# HYDROGEOLOGICAL MAP OF ZANZIBAR

INCLUDING THE ISLANDS OF ZANZIBAR AND PEMBA
THE UNITED REPUBLIC OF TANZANIA


## CLIMATOLOGICAL DATA SUMMARY FOR ZANZIBAR and PEMBA

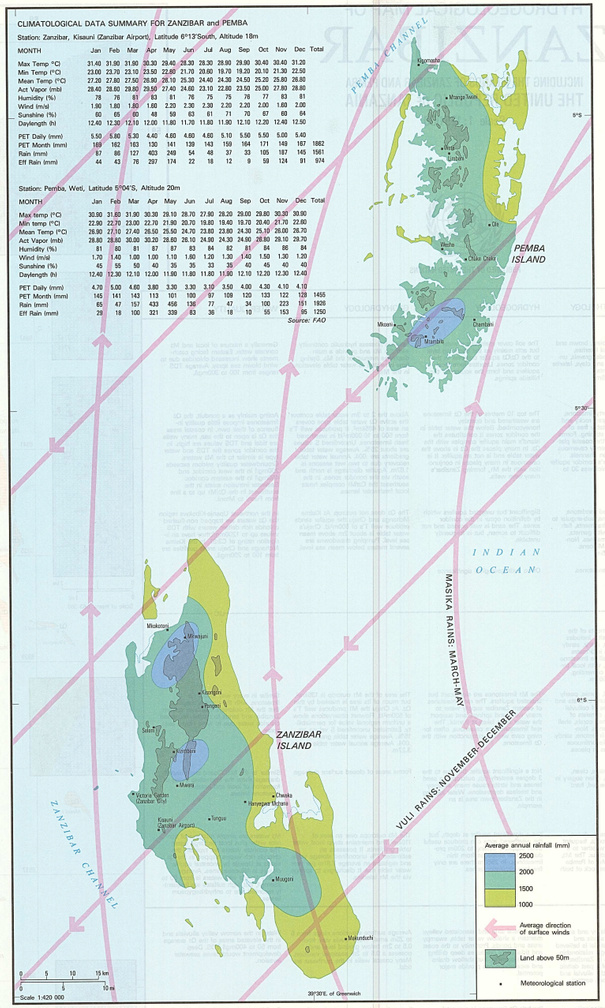
Station: Zanzibar, Kisauni (Zanzibar Airport), Latitude 6°13'South, Altitude 18m

| MONTH | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Max Temp (°C) | 31.40 | 31.90 | 31.90 | 30.30 | 29.40 | 28.30 | 28.30 | 28.90 | 29.90 | 30.40 | 30.40 | 31.20 | |
| Min Temp (°C) | 23.00 | 23.70 | 23.10 | 23.50 | 22.80 | 21.70 | 20.60 | 19.70 | 19.20 | 20.10 | 21.30 | 22.50 | |
| Mean Temp (°C) | 27.20 | 27.80 | 27.50 | 26.90 | 26.10 | 25.30 | 24.40 | 24.30 | 24.50 | 25.20 | 25.80 | 26.80 | |
| Act Vapor (mb) | 28.40 | 28.60 | 29.80 | 29.50 | 27.40 | 24.60 | 23.10 | 22.80 | 23.50 | 25.00 | 27.80 | 28.80 | |
| Humidity (%) | 78 | 78 | 83 | 83 | 81 | 76 | 75 | 76 | 78 | 77 | 83 | 81 | |
| Wind (m/s) | 1.80 | 1.80 | 1.80 | 1.60 | 2.20 | 2.30 | 2.30 | 2.20 | 2.20 | 2.00 | 1.60 | 2.00 | |
| Sunshine (%) | 60 | 65 | 60 | 48 | 59 | 63 | 61 | 71 | 70 | 67 | 60 | 64 | |
| Daylength (h) | 12.40 | 12.30 | 12.10 | 12.00 | 11.80 | 11.70 | 11.80 | 11.90 | 12.10 | 12.20 | 12.40 | 12.50 | |
| PET Daily (mm) | 5.50 | 5.80 | 5.30 | 4.40 | 4.60 | 4.60 | 4.60 | 5.10 | 5.50 | 5.50 | 5.00 | 5.40 | |
| PET Month (mm) | 169 | 162 | 163 | 130 | 141 | 139 | 143 | 159 | 164 | 171 | 149 | 167 | 1862 |
| Rain (mm) | 57 | 86 | 127 | 403 | 249 | 54 | 48 | 37 | 33 | 105 | 187 | 145 | 1561 |
| Eff Rain (mm) | 44 | 43 | 76 | 297 | 174 | 22 | 18 | 12 | 9 | 59 | 124 | 91 | 974 |

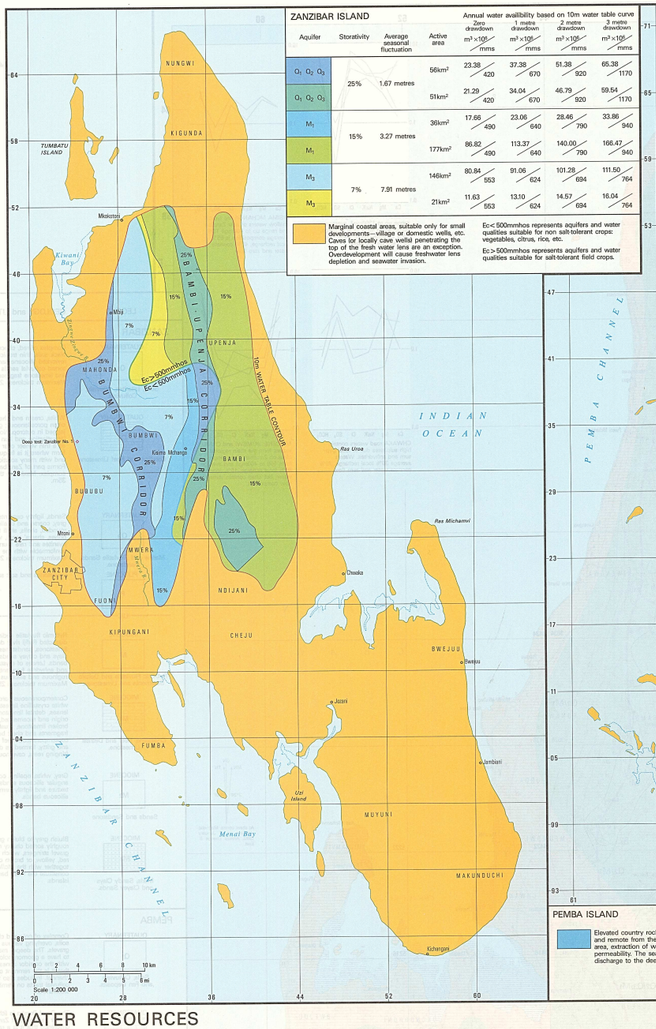
Station: Pemba, West, Latitude 5°04'S, Altitude 20m

| MONTH | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Max temp (°C) | 30.90 | 31.60 | 31.90 | 30.30 | 29.10 | 28.70 | 27.90 | 28.20 | 29.00 | 29.80 | 30.30 | 30.90 | |
| Min temp (°C) | 22.80 | 22.70 | 23.00 | 22.70 | 21.90 | 20.70 | 19.80 | 19.40 | 19.70 | 20.40 | 21.70 | 22.60 | |
| Mean Temp (°C) | 26.90 | 27.10 | 27.40 | 26.50 | 25.50 | 24.70 | 23.80 | 23.80 | 24.30 | 25.10 | 26.00 | 26.70 | |
| Act Vapor (mb) | 28.80 | 28.80 | 30.00 | 30.20 | 28.60 | 26.10 | 24.90 | 24.30 | 24.90 | 26.80 | 28.10 | 28.70 | |
| Humidity (%) | 81 | 80 | 81 | 87 | 87 | 83 | 84 | 82 | 81 | 84 | 86 | 84 | |
| Wind (m/s) | 1.70 | 1.40 | 1.00 | 1.00 | 1.10 | 1.60 | 1.20 | 1.30 | 1.40 | 1.50 | 1.30 | 1.20 | |
| Sunshine (%) | 45 | 55 | 50 | 40 | 35 | 33 | 35 | 40 | 45 | 40 | 40 | 40 | |
| Daylength (h) | 12.40 | 12.30 | 12.10 | 12.00 | 11.90 | 11.80 | 11.80 | 11.90 | 12.10 | 12.20 | 12.30 | 12.40 | |
| PET Daily (mm) | 4.70 | 5.00 | 4.60 | 3.80 | 3.30 | 3.30 | 3.10 | 3.50 | 4.00 | 4.30 | 4.10 | 4.10 | |
| PET Month (mm) | 145 | 141 | 143 | 113 | 101 | 100 | 97 | 109 | 120 | 133 | 122 | 123 | 1455 |
| Rain (mm) | 65 | 47 | 157 | 433 | 408 | 136 | 77 | 47 | 34 | 100 | 223 | 151 | 1926 |
| Eff Rain (mm) | 29 | 18 | 100 | 321 | 339 | 63 | 36 | 18 | 10 | 55 | 153 | 95 | 1250 |

Source: FAO




## CLIMATE




## WATER RESOURCES

### HYDROGEOLOGY OF THE ISLANDS OF ZANZIBAR AND PEMBA

Zanzibar and Pemba are part of the ancient Miocene Rufiji/Ruvu river delta, and due to periods of isostatic movement and block faulting over the coastal Tanzania and offshore deltaic zone, only Zanzibar, Pemba, Mafia and the Latham Island areas remain above sea level as land blocks of the original delta. The present delta is a 2560-metre section of rhythmic sediments, and mainly marls, clays and clayey sands. Pemba is a simple fault block and raised higher than Zanzibar; it is thus composed of lower stratigraphic rocks. Zanzibar, on the other hand, is a complex junction of four blocks with evidence of past artesian leakage with ferruginous and siliceous cements, and anhydrite deposits over most of eastern Zanzibar. Whereas Zanzibar still retains extensions of mainland structures, mainly prior stream systems, such structures do not continue on to Pemba.

The topography can be separated into three distinct landforms which relate directly to the geology:

- the undulating and elevated to precipitous and broken Miocene country rock,
- the channel country, in Zanzibar and on the east coast of Pemba,
- the flat coastal periphery or "coral rag" country, developed mainly on Zanzibar and to a lesser extent on Pemba.

Zanzibar's geology is composed of Lower Miocene $M_1$, $M_2$ and $M_3$ rocks, overlain by Quaternary $Q_1$, $Q_2$ and $Q_3$. Its geomorphology records periods of higher sea level, marine erosion with wave-cut cliffs and platforms, reworked marine and fluviatile sediments, plus tilting or east-west rocking with raised abandoned sea cliffs and beaches, raised and submerged coastal reefs, etc. On Pemba, similar geomorphological evidence exists with the addition of drowned valley mouths and inlets. Producing the general shape and north-south trend of the islands, erosion fronts have been advancing inland from the east and west coasts. In places, these fronts have overlapped, producing sharp and jagged skylines flanked with steep and broken country. In north Pemba, the erosion fronts have not yet met, thus preserving a section of the original deltaic plain. During one period of submersion, Zanzibar was transformed into a small group of islands. During this period, tidal erosion reworked much of the unconsolidated fluviatile bed lode material from the old channel and prior streams system. In its place was deposited the reworked fluviatile sands, with their concentrations of heavy minerals, and garnets, kyanites, tourmalines, etc., plus an abundance of sharks' teeth and fish bones. These are the $Q_3$ sands. On these, in the same prior stream channels or corridors (so-called), is deposited a coralline reef limestone, the $Q_2$, which extends to, and covers, the shallower coastal Miocene surfaces with a thin limestone veneer. In the corridors and the deeper channels, there is a maximum thickness of 35m of coralline limestone. As Zanzibar emerged from the sea, the top 10m of the $Q_2$ became weathered and developed a characteristic and coarsely honeycombed structure, which today is visible around most of the coastal periphery and over the south east of the island. In the prior stream channels, eventual erosion and colluvial accumulations covered the $Q_2$ corridor limestones with a thick 20 to 25m mantle of $Q_1$ sands, clays and red fertile soils. Zanzibar is threaded, therefore, with what geologists might call "shoestring limestones". The same shoestring limestones are threaded through the network of smaller distributary channels and buried tributary drainage systems that developed marginal to the corridor zones and around the coast. Many of these zones are important aquifers, but are elusive as deep leads, since they were deposited on old buried topographic surfaces which bear little resemblance to the present topography.

Pemba, by contrast, is purely a homogeneous landmass of Miocene material, without the coral shoestrings of Zanzibar. Geological mapping on Pemba has recognised two divisions of the $M_3$: the Chake Beds ($Mc$), and the Weti Beds ($Mw$). The Vitongoge Beds (so-called) on the eastern coast are recognised as Pliocene, although they do resemble the deposits of the channel complex on Zanzibar. (NOTE: Pliocene Beds also occur on Zanzibar but they are not discussed, since they have no hydrogeological significance.) Hydrogeologically and lithologically, the country rock is similar to Zanzibar's $M_3$, but it is notably of finer grain size, more clayey, more compacted and shaley with measurable dips and strike; this latter feature is a fine mind from Zanzibar. Topographically, Pemba is a single ridge and watershed with a raised east coast $Q_2$ coral platform, and a drowned and often precipitous west coast, where tidal inlets penetrate deeply into the Pemba landmass. The valleys of the eastern watershed are flat-bottomed and filled with eroded silts, clays and occasionally re-worked pebbles; the eastern coastal strip is flat and fertile, but often water-logged. The shallow waters in these unconsolidated materials constitute the principal water source of Pemba.

On both islands the geology and topography are outlined by the pattern of clove trees and spice plantations. The clove trees, in particular, do not grow on the poor soils of the $Q_3$, nor on the seasonally water-logged soils of the corridor zones of Zanzibar and the coastal strip of eastern Pemba. Thus, the Miocene rocks are conveniently demarcated by the vegetation, i.e., clove trees and spices on the Miocene; grasslands, rice and sugar, etc., on the corridor zones and water-logged areas; stunted trees, tangled scrub and thicket on the $Q_2$ coral rag. Coconut trees record the path of a disastrous hurricane on Zanzibar in 1872, after which ruined clove trees were replaced by coconut palms.

The climate of Zanzibar and Pemba is dominated by two annual and reliable wet seasons, the Masika Rains from the south through March to May, and the Vuli Rains from the northeast during November and December. Wet season showers and storms are usually scattered, local, torrential and of short duration. Average rainfalls for north Zanzibar are 1800mm and for south Zanzibar 1500mm. Pemba receives a higher rainfall with a similar irregular pattern. The average is 2000mm, but the figures trend from a high 2500mm in the south to a low 1500mm in the northeast. Well hydrographs show the Masika Rains to be the most important as regards groundwater recharge; during this period, the water table recoveries almost double those recoveries recorded in the Vuli Rains. Infiltration is rapid during the heavy rains, and water table recoveries are immediately registered. Surface runoff is short and sharp, and sustained flow beyond the end of storms is rare. On Zanzibar it is unusual that streams flow into the sea, as most become lost in the peripheral $Q_2$ limestone; the Mwera River, for example, flows directly into a cave and does not re-appear. Other streams flow underground for short periods, re-appearing occasionally as spring zones. The best example of this case is the Zingwe Zingwe River that flows north from Mahonda towards the northern Kiwani Bay.

Generally, all the Zanzibar and Pemba strata have aquifer potential to a greater or lesser extent; all have measurable permeability and porosity, and a defined recharge and discharge regime. The water table or unconfined aquifer is everywhere the main aquifer. Locally, it can be confined, but on pumping, these aquifers quickly become unconfined. Perched aquifers are a common occurrence and these often give misleading water table readings and variations in many areas. The Miocene-$M_3$ is the least productive aquifer, although most wells and boreholes get useful yields from laterites, sand bands and limestone lenses. The average water-table rise suggests a storage value of 7 to 8%. Frequently, holes penetrating $Q_2$ channels through the $M_3$ penetrate strings of limestone and develop high yields, as the Mbiji borehole on Zanzibar. The Miocene-$M_2$ is not a discrete aquifer, and is usually developed in conjunction with the $M_3$. The Miocene-$M_1$ reef or non-contemporaneous limestones are, on the other hand, a significant but untested aquifer. The $M_1$ is cavernous in many places, and most cave wells appear to have their lower levels in this material. Based again on water table rises for wells in the weathered $M_1$ mantle, the indicated storage value is 15%. The islands' outstanding aquifer complex occurs on Zanzibar in the corridor zones. These are most significant aquifers being from 2 to 4km wide and about 50m thick. At Kibokwa, some holes did not reach Miocene in over 120m of drilling (nearly 70m below sea level).

These productive corridor zones on Zanzibar are a complex of $Q_1$, $Q_2$ and $Q_3$ strata with the $Q_2$ and the $Q_3$ being the transmissive strata. The main permeable zone is the top weathered 10m of the $Q_2$. The relative elevations of this top $Q_2$ zone and the water table determine whether this zone is saturated and functioning as an aquifer or not. Whereas the upper $Q_2$ surface, though undulating and bumpy, is relatively flat, the water table, by contrast, has a steep gradient from a 40m high at Bumbwi and Upenja grading down to sea level. At Bumbwi, the top of the $Q_2$ varies from 10 to 15m below the water table; at Kibokwa in the Bambi-Upenja corridor and at Kisima Mchanga, both are at about the same level. With the elevation of the bottom of the upper $Q_2$ 10m zone at about 10m above msl, this principal aquifer zone will only be active above the 10m water level contour. Where the top $Q_2$ zone is not a factor in borehole transmissivities, T values from 500 to 800m²/d are commonly developed. When the top $Q_2$ zone is present and active (at Bumbwi and Kibokwa and generally along Zanzibar's central corridor margins), T values up to 10000m²/d are developed. Well yields in these latter cases were of the order of 225 l/s or 3000 imperial GPM. Long-term pumping records and observations at Bumbwi indicate a 27% unconfined storativity value, and similar hydraulic coefficients are indicated in other corridor zones. In cases where the $Q_3$ aquifer is developed without assistance from the $Q_2$, as at Kisima Mchanga and on the plain at Cheju, T values of 500 to 1000m²/d are developed in a somewhat unstable but screenable sand.

The unknown aquifer on Zanzibar is the Miocene-$M_1$ limestone. It has been drilled and tested at Cheju and at Matemwe. The Cheju wells gave T's of 500m²/d; the Matemwe well gave 20000m²/d. The Miocene-$M_1$ is regarded as an aquifer of major importance, and one that requires investigation.

The $Q_2$ and $M_1$ limestone aquifers of Zanzibar do not exist on Pemba, where the main aquifer is the Miocene-$M_3$. Boreholes on Pemba drill the Weti Beds and pump their water from limestone and sandstone bands. The aquifer is extremely friable and running sands are a continuous problem. Test results are not available from Pemba boreholes, but an exactly similar borehole on Zanzibar, Bumbwi No. 1, which is slotted and gravel-packed throughout the weathered zone, gave a yield of 8 l/s for the maximum available draw down. It proved impossible to control the inflow of fine silts and sands. Such is the case with most of Pemba's boreholes. There is an additional problem in Pemba relating to water quality and water saturation with bicarbonate ion. Calcium carbonate deposition is a continual problem with Pemba boreholes.

The recharge, discharge and flow regime and the hydrogeologic model for both islands are presented by the water table contours and the gradients. The models for both islands are essentially the same; general recharge from rainfall infiltration, overland flow and spring flow to the corridors in the case of Zanzibar, or to the narrow re-entrant valleys in the case of Pemba. Discharge to the sea occurs by down-valley (or corridor) flow in Zanzibar, and by frontal discharge to the east coast in Pemba. Coastal catchments discharge directly by spring flow into the sea, and usually by fissures and channels in the coastal $Q_2$ perimeter. Chemical evidence suggests that much of the distributary system for recharge waters is effected by overland flow, and it is recorded that water tables rise most dramatically after stream flow has commenced. In the intervening dry periods the sub-surface flow component, with one exception, is controlled by the topography and the geology. The exception is a probable watershed leakage situation between Zanzibar's south Bumbwi corridor and the Kisima Mchanga corridor. It is noteworthy that the water-table elevations are such that the west-coast Zanzibar springs, including Bububu spring, could provide an avenue for aquifer discharge from the Bumbwi region.

The main aquifer is the surface unconfined aquifer. Storage values determined from long-term wellfield pumping records and a regional observation network are Q2 - 25%, $M_1$ - 15% and the $M_3$ - 7%. Total average annual water table rises, unless affected by the proximity of broken country, flowing streams or the sea, are 1, 2.2 and 8m, respectively. If one assumes that the total water receipts for an average year are these values, then Zanzibar's water budget is based on an annual 321 million cubic metres. Based on a conservative 1500mm rainfall figure, this represents a realistic 30% of the rainfall, which is of the correct order for ocean island environments. Estimated accessible resources for Zanzibar, via the corridor aquifers, are 102 million cubic metres for the western Bumbwi Corridor, and 170 million cubic metres for the eastern Bambi-Upenja Corridor, annually.

Similar estimates for Pemba would be meaningless for two reasons: first, the absence of highly transmissive aquifer materials will always dictate small local schemes, as opposed to the larger developments feasible on Zanzibar; second, the order of accuracy attainable with the Mc/Mw - $Q_1$/$Q_2$ ratio would be high and exceedingly difficult to determine. However, as developments on Pemba will be based on draining the top metres of the water table, the water table cannot fall below sea level.

The important area of southeast Zanzibar is a complex of $M_1$/$Q_2$ rocks. These strata are in places intrinsically porous, fissured and cavernous, with the aquifer being either a discontinuous lens or perched aquifer situation, with uneven recharge due to local topography and local concentrations of runoff. In the intrinsically porous sections, pumping causes upconing and invasion of supplies developed by borehole. In the cave situation, the open area extends into the top of the lens, leaving pools of fresh water at the cave bottoms. Whereas the cave is a good development proposition for rural water supply, the intrinsically porous situation is not. Village wells in this same region often develop a shallow perched aquifer overlying a saline aquifer. Severe seasonal conditions can often deplete the shallow aquifer, producing a local water hardship in areas where water is abundant.

Most waters encountered on the islands are suitable for all domestic, industrial and irrigation usage. Average TDS values can be as low as 50 and as high as 600mg/l. Local high TDS values to 1200mg/l exist in the deeper sections of the Bambi-Upenja corridor at Kibokwa. These salts are due to ancestrally trapped deltaic or connate water. A similar but subdued water type is noted in most wells on Zanzibar and Pemba as a connate water mixture in various ratios with locally recharged water. Other local high TDS values are due to anhydrite lenses and to shallow seawater intrusion around the coast, due to the 4 to 5-metre tide. Slopes facing the active sea coast are contaminated with sea spray, although there is a competing theory of island rocking and immersion, which is said to account for the high sodium chloride waters on Zanzibar's east coast.

It is evident that seawater has intruded the lower aquifer up to a line approximately joining Fuoni to Mtoni. This zone covers the Zanzibar City water supply boreholes at Fuoni. There will be a need to relocate Zanzibar's town water supply system further north into the southern Bumbwi corridor.

It is notable that the deep Karroo aquifers are continuous under Zanzibar Island, and that these deep aquifers are recharged on the mainland. It is recorded that water of 5000ppm flows through the interval 3839-3881m intersected by Zanzibar No. 1 Deep Borehole. This same borehole recorded a sharp transformation to saline drilling mud at 791.5m, which coincidentally or otherwise agrees with the Ghyben-Hertzberg ratio for freshwater lenses in sea water environments.