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Hydrogeological mapping and estimation of potential evapotranspiration and recharge rate of Quaternary sand aquifers in Dar-es-Salaam, Tanzania

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ABSTRACT

Dar-es-Salaam City is the largest urban centre in Tanzania, with a population of over 4 million. It gets water for domestic use from surface water (Ruvu and Kizinga rivers) and groundwater. The groundwater was used to supplement surface water supply and has by now become the major source of water supply in the city. However, despite the importance of groundwater in the city, limited researches on water quantity and quality have been conducted and generally the groundwater database is inadequate. The main objective of this research is to investigate the availability of groundwater by developing a hydrogeological map of the area and estimate the groundwater recharge rate of the Quaternary sand aquifer in the plain. The deposits in the study area cover two major periods, Quaternary and Neogene. They are made up of sedimentary rocks, which were proposed to be deposited in a fluviatile/deltaic environment with marine intercalations along the seaward margin. The Uluguru Mountains were probably the source of much of the materials deposited in the area. Nearly 150 m of Quaternary deposits consist of basically three geological layers: alluvial, coastal plain and coral reef limestone deposits. These deposits are mostly of Pleistocene to recent age and are found mainly moving from the coast towards the mainland within the river valleys. The Neogene deposits are of Miocene and Pliocene period. Two types of formations characterize these deposits: undifferentiated deposits (Mio-Pliocene clay-bound sands and gravels) and the fluviatile kaolinitic Pugu Sandstone (Lower Miocene). Hydrogeologically, the study area has two types of aquifers in the Quaternary deposits: an upper unconfined sand aquifer (5-50 m thick) and the lower semi-confined sand aquifer (the most productive zone 10-100 m thick). The groundwater recharge is estimated by using monthly precipitation data for 36 years, runoff and potential evapotranspiration. The average groundwater recharge rate in the area is 121.7 mm per year. This delivers substantial amounts of groundwater stored in the sand aquifers of the area.

Keywords: Quaternary aquifers, Hydrogeological mapping, potential evapotranspiration, Groundwater recharge, Tanzania

1. Introduction

The shortage of good quality water from surface sources has made groundwater to be an important source in many urban areas, including Dar-es-Salaam. The Dar-es-Salaam City is the largest urban center in Tanzania, with a population of about 3 million (Mato, 2002). Due to population growth in the area, to get a safe and reliable water source to meet the demand has been a problem since many years. The primary objective of this study was to investigate groundwater quantity by understanding at first the hydrogeological settings of the coastal aquifer in the area and to estimate groundwater recharge in the next step.

The study area comprises three major parts, distinguished by the geological formations outcropping: the central coastal plain with Quaternary fluviatile-deltaic sediments, the deltaic Mio-Pliocene clay-bound sands and gravels in the northwest and southeast and the Lower Miocene fluviatile sandstones of Pugu Hills in the west of the study area. The main groundwater reservoir is within the coastal plain, in the Quaternary sediments and has a thickness of about 150 m (Bartholomew, 1963; Kent et al., 1971). The Mio-Pliocene deltaic clay-bound sand and gravel deposits of more than 740 m thickness form the base of the groundwater reservoir. Underlying the clay-bound sands and gravels are the kaolinitic Pugu Sandstones with a thickness of more than 1000 m that are well developed in the central part of the Dar-es-Salaam embayment. However in Pugu Hills they are found with a thickness of only 300 m, since part of it, together with the clay-bound sands has been eroded to fill the Pleistocene coastal plain. This paper focuses on the hydrogeological characteristics of the unconsolidated sediments of quaternary age, which form the major aquifer in the coastal area of Dar-es-Salaam region. It is based on data acquired from previous studies and fieldwork campaigns conducted between 2004 and 2006 (Mjemah, 2007). It deals with two main subjects; hydrogeological mapping (in which groundwater reservoir and groundwater flow system were mapped) and estimation of groundwater recharge rate.

2. The study area

The study area extends from the Kisarawe/Pugu Hills west of Dar-es-Salaam City to the Indian Ocean in the east, and from the Mzinga River in the south to the Mbezi River in the north. It was delimited based on the hydrogeological boundaries. The area covers part of two administrative regions: Coast Region and Dar-es-Salaam Region, where the recharge and discharge areas are located. It is located at latitudes 6°44'S and 7°00'S; longitudes 39°00'E and 39°19'E, with an area of about 700 km2 (Figure 1).

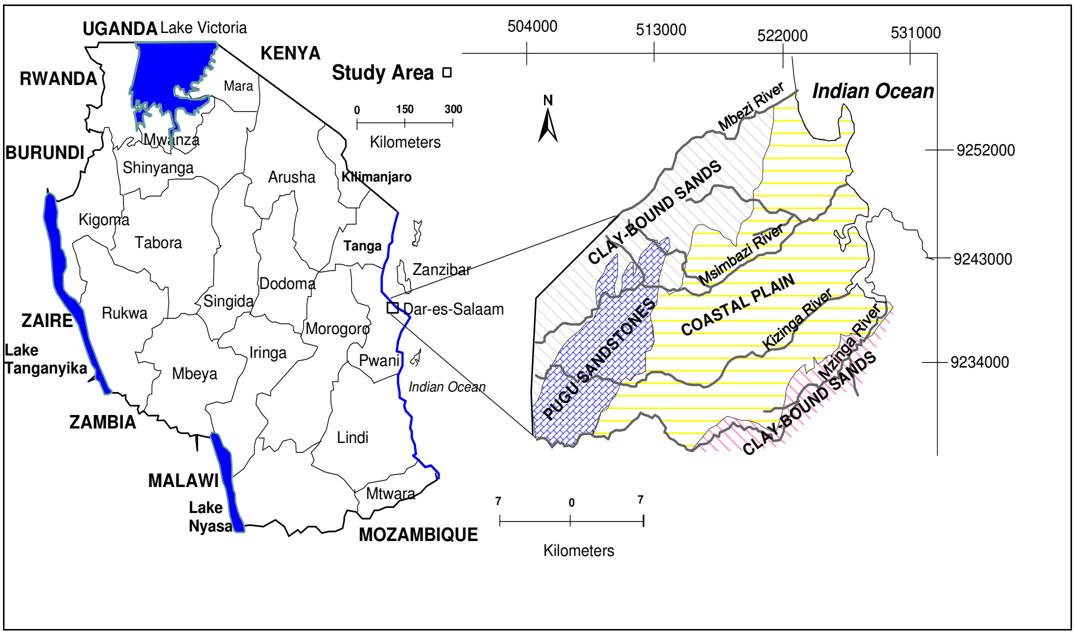

Figure 1: Map of Tanzania showing study area

In 2002, the estimated population of Dar-es-Salaam, according to a national census, was 2.5 million. But the current population of Dar-es-Salaam is estimated at more than 4 million. The population constitutes one third of the country's urban population with an estimated growth rate of 7.2% per annum (Mato, 2002).

2.1 Climatic conditions

The climate in the study area is influenced by the south to southeast monsoon from April to October, and by the northeast monsoon between November and March. The data were obtained from the climatic data archive of Tanzania Meteorological Agency (TMA). In Figure 2, it can be observed that the area has two peaks of rainfall, one is between March and May on the average, and the second is between November and December. These peaks are referred to as the "Long rains" and "Short rains" respectively. November and April are the wettest months within each rainy season.

The Dar-es-Salaam Region experiences a tropical coastal climate with monthly mean temperature ranging between 24°C and 28°C, having a mean annual temperature of 25.8oC and relative humidity of 71%. The average of monthly mean rainfall was calculated from precipitation data of 36 years (i.e. 1971 – 2006). The "Long rains" between March and May have a monthly means peak of 254 mm, while the "Short rains" with storms of limited duration during November and December, provide an average of 116 to 125 mm per month. The annual rainfall average is 1149 mm. As the period June to October is dry, annual Potential Evapotranspiration (PET) is generally greater than annual precipitation. The total average evapotranspiration rate is 1965 mm per annum. The Potential Evapotranspiration (PET) was estimated using the standardized Penman-Monteith method from monthly means climatic data for 36 years (1971 – 2006).

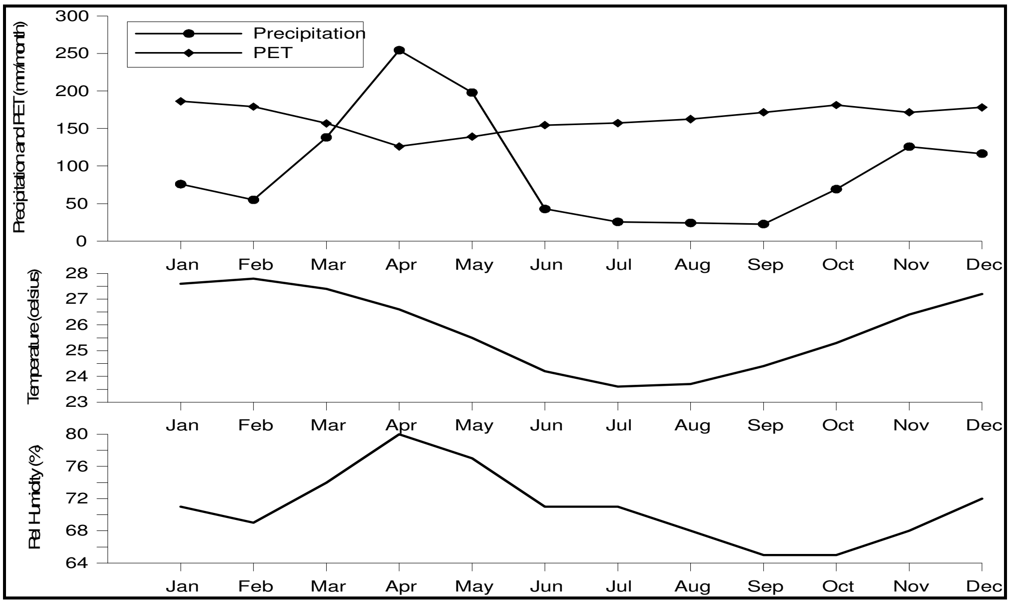

Figure 2: Average of monthly means of precipitation (P), temperature (T), relative humidity (RH) and potential evapotranspiration (PET) (1971– 2006)

Figure 3 shows average yearly rainfall distribution in the study area. The average annual rainfall was mapped from 5 meteorological stations namely: Ubungo Maji, University of Dar-es-Salaam, Dar-es-Salaam International Airport, Kisarawe and Dar-es-Salaam. It indicates rainfall variation from 818 to 1166 mm, whereby 80 per cent of the study area has a mean annual rainfall above 1000 mm. The high precipitation in the Pugu/Kisarawe Hills and central part of the study area can be due to orographic rainfall (CBA Engineering Ltd, 1979). Orographic precipitation, also known as relief precipitation, is precipitation generated by a forced upward movement of air upon encountering a physiographic upland. This upward movement cools the air, resulting in cloud formation and rainfall (Sibley, 2005; Barry, 1992; Chen and Lin, 2003).

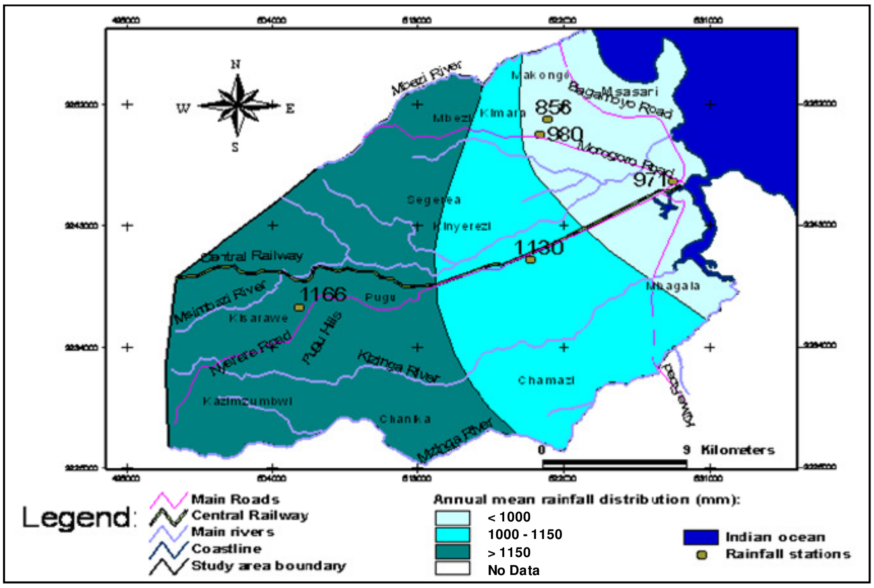

Figure 3: Average yearly rainfall distribution map of Dar-es-Salaam area

3. Materials and methods

3.1 Hydrogeological mapping

Hydrogeological mapping and clarifying the geometry of the groundwater reservoir, is the first requirement in any hydrogeological study. The information used to make a hydrogeological map and cross-sections was obtained chiefly from well logs and previous research reports (*e.g.* Bartholomew, 1963; Kent et al., 1971; Msindai, 1988). When a well is drilled or a boring is made, a descriptive log of the strata encountered normally is made. However, because the educational level and understanding of geology varies widely from one driller to another, the quality of their well logs can also vary. Hence, it is important to combine data from different sources. The geometry of the groundwater reservoir was established based on geology, and by attributing hydrogeological properties (aquifer/aquitard) to the geological formations. This resulted in a hydrogeological map and several hydrogeological cross-sections. The water level of 84 boreholes was taken during the fieldwork campaigns performed in August 2004, August 2005 and August 2006, of which 54 boreholes are located in the upper aquifer and 30 in the lower aquifer. The boreholes were used to map water table and potentiometric surface contours.

3.2 Estimation of groundwater recharge rate

3.2.1 Estimation of potential evapotranspiration

Evapotranspiration, which includes evaporation of water from lands and water surfaces and transpiration by vegetation, is of foremost importance in water resources planning and management. In 1956 Penman redefined potential evapotranspiration as "the amount of water transpired by a short green crop, completely shading the ground, of uniform height and never short of water" and since then the term reference evapotranspiration is used instead. In order to be consistent in this section the potential evapotranspiration (PET) term is used. The

Penman-Monteith (PM) equation is adopted world-wide as the most reliable and accurate method for computing potential evapotranspiration (Anyadike, 1987). The major limitation to the Penman family of models is that they require many meteorological inputs, thereby limiting their utility in data-sparse areas (Dingman, 1994).

The calculation of potential evapotranspiration was done using the monthly weather data of Dar-es-Salaam International Airport of 36 years (1971-2006) obtained from Tanzania Meteorological Agency (TMA). Since the wind speed was measured at 10.0 m height, it has to be converted to a height of 2.0 m. The wind speed at 2.0 m height (U_2) was estimated based on the Eq. 1. The calculation for both the radiation and aerodynamic terms was performed using the Penman-Monteith standardized equation (ASCE-EWRI, 2004) for short canopy PET (Equations 2 and 3 respectively). As the reference grass surface concept was introduced and its parameters were defined, Allen et al. (1998) modified the basic form of PM to incorporate these variables and to produce a simplified PM equation, which combines radiation and aerodynamic terms (Eq.5).

$$U_2 = U_Z\left(\frac{4.87}{\ln(67.8z_W - 5.42)}\right) \tag{1}$$

where, U_Z = wind speed (m s^{-1}) at height z_W (10.0 m) above the ground.

R_o = radiation term of the Penman-Monteith equation for short canopy P_{ET} with U_2 the wind speed at 2.0 m height, is given by:

$$R_O = \frac{0.408\Delta(R_n - G)}{\Delta + \gamma(1 + 0.34U_2)} \tag{2}$$

A_o = aerodynamic term of the Penman-Monteith equation for short canopy PET with U_2 the wind speed at 2.0 m height, is given by:

$$A_O = \frac{\left(\frac{\Phi\gamma}{T_M + 273}\right)U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \tag{3}$$

The standardized Reference (or Potential) Evapotranspiration (P_{ET}) for a short crop (0.12 m high), occupying the reference surface, in mm d^{-1} is:

$$PET = R_o + A_o \tag{4}$$

The final form is described by combining radiation (R_o) and aerodynamic (A_o) equations

$$PET = \underbrace{\frac{0.408\Delta(R_n - G)}{\Delta + \gamma(1 + 0.34U_2)}}_{1} + \underbrace{\frac{\left(\frac{\Phi\gamma}{T_M + 273}\right)U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)}}_{2} \tag{5}$$

Where, the first term refers to the radiation term of the Penman-Monteith equation, while the second term refers to the aerodynamic term of the Penman-Monteith equation.

0.408 = ½.45 converts the units from $MJm^{-2}d^{-1}$ to mmd^{-1}
Δ = slope of the saturation vapor pressure curve (kPa $^oC^{-1}$)
R_n = net radiation over grass ($MJm^{-2}d^{-1}$)
G = soil heat flux density ($MJm^{-2}d^{-1}$)

ϕ =900 and 1600 constants for short (0.12 m) and tall (0.5 m) canopy reference ET respectively
U_2 = wind speed at 2.0 m height
γ = psychrometric constant (kPa $^{o}C^{-1}$)
T_M = Mean daily temperature (^{o}C)
e_s = saturation vapour pressure (kPa) from maximum (T_x) and minimum (T_n) daily temperature
e_a = actual vapour pressure (kPa) from maximum (RH_x) and minimum (RH_n) daily humidity
e_s - e_a = saturation vapour pressure deficit (kPa)

The Excel Program used to estimate Potential (reference) Evapotranspiration (PET) for short canopies is written by Snyder and Eching, 2003 using the Environmental Water Resources Institute of the American Society of Civil Engineers method (ASCE-EWRI, 2004). The method is based on the standardized Penman-Monteith equation using monthly means weather data (i.e. temperature (T), solar radiation (R_s), relative humidity (RH) and wind speed (U)) (Table 2) and the output is daily mean PET by month.

3.2.2 Estimation of groundwater recharge rate

The study area is drained by Mzinga, Kizinga and Msimbazi Rivers having their upper reaches in Pugu and Kisarawe hills. Matondo (1978) and Mkwizu (2002) found that the Kizinga catchment area is a potential recharge source for Dar-es-Salaam aquifer and only 8% of mean annual rainfall appears as total runoff while the major part of the rainfall volume is infiltrating to the ground. The CBA Engineering Ltd (1979) estimated the mean monthly runoff at 7.59 mm from generated monthly runoff data for the Kizinga River from 1894 to 1976, which is also equivalent to 8% of mean annual rainfall loss as runoff.

For budgeting calculations, it is necessary to know the available water-holding capacity in a soil profile. This value is typically expressed in mm and can be obtained by integrating the water-holding capacity over the effective depth of the soil layer. For instance a one-meter roots depth (or soil layer) with a uniform water-holding capacity of 0.15 has a total available water-holding capacity of 150 mm for the case of fine sandy loam. The study area is characterized by fine sand (vadose zone) and shallow-rooted vegetation cover (0.5 m). After Dunne and Leopold (1978), the available water holding capacity of fine sands can be deduced to be 0.10. Hence, the total water-holding capacity can be estimated at 50 mm.

The key environmental factors controlling recharge are climate, soil texture and structure, vegetation and land use, topography, and depth to water table (Thornthwaite and Mather, 1957). The concept presented here is used to estimate the groundwater recharge, R_N, based on the annual water balance of the unsaturated zone (Thornthwaite and Mather, 1957). The method requires keeping track of the accumulated potential water loss (APWL) and the amount of water in the soil.

The following are notations used in the method:

$P-R_o$ = Precipitation - Runoff (mm)
R_o = Mean monthly runoff (7.59 mm)
PET = Potential Evapotranspiration (mm)
PWL= Accumulated Potential Water Loss (mm) (PET – (P – R_O) accumulated for subsequent dry months
AET = Actual Evapotranspiration (mm)
S_B = Water stored in soil, $S_B = CAP*e^{-APWL/CAP}$

CAP: maximum water content of soil, without gravitational water
CAP = Soil Capacity (mm) (= average rooting depth (mm) * water content at field capacity (in volume %) (*i.e.*: 500mm * 10% = 50mm)
ΔS_B = Change in S_B
DEF = Deficit (PET-AET) (mm)
SUR = Surplus (($P-R_o$)-AET) (mm)
R_N = Natural groundwater recharge (SUR-ΔS_B) (mm)

Table 1: Annual soil-water budget calculations

	Wet Season SUR = ($P-R_o$) – PET > 0			Dry Season SUR = ($P-R_o$)-PET < 0
	S_B = CAP	S_B < CAP		
		($P-R_o$)-PET ≤ CAP-S_B	($P-R_o$)-PET > CAP-S_B	
S_B	CAP	S_B + ($P-R_o$)-PET	C_{AP}	CAP*$e^{-APWL/CAP}$
R_N	($P-R_o$) - P_{ET}	0	($P-R_o$)-PET – (CAP-S_B)	0
AET	PET	PET	PET	($P-R_o$) + ΔS_B
DEF	0	0	0	PET - AET

Table 1 shows the concept applied for the estimation of groundwater recharge rate, R_N, during the wet and dry seasons. For instance, during the dry season there is no rainfall surplus since ($P-R_o$) – PET is less than 0, whereas during the wet season there is rainfall surplus when ($P-R_o$) - PET is greater than 0 and S_B = CAP, but if S_B is less than CAP then, there is no recharge (R_N). The concept of field capacity is a useful idea in soil science to denote an upper limit of moisture content in soils. Soil capacity CAP is affected by soil type as well as vegetation type (rooting depth). At field capacity the soil is holding all the water it can under the pull of gravity. In a conceptual sense, groundwater recharge can commence when the moisture content exceeds field capacity.

Calculations to determine S_B and APWL are performed for each month using monthly precipitation (P) and potential evapotranspiration (PET). Excess water, *i.e.*, net precipitation in excess of the soil's water holding capacity (CAP) leaves the soil and is stored in the groundwater storage and eventually released to the river.

4. Results and discussion

4.1 Groundwater reservoir mapping

Groundwater occurrence in Dar-es-Salaam is highly controlled by geological factors such as lithology, type and texture of formations and structure. The Quaternary aquifer system in the study area has been divided into an upper unconfined and a lower semi-confined aquifer separated by a unit of lower permeability. The sediment type for both aquifers is almost the same; the difference is the percentage of different textures. These are Quaternary deposits of Pleistocene to Recent periods and their total thickness is approximately 150 m within Dar-es-Salaam City area. The Quaternary deposits overlay the deltaic deposits of Mio-Pliocene age, which consist of clay-bound sands and gravels, with a thickness of more than 740 m (Kent et al., 1971); they are in this paper considered as the base of the groundwater reservoir, due to their higher clay content compared to the overlying Quaternary sands. However, locally some wells exploit these Mio-Pliocene deposits.

At Kisarawe area there are three boreholes: number 12/2001 (78 m), and number 454/2000 (30 m), both drilled in the clay-bound sands down to Pugu Sandstone formation, and number 476/99 (40 m) drilled in the Pugu Sandstone formation. But they did not reach to the water table as they are completely dry. In the clay-bound sands and gravels area, there are several boreholes but with little yield. The wells with high yield are located in the Quaternary deposits (coastal plain). Hence, the important aquifers in the study area are considered to be in the coastal plain sediments of Pleistocene to Recent age.

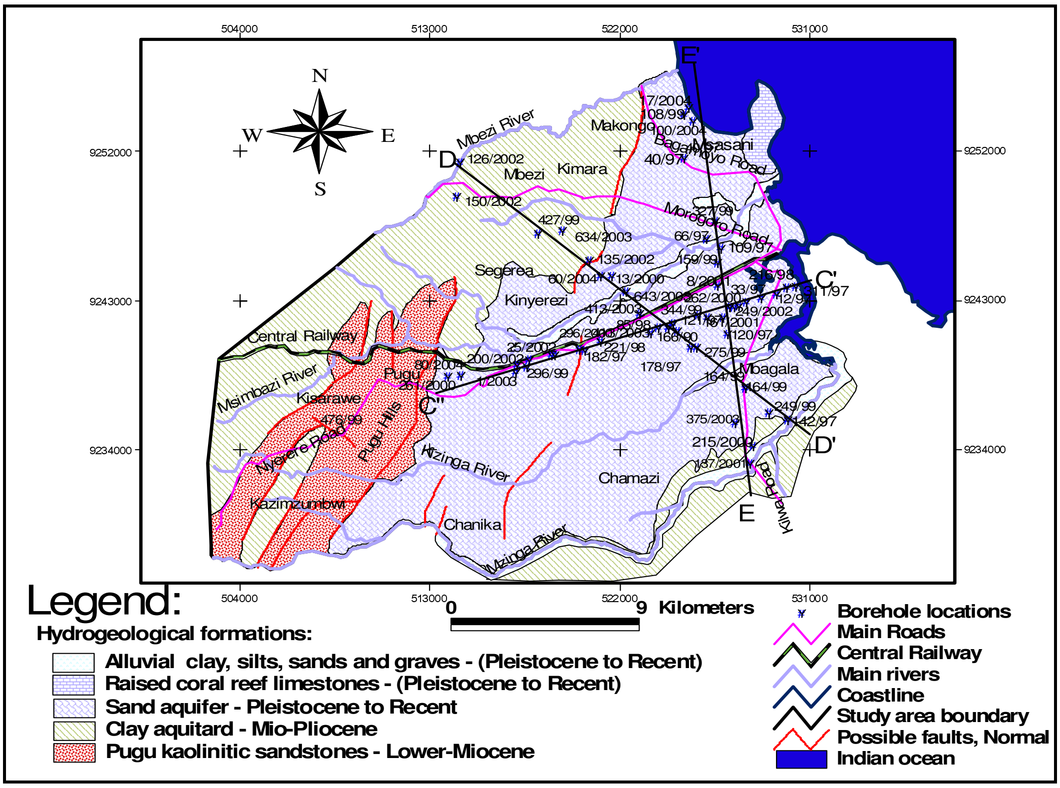

Figure 4: Hydrogeological map of the study area with location of boreholes used in the cross sections

Table 2 summarizes the hydrogeological formations in the study area, that are further described below. The deposits are made up of unconsolidated sediments, which were proposed to be deposited in a fluviatile/deltaic environment with marine intercalations along the seaward margin.

Table 2: Hydrogeological formations in the study area

Aquifer/Aquitard	Period	Epoch	Lithology	Thickness (m)
Unconfined aquifer	Quaternary	Pleistocene to Recent	Fine sand to medium sand with silts and clay, coral reef limestones and calcareous, alluvial clay, silts and gravels	5 - 50
Aquitard	Quaternary	Pleistocene to	Clay, sandy clay (clay)	10 - 50

		Recent		
Semi-confined aquifer	Quaternary	Pleistocene to Recent	Medium to Coarse sand and gravels with clay	10 - 100
Aquitard	Neogene	Mio-Pliocene	Clay-bound sands and gravels (clay), dolomite, calcareous rocks	~1000

4.2 Unconfined aquifer

The uppermost water-bearing unit in the study area is the unconfined aquifer, which consists primarily of unconsolidated materials. The unconfined aquifer is shallow in the south-western part with an average thickness of 10 m, and deep in the eastern part of the study area, up to 50 m thickness. The extent of the unconfined aquifer is shown in Figures 5, 6 and 7.

The thickness is varying from 5 to 50 meters and the greatest depth of approximately 50 m is found near the Indian Ocean. The unconfined aquifer is described as consisting mainly of fine to medium sand that contains varying amounts of silt and clay. Along the coastal strip of the Indian Ocean, it consists of coral reef limestones. Alluvial clay, silts, sand and gravel deposits occur widely along the watercourses and they are found in the channels of the river and tributary creeks of Mzinga, Kizinga and Msimbazi Rivers. The depth of the water table in the unconfined aquifer ranges from at or near to land surface in low-lying areas, to tens of meters below the land surface in areas of higher elevations.

4.3 Semi-confined aquifer

The lower aquifer system is under semi-confined conditions in unconsolidated sediments and is mainly comprised of medium to coarse sands, and sometimes gravels and pebbles, always in a clay matrix. This lower aquifer of 10-100 m thick is of special significance for the water supply, hence is referred to as the main producing zone, because most of the groundwater used in Dar-es-Salaam City is withdrawn from this zone. It overlays the base of the groundwater reservoir, formed by the Mio-Pliocene clay-bound sands, forming an aquitard of about 1000 m thickness.

4.4 Aquitards

The unconfined and semi-confined aquifers are separated by a clay aquitard of varying thickness between 10 and 50 m. However, in the area close to the Indian Ocean, the aquitard is not a continuous layer, forming some clay lenses, probably due to erosion (Figures 5, 6 and 7). The aquitard separating upper and lower aquifers is considered as Pleistocene deposits.

The underlying clay-bound sands layer is probably of Mio-Pliocene age. It is conceived as a clay aquitard. The maximum thickness of the clay-bound sands layer is not yet well known, but it may be estimated at about 1000 m. This layer is found in the western to north-eastern as well as in the south-eastern part of the study area with a thickness reaching over 160 m as found in borehole number 135/2002 in Figure 6. At Pugu Hills this clay-bound sands layer with a thickness of about 100 m is overlying the Pugu kaolinitic sandstone. According to Bartholomew (1963) the clay-bound sands are possibly unconformably resting upon the Pugu sandstones, since they dip westwards but at an apparently smaller angle than the kaolinitic Pugu sandstones.

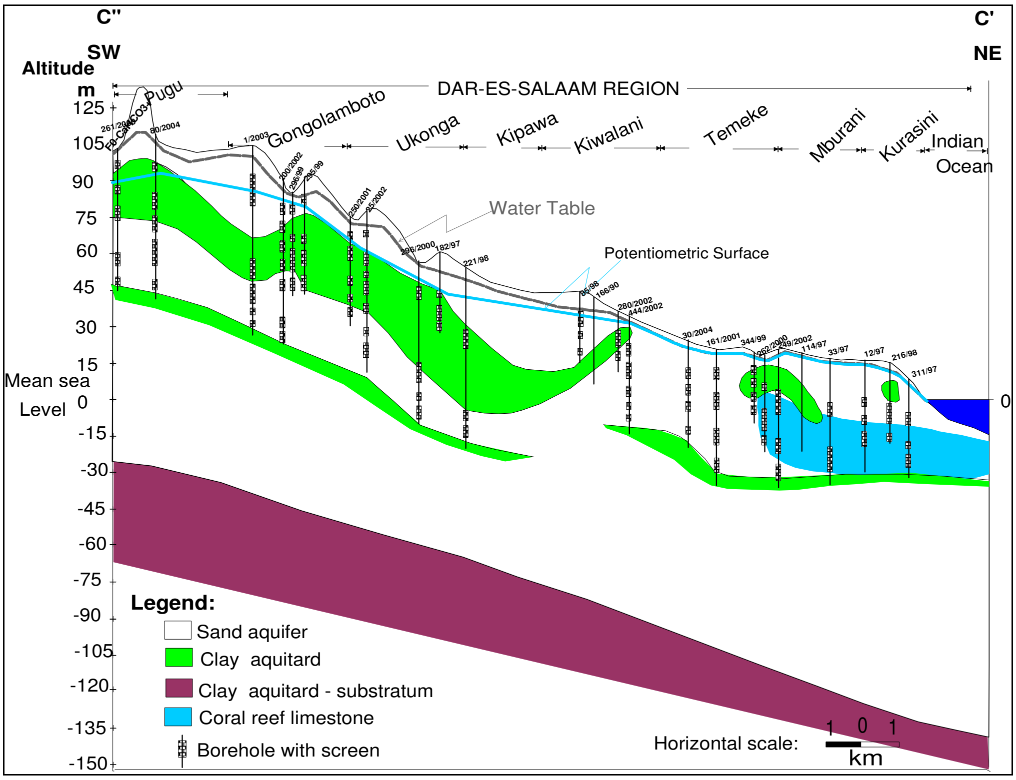

Figure 5: Hydrogeological cross section C''-C' of the study area, location of the profile is shown in Figure 4

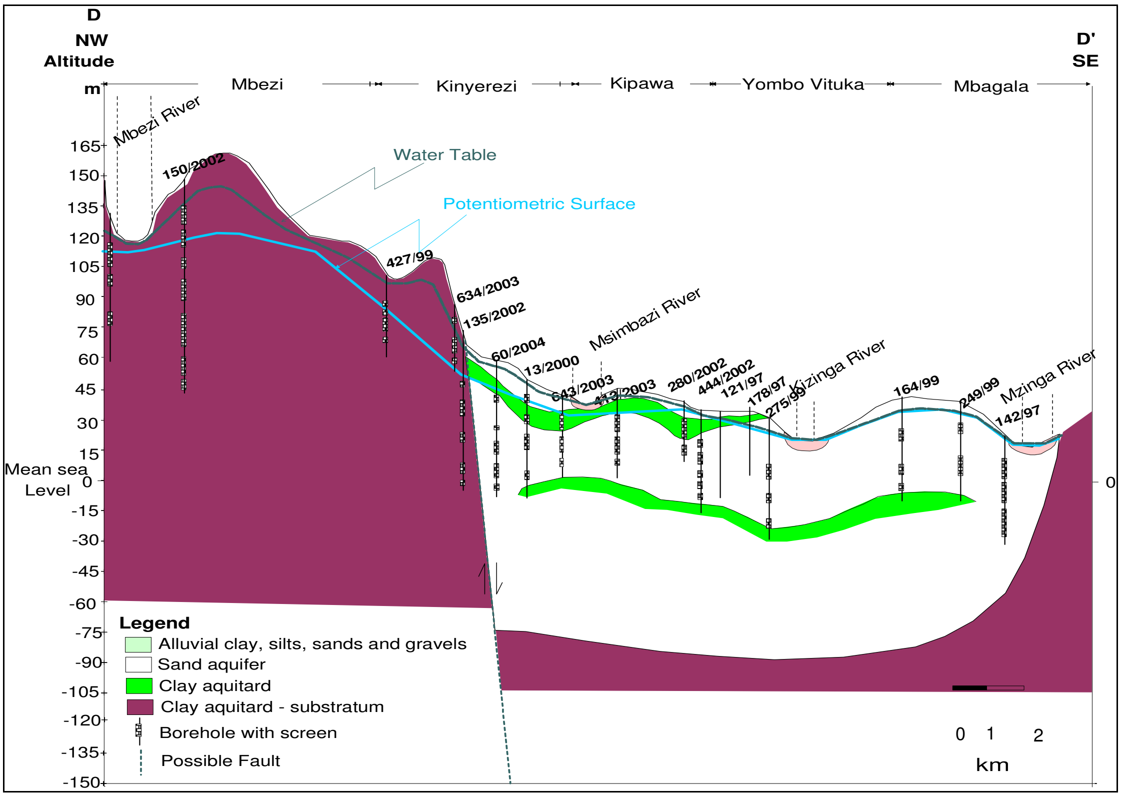

Figure 6: Hydrogeological cross section D-D' of the study area, location of the profile is shown on Figure 4

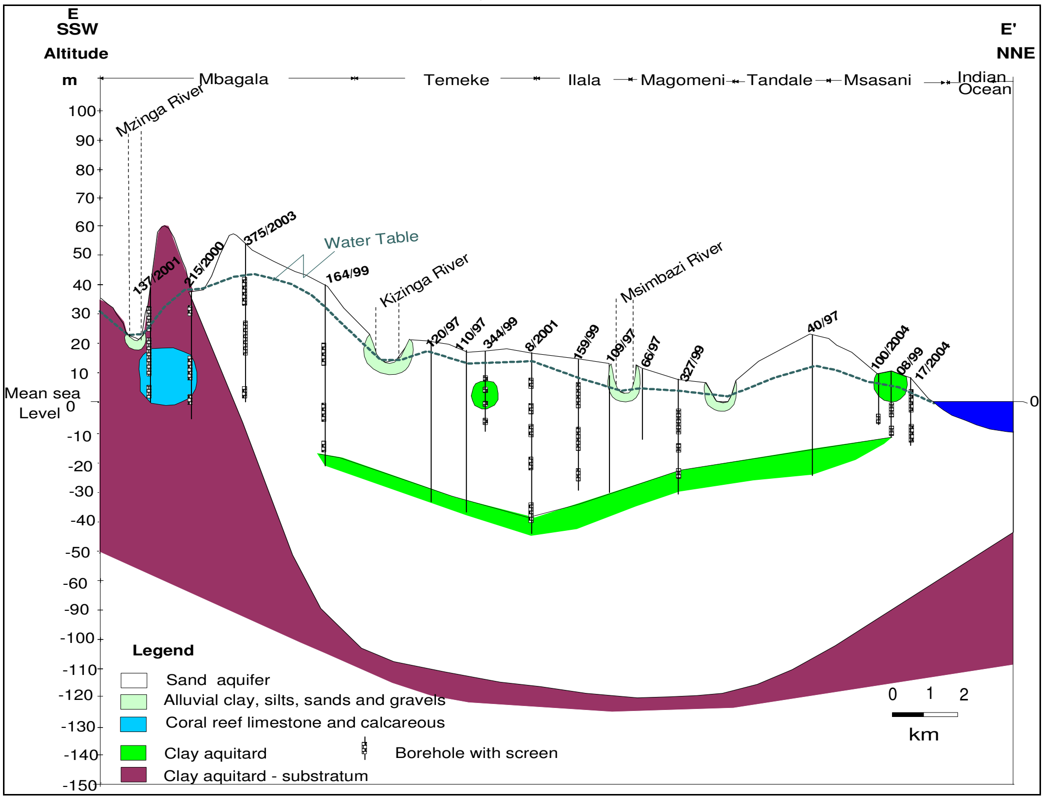

Figure 7: Hydrogeological cross section E-E' of the study area, location of the profile is shown on Figure 4

4.2 Groundwater flow system mapping

Groundwater is normally hidden from view. Many people have difficulty visualizing its occurrence and movement (Heath, 1983). This difficulty adversely affects the ability to understand and to deal effectively with groundwater related problems (Winter et al., 1998). This could be partly solved through the use of groundwater flow nets, which are one of the most effective means yet devised for showing conditions in groundwater systems. By knowing the direction of groundwater flow, it can help to map out the land area that recharges the public water supply wells, streams, rivers, lakes, etc and thereby take steps to ensure that land use activities in the recharge area will not pose a threat to the quality of the groundwater and the resources dependent on it. Since contaminants generally move in the direction of groundwater flow, this knowledge can also help to predict how contaminants might move through the local groundwater system.

Analysis of groundwater levels and flow revealed that the Indian Ocean is the major receiving surface water body for groundwater in the study area. Specifically, groundwater flow from Kisarawe and Pugu Hills areas generally is toward the Indian Ocean. The general direction of the groundwater flow is west to east. The depths to water level in the study area range from less than 10 m in the south and along some of the stream valleys to about 50 m in the southeast and northwest of the basin. The shallowest groundwater was found in the alluvium of the Msimbazi River near to the Indian Ocean and upstream of Mzinga and Kizinga Rivers. However, in the western part of the study area (Pugu Hills) depth to water level was not mapped because the boreholes drilled up to the depth of 78 m were found dry.

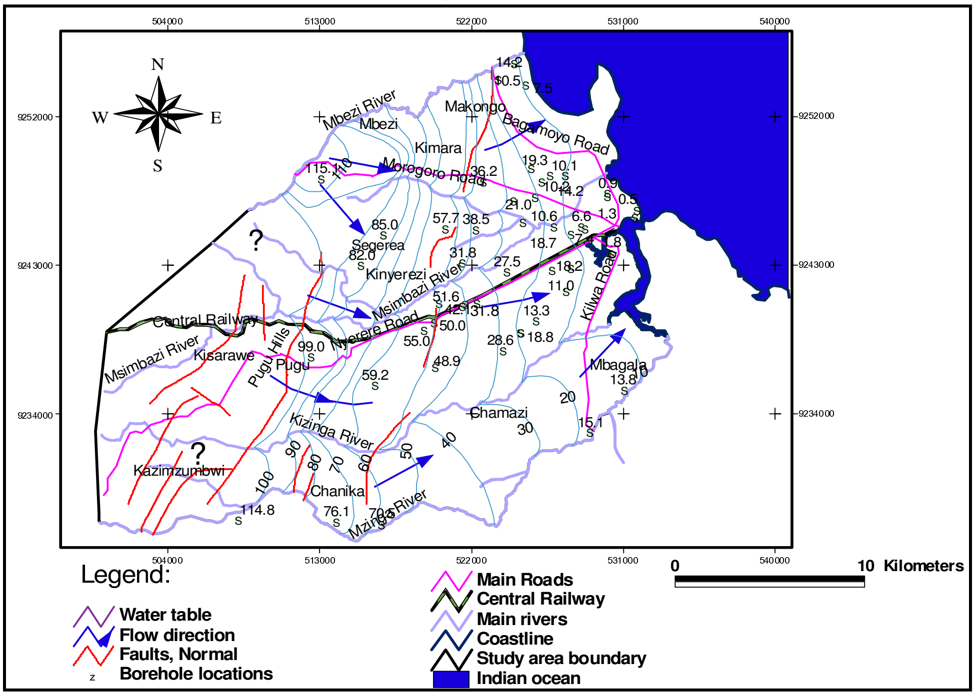

Figure 8: Water table contour map of the upper aquifer

The water table contours form V's with the rivers and their tributaries, pointing upstream. That is because the rivers are "gaining" rivers. They are receiving recharge from the aquifer (Figure 8). The opposite of a gaining stream is a "loosing" stream. It arises when the water table at the stream channel is lower than the stream's elevation, or stage, and stream water flows downward through the channel to the water table. This is very common during the dry season or in dryer regions, like Central Tanzania, which is characterized by semi-arid conditions. In the case of a loosing stream, the V will point downstream, instead of upstream. The arrows in Figure 8 indicate the direction of the groundwater flow.

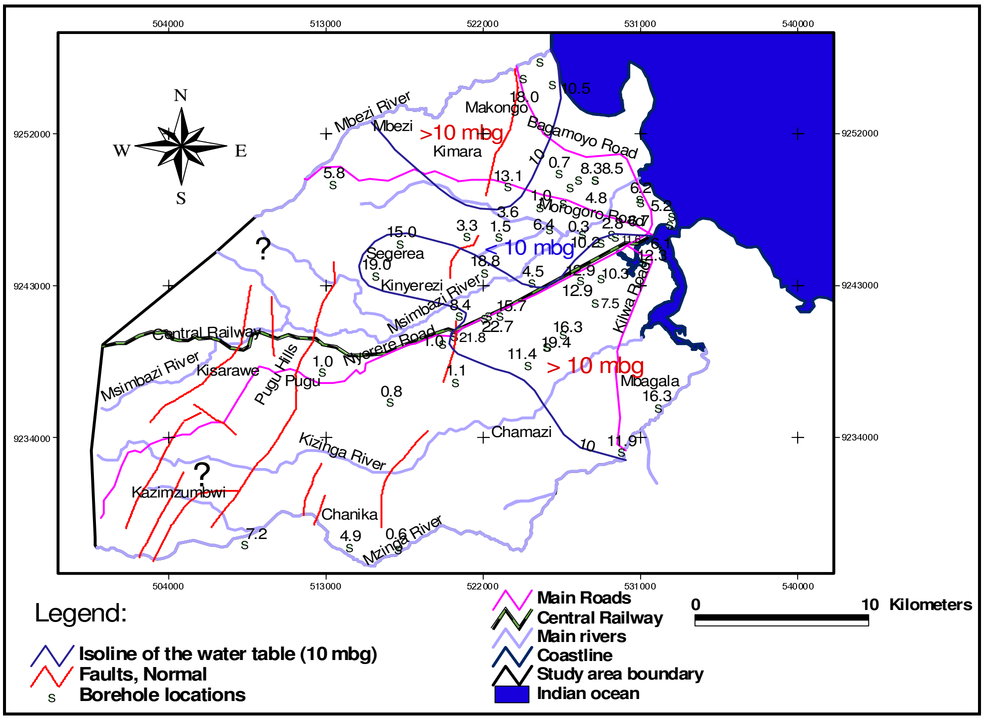

Figure 9: Map showing the depth to the water table (mbg: meter below ground surface)

In general the direction of groundwater is from higher topography in the west to the sea in the east. However, considering it locally, flow can be divided into two components, one is to the east especially in the northern part of the area and a second component is to the south: between central railway and Kizinga River, flow is clearly to southeast. The water table in the study area was found at a depth of 0 to 10 m in most part of the discharge areas except in Makongo, Mbezi, Kimara, Segerea and Kinyerezi, where it was located at a depth up to 50 m (Figure 9). Pugu Hills and Kisarawe areas are completely dry as revealed by the boreholes drilled up to 78 m in depth. However, in river valleys, the water table was found from seasonal shallow wells at depths varying from 1 to 3 m. The shallow wells are located in the perched aquifer since they have water only during the rainfall season.

Figure 10 shows the potentiometric surface mapped from 30 boreholes drilled up to the lower semi-confined aquifer. The potentiometric surface map is a contour map that represents the top of the groundwater surface in an aquifer. The potentiometric surface map is very similar to a water table map in that both show the horizontal direction and gradient of groundwater flow. However, a water table map shows the level of saturation in an unconfined aquifer. The potentiometric surface is generally not the physical top of the water table but is a representation of the pressure energy that is available to move the groundwater in a semi-confined aquifer. In the study area the potentiometric surface is varying from place to place, in another area outside the study area, it was found above the ground surface (artesian well), while other parts of the study area are completely dry such as boreholes No. Co.476/99 (40 m) and No. Co.454/2000 (30 m) located at Kisarawe Lutheran Junior Seminary and borehole No. Co.12/2001 at Kazimzumbwi drilled to a depth of 78 m.

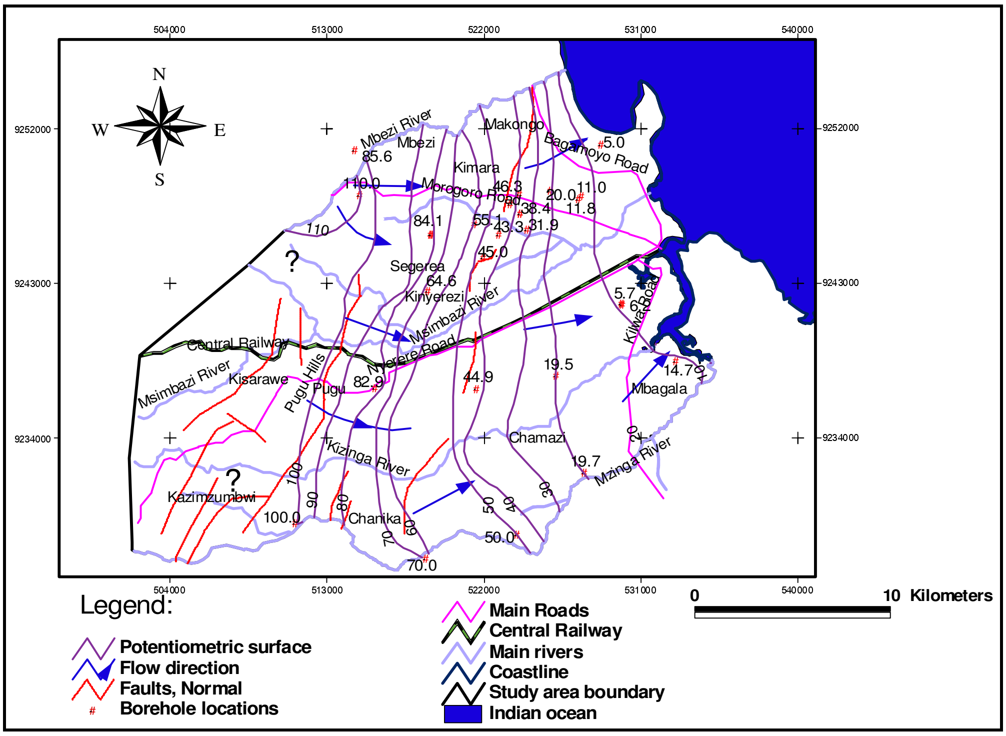

Figure 10: Potentiometric surface map of the lower aquifer

4.3 Estimation of potential evapotranspiration and groundwater recharge rate

Table 3 shows the monthly mean PET calculated based on averages of monthly means of climatic data for 36 years (1971-2006).

Table 3: Average of monthly means climatic data for 36 years (1971-2006)

Month	P (mm)	T (°C)	R_s(MJm^{-2})	R_H (%)	U_2 (m s^{-1})	PET (mm)
Jan	76.0	27.6	19.40	71	6.34	186.4
Feb	55.1	27.8	20.23	69	6.21	179.2
Mar	138.2	27.4	18.10	74	4.09	156.9
Apr	254.3	26.6	15.74	80	4.50	126.0
May	197.9	25.5	15.90	77	5.41	139.3
Jun	42.9	24.2	16.94	71	6.11	154.6
Jul	25.7	23.6	16.89	71	5.81	157.3
Aug	24.3	23.7	17.64	68	4.88	162.5
Sep	22.8	24.4	18.57	65	4.96	171.5
Oct	69.3	25.3	19.12	65	4.90	181.3
Nov	125.9	26.4	19.81	68	4.75	171.7
Dec	116.6	27.2	19.71	72	5.59	178.2

Table 4 summarizes the results of the recharge rate estimation. It can be observed that the surplus and eventually groundwater recharge take place only in April and May during the high rainfall period reaching 246.7 and 190.3 mm. Hence a water surplus for both months of 171.7 mm is realized. This surplus immediately goes into building the soil moisture component. After the soil has reached CAP (= 50 mm), it releases the excess moisture to the underlying groundwater with 121.7 mm. During the wet period, the potential evapotranspiration of April (i.e. 126.0 mm) and May (i.e. 139.3 mm) equals the actual evapotranspiration (PET = AET). However, it can be observed that when P-R_o < PET, water stored in soil starts to decrease until the soil becomes depleted of its moisture, until S_B = 0. In this period, that is from June to March, there is no surplus and the actual evapotranspiration (AET) is less than the potential evapotranspiration (PET).

Table 4: The estimation of groundwater recharge from monthly mean precipitation and potential evapotranspiration (years 1971-2006) (Mjemah, 2007)

Month	P-R_o(mm)	PET(mm)	PET- (P-R_o)	APWL	S_B	ΔS_B	AET	DEF	SUR	R_N
June	35.3	154.6	119.3	119.3	4.6	-45.4	80.71	73.9	0.0	0.0
July	18.1	157.3	139.2	258.5	0.28	-4.32	22.4	134.9	0.0	0.0
August	16.7	162.5	145.8	404.3	0	-0.28	16.98	146.1	0.0	0.0
September	15.2	171.5	156.3	560.6	0	0	15.2	156.3	0.0	0.0
October	61.7	181.3	119.6	680.2	0	0	61.7	119.6	0.0	0.0
November	118.3	171.7	53.4	733.5	0	0	118.3	53.4	0.0	0.0
December	109.0	178.2	69.2	802.7	0	0	109.0	69.2	0.0	0.0
January	68.4	186.4	118.0	920.7	0	0	68.4	118.0	0.0	0.0
February	47.5	179.2	131.7	1052.4	0	0	47.5	131.7	0.0	0.0
March	130.6	156.9	26.3	1078.7	0	0	130.6	26.3	0.0	0.0
April	246.7	126.0			50	50	126.0	0.0	120.7	70.7
May	190.3	139.3			50	0	139.3	0.0	51.0	51.0
					Total Recharge (mm)					**121.7**

The groundwater recharge rate (RN) was calculated for different values of CAP in order to study the relationship between them. In Figure 11, it can be observed, that there is a decrease in groundwater recharge rate, RN, with increasing CAP. This shows that the soil capacity (CAP) plays a major role in groundwater recharge. As stated in the previous section, CAP depends on the soil texture and rooting depth. However, the calculated CAP of 10, 25, 50, 75 and 100 mm in this case is based only on different rooting depths by assuming the recharge area has fine sandy soil type occupying the vadose zone. Hence the water-holding capacity was taken at 10% (Dunne and Leopold, 1978). The different values for CAP range from shallow rooted vegetation of 100 mm to deep rooted vegetation of 1000 mm. The obtained CAP then was used to calculate groundwater recharge by using the method described earlier. It can be noticed that, as the rooting depth increases, the groundwater recharge decreases. For shallow rooted vegetation (100 mm) the groundwater recharge rate is 161.7 mm/year, while for the deep rooted vegetation (1000 mm), it decreases to 71.7 mm/year. In the study area an average rooting depth of 500 mm was assumed, which gave a groundwater recharge of 121.7 mm/year.

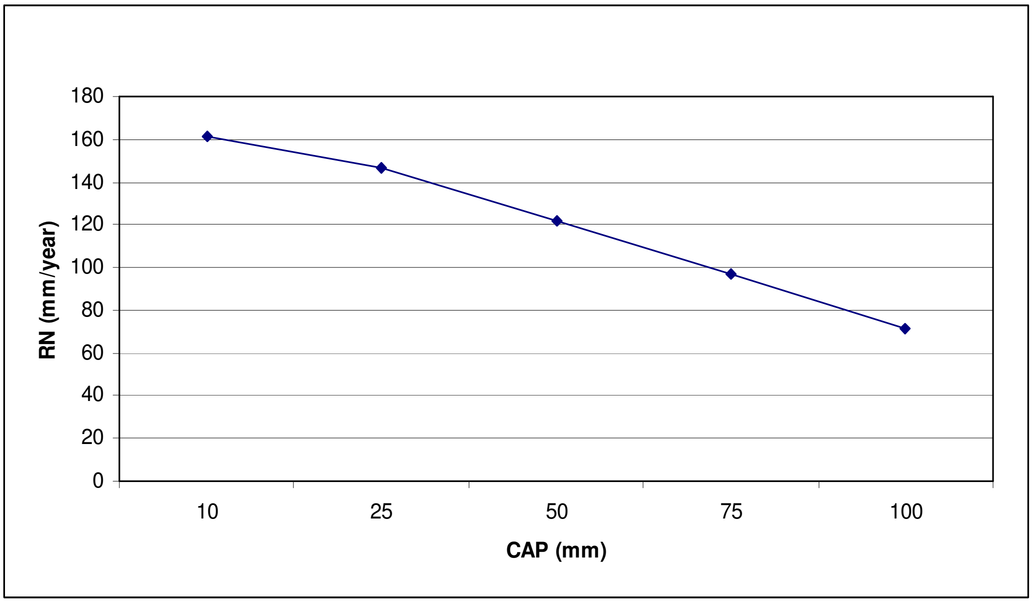

Figure 11: The relationship between groundwater recharge rate (R_N) and soil capacity (CAP)

5. Conclusions and recommendations

Groundwater in Dar-es-Salaam is highly controlled by geological factors such as lithology, type and texture of formations and structure. Kisarawe (in clay-bound sands formation) and Pugu Hills (in sandstone formation) areas are completely dry as revealed by the boreholes drilled up to 78 m in depths. Most boreholes that are drilled in the coastal plain sediments of Pleistocene to Recent age (Quaternary deposits), have high yield, and hence, the important aquifers in the study area are considered to be located in the coastal plain, within the Quaternary deposits. The Quaternary aquifer system in the plain has been subdivided into an upper (unconfined) and a lower (semi-confined) aquifer, separated by a unit of lower permeability. The sediment type for both aquifers is almost the same; the difference is the percentage of different textures.

The results of the water level measurements from 84 boreholes show that the groundwater flow generally is from Kisarawe and Pugu Hills areas toward the Indian Ocean. The general direction of the groundwater flow is west to east. The depths to water level in the study area range from less than 10 m in the centre of the coastal plain to about 50 m in the southeast and northwest of the basin.

The groundwater recharge is considered to be both of regional and local type, and is contributed by the faults present in the study area as well as by the nature of the sandy soil type within the coastal plain. The major source of renewable groundwater in the aquifer is rainfall. In the study area an average rooting depth of 0.5 m was assumed, which gave a groundwater recharge by precipitation of 121.7 mm/year. This delivers substantial amounts of groundwater stored in the sand aquifers. The fact that groundwater exploitation has largely increased recently, calls for a directed attention towards possible problems of aquifer overexploitation, that may arise in the near future. Installation of piezometers is proposed, for careful and regular monitoring of the piezometric levels of both aquifers (for detection of propagating depression cones and regional lowering of piezometric levels) and for monitoring of groundwater quality, e.g. possible salinization resulting from overexploitation, especially in the area near to the Ocean.

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