

Groundwater exploitation and recharge rate estimation of a quaternary sand aquifer in Dar-es-Salaam area, Tanzania

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Abstract Dar-es-Salaam City gets water supply from surface water and groundwater. The groundwater is used to supplement surface water supply and has increasingly become a major source of water supply in the city. The study area comprises three major parts: the central coastal plain with quaternary fluvial–deltaic sediments, the deltaic Mio-Pliocene clay-bound sands and gravels in the northwest and southeast and the Lower Miocene fluvatile sandstones of Pugu Hills in the west of the study area. The main objective of this study was to quantify the integrated water balance. The major source of renewable groundwater in the aquifer is rainfall. Hence, the average recharge of 256.2 mm/year (for the year 2006) to the aquifer was estimated using the balance method of Thornthwaite and Mather, which is equal to 99.4 hm³/year for the whole alluvial aquifer. This value was balanced with total groundwater abstraction of 8.59 hm³/year, baseflow to rivers of 75.7 hm³/year and discharge into the sea (15.11 hm³/year).

Keywords Dar-es-Salaam · Quaternary aquifer · Groundwater exploitation · Groundwater recharge · River discharge

Introduction

Background

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). Owing to population growth in the area, a safe and reliable water source to meet the demand has been a problem since many years.

The study area comprises three major parts, distinguished by the geological formations outcropping: the central coastal plain with quaternary fluvial–deltaic sediments, the deltaic Mio-Pliocene clay-bound sands and gravels in the northwest and southeast and the Lower Miocene fluvatile sandstones of Pugu Hills in the west of the study area. The 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; Msindai 1988). 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 1,000 m that are well developed in the central part of the Dar-es-Salaam embayment (Kent et al. 1971) (Fig. 1). 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 groundwater quantity, specifically the estimation of groundwater recharge rate, assessment of groundwater exploitation and groundwater contribution to rivers (baseflow).

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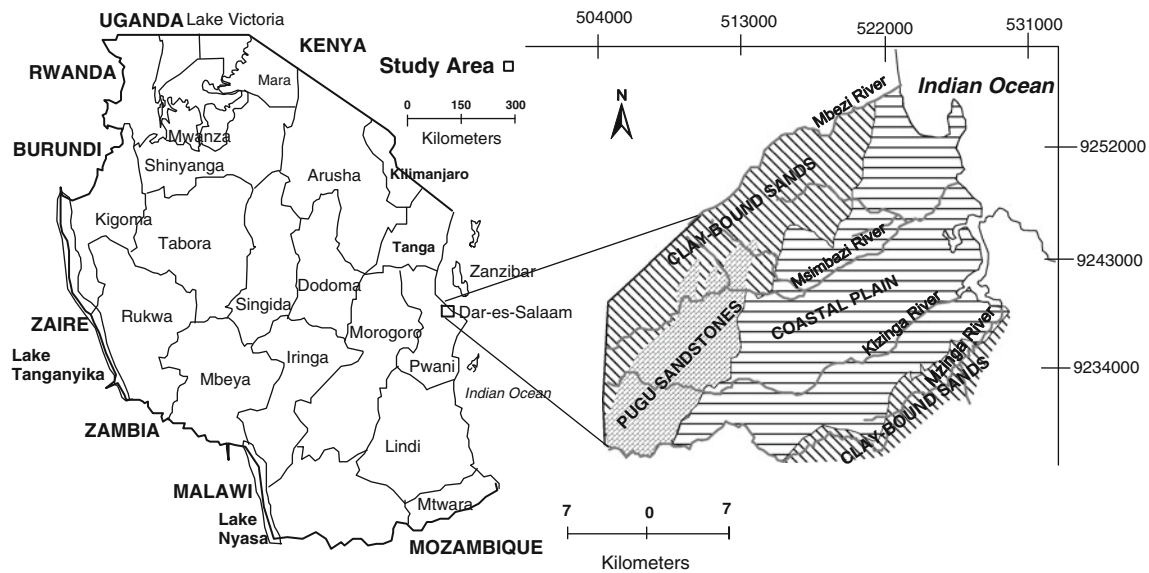
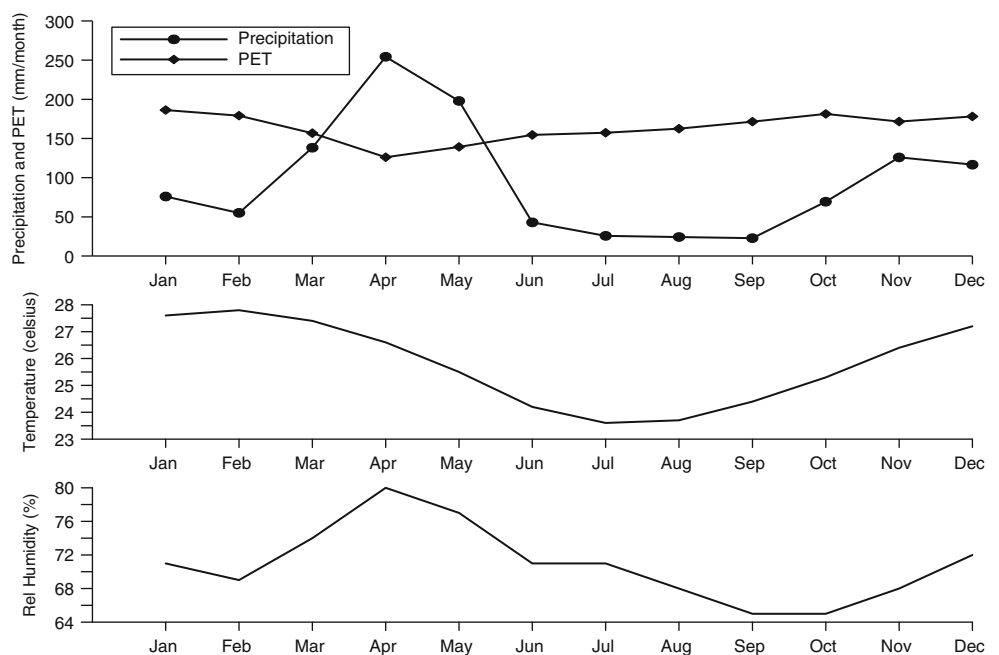


Fig. 1 Map of Tanzania showing study area (geological map)

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



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 selected based on the hydrogeological boundaries (Mjemah 2007). 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 (Fig. 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 Fig. 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

from November to December. These peaks are referred to as the “Long rains” and “Short rains” respectively. 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 116–125 mm/month. The Dar-es-Salaam Region experiences a tropical coastal climate with monthly mean temperature ranging between 24 and 28°C having a mean annual temperature of 25.8°C and relative humidity of 71%. The average of monthly mean rainfall was calculated from precipitation data of 36 years (i.e., 1971–2006). The annual rainfall average is 1,133 mm (ranging between 1,000 and 1,400 mm). As the period June to October is dry, annual potential evapotranspiration (PET) is generally greater than annual precipitation. The total average PET is 1,715 mm per year. PET was estimated using the standardized Penman–Monteith (PM) method from monthly means climatic data for 36 years (1971–2006).

Groundwater exploitation

Groundwater is used as a source of water supply for the Dar-es-Salaam City since 1943, after the first borehole was drilled at Temeke Dairy Plant with a depth of 30 m and a yield of 8 m³/h (Service Plan 1997). Some other industries started to use groundwater later on to a limited extent. In 1949, surface water started to be the main source of water supply after the Mtoni Water Treatment Plant on Kizinga River was constructed, and this was further increased after the construction of Upper and Lower Ruvu Water Treatment Plants on River Ruvu in 1959 and 1975, respectively. From 1975 to 1997, the pace of borehole drilling remained very low, except for shallow wells in areas without piped water connections. In 1997, Tanzania experienced a severe drought, causing Dar-es-Salaam Water and Sewerage Authority (DAWASA) to set a task force “Emergency Programme” to drill extra boreholes to meet the water demand. Many of the existing boreholes in Dar-es-Salaam were constructed during this period. Various development programs were supported with funding made available by financial institutions for drilling and mechanizing wells and with professional assistance for locating the best sites for them. Today, there are more than 1,300 boreholes for domestic, water supply and industrial purposes.

However, during the field campaign conducted in the period 2004–2005, it was found that many boreholes are not operating due to either pump failure or they were abandoned due to high salinity. Only 283 boreholes out of 400 wells visited were operating.

More than 35 boreholes are connected to the main distribution system of the city, supplying water without any

treatment (Mato 2002). Yet, many private well owners (with unconnected wells) also sell their water, supplying the population with drinking water. Fifty-eight boreholes (visited during the field campaigns in 2004 and 2005) supplying drinking water (both connected and unconnected to the distribution system) are drilled at 20–70 m deep. About 60% of these boreholes have yield greater than 10 m³/h. Some areas, such as Mbagala have outstandingly high yield of over 20 m³/h (Fig. 3).

Out of the 283 productive boreholes, which were visited in 2004–2005, 7% show high yield above 20 m³/h. The borehole with highest yield (121.85 m³/h) in the study area is located in Kinondoni municipality. However, Temeke municipality, especially Mbagala, is the area with a high density of boreholes with high yields and many are used for water supply.

Table 1 shows the estimation of groundwater pumped for different purposes, based on the yield data collected during the 2004–2005 field campaigns. The pumping yield data per well was considered together with the use the well is serving, to produce the yearly yield of the well. Wells used for domestic purposes were assumed to be pumped during 1 h/day, at every day of the year. Wells used for public water supply were assumed to be pumped for 6 h/day, during 365 days/year. The industrial wells were assumed to be pumped for 6 h/day, during 260 days/year. The yearly totals per well were then summed. The total amount of groundwater pumped of these visited operating wells was thus calculated to be 2.64 × 10⁶ m³/year.

Table 2 shows the estimation of groundwater pumped in the whole study area for different purposes, based on the yield data collected during the 2004–2005 field campaigns. The estimated value of 2.64 × 10⁶ m³/year was then considered as representing total yield for the 400 wells visited (during fieldwork); for assessing yield per well, this had to be divided by 400, and to be multiplied by the total number of wells in the study area (i.e., 1,300) for obtaining total abstraction of groundwater in the study area. It may indeed be expected that part of the not visited wells, will not be productive, just as for the 400 visited ones. This

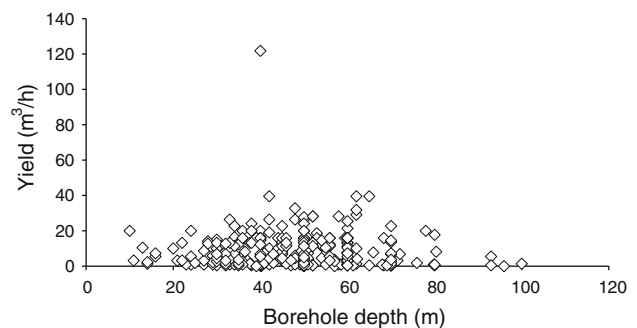


Fig. 3 Relationship between yield and borehole depth

Table 1 Estimation of yearly yields in the 283 productive boreholes that were visited during the 2004–2005 field campaigns

Purpose	No. of wells	Yield (m ³ /h)	Pumping duration considered	Total yield (×10 ⁶ m ³ /year)
Domestic	204	1,481.92	1 h × 365 days	0.54
Water supply	58	774.04	6 h × 365 days	1.70
Industrial	21	261.31	6 h × 260 days	0.40
Total	283	2,517.27		2.64

Table 2 Estimation of groundwater utilization in the whole study area from data of the 283 productive boreholes that were visited during the 2004–2005 field campaigns

Purpose	No. of wells	Total yield (×10 ⁶ m ³ /year)	Pumped amount for whole study area (×10 ⁶ m ³ /year)
Domestic	204	0.54	1.76
Water supply	58	1.70	5.51
Industrial	21	0.40	1.32
Total	283	2.64	8.59

calculation produces an estimation of the total groundwater abstraction in the whole study area which amounts to 8.59×10^6 m³/year (Table 2). For water supply and industrial wells together, the amount pumped was estimated to be 6.83×10^6 m³/year.

Surface water discharge measurements

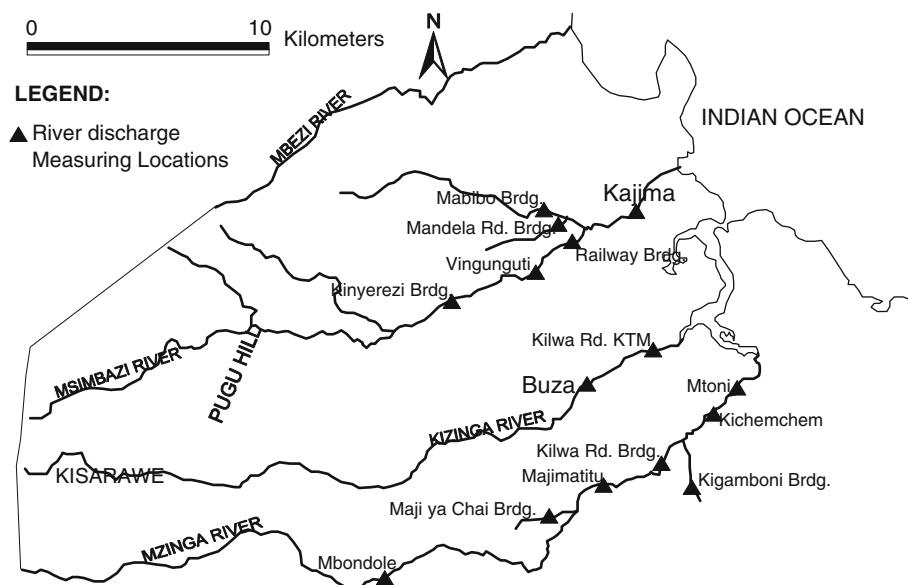
Background and methodology

Rivers increase in discharge and size (geometry) with increasing distance downstream. A river in its headwater area (the area where a river begins) is only draining a small

part of land. The same river farther downstream is draining a larger area, and has received water from tributary streams (smaller streams that flow into a river) as well as baseflow. The amount of overland flow reaching a river not only depends on the watershed area and amount of precipitation received, but also on the amount of water that infiltrates into the soil rather than running over the land surface.

River discharge measurements in the study area were performed during the dry period (i.e., July) in the absence of rain events. In this period river flow is assumed to be sustained mostly by contribution from groundwater. Surface water elevations (stage) measured in the rivers are lower than adjacent shallow groundwater elevations, implying groundwater discharges to the rivers. Differences in discharge between points in a river are thus related to interaction with the groundwater. Increasing river discharge (in the down-flow direction) indicates that the river is recharged by groundwater discharge, if not from tributaries. In the opposite case, where river discharge decreases down-flow, water is lost to the groundwater reservoir.

During the fieldwork campaigns (Mjemah 2007), the river discharge measurements were taken in the three perennial rivers Mzinga, Kizinga and Msimbazi (Fig. 4). Mbezi River in the north is usually dry except for flash floods during the rainy periods. The method used for

Fig. 4 The locations of river discharge measurements

discharge measurements was wading position 0.6 (six-tenths depth) with Pygmy Current meter, A.OTT Propeller Type (Østen 1979). The method has been described by Rantz (1982) and error on the method was intensively quantified by Sauer and Meyer (1992).

The method for determination of river discharge measurements at a cross section requires determination of the mean velocity in each of the selected verticals. In the 0.6-depth method, an observation of velocity made in the vertical at 0.6 of the depth below the surface is used as the mean velocity in the vertical. The total discharge within the river is the sum of the individual subsection discharges. The area and mean velocity in each subsection are used to compute the subsection discharge. Actual observation and mathematical theory have shown that the 0.6-depth method gives reliable results (Rantz 1982).

Results and discussion

Mzinga River

Figure 5a shows the measured discharges and the trend of groundwater contribution (baseflow) downstream. The calculations are included in Table 3. The baseflow was calculated between two measuring points. Baseflow

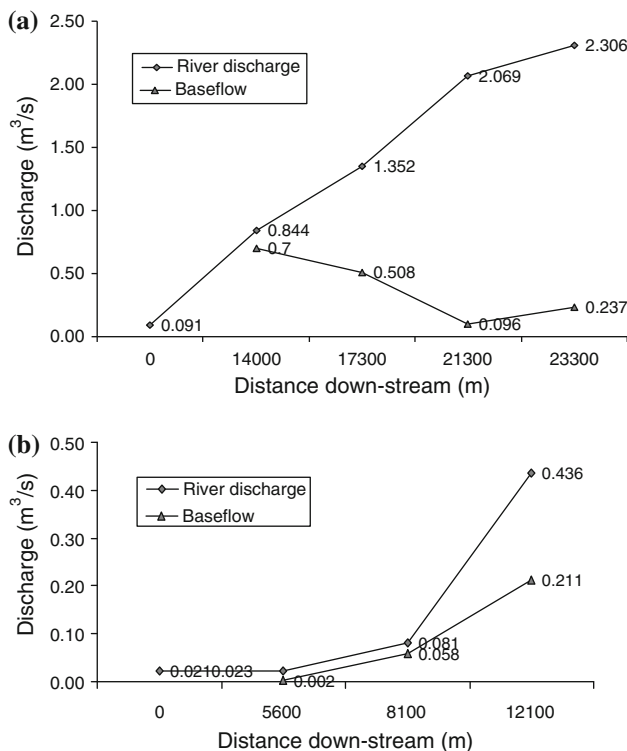


Fig. 5 Discharge rate and baseflow along **a** Mzinga River and **b** Msimbazi River measured in July 2006

obtained between Mbondole and Majimatitu was $0.7 \text{ m}^3/\text{s}$ [(i.e., $0.844 - 0.053 - 0.091$]. The discharge at Maji ya Chai Bridge was subtracted from that of Majimatitu since it is a tributary of Mzinga River, and contributed an amount of $0.053 \text{ m}^3/\text{s}$ to Majimatitu discharge point. The river discharge rate was increasing downstream. The minimum baseflow per meter river length was obtained between Kilwa Road Bridge, Kongowe and Kichemchem measuring points and amounts to $2.4 \times 10^{-5} \text{ m}^2/\text{s}$, while the maximum baseflow per meter ($1.5 \times 10^{-4} \text{ m}^2/\text{s}$) occurred between Majimatitu and Kilwa Road Bridge measuring points. The total baseflow between the first measuring point and the last one at distance of 23.3 km was $1.541 \text{ m}^3/\text{s}$, which is equal to $6.6 \times 10^{-5} \text{ m}^3/\text{s}$ per meter river length.

The decrease and increase in baseflow between subsequent measuring stations depends on the hydraulic connection between the aquifer and the river, the size of catchment area as well as the regional water table elevation, which can vary by several centimeters over 1 year. The total length of Mzinga River system within the coastal plain, including its tributaries is 15,376 m. Assuming the calculated baseflow per distance to be representative for the whole river drainage basin in the plain, total baseflow can be estimated at $32.0 \times 10^6 \text{ m}^3/\text{year}$ (Table 4). South of the Mzinga River, the landscape becomes more hilly and runoff will be larger than in the flat alluvial plain. Therefore, it cannot be excluded that the calculated baseflow rate for the Mzinga River still contains a runoff component.

Msimbazi River

Figure 5b shows the river discharge and baseflow profiles along the Msimbazi River for 2006. Examination of these profiles indicates that there is a significant increase in discharge as well as baseflow downstream between Kinyerezi and Railway Bridge with a further increase to Kajima. There is minimal baseflow per meter between the measuring points at Kinyerezi Bridge and Vingunguti ($3.6 \times 10^{-7} \text{ m}^2/\text{s}$) and maximal ($5.3 \times 10^{-5} \text{ m}^2/\text{s}$) between Railway Bridge and Kajima measuring points. The total baseflow between the first measuring point and the last one at a distance of 12.1 km was $0.271 \text{ m}^3/\text{s}$, which is equal to $2.2 \times 10^{-5} \text{ m}^3/\text{s}$ per meter distance along the river. With the total length of Msimbazi River system within the coastal plain, including its tributaries, equal to 35,997 m, total baseflow is calculated at $25.0 \times 10^6 \text{ m}^3/\text{year}$ (Table 4).

Kizinga River

The discharge measurements were taken at Buza ($0.457 \text{ m}^3/\text{s}$) and Kilwa Road, KTM ($0.151 \text{ m}^3/\text{s}$). However, the discharge measured at Kilwa Road, KTM, as of $0.151 \text{ m}^3/\text{s}$ is not representative to decide whether there is an increase or

Table 3 Discharge contributions to the river at measuring point (measurements of July 2006)

River's name	Tributary	Measuring location	Total discharge ^a (m ³ /s)	Net discharge ^b (m ³ /s)	Baseflow ^c (m ³ /s)	Distance between points (m)	Baseflow/distance (m ² /s)
Mzinga	Maji ya Chai	Mbondole	0.091	0.091			
		Maji ya Chain Bridge	0.053				
		Majimatitu	0.844	0.791	0.700	1,4000	5.0×10^{-5}
	Mkokozi	Kilwa Road Bridge	1.352	1.352	0.508	3,300	1.5×10^{-4}
		Kigamboni Bridge	0.621				
		Kichemchem	2.069	1.448	0.096	4,000	2.4×10^{-5}
		Mtoni	2.306	2.306	0.237	2,000	1.2×10^{-4}
Total				1.541	23,300	6.6×10^{-5}	
Kizinga		Buza	0.457				
		Kilwa Road, KTM	0.151				
Msimbazi		Kinyerezi Bridge	0.021	0.021			
		Vingunguti	0.023	0.023	0.002	5,600	3.6×10^{-7}
		Railway Bridge	0.081	0.081	0.058	2,500	2.3×10^{-5}
	Tenge	Mandelea Bridge	0.058				
		Kibangu	Mabibo Bridge	0.086			
			Kajima	0.436	0.292	0.211	4,000
Total				0.271	12,100	2.2×10^{-5}	

^a Total discharge is the volume per second of water at particular point from various contributors [for instance groundwater and tributary (ies)]

^b Net discharge includes: amount from previous measuring point along the main river and added amount from groundwater (baseflow); obtained by subtracting discharge contributed by tributary(ies) from total discharge

^c Baseflow calculated

Table 4 Calculations of annual total baseflow

River	Total length ^a (m)	Baseflow/length (m ² /s)	Baseflow ($\times 10^6$ m ³ /year)
Mzinga	15,376	6.6×10^{-5}	32.0
Kizinga	26,982	2.2×10^{-5b}	18.7
Msimbazi	35,997	2.2×10^{-5}	25.0
Total baseflow			75.7

^a Total length of the river includes its tributaries

^b The baseflow per distance for Kizinga River was assumed to be equal to that obtained in Msimbazi River since both rivers are within the same hydrogeological conditions

decrease of discharge downstream, since, in front of the measuring point, there is a swamp as well as water supply intake. Hence, the difference in discharge between these two measuring points (decrease of 0.306 m³/s) is also related to the amount supplied to the community that was estimated at 6,000 m³/day (0.07 m³/s) by Mato (2002). For this reason, no baseflow calculation was done for Kizinga River. However, the baseflow per distance was assumed to be equal to that obtained for Msimbazi River (i.e. 2.2×10^{-5} m²/s), since both rivers are within the same hydrogeological conditions. With 26,982 m total length of Kizinga River system in the coastal plain, total baseflow is calculated at 18.7×10^6 m³/year (Table 4).

Total baseflow to rivers in the whole coastal plain is then obtained at 75.7×10^6 m³/year (Table 4).

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) reported 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 into 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.

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

Table 5 Annual soil–water budget calculations

	WET SEASON SUR = (P-Ro) - PET > 0			DRY SEASON SUR = (P-Ro)-PET < 0
	S _B = CAP	S _B < CAP (P-Ro)-PET ≤ CAP-S _B	(P-Ro)-PET > CAP-S _B	
S _B	CAP	S _B + (P-Ro)-PET	CAP	CAP * e ^{-APWL/CAP}
R _N	(P-Ro) - PET	0	(P-Ro)-PET - (CAP-S _B)	0
AET	PET	PET	PET	(P-Ro) + ΔS _B
DEF	0	0	0	PET - AET

The following are notations used in the method: $P - R_o$ = Precipitation - Runoff (mm), R_o mean monthly runoff (mm), PET potential evapotranspiration (mm), $APWL$ accumulated potential water loss (mm) $[PET - (P - R_o)]$ accumulated for subsequent dry months, AET actual evapotranspiration (mm), S_B water stored in soil, $S_B = CAP \times e^{-APWL/CAP}$, CAP soil capacity (mm), i.e. maximum water content of soil, without gravitational water [=average rooting depth (mm) × water content at field capacity (in volume %), e.g. 500 mm × 10% = 50 mm], ΔS_B change in S_B , DEF deficit (PET - AET) (mm), SUR surplus $[(P - R_o) - PET]$ (mm), R_N natural groundwater recharge (SUR - ΔS_B) (mm)

the reference grass surface concept was introduced and its parameters were defined, Allen et al. (1998) modified the basic form of the PM equation to incorporate these variables and to produce a simplified equation, which combines radiation and aerodynamic terms (ASCE-EWRI 2004). The method is based on the standardized PM equation using monthly means weather data (i.e., temperature, solar radiation, relative humidity and wind speed) and the output is mean PET by month.

The key environmental factors controlling recharge are climate, soil texture and structure, vegetation and land use, topography and depth to water table (Thorntwaite and Mather 1957). The concept presented here is used to estimate the groundwater recharge, R_N , based on the monthly water balance of the unsaturated zone (Thorntwaite and Mather 1957). For budgeting calculations, it is necessary to know the total water-holding capacity in a soil profile. This value is typically expressed in millimeter and can be obtained by integrating the water-holding capacity over the effective depth of the soil layer (Dunne and Leopold 1978). The method requires keeping track of the accumulated potential water loss (APWL) and the amount of water in the soil.

The concept of field capacity is a useful idea in soil science to denote an upper limit of moisture content a soil can hold against the pull of gravity. Soil capacity CAP is affected by soil type as well as vegetation type (rooting depth), and is found as the product of water content at field capacity and average rooting depth. In a conceptual sense, groundwater recharge can commence when the moisture content exceeds field capacity (Dunne and Leopold 1978).

Table 5 shows the concept applied for the estimation of groundwater recharge rate, R_N , during the wet and dry seasons. During the dry season, there is no rainfall surplus, since $(P - R_o) - PET$ is <0, and there is no groundwater recharge. However, during the wet season, there is rainfall surplus when $(P - R_o) - PET$ is greater than 0; there will

be groundwater recharge as soon as the soil is at field capacity ($S_B = CAP$), but if S_B is less than CAP, then there is no recharge ($R_N = 0$).

Calculations to determine S_B and APWL are performed for each month using monthly mean 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 rivers.

The study area is characterized by fine sand (vadose zone) and vegetation cover (grass) of shallow roots (0.5 m). Hence, the CAP can be estimated at 50 mm. Table 6 shows the calculations for estimation of groundwater recharge for the year 2006. It can be observed that a surplus and eventually groundwater recharge occur in both short and long rainfall periods. During the short rains, which occur in November and December, the groundwater recharge (R_N) amounts to 81.8 mm, while during the long rains it amounts to 174.4 mm. In this period, the water stored in the soil, S_B , becomes equal to the soil capacity (50 mm) since $P - R_o > PET$, and the surplus is sufficient for soil capacity to be reached. Hence, a total water surplus for both periods of 356.2 mm is realized. This surplus, at the onset of both rainy periods, at first goes into building the soil moisture component. Consequently, because the soil has reached CAP, it releases the excess moisture to the underlying groundwater with a total of 256.2 mm. The calculated average yearly recharge value of 256.2 mm is conforming to values found in another Tanzanian region also using a soil–moisture balance approach for different vegetation covers (Sandström 1995). The magnitude of the recharge estimated by the use of the soil moisture balance agrees well with the previous recharge investigations in equatorial Africa found by Taylor and Howard (1996) and Houston (1982), which is in the order of 200 mm/year and is dependent on the number of heavy rainfall events.

The difference between total surplus and groundwater recharge is 100 mm, i.e. building up the full soil capacity

Table 6 The estimation of groundwater recharge from monthly mean precipitation and potential evapotranspiration for the year 2006 (all expressed in mm)

Month	$P - R_o$	PET	$PET - (P - R_o)$	APWL	S_B	ΔS_B	AET	DEF	SUR	R_N
July	7.4	150.2	142.8	142.8	2.87	47.13	54.5	95.7	0.0	0.0
August	6.5	190.1	183.6	326.4	0	2.87	9.4	180.7	0.0	0.0
September	23.8	178.9	155.1	481.5	0	0	23.8	155.1	0.0	0.0
October	78.1	189.1	111.0	592.5	0	0	78.1	111.0	0.0	0.0
November	233.3	155.4			50.0	50	155.4	0.0	78.0	28.0
December	222.8	169.1			50.0	0	169.1	0.0	53.8	53.8
January	8.5	191.0	182.5	182.5	1.3	48.7	57.2	133.8	0.0	0.0
February	44.0	178.9	134.9	317.4	0	1.3	45.3	133.6	0.0	0.0
March	259.3	152.0			50	50	152.0	0.0	107.4	57.4
April	219.1	136.4			50	0	136.4	0.0	82.7	82.7
May	158.8	126.3			50	0	126.3	0.0	32.5	32.5
June	135.3	133.6			50	0	133.6	0.0	1.8	1.8
Total recharge (mm/year)										256.2

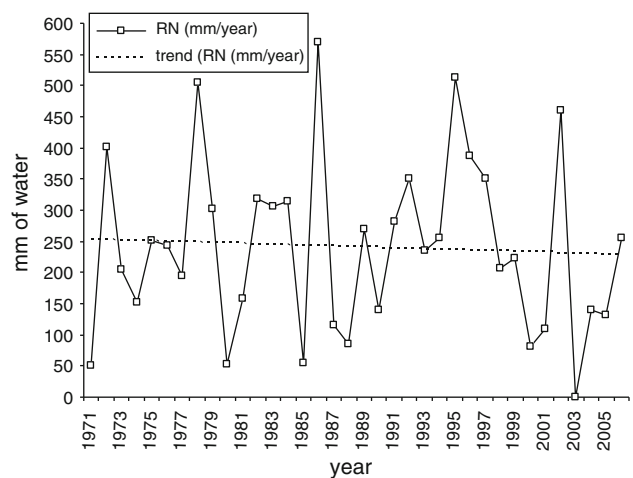
from 0 to 50 mm for two times. During the wet periods, the potential evapotranspiration equals the actual evapotranspiration ($PET = AET$). However, it can be observed that when $P - R_o < PET$, water stored in the soil starts to decrease until the soil becomes possibly depleted of its moisture, and $S_B = 0$. In this period, that is from July to October and January to February, there is no surplus and the actual evapotranspiration is less than the potential evapotranspiration ($AET < PET$).

Figure 6 shows the variation of natural groundwater recharge rate calculated for each year from 1971 to 2006. It can be observed that the highest groundwater recharge rate of 569.2 mm/year occurred in 1986 while in 2003, no groundwater recharge occurred ($R_N = 0$).

The average groundwater recharge rate for 36 years is 240.7 mm/year. The general trend shows that there is a decrease in groundwater recharge rate. As precipitation shows a rather slightly increasing trend with 1.2 mm/year (Fig. 7), it may be assumed that the impact of increasing temperatures (Fig. 8) on decreasing groundwater recharge rates is more important. Variations of precipitation on timescales of decades may be significant. The precipitation records from 1971 in Fig. 7 show an alternation of dryer (1970–1975, 1985–1990, 2000–2005) and wetter (mid-1990s, 1975–1980) periods. Changes in the strength of these cyclic fluctuations can cause systematic trends in the recharge component of the aquifer water balance.

Integrated water balance

Water balances are a necessary tool for evaluating the hydrodynamical situation of aquifer systems and groundwater reservoirs, as they compare amounts of inflowing and

**Fig. 6** Annual groundwater recharge rate variation for 36 years (1971–2006)

outflowing water and can give indications about sustainability of aquifer exploitation and impact on the long time evolution of water levels. The results of the three quantified balance contributions were fit together to produce a total balance of the system (Table 7). The recharge component was derived by integrating the average value of 256.2 mm/year over the total area of the alluvial aquifer (388 km²) for the year 2006 as the other components were measured in the same year. Discharge to the sea occurs along the shoreline and was quantified as the remaining part to fit the balance and was thus not derived from observations or measurements.

Also included in the table is the relative contribution of each outflowing component as a fraction of the total aquifer recharge. It can be seen that exploitation accounts for 8.6% of the inflowing water. This amount has been compensated

Fig. 7 Total yearly precipitation (mm) in the period 1971–2006

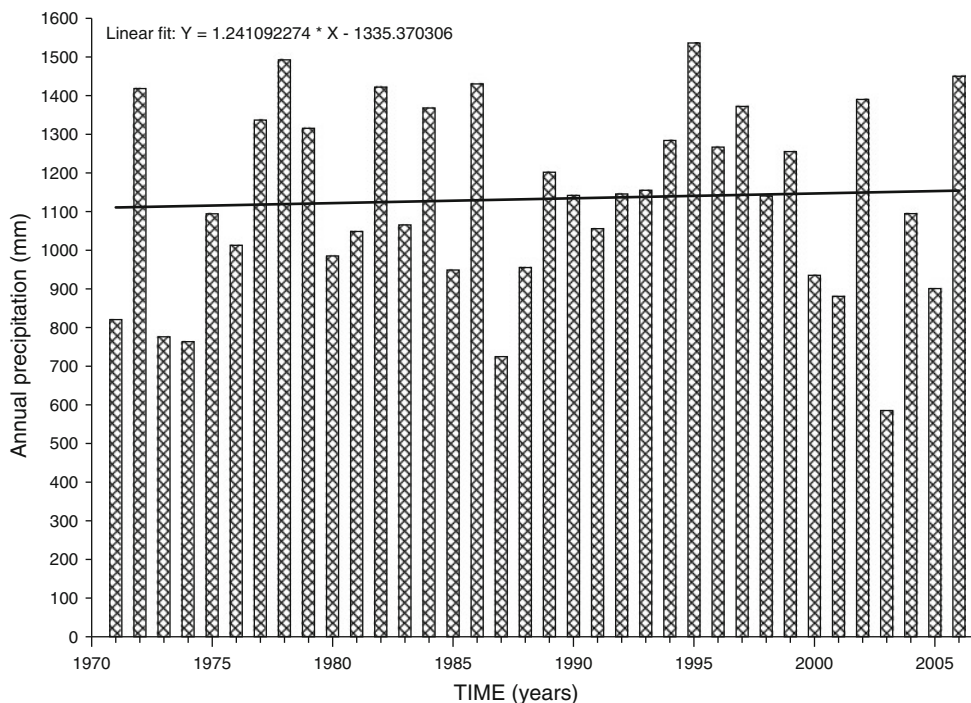
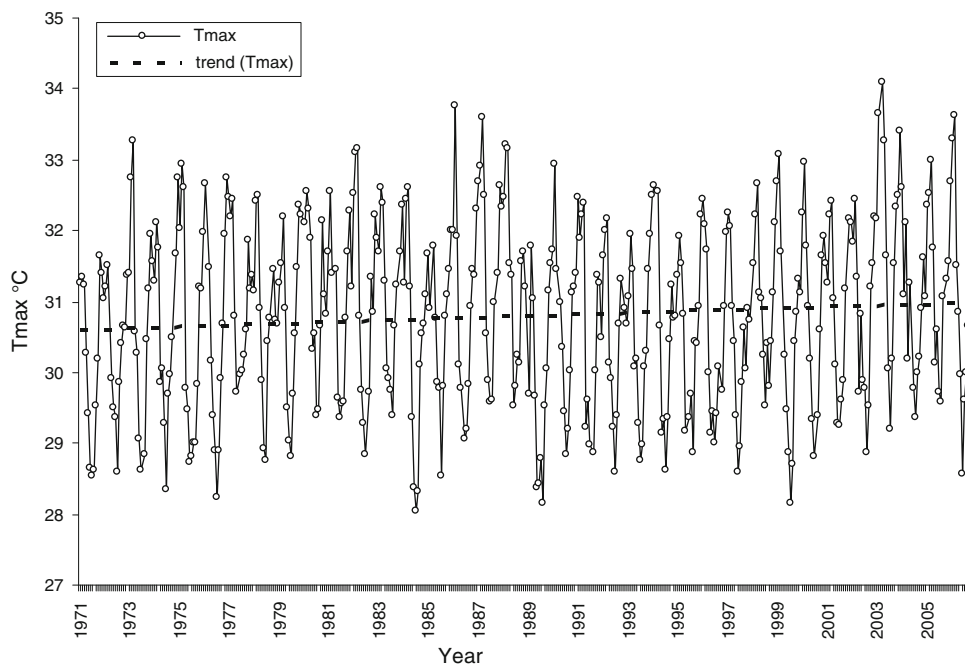


Fig. 8 Mean monthly maximum temperature (T_{max}) variation for 36 years (i.e., from year 1971 to 2006)



by a decrease in baseflow to rivers (now at 76.2.0%) and by a decrease in discharge to the sea (now at 15.2%).

It should be noted that the proposed balance does not account for lateral groundwater inflow over the outer boundaries of the Dar-es-Salaam aquifer. As the alluvial plain is topographically lower than the surrounding hilly regions (including the Pugu Hills), it can be expected that regional flow cycles will drain water towards the plain. As

both the northern and the southern bordering regions have a geologic substratum consisting of the Miocene deltaic sequence called the “clay-bound sands”, flow in these lesser permeable sediments will be more limited than in the quaternary fluvial coastal plain deposits. Therefore, lateral inflow will be limited. It was however at the moment not possible to obtain a realistic estimate of this lateral inflow from field data.

Table 7 Integrated water balance of the Dar-es-Salaam aquifer

Water balance component	Amount (hm ³ /year) (+ inflow, – outflow)	Fraction of total recharge (%)
Recharge	+99.4	
Pumping	–8.59	8.6
River baseflow	–75.7	76.2
Discharge to sea	–15.11	15.2

Conclusions

The Dar-es-Salaam aquifer is a quaternary fluvial sand aquifer west of Dar-es-Salaam City and is increasingly important for the water supply of the city. As groundwater extraction is stressing groundwater resources, water balance components, including groundwater extraction, aquifer recharge and baseflow to rivers were estimated from field data and integrated into a global balance to evaluate the present situation.

A total of around 1,300 wells are used for groundwater exploitation in the region, but no statistical data were available or systematically collected until now. During a field campaign in 2004–2005, a subset of 400 wells was visited and inspected, and technical and operational information was gathered. Of the visited 400 wells, 117 wells or around 30% were abandoned because of operational problems or increased salinity. Wells are used for domestic, industrial or public water supply use. To estimate total groundwater extraction, a calculation scheme was applied that uses individual well yield, number of working hours a day and working days a week, depending on the water use application. The results for the 400 wells were then extrapolated to the total of 1,300 existing wells. This results in an estimated total of ca 8.59 hm³/year of extracted groundwater.

Three main rivers (and some tributaries) drain the aquifer basin. Only rivers inside the alluvial aquifer plain are perennial, waterways in the more hilly surroundings are seasonal because the less permeable basement (clay-bound sands) limits the draining flow cycles. River flow in the seasonal rivers is mainly peakflow during the rainy season, and these rivers cannot be used for water supply during the dry months. On different points along the perennial rivers (Mzingo, Kizinga and Msimbazi), flow rate measurements were done during the dry season in 2006. It was assumed that at that time only baseflow accounted for river flow and groundwater discharge rates were derived for different sections. Using average groundwater discharge rates and length of the rivers in the plain, the total loss of groundwater to river baseflow was estimated at 75.7 hm³/year. It should be realized that this number is based on a limited number of measurements in a restricted time period.

Rainfall is the main source of aquifer recharge and the Dar-es-Salaam region has two distinct rainy seasons. The main rainy season arrives in springtime and usually lasts from March to May, April being the wettest month with an average rainfall of 254 mm. The second shorter rainy season is in November and December. Because of the tropical climate, potential evapotranspiration is high year-round between 120 and 190 mm/month. PET values were estimated using the PM method and used to calculate aquifer recharge using the soil moisture balance method of Thornthwaite and Mather. For the period 1971 till 2006, the average aquifer recharge is sized at 240.7 mm/year. However, for the water balance, the aquifer recharge for the year 2006 (i.e. 256.2 mm/year) was used instead since the other components were measured in 2006. This translates into a total recharge of 99.4 hm³ for the whole alluvial aquifer in the year 2006.

Groundwater discharge into the sea is also important; it was not quantified separately, but found by fitting the total water balance. Comparison of inflowing (recharge) and outflowing (pumping, baseflow to rivers and discharge into the sea) amounts shows that in recent years groundwater pumping accounted for 8.6% of aquifer recharge.

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