were not included, only the following were modelled in SWAT.

Class - SWAT Code
Mangrove - WETF
Sugarcane - SUGR
Woods / Mixed forest - FRST
Scrub and bush areas - RNGB
Undifferentiated agricultural land - AGRL
Grass / farrow / pasture - PAST
Urban area/Settlements - URBN
Rice with supplemental irrigation - RICE

Table 6. Final land cover modelled

4.1.2.3. Soil

The soil map input to SWAT is shown in Figure 3a In order for SWAT to model the soil, properties of each soil must be input into the SWAT database. These soil properties include: moist bulk density, available water capacity of the soil layer, organic carbon, silt, sand and clay content. Basic soil data were gathered from Hettige (1990) and Klein (2008) and also few taken from the field. Soil transfer functions within the USDA software Soil Pond and Water (SPAW) were used to derive the soil characteristics such as bulk density and hydraulic conductivity.

4.1.3. Climate data

Weather inputs required by SWAT include daily values of precipitation, maximum and minimum temperature, solar radiation, wind speed and relative humidity. These values are read by SWAT from separate files provided by the user or daily values can be generated by SWAT using monthly average data summarized over a number of years. WXGEN is the weather generator used by SWAT for simulation of weather. A weather generator file from the monthly averaged data is required. Table 7 shows a weather generator input file used in the Zanzibar simulation. Of the 6 weather stations shown in Table 3, only the Airport and Kizimbani stations have more complete weather information from which to compute the statistics (Table 7) needed for the weather generation that can be used as SWAT input.

Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Description**
TMPMX1	31.37	32.13	31.70	30.15	29.52	28.33	28.08	28.25	29.02	29.95	30.57	31.22	Average daily maximum air temperature for month.
TMPMN1	23.18	25.16	23.52	23.33	22.58	22.07	20.45	20.41	18.95	19.36	22.19	21.30	Average daily minimum air temperature for month.
TMPSTDMX1	1.10	1.34	1.33	2.00	1.33	1.18	0.86	1.00	1.25	0.98	1.36	0.99	Standard deviation for daily maximum air temperature in month.
TMPSTDMN1	1.95	0.94	0.81	0.88	0.94	1.26	1.02	1.36	1.27	1.31	1.08	1.40	Standard deviation for daily minimum air temperature in month.
PCPMM1	87.66	50.92	196.05	382.17	275.52	91.03	66.16	60.70	67.51	125.45	199.05	180.55	Average amount of precipitation falling in month.
PCPSTD1	79.66	52.94	86.88	135.43	159.85	79.94	44.55	44.67	42.47	106.20	125.97	119.15	Standard deviation for daily precipitation in month.
PCPSKW1	1.50	1.27	0.18	0.37	0.74	0.85	0.54	0.90	1.26	2.31	0.94	0.38	Skew coefficient for daily precipitation in month.
PR_W1_1	0.12	0.15	0.28	0.60	0.31	0.18	0.20	0.24	0.28	0.34	0.24	0.15	Probability of a wet day following a dry day in the month.
PR_W2_1	0.46	0.31	0.65	0.71	0.65	0.43	0.49	0.49	0.35	0.48	0.59	0.57	Probability of a wet day following a wet day in the month.
PCPD1	6.86	5.29	15.76	21.10	17.23	9.81	10.20	11.38	11.82	12.15	13.14	11.57	Average number of days of precipitation in month.
RAINHHMX1	63.60	42.00	65.70	125.00	125.00	72.00	49.88	52.65	44.63	105.45	54.00	84.38	Maximum 0.5 hour rainfall in entire period of record for month.
SOLARAV1	18.70	19.05	17.85	16.16	16.12	16.25	16.82	17.40	18.97	18.97	16.85	17.17	Average daily solar radiation in month.
DEWPT1	22.98	23.12	24.70	25.11	22.72	21.08	20.02	20.50	21.29	21.64	23.35	21.90	Average daily dew point temperature in month.
WNDAV1	1.25	1.16	0.79	0.80	0.85	0.94	0.96	0.81	0.75	0.71	0.65	0.87	Average daily wind speed in month.

Table 7. Weather generator data for Kizimbani Station.

4.1.4. Parameter input set-up

Assigning hydrological parameters to sub-basins and HRUs, depend on whether the areas are within real existing watersheds (whether the streams have perennial flow or are ephemeral) or virtual watersheds (with no channelized runoff). The NDVI maps served as guide to estimate the likely spatial distribution of vegetation and bare areas due to growing seasons.

4.1.4.1. Definition of some parameters that affect recharge, runoff and evapotranspiration

Some of the parameters that affect recharge, runoff and evapotranspiration are listed in Table 8

Parameter	Definition
ESCO	Soil evaporation compensation factor. This allows for the modification of the depth distribution used to meet the evaporative requirements of the soil
EPCO	Plant uptake compensation factor. This allows for the use of lower layers of soil to compensate for the water needs of plants
GWQMN	Threshold depth of water in the shallow aquifer required for groundwater flow contribution to stream
GW_REVAP	Groundwater "revap" coefficient. This allows for water to move from the shallow aquifer into the unsaturated zone via capillary fringe to replace the water lost to evaporation
REVAPMN	The depth of water in the shallow aquifer at which "revap" or percolation to the deep aquifer is allowed to occur

Table 8. Parameters that control recharge, runoff and evapotranspiration

4.1.4.2. Management parameters

Management parameters pertain to the schedules of planting/growing season and harvesting/end of growing season of crops and trees. This is used in SWAT in the modelling of canopy characteristics, which is then used for the subsequent computation of potential evapotranspiration. The planting/harvesting season of rice and other agricultural crops (except sugarcane) were based on the timing of Masika (JICA, 2003). In the irrigated rice areas, irrigation from boreholes is used as supplement to Masika and Vuli rains. The sugarcane is assumed to be cultivated year round.

Crop	Planting Schedule	Harvest Schedule
AGRL	March –June; June-July; September-October	July-August; August-September; February
RICE	March –June; September -December	June-July; February
SUGR	January-December	December

Table 9. Cropping Schedule

4.2. SWAT Simulation

Simulation was run from 2005 to 2009, with the first two years as warm-up period. Thus the simulation was setup such that only the output for the last 3 years was shown.

4.2.1. Visualization of data and parameter adjustment

The outputs of SWAT are text files that can be automatically imported as an MSAccess database file. Queries are done to extract the relevant data which are then exported as excel files that become attribute data of shapefiles which are then converted to raster in ArcGIS for visualization and spatial analysis. Parameters were adjusted in such a way that the virtual streams will have minimized or zero flow, and that the real streams will have flow, taking into consideration historical records.

4.3. Validating SWAT-ET

The results of the simulation of SEBS ET_{act} are used for validation of the SWAT ET_{act}. Validation is only comparing of values from an independent source of information.

During selection of MODIS images, only images for the days within each month having 0-0.1 mm rainfall are noted and considered for selection. Unfortunately, most of the images show the Island covered with clouds. Only the image of Jan 8, 2009 is considerably cloud-free at the middle portion of Zanzibar. Another image taken on Mar 6 2008 is of lower quality than the Jan 8 image but considerably better than the rest of the images.

The images were pre-processed in ILWIS using SEBS tools. Pre- processing includes, conversion of raw data into radiances/reflectances, atmospheric correction, computation of brightness temperature, albedo, surface emissivity and land surface temperature.

One of the inputs that are important in SEBS is the canopy information. This is used in the calculation of aerodynamic and canopy resistance parameters needed in ET_{act} calculation. Generally, this can be taken from the land cover data. However, this was not used as input to let ILWIS run automatic algorithms. The reason for this is that, ground truth data is limited. The mixed trees in the FRST land cover are in different stages of maturity and have different canopy heights which are difficult to differentiate from remote sensing data alone. The only information available is for Jozani trees from the work of Finnie (2003).

4.4. Isotope characterization

Water samples from several local wells, springs and ZAWA boreholes, including rain, were taken and put in 50ml double capped bottles during the fieldwork from September to October. These were sent to the laboratory of AIT Austrian Institute of Technology GmbH for isotope analysis.

The results of analysis were then used to validate possible seasonal variations in recharge.

5. RECHARGE ASSESSMENT

5.1. SWAT Results

Figure 10 shows the monthly recharge distribution. These are monthly average values of 2007 to 2009. The maps show that while the major rainy season (Masika) occurs in March to May, higher recharge happens in April and May. Moreover, March has even lower recharge than June. A similar situation appears in the minor rainy season (Vuli), wherein higher recharge occurs only during the last two months of the season, and there is still some recharge occurring in the first month of the dry season (January). As you go from month to month, it can be seen that the areas underlain by bushes give higher recharge. Furthermore, it is interesting to note that there is a marked difference in recharge values between the northern and southern parts of the Island.

Figure 11 shows the changes in recharge through the seasons. The areas underlain by clay with slowly permeable layer has marked lower recharge than its surroundings. This is exemplified by the rice areas underlain by Greyish Mchanga. The Jozani trough is shown to have consistently low recharge. This is because the area has a very high water table, the reason why the forest within this low area is termed by Finnie (2003) as "groundwater forest".

Also shown in Figure 10 are the monthly changes in ET_{act}. The months of January and December have the highest ET_{act}. Jozani forest consistently gives high ET. The change in ET in the rice and other agricultural areas are also observed coinciding with the planting and harvest seasons.

The graph of monthly recharge (R) is shown in Figure 12 together with the monthly precipitation (P), ET_{act}, surface runoff (SRO). The peaks in the values of P, R and SRO coincide with the rainy months. Table 10 shows the major watershed processes and their monthly means (average of years 2007-2009). The highest rains of Masika season gives an average annual recharge totals 359 mm, while that of the Vuli recharge is 146 mm, approximately totaling 28% of the average yearly rain. The total runoff, meanwhile, is only 8% the mean annual rain.

MON	PRECIP mm	ETact mm	SRO mm	GWRCHG mm
1	110.22	127.21	7.82	46.35
2	49.18	70.85	0.03	7.93
3	125.91	90.89	0.66	14.89
4	385.45	114.83	43.14	129.97
5	403.86	123.55	75.23	214.30
6	63.60	107.39	0.75	41.06
7	24.37	68.59	0.10	2.10
8	58.74	57.84	0.02	2.50
9	25.06	45.89	0.00	2.16
10	57.85	56.84	0.00	5.62
11	318.12	98.52	11.48	74.71
12	205.84	134.52	12.66	65.97
TOTAL	1828.19	1096.93	151.90	607.56

Table 10. Averages of monthly hydrological processes

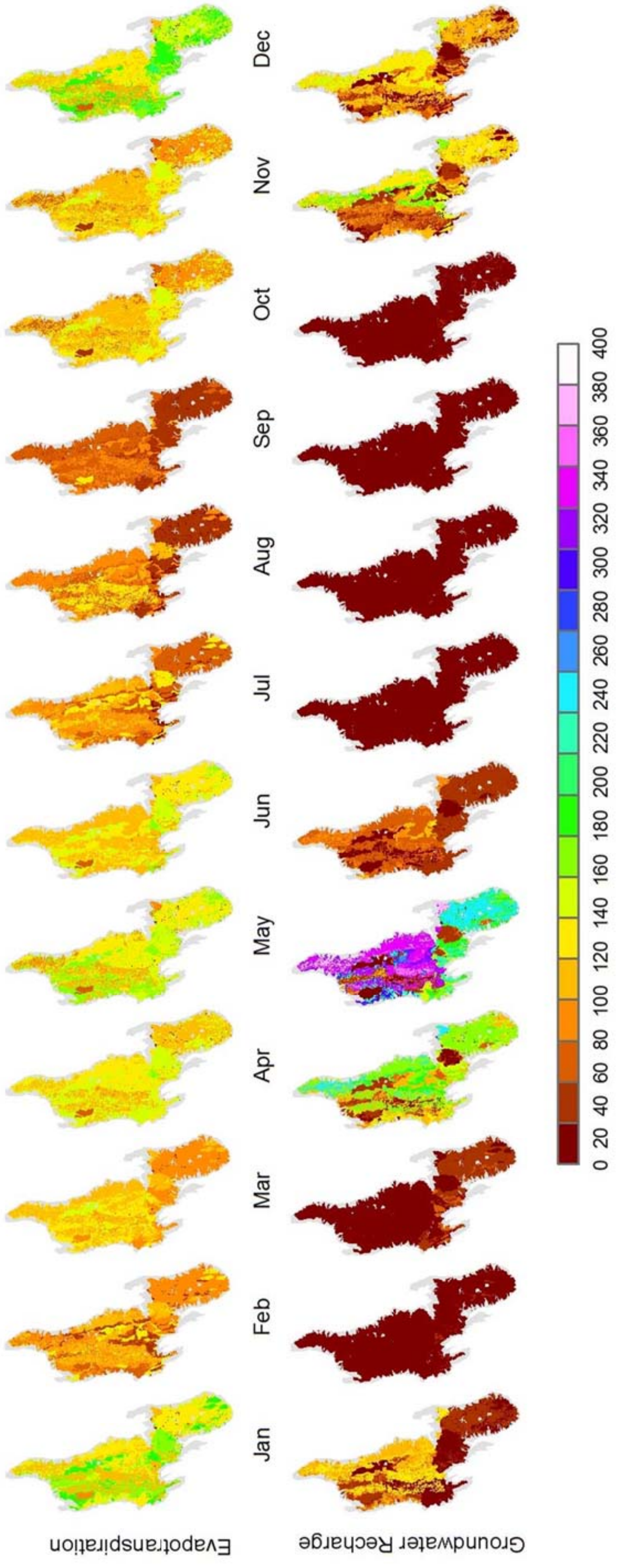

Evapotranspiration
Groundwater Recharge
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340 360 380 400

Figure 10. (SHOWN IN OPPOSITE PAGE) Monthly variations in Recharge and ET_{act}

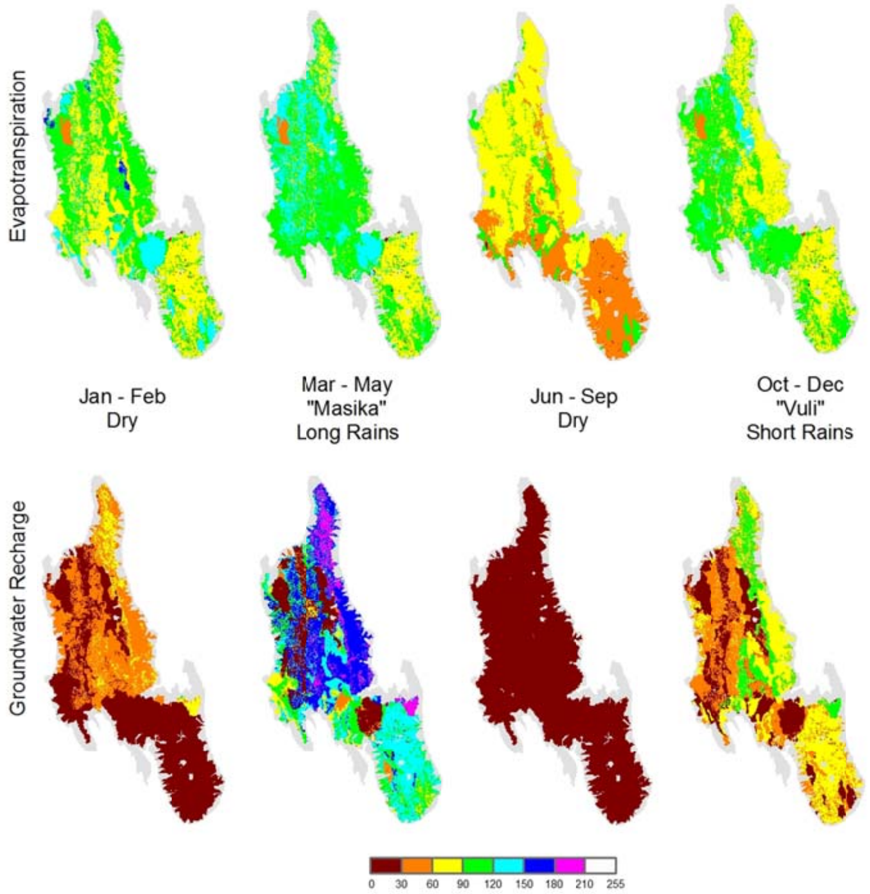


Figure 11. Seasonal variations in R and ET

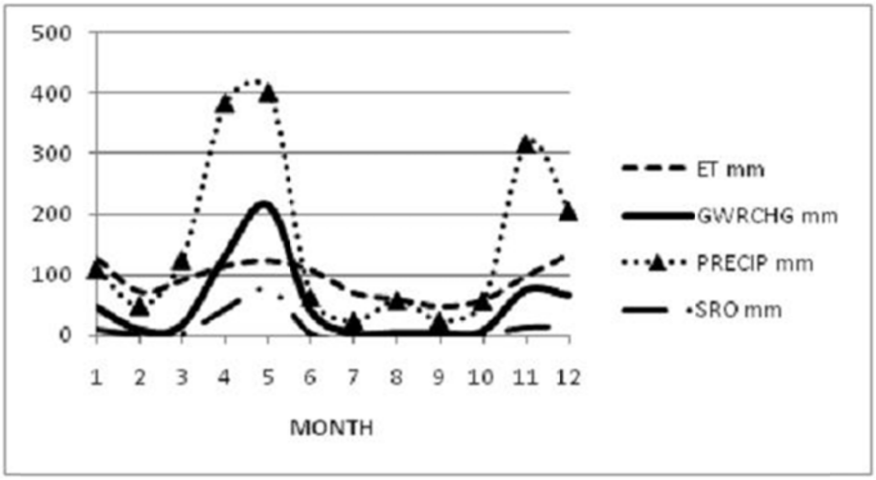


Figure 12. Monthly Precipitation (Precip), actual evapotranspiration (ET), surface runoff (SRO) and recharge (GWRCHG) as modelled in SWAT

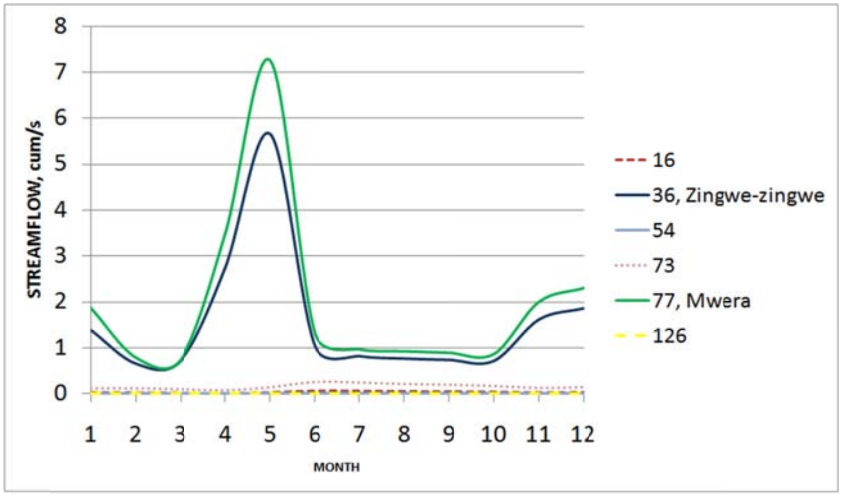


Figure 13. Hydrograph of stream flow for selected streams.

The stream flow hydrograph in some of the streams in the model are shown in Figure 13. The two hydrographs Nos. 36 and 77 represent the 2 major streams, Zingwe-zingwe and Mwera, respectively, in the western portion of the Island. The rest of the hydrographs represent the virtual streams of the model in the east and south of the Island. It is shown that the stream flow for these streams is virtually insignificant.

5.2. Discussion of SWAT Recharge

Zanzibar recharge is affected temporally by the seasonal occurrence of rain and spatially by the amount and distribution of rain (North has more rain than in the south; Masika rains are higher in amounts). The recharge in February and July to October is small and it ranges from 2 – 8 mm. Rains of less than 100 mm have produced this recharge. These rain values are small compared to the rain values of 190- 200 mm, which is the range of monthly threshold precipitation that produces recharge via rapid infiltration. This threshold was established by Jones, et al. (2000) using oxygen isotopes for the tropical islands of Barbados, Guam and Puerto Rico. These islands are likewise underlain by karst limestones.

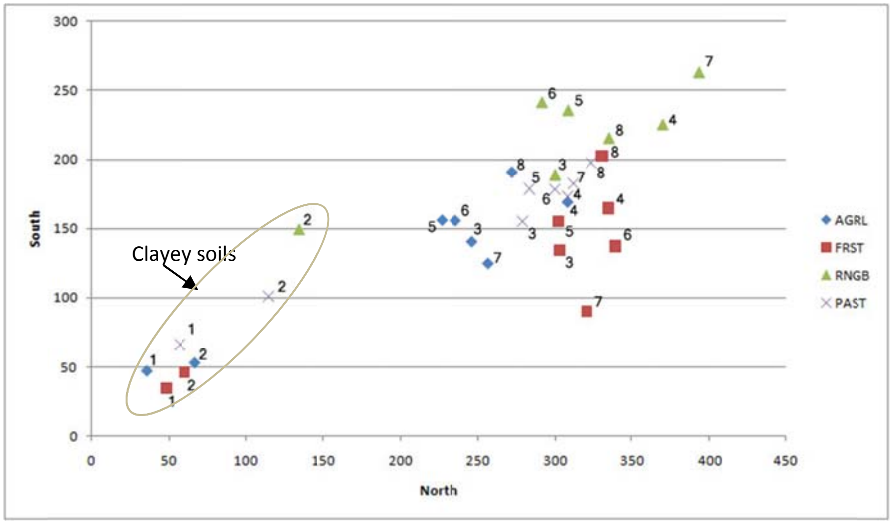


Figure 14. Comparing recharge for May of selected HRUs in the northern and southern parts of Zanzibar.
Values in mm. Numbers on points represent the following soils
1 Greyish Mchanga 2 Kinamo 3 Kinongo 4 Maweni 5 Sandy Mchanga 6 Reddish Mchanga 7 Swampy Wanda 8 Uwanda

Recharge in Zanzibar is also affected spatially by land cover and soils. Figure 14 is a plot of the average recharge of selected HRUs for the month of May (highest amount of rain). These HRUs are the combination of the major land uses (higher acreage) AGRL, FRST, RNGB and PAST with the soils in the northern and southern portions of the Island.

The figure clearly shows that higher recharge occur in the northern half of the Island. Most land use over clayey soils (with impermeable layers) has similar low recharge values for both North and South. Sandy Mchanga, although described as being pure sand, is not remarkable in its recharge characteristics probably because it has reduced hydraulic conductivity near the bottom of its profile suggesting that the hard Miocene Sandstone parent is just below.

The soils with significant recharge are the loamy soils Maweni, Uwanda and Swampy Wanda, which came from the same parent rock, the coralline limestone that according to Hettige (1990) acts like a sieve. However, while Jozani Forest lies over the coralline limestone, it has consistently low recharge. There is a very shallow groundwater close to the surface in Jozani Forest, suggesting that this area is more of a discharge rather than a recharge area. This was modeled in SWAT as having a slowly permeable layer to account for the high water table. For this reason, it will have a high ET and low recharge.

In general, as can be seen from Figure 14, recharge in forests is still relatively high. But they have lower recharge in comparison with the bushes underlain by the loamy soils. The bushes allow higher recharge than the rest of the other land cover in the south, as can be seen also in Figures 10 and 11. As for the other land use AGRL and PAST, the latter has generally higher recharge than the latter.

In modeling the recharge, or essentially the whole water balance in SWAT, parameter inputs are changed to make sure the virtual watersheds in the eastern and southern parts of Zanzibar to have negligible stream flow. And the real streams to have significant stream flow. There are small streams draining into the west coast of Zanzibar. Some even have minimal flow during the dry season - meaning there is groundwater contribution to flow. The flow measured (during fieldwork in September 2010) for a stream and a spring along the upper slopes of basin 67 (Bububu Stream) are 0.027 cum/s and 0.0027 cum/s respectively. Mwera is a sinking stream and it has the largest stream flow in Zanzibar – the reason for its use in irrigation. The stream flow measured by Halcrow (1994) from April to May for Zingwe-zingwe and Mwera were 1.6 and 5.7 cum/s respectively. This gives an idea of the stream flow values in the major streams.

Still, Figure 13 shows that there is stream flow in the virtual watersheds however small it may be. The simulated peak flows of Zingwe-zingwe and Mwera are 5.6 and 7.3 cum/s, respectively. Comparing the historical with the simulated peak flows for Zingwe-zingwe and Mwera, the simulated stream flows may be even excessive. Mwera and other smaller sinking streams (sub-basin 26, 38, 48, 49 and 56) shown in Figure 9 are recharging the groundwater through "poikaisi" or sinkholes. The simulated monthly flows of these other streams range from 0.2 to 0.7 cum/s. The average mean monthly flows for all the sinking streams total 5.7 cum/s. However, these values would have to be verified in the field.

The fact that there is no real stream in the east and south doesn't necessarily indicate that there is no runoff. It is only natural that there is runoff after rains and especially during heavy continuous rains. However, overland flow is possibly more dominant and at some distances the water infiltrates fast into the ground through the thin soils of Maweni and Uwanda or directly to the limestone in areas without soil cover. Hettige (1990) described the Maweni soils overlying the limestone as excessively drained soils.

Some parameters that control runoff are also the same ones that affect recharge and evapotranspiration. Abraham, Roehrig, and Chekol (2007) showed that the parameters that tend to generate a positive effect on surface flow when increase are curve number (CN2), ESCO and soil available water content (AWC). When GW_REVAP and GWQMN are increased, there is a decrease in baseflow and subsequently the surface flow. For the Zanzibar model, increasing ESCO and decreasing EPCO decrease ET and increase both recharge and runoff.

The ET_{act} is affected by the canopy characteristics and root development, which are in turn affected by the timing of planting, growing and harvesting of vegetation. For example in sugarcane, the time ET_{act} starts to rise is July to August possibly coinciding with the growth of the canopy. Upon reaching maturity it will stop growing and will not require water (Neitsch, et al., 2005) so plant water uptake will be low to nil, and consequently low ET_{act}. All of the sugarcane areas may not be completely covered with plants at the same time. Better acreages are needed for all the crops and other vegetation. There is no available information on the acreages, only observations in the field. Also, intercropping is being done especially in AGRL and RICE areas, but there is no available information on the timing and the actual crops planted.

5.3. Validating SWAT with Evapotranspiration derived from SEBS

The results of the ET_{act} modelling by SEBS for Jan8 and Mar 6 2009 are shown in Figure15. The results are superimposed on the outline of Zanzibar, which is the gray outline. Where the clouds are removed (based on the emissivity and albedo maps) the grey area appears. Also shown are the SWAT results for those days. The resolution used in the SEBS ET_{act} is 1000m based on the resolution of the MODIS thermal images used. Thus the resolution of SWAT ET_{act} used for the two days is also the same.

SEBS ET_{act} values are between 6.8 and 8.7 mm. In contrast, SWAT ET_{act} has wider range of values from 1 – 7.8 mm. Although the range of values between SWAT and SEBS ET_{act} are different, some similarities exist. An example is in the forest area of Jozani. It has high ET_{act} in both SEBS images while SWAT ET_{act} is also high in these areas. Another is the sugarcane area, where the ET_{act} values are low in both SEBS and SWAT. There is a long patch of lowest ET_{act} in the January SEBS image. Some portions of this can be seen in the March SEBS image. It coincides with the rice and some bush areas. In SWAT the rice land is still covered with vegetation in January and by February it is harvested. It may be possible that in reality by January, the crops are already harvested, thus the low ET_{act} values.

The reason for the difference in ET_{act} values lies in how actual ET_{act} is modelled in both SWAT and SEBS. In SEBS, the solar radiation used is much higher than the input in SWAT. Computed solar radiation is twice than that of the meteorological station data (Figure 5a). In the work of Immerzeel and Droogers (2008), they have observed that the calculated potential ET in SWAT is always lower than that on SEBAL, with an average monthly difference of 16mm/month. For this reason they performed an adjustment on the SWAT input solar radiation per month and per sub-basin (average increase of 3.5% per month, maximum 7% for one sub-basin) to ensure that calculated potential ET in SWAT and SEBAL potential ET are equal. Immerzeel and Droogers (2008) reasoned that the for the difference in potential ET in SWAT and SEBAL is because in SEBAL, a DEM-based correction is incorporated to account for the impacts of slope and aspect on solar radiation.

In this paper, the solar radiation used was the values from the meteorological station because of the fact that the measured solar radiation values appear to reflect the situation over Zanzibar. The perennial cloudiness appears to prevent the top of the atmosphere solar radiation from reaching the surface of Zanzibar. Another reason for the difference in the values of ET_{act} in SWAT and SEBS is the timing of planting and irrigation schedule in SWAT. It possibly did not capture the actual situation seen by MODIS. For this reason, this schedule may need to be improved.

Another important consideration is the canopy height data, which is required to compute for the roughness parameters in SEBS-ILWIS. If the user opts for ILWIS to estimate this, programmed algorithms will run to compute for it. It seems the canopy height used has a maximum of 2.5 m as shown in the ILWIS help files for SEBS. While, in Zanzibar the maximum may be at 30 m for the mature forest trees and about 6 to 8 meters for the bushes which occupy a large part of the Island.

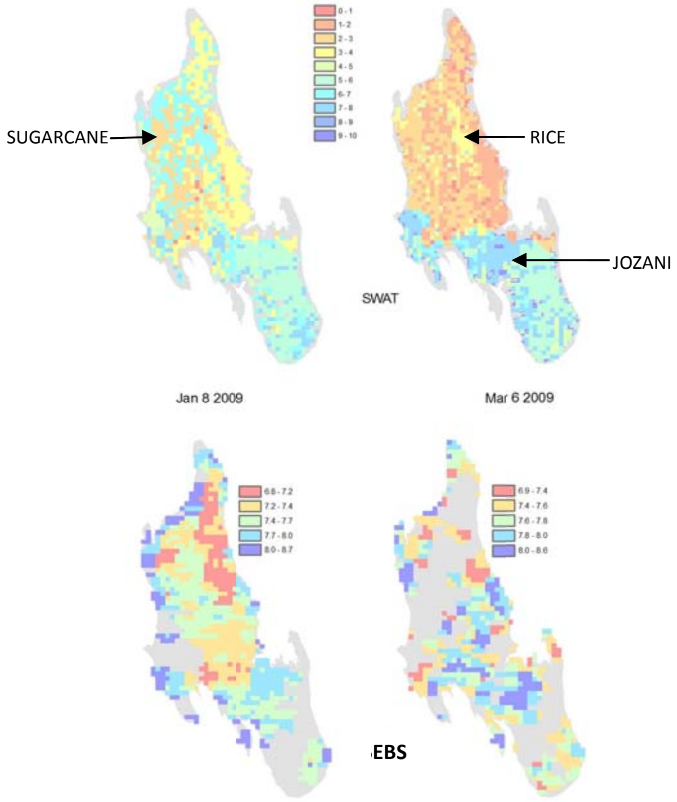


Figure 15. SWAT and SEBS daily ET_{act} for dates: January 8 2009 and March 6 2009

5.4. Deuterium and oxygen-18

Figure 16 shows the graph of the results of the laboratory analysis of D and ^{18}O. The groundwater sampling sites are shown in Figure 17.

In a water sample, the heavy isotope content is reported as its relative deviation, delta, δ, from a standard. The most widely used standard is the SMOW, or the Standard Mean Ocean Water of Craig (1961). The isotope content is reported as per mil (‰) deviations:

$$\delta = \frac{\sigma_{\text{sample}} - \sigma_{\text{standard}}}{\sigma_{\text{standard}}} \times 1000‰ \qquad \text{Equation 7}$$

Where σ denotes the ratio of the heavy to light isotope. If the water sample has higher isotopic ratio than SMOW, δ will be positive; if it has lower isotopic ratio than SMOW, then δ will be negative (Kendall & McDonnell, 1998).

The values of δD and δ^{18}O can be plot against the Global Meteoric Water Line (GMWL), which is the graph (δD vs. δ^{18}O) of isotopic compositions of rain samples from around the world with a best fit line described by the following equation (Craig, 1961):

$$\delta \mathrm{D} = 8 \cdot \delta^{18}\mathrm{O} + 10 \qquad \text{Equation 8}$$

Rains which are a product of a first stage condensation (from the ocean) which have undergone evaporation will have a slope less than 8 and will plot below the GMWL (Kendall & McDonnell, 1998). This is the case for tropical islands. But a more useful parameter to determine the occurrence of evaporation in precipitation prior to groundwater recharge is the deuterium excess, d, of Dansgaard (1964) which is equivalent to:

$$d = \delta \mathrm{D} - 8\,\delta^{18}\mathrm{O} \qquad \text{Equation 9}$$

Evaporating water produces vapor fluxes with high d values and, consequently, the rain product will likewise retain the high d signature (Gat, 1996). If water has d values lower than its precipitation source, then it means that it has undergone evaporation; while water with high d values than their associated rains must have combined with evaporative water (Gat, 1996).

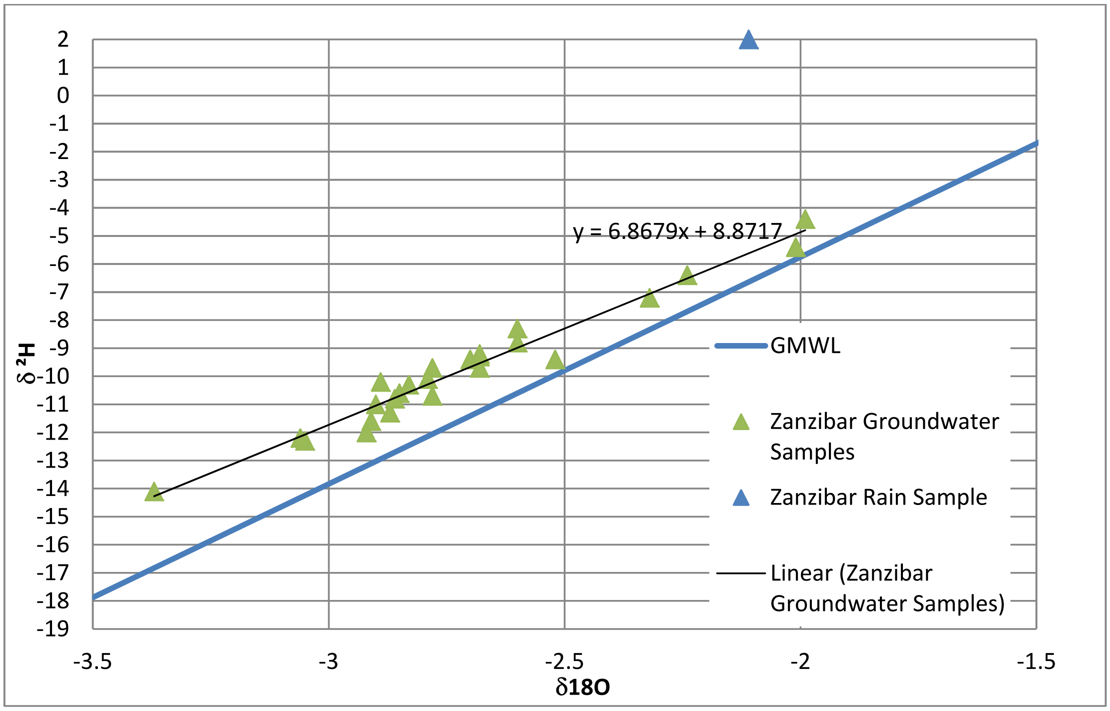
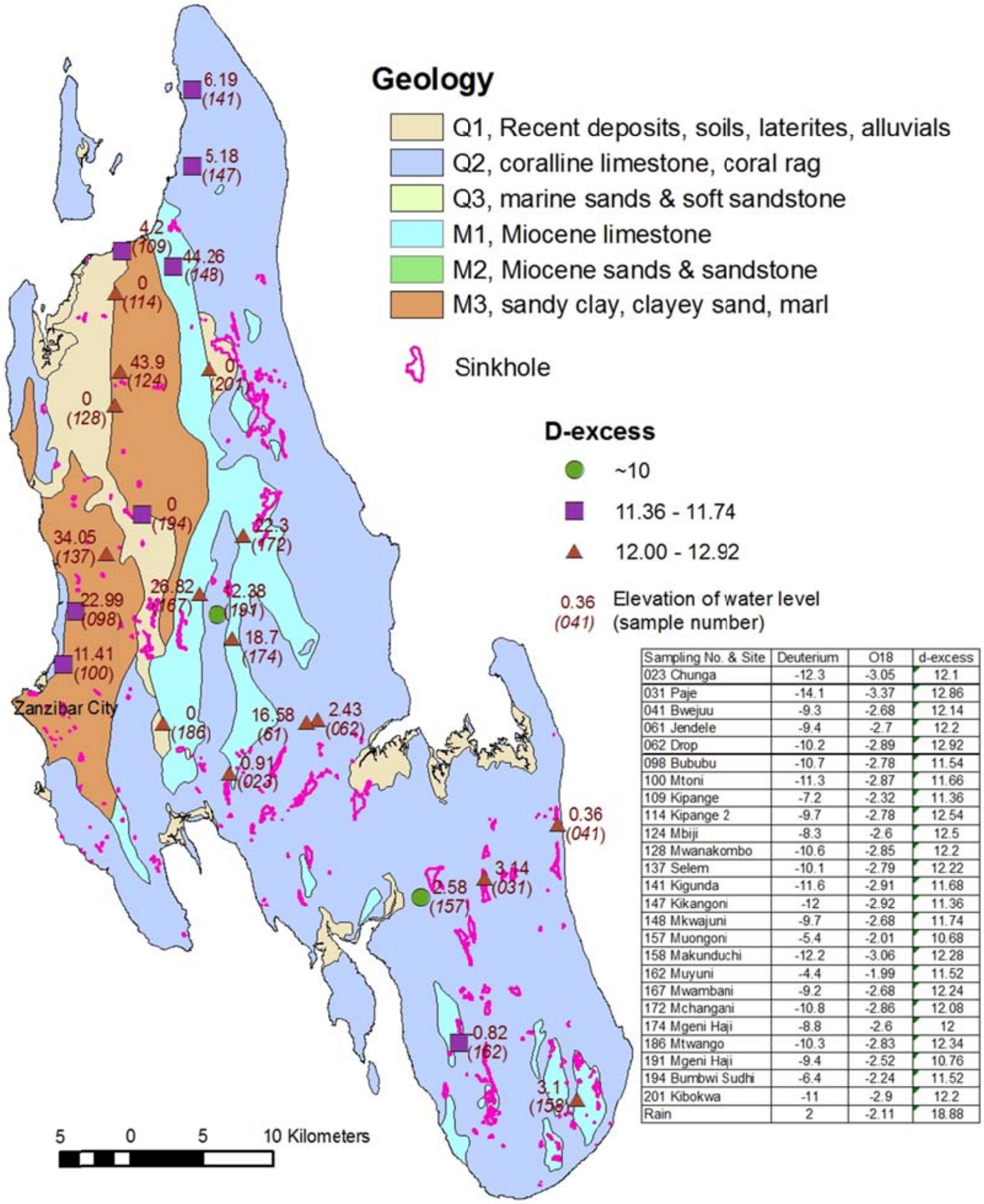


Figure 16. Deuterium- O18 plot of Zanzibar water samples

The rain sample was collected during the end of the second dry season of Zanzibar. The result of the isotope analysis shows that δD and δ^{18}O of rain are enriched in contrast with the groundwater. The rain isotope values plot above the values of the groundwater in Figure 16. The slope of the plot of the groundwater is less than 8 but it is still above the GMWL.

The water vapor that leaves the ocean and that becomes rain has lower δ values than the ocean. However, the heavy water molecules tend to condense more efficiently, and when it rains, the isotopes go with the rain (Mazor, 1991). This happens mostly with light rains. Therefore, this type of rain has more δD and δ^{18}O.

It seems that this is the case for the rain that was sampled in Zanzibar. The season was during the occurrence of light rains. That is why it is difficult to catch the rain within the fieldwork time.



Sampling No. & Site	Deuterium	O18	d-excess
023 Chunga	-12.3	-3.05	12.1
031 Paje	-14.1	-3.37	12.86
041 Bwejuu	-9.3	-2.68	12.14
061 Jendele	-9.4	-2.7	12.2
062 Drop	-10.2	-2.89	12.92
098 Bububu	-10.7	-2.78	11.54
100 Mtoni	-11.3	-2.87	11.66
109 Kipange	-7.2	-2.32	11.36
114 Kipange 2	-9.7	-2.78	12.54
124 Mbiji	-8.3	-2.6	12.5
128 Mwanakombo	-10.6	-2.85	12.2
137 Selem	-10.1	-2.79	12.22
141 Kigunda	-11.6	-2.91	11.68
147 Kikangoni	-12	-2.92	11.36
148 Mkwajuni	-9.7	-2.68	11.74
157 Muongoni	-5.4	-2.01	10.68
158 Makunduchi	-12.2	-3.06	12.28
162 Muyuni	-4.4	-1.99	11.52
167 Mwambani	-9.2	-2.68	12.24
172 Mchangani	-10.8	-2.86	12.08
174 Mgeni Haji	-8.8	-2.6	12
186 Mtwango	-10.3	-2.83	12.34
191 Mgeni Haji	-9.4	-2.52	10.76
194 Bumbwi Sudhi	-6.4	-2.24	11.52
201 Kibokwa	-11	-2.9	12.2
Rain	2	-2.11	18.88

Figure 17. Water sample map

According to Mazor (1991) there will be lower isotopic content in rain (therefore more negative values of δ) during heavy rains due to the "amount effect" of Dansgaard (1964). The δ values of the groundwater suggest that their original recharge could not come from the light rains that occur in September during the time of sampling. However, it will be difficult to say that the recharge for the groundwater comes from the heavy Masika rains simply because there are no rain samples during that season to compare the results with.

The high values of δ for the rain should be further verified because the rainfall is sampled one time only and may not be representative. Representative result of rain can be established only if there are a number of samples collected periodically, especially to represent every season of rain. Whether it is rain or groundwater, one-time analyses are meaningful only if there is a single component source supplying the water under scrutiny (Mazor, 1976). To determine if Vuli rains give significant recharge to the groundwater, another different campaign must be done.

The deuterium excess of the water samples is shown in Figure 17. Only the rain sample has the highest d-excess. The range of d-excess of the groundwater is between 10.68 – 12.92 ‰. Generally low values of d are between 5 – 10 ‰, while high values range from 15 – 25 ‰ according to Ichiyanagi (2009). Only two samples have somewhat low values of deuterium excess. Spatially, it appears that there is no pattern in the water samples that can be related to the lithology (Figure 17).

It seems that without a complete monthly mean isotope data, it will be difficult to associate the groundwater with either a Masika or Vuli recharge source. However, it is interesting to note the differences in the d-excess and δ values between the rain and the groundwater which may only suggest that their origins are not related.

6. CONCLUSIONS AND RECOMMENDATIONS

The objective of the study is to assess the temporal and spatial distribution of recharge in the Island of Zanzibar. A SWAT model for the Island of Zanzibar was simulated for the years 2007-2009 and it shows the spatial and temporal variations in the distribution of recharge. The mean recharge contributed by Masika and Vuli rains was estimated to be 28% of the average yearly rain. However, higher recharge occurs during April to May and November to January, deviation of one month each from the regular rainy seasons. The percentage mentioned does not include the amount of recharge coming from the sinking streams which contribute to groundwater directly through sinkholes. The simulated average mean monthly flows for all the sinking streams total 5.7 cum/s.

Zanzibar is underlain by sandy, clayey, loamy soils and that originate from Miocene sandstone and marls and Quaternary alluvium and limestone. These materials, the type of land cover and the seasonal and spatial distribution of rain affect the temporal and spatial variations of recharge in Zanzibar.

Most land cover over clayey soils with slowly permeable layer has marked low recharge compared to other land cover. The soils of significant recharge are the loamy soil products of the coralline limestone. Bushes overlying these soils show higher recharge than other land cover.

While the spatial and temporal variations of recharge have been shown, the reliability of estimated values needs to be verified. The limited current and historical stream flow data and the distribution of real streams, as well as NDVI, are only used to guide the parameterization of inputs to the model. Independent data from remote sensing was used as validation of the results of SWAT. This is ET_{act} derived using SEBS for two dates (Jan 8 2009 & Mar 6 2009). SWAT ET_{act} and SEBS ET_{act} have different value ranges but there are some similarities in the distribution of the high and low ET values. The reason for the difference in ET_{act} values lies in how actual ET_{act} is modelled in both SWAT and SEBS. In SEBS, the solar radiation used is much higher than the input in SWAT. Computed solar radiation is twice than that of the meteorological station data. Another reason is that the timing of planting and irrigation schedule in SWAT may not exactly represent the actual which and may need to be revised in detail. Furthermore, the land cover map may need to be improved by defining also the different canopy characteristics for perennials and trees and determining the acreages of and distribution of crops cultivated at different times.

Stable isotope results (δD and δ^{18}O)from rain and groundwater samples of Zanzibar were also used to verify (in part) the temporal variation in recharge. While better comparison can be done when using monthly average values of rainfall, it is still interesting to see that the rain sampled is heavier in δD and δ^{18}O than the groundwater sampled. The deuterium-excess values of groundwater and rain are also markedly different. These results suggest that the light rains during the time of sampling are not the recharge source for the groundwater sampled. Generally, at a certain time of sampling, if the groundwater sampled is lighter in isotopes than the mean monthly precipitation characterized by light rains, it usually indicates that the recharge for the groundwater comes from heavier rains. The monthly sampling of rain and groundwater is a better and more complete method to establish the differences in isotope characteristics which may reveal seasonal recharge.

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