EVALUATION OF WATER LEVELS IN RELATION TO THE DESIGN OF COASTAL STRUCTURES IN TANZANIA

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Water levels on the coastline of Tanzania vary under the influence of meteorological conditions (winds and barometric pressure) and the East African Coastal Current, whose strength varies with the monsoon winds. Available tidal information is not enough to warrant statistical analysis for evaluating extreme water levels. The highest mean water springs occur at Bagamoyo and Pangani (3.93 m) and the lowest are found at Lindi (2.96 m). The highest astronomical tide is 3.7 m for Dar es Salaam and 4.6 m for Zanzibar, both of which occur during March/April and November. Measured highest water levels approach 4.80 m for Dar es Salaam and are about 1 metre above the highest astronomical tide. Meteorological conditions and the East African Coastal Current contribute significantly to the differences between predicted heights and the actual tide heights. Bagamoyo experiences the highest wind set-up to the order of 20 cm during the southerly monsoons and 10 cm during the northerly monsoons. Sea level increase due to atmospheric pressure shows a decreasing trend since 1972. The highest sea level above the mean level of all oceans is observed in January/February to the order of 10 cm and the lowest is observed during July to the order of 5 cm. Local peaks in sea level are observed.

KEYWORDS: Tanzania, water levels, meteorological conditions

INTRODUCTION

The effective planning of any coastal or shoreline protection system against erosion needs a reliable set of basic input of parameters, which describe the coastal water environment. The parameters must be defined in terms of both normal conditions and the extreme values with some stated probability during the lifetime of the protection system. The data required for the design are beach profiles, near-shore topography and bathymetry, wind, wave climate and the associated currents and water levels, geotechnical data and construction technology. The basic data input is normally derived from two principal sources (Pilarczyk, 1990): (1) from the existing archived data and (2) from the site specific recorded data. In Tanzania, there is hardly any site specific recorded data and consequently we must rely on limited information from different sources for the evaluation of water levels for the design of coastal structures.

A water level is the mean elevation of the water surface in relation to a specified datum, recorded over a long enough period to eliminate the influence of surface gravity waves. There are four principle categories of water levels, which are tides, surges, and secular changes in mean sea level and wave set-up. Tide constituents can be computed and heights predicted from harmonic analysis of a tidal record of at least a month. Surges are a result of a shear stress due to strong winds. Since wind set-up is inversely proportional to water depth, shallow water areas will be subjected to abnormally high water levels during storms. A drop in barometric pressure will result in a temporary increase in water level.

Evaluation of a surge level, especially the worst combination of tides, wind set-up and sea level rise, is important when determining the design wave height, which is dependent on water depth and has an impact on the structural design of coastal structures. High waves, in combination with wind-induced surge during high tides, account for most of the damage to coastal engineering works and are the most significant natural erosive force. Damage to coastal structures will appear in terms of severe scouring around structures and displacement of stone armour units of jetties, groynes, and breakwaters. Other effects of surges on near-shore zones are the erosion and accretion of beach materials, cutting of new inlets through barrier beaches and shoaling of navigational channels. Moreover, surges can increase hazards to navigation, impede vessel traffic and hamper harbour operations. It is therefore necessary to acquire knowledge of the increase or decrease in water levels that can be expected during the lifetime of a coastal structure and the associated coastal processes.

The East African coastal waters are subjected to two alternating seasons, namely the southern and northern monsoons (Newell, 1957). The southern monsoons, which begin in April and end in October/November, are usually strong and are predominantly southerly. The northern monsoons, which begin in November and end in March, are lighter and are predominantly northerly.

The geometry, bathymetry and hydrographic conditions of the Zanzibar Channel directly affect Bagamoyo, Zanzibar and Dar es Salaam. The Zanzibar Channel, which separates Zanzibar Is. from the Mainland, lies between latitudes 5° 30′ S – 6° 45′ S and longitudes 38° 40′E –39° 30′E and its depth varies between 40 metres and 80 metres (see Figure 1).

This paper evaluates water level variations due to winds, change in barometric pressure and the East African Coastal Current (EACC) for use in the design of coastal structures in Tanzania.

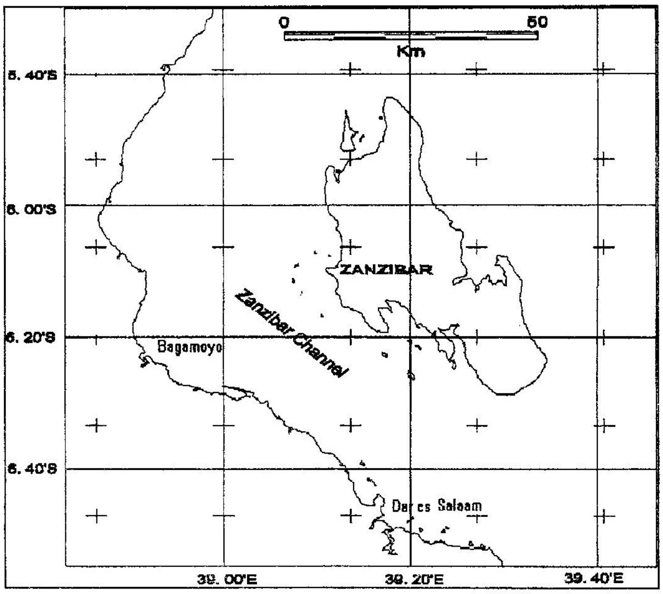

Figure 1. The Zanzibar Channel

THE DESIGN TOTAL WATER DEPTH

The total rise in water level along a coast is a combination of all the components that lead to changes in water level resulting from a meteorological storm plus those, which are not related to the storm, but occur simultaneously. The basic equation of the design total water depth is (Bretschneider, 1985)

$d_T = d_o + A_s + S_o + S_p + S_x + S_y + \alpha H_b$ ....(1)

where

- d_o mean low water level, which can be determined from available hydrographic charts or from soundings over the area of interest.
- A_s is astronomical tide which is determined by use of published tide tables.
- S_o is initial rise in tide caused by the storm approaching the continental shelf prior to the arrival of the winds. This component is not easily predicted, but can be determined from past hurricane records. Depending on the width of the continental shelf, So is between 1 and 2.5 ft.
- S_p is that component of a storm surge due to atmospheric pressure reduction from normal. This is commonly known as the inverted barometer effect and is given by
- S = S_x + S_y is the storm surge contribution. S_x is the wind tide due to the direct wind stress component perpendicular to the coast and S_y is the storm surge due to wind driven current parallel to the coastline caused by the wind stress component parallel to the coastline. For the Tanzania coast, contribution due to the East African Coastal current should be included in this component.
- αH_b is wave set-up due to breaking waves in the surf zone, where H_b is the breaking wave height and α = 0.1 to 0.24.

Wind stress and barometric pressure

In coastal areas, the direct effect of wind stress is the bodily movement of water, which in turn leads to sea level variations from the predicted tide heights. In shallow water areas storm surges are particularly dangerous, as the associated wind set up is directly proportional to the square of the wind speed and inversely proportional to the water depth. A drop in barometric pressure results in a temporary increase in the water level. The combined effect of the wind stress and barometric pressure on the mean sea level is given by the depth-integrated equations (e.g. Bowden, 1983):

$$\frac{dU}{dt} - fV = -\frac{h}{\rho}\frac{\partial p_a}{\partial x} - gh\frac{\partial \zeta}{\partial x} + \frac{\tau_{sx} - \tau_{bx}}{\rho} \quad \text{.............. (2)}$$

$$\frac{dV}{dt} + fU = -\frac{h}{\rho}\frac{\partial p_a}{\partial y} - gh\frac{\partial \zeta}{\partial y} + \frac{\tau_{sy} - \tau_{by}}{\rho} \quad \text{..............(3)}$$

$$\frac{\partial U}{\partial x} + \frac{\partial V}{y} + \frac{\partial \zeta}{\partial t} = 0 \quad \text{..............(4)}$$

In these equations the origin of the right-handed rectangular axes are taken with the origin in the mean sea surface, the *x*- and *y*-axes horizontal and the *z*-axis vertically upward. ζ is the elevation of the sea surface above its undisturbed value, taken as zero for the *x*, *y* plane and $f = 2\omega \sin \varphi$, where ω is the angular rate of rotation of the earth (= 7.29 x 10^{-5} radians per second) and φ is the latitude, positive to the north of the equator. $-fV$ and fU are the Coriolis or geostrophic acceleration terms arising from the earth rotation. τ_{sx} and τ_{sy} are components of the stress on the surface and τ_{bx} and τ_{by} are the components of the stress at the bottom.

The stress of the wind on the sea surface acts in the direction of the wind relative to the sea surface and its magnitude is proportional to the square of the wind speed relative to the sea surface. Thus

$$\tau_s = C_D \rho_a W^2 \quad \text{.......(5)}$$

where W is the wind speed measured at 10 meters above the sea surface, ρ_a is the density of the air ($\cong$ 1.25 kg/m^3) and C_D is a drag coefficient depending on the height at which W is measured, the stability of the lowest few meters of the atmosphere and the roughness of the sea surface as affected by the waves. At 10 meters, where most wind measurements are made (e.g. Silvester, 1974), $C_{D10} = 2.6\text{x}10^{-3}$ can be applied to limited bodies of water when $W_{10} \geq 15$ m/s (30 knots). The optimum for the open ocean is $C_{D10} = 2.4 \text{ x } 10^{-3}$. For winds less than this a relationship of

$$C_{D10} = 0.65x10^{-3} W_{10}^{1/2} \quad \text{.......(6)}$$

is applied when W_{10} is expressed in m/s. Wind velocities at other levels can be converted to values at 10 meters height by use of an approximation formula (Shore Protection Manual I, page 3-26):

$$W_{10} = W_z \left(\frac{10}{z}\right)^{1/7} \text{ for } z < 20 \text{ meters} \quad \text{.......(7)}$$

where W_z is the observed wind speed at elevation z.

The bottom stress may be related to the bottom current U_b by a quadratic law (e.g. Bowden, 1983) i.e.

$$\tau_b = k\rho U_b^2 \quad \text{.......(8)}$$

where k is a coefficient of friction with atypical value of $2\text{x}10^{-3}$ and ρ is the density of water.

A number of solutions to the dynamical equations have been obtained for areas of simple geometry under certain assumptions. If we consider a narrow channel with sides parallel to the x-axis so that $V = 0$, the surface elevation due to the effect of atmospheric pressure alone (Bowden, 1983), Eq. (8) reduces to

$$\frac{\partial \zeta}{\partial x} = -\frac{1}{\rho g}\frac{\partial P_a}{\partial x} \quad \text{.......(9)}$$

If $\Delta\zeta$ and ΔP_a represent changes over a finite horizontal distance Δx, this gives

$$\Delta \zeta = -\frac{1}{\rho g}\Delta P_a \quad \text{.......(10)}$$

This is the well known " inverted barometer effect". This means that if there is a fall of 1 *mbar* in atmospheric pressure, there will be a rise of 1 *cm* in sea level. For wind stress effect only, the dynamical equations reduce to

$$\frac{\partial \zeta}{\partial x} = \frac{\tau_{sx} - \tau_{bx}}{\rho g (h + \zeta)} \quad \text{.......(11)}$$

In the case of a wind blowing towards the head of a gulf, a steady state will be reached such that the longitudinal transport $U = 0$, although there will still be a surface flow in the direction of the wind compensated by the sinking of water near the head. For this situation, the surface elevation may be approximated as

$$\frac{\partial \zeta}{\partial x} = C\frac{\tau_{sx}}{\rho g h} \quad \text{.......(12)}$$

where $1 < C < 1.5$ (taken to be closer to 1 than 1.5 in practice). The bottom shear stress is considered to lie somewhere between zero and $-\tau_{sx}/2$ and the elevation ζ is considered small compared to the mean water depth h.

In the case of open ocean and if the width of the continental shelf is designated L, the surge height above the mean water level (MWL) is given as (Bretschneider, 1966)

$$S = \frac{k_s W^2 L}{g(d_1 - d_2 - S}\ln\left(\frac{d_1}{d_2 + S}\right) \quad \text{.......(13)}$$

where k_s is a coefficient equal to 3 x 10^{-6}. Since S is small compared to d_2, Eq. (13) can be reduced to

$$\frac{S}{d_1} = \frac{k_s W^2 L}{g d_1^2 (1 - d_2 / d_1)} \ln\left(\frac{d_1}{d_2}\right) \quad \text{.................(14)}$$

where d_1 is the depth at the continental shelf edge and d_2 is the depth at the coast. The water depth at the continental shelf is taken as d_1 = 100 meters and the ratio d_1/d_2 = 1001 can approximate for $d_2 = 0$.

The East African Coastal Current (EACC)

The coastal waters of East Africa are also influenced by the East Africa Coastal Current, which is described by Newell (1957) as a current that moves northward throughout the year, but changes speeds during the two monsoon seasons. During the southerly monsoons, it moves with a speed of about 4 knots after being accelerated by the trade winds across the Indian Ocean and by the southerly winds. The current is pressed in towards the western side of the ocean due to the effect of the Coriolis force. During the northerly monsoons, the current is impeded by the northerly winds and from the equator northwards; it is reversed to flow in the southerly direction. The reversed current meets the much-decelerated EACC at about 1^0S, where both are deflected out to the sea forming the Equatorial Counter Current.

Lisitzin (1974) gives the deviation in the height of sea level as

$$\Delta S = \frac{2\omega V_c L_c \sin\varphi}{g} \quad \text{..........................(15)}$$

where ω = 7.29 x 10^{-5} sec^{-1} is the angular speed of the Earth's rotation, V_c is the current speed, L_c is the distance of EACC axis from the coast, φ is the geographical latitude of the location and g = 9.80 is the gravitational acceleration.

METHOD

Estimation of the various components of the design total water depth has involved information collected from several sources. The datum, to which the levels are reduced, is that of the Admiralty Charts (Approaches to Dar es Salaam of 1954). This datum is 30.39 ft below a Bench Mark on the entrance to the steps at the left side of the Post Office, or 18.0 ft below a Bench Mark out on the Dar es Salaam Dockyard Pier.

The prediction of wind set-up can be done using either statistics of wind fields or statistics of the measured wind set-up. Although the latter gives the best results, we shall use the former method of using statistics of wind fields because of the absence of measured wind set-up in Tanzania. Data on atmospheric pressure, wind speed and direction were obtained from the Directorate of Meteorology of Tanzania for the period between 1972 and 1996 for Tanga, Dar es Salaam, Zanzibar and Mtwara.

Dubi (1998) analysed 25-year wind data collected between 1972 and 1996 at Tanga, Dar es Salaam, Zanzibar and Mtwara and found the 50-year return wind speeds to be 26 knots for Tanga, 27 knots for Dar es salaam, 29 knots for Zanzibar and 36 knots for Mtwara. The return wind speeds are used to evaluate wind set-up at different locations on the coastline of Tanzania.

The Mean High Water Springs and Neaps and the Mean Low Water Springs and Neaps are obtained from Admiralty Chart No.3310. Astronomical tide heights are obtained from published tide-tables published by the Tanzania Harbours Authority for Tanzania ports. Use is also made of the limited tide records.

The Admiralty Chart No. 3310 also describes the East African Coastal Current as a current that sets predominantly northward, following the trend of the coast. It reaches a speed of about 4 knots during the SW Monsoon and 3 knots during the NE Monsoon. In between Pemba Island and the Mainland, it sets fairly in the channel while tending to be deflected locally by islands and reefs. The speed of this current is used to evaluate the water level variations on both sides of the Zanzibar Channel.

RESULTS

Tidal information

Tidal information extracted from the Admiralty Chart shows that water levels along the coastline of Tanzania are varied. Pangani, Zanzibar and Bagamoyo have the highest mean water levels with Bagamoyo having the highest (4.12 metres) and Zanzibar and Pangani having the same heights of 3.93 metres above chart datum. Lindi has the lowest mean water levels followed by Dar es Salaam (See Table 1 and Figure 2.)

Table 1. Tidal information extracted from Admiralty Chart Datum

	HIGH WATER (m)		LOW WATER (m)	
LOCATION	Mean Springs	Mean Neaps	Mean Springs	Mean Neaps
Pangani Bay	3.93	2.90	0.73	1.80
Tanga Bay	3.32	2.29	0.09	1.16
Mkoani (Pemba)	3.42	2.29	0.12	1.22
Bagamoyo	4.12	2.90	0.34	1.65
Zanzibar	3.93	2.71	0.15	1.46
Dar es Salaam	3.14	2.07	-0.09	0.95
Mafia	3.40	2.38	0.60	1.50
Kilwa Masoko	3.63	2.53	0.31	1.37
Lindi	2.96	1.92	-0.21	0.82
Mtwara	3.60	2.56	0.31	1.34

The predicted astronomical tide heights for Zanzibar and Dar es Salaam for 1998 show that Zanzibar has higher heights and that both stations experience the highest water levels during the months of March/April and November (Figure 3).

Tidal predictions are usually computed for average barometric pressure. As it was noted earlier in section 2.1, a low barometric pressure will tend to raise sea level and a high barometer will tend to depress it. Data for Dar es Salaam shows that the barometer increases from January and reaches a maximum in July from where it drops reaching a minimum in December. The associated rise in sea level due to the difference in pressures between July and December is shown in Figure 4.

If P_n is the average monthly atmospheric pressure at a given locality in an oceanic area and P_0 the average atmospheric pressure over all oceans for the same month then the theoretical response of the water surface relative to the mean sea level of the total area covered by seawater is (Lisitzin, 1974):

$$c' = P_n - P_0 \qquad (16)$$

where P_0 is identical for all localities and given in Lisitzin (1974). The theoretical rise in sea level relative to the mean sea level of the all oceans is shown in Figure 5.

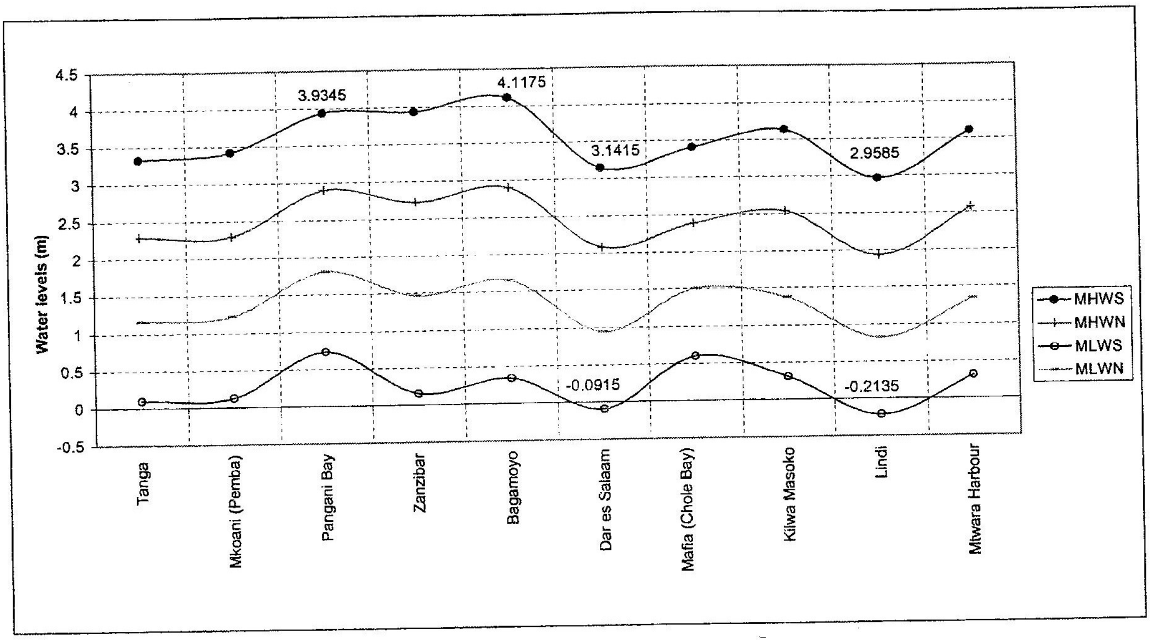

Figure 2. Mean water levels along the coastline of Tanzania. (MHWS = Mean High Water Springs, MHWN = Mean High Water Neaps, MLWS = Mean Low Water Springs, MLWN = Mean Low Water Neaps).

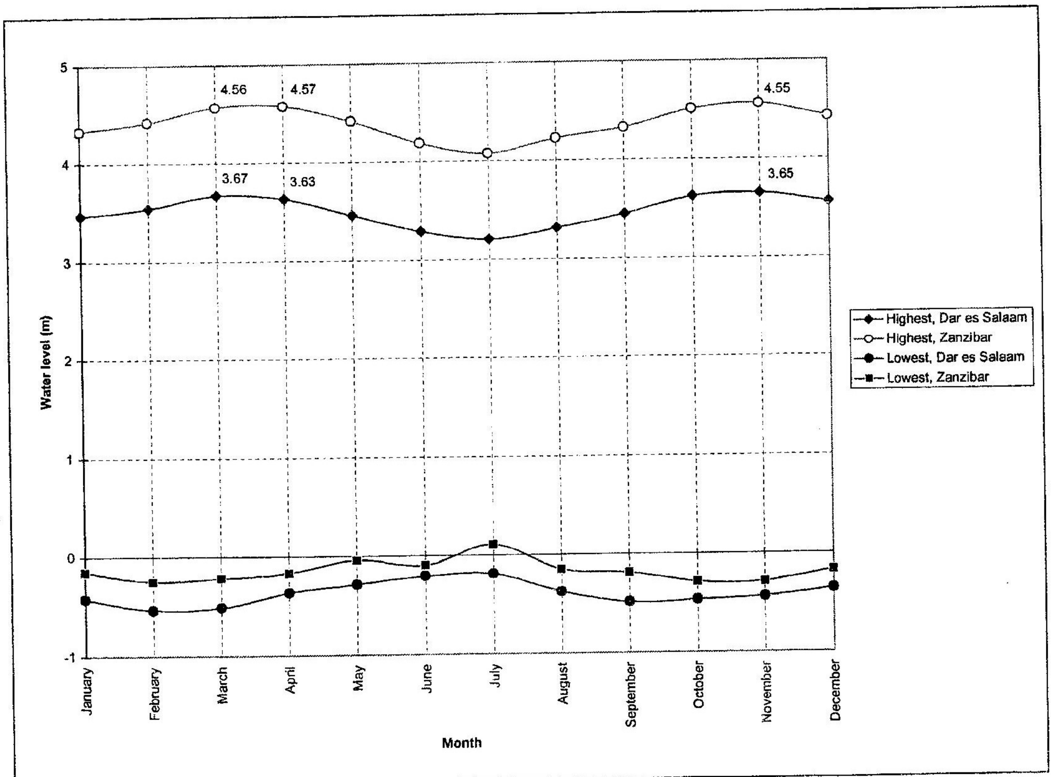

Figure 3. A comparison of predicted heights of high and low waters for Dar es Salaam and Zanzibar, 1998

Wind set-up

In evaluating wind set-up for the East African coastal waters, we have assumed a uniform variation of the water depth at the shelf edge to water depth at the coast during the highest astronomical tide. The effective shelf width for different locations, as deduced from Admiralty Charts, for the two monsoon seasons is shown in Table 2. Figure 6 shows the estimated wind set-up due to recorded maximum wind speeds that occurred in the period 1972-1996.

Table 2. Effective shelf width for different locations along the coastline of Tanzania

Location	Average effective shelf width, L (km)		Wind set-up S (cm) for 50-year return wind speed (Eq. 13)	
	Northerly Monsoon	Southerly Monsoon	Northerly Monsoon	Southerly Monsoon
Tanga	21	10.5	7.5	3.8
Bagamoyo	90	57	11.2	22
Zanzibar	65	56	9.3	8
Dar es Salaam	45	6	6.9	2.3
Mtwara	10	20	6.9	13.7

The East African Coastal Current (EACC)

Since the EACC flows almost parallel to the coastline, a slope perpendicular to the direction of the current will be created. Due to the effect of the Coriolis force, the water mass will be deflected to left in the southern hemisphere, when looking in the direction of the current (Lisitzin, 1974). As a result of this deflection and considering that the current passes in the Zanzibar and Pemba Channels, locations on Mainland Tanzania will experience sea level rise while those on Zanzibar experience a fall in sea level. The estimated rise in water level due to the current is shown in Table 3.

Table 3. Approximate sea level rise due to the East African Coastal Current (EACC)

Location	Latitude	Distance of EACC axis from the coast (km)	Speed of EACC (knots)		Approximate rise of sea level due to the EACC (cm) Eq. (14)	
			NE-Monsoon	SE-Monsoon	NE-Monsoon	SE-Monsoon
Tanga	5^0 S	19	3	4	3.7	4.9
Bagamoyo	$6^0 30'$ S	22.5	3	4	5.7	7.6
Zanzibar	$6^0 15'$ S	22.5	3	4	-5.5	-7.3
Dar es Salaam	$6^0 50'$ S	18	3	4	4.8	6.4
Mtwara	$10^0 20'$ S	20	3	4	8	10.7

DISCUSSION AND CONCLUSION

The highest astronomical tide for Dar es Salaam can be taken to be 3.7 metres and for Zanzibar 4.6 metres and occur during March/April and October/November as can be seen in Figure 3. These levels are predicted to occur under average meteorological conditions and under any combination of astronomical conditions. Higher levels than these can be reached under extreme meteorological conditions. This can be seen when we compare predicted and measured tide heights in Figures 7 and 8.

Meteorological conditions and the East African Coastal Current cause the differences between predicted tide heights and the actual tide heights. For locations on the coastline of Tanzania, wind set-up is dependent mainly on the effective width of the continental shelf. Bagamoyo has the widest continental shelf and hence the highest wind set-up. The monthly barometric pressure has been below the average atmospheric pressure over all oceans since 1972, but over the years, the pressure has been increasing, resulting in the decrease of the risen water level.

During the southerly monsoons, especially in July, Bagamoyo has the highest wind set-up reaching a value of approximately 20 centimetres, followed by Mtwara, Zanzibar and Tanga. Dar es Salaam has the lowest wind set-up in the said month. During the northerly monsoons, in January, Zanzibar experiences the highest wind set-up followed by Tanga, Bagamoyo and Mtwara. Dar es Salaam has the lowest set-up.

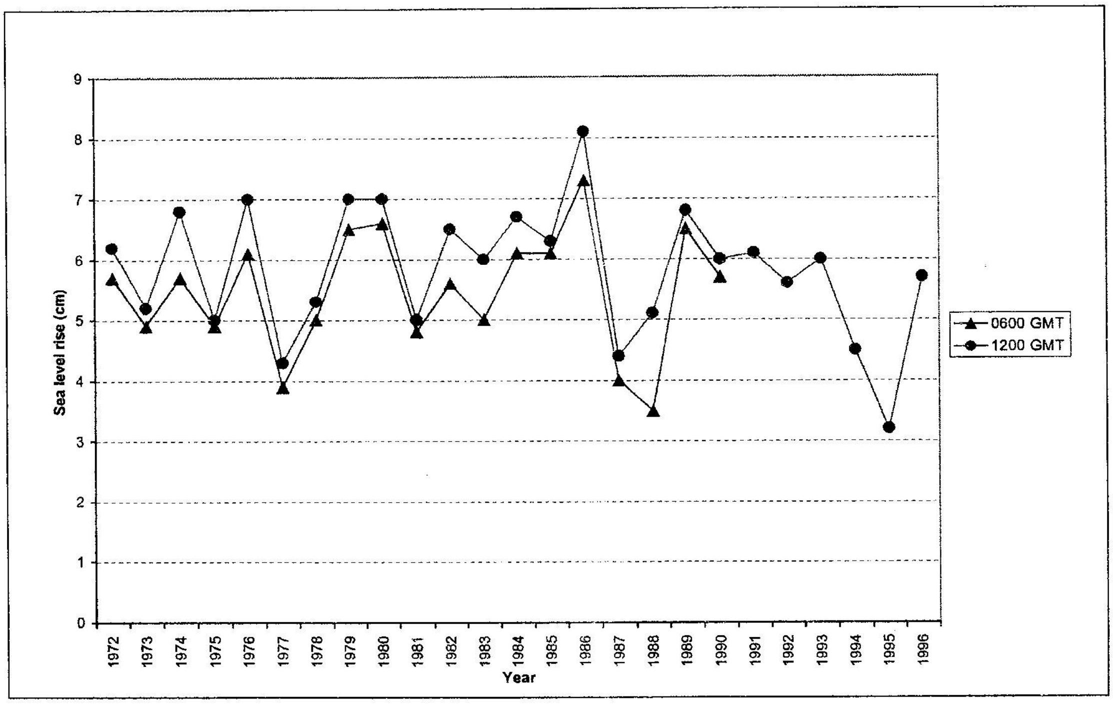

Figure 4. Sea level rise due to the difference in July pressure and December pressure

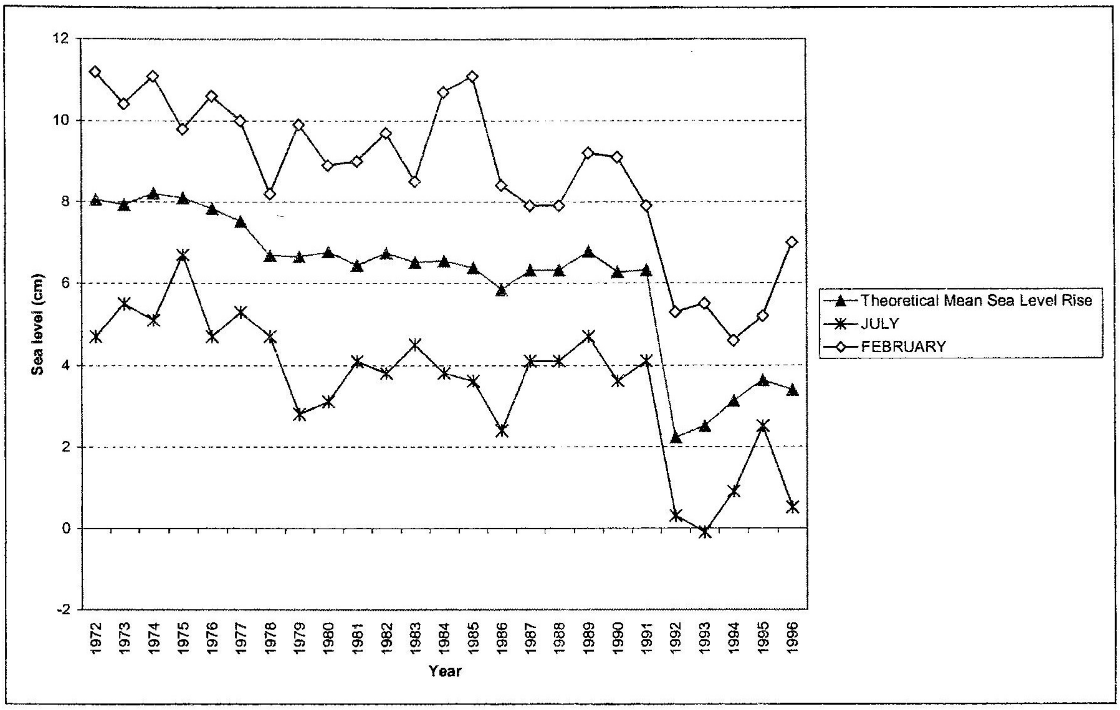

Figure 5. Rise in sea level at Dar es Salaam relative to mean sea level of all oceans.

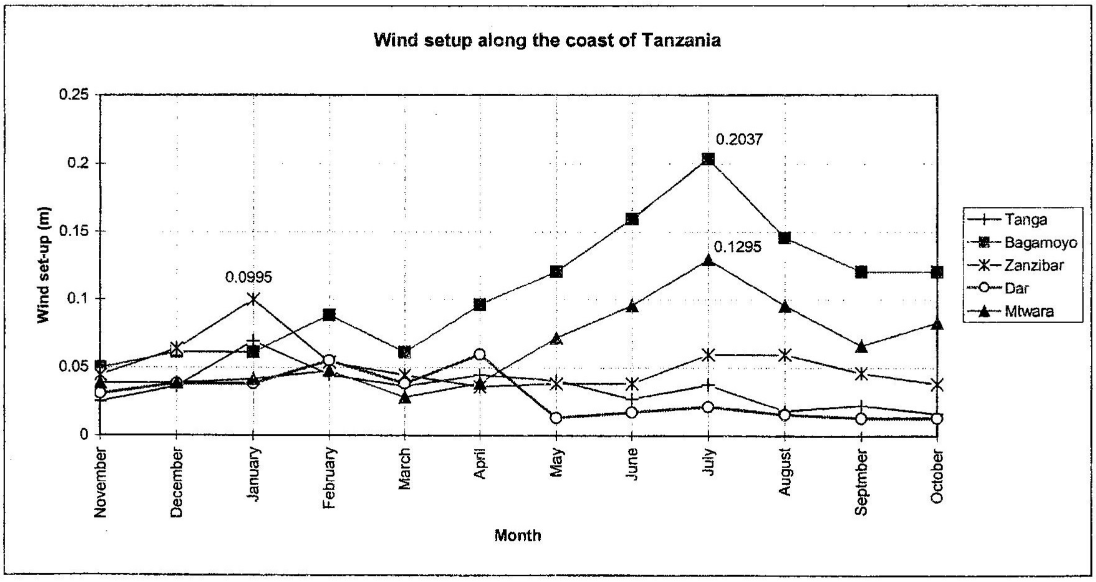

Figure 6. Wind set-up estimated using maximum wind speeds during 1972-1996

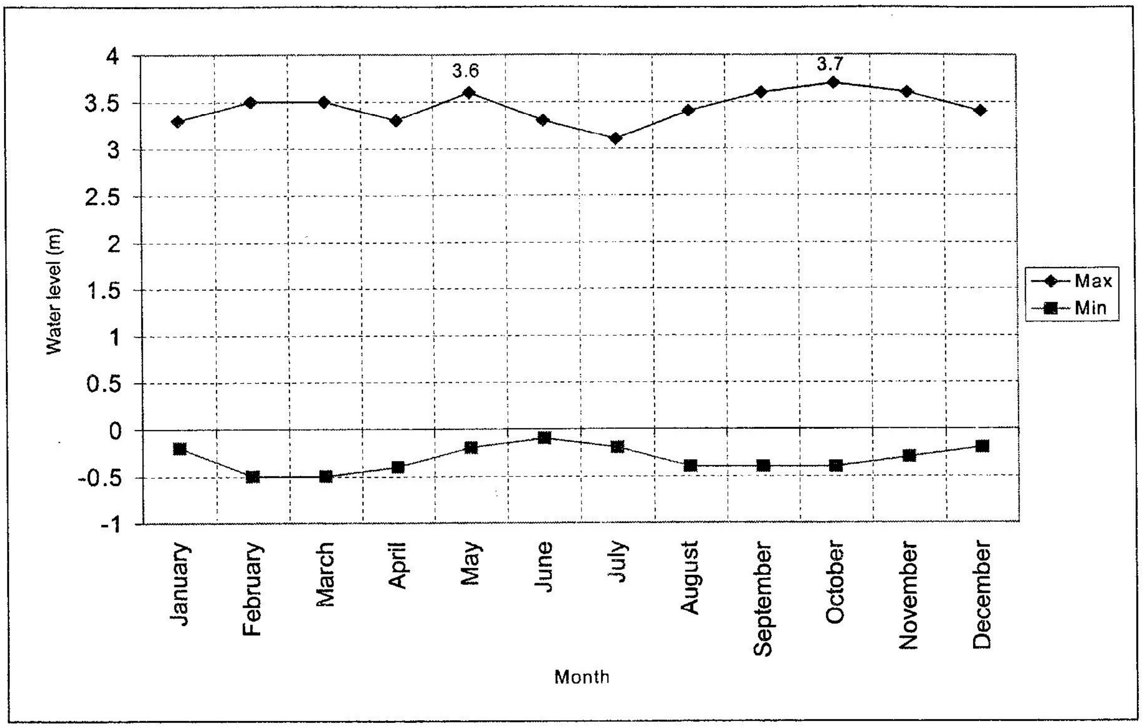

Figure 7 Predicted tide heights for Dar es Salaam for 1989

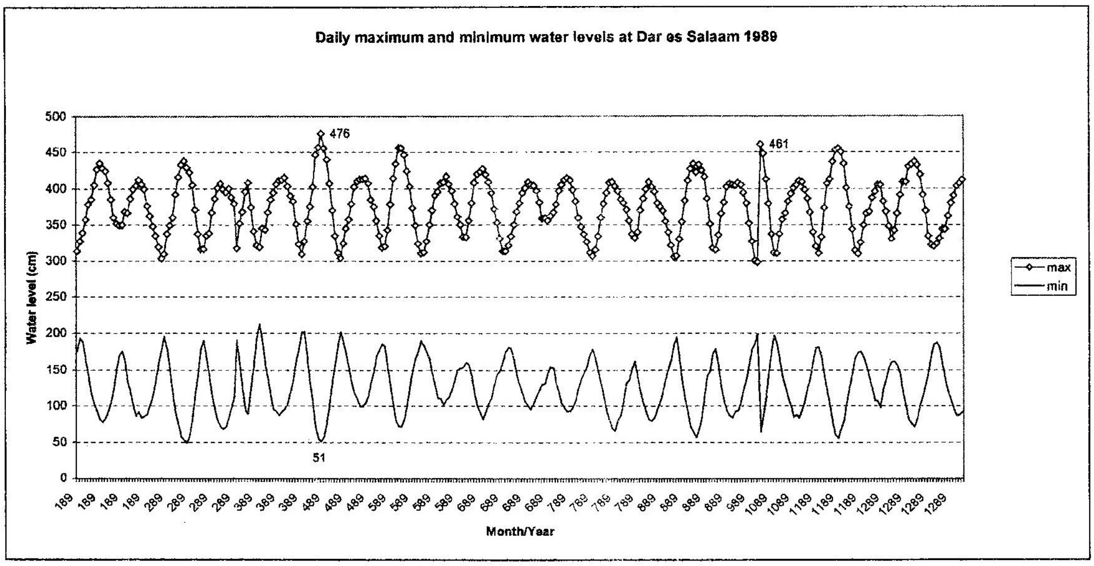

Figure 8. Measured daily maximum and minimum water levels at Dar es Salaam in 1989

NOMENCLATURE

A_s	astronomical tide
C	coefficient taken to be closer to 1 than 1.5 in practice
c'	theoretical rise of the water surface relative to the mean sea level
C_D	a drag coefficient depending on the height at which W is measured.
C_{D10}	the drag coefficient approximately equal to 2.6×10^{-3} at 10 meters height
d_1	water depth at the continental shelf
d_2	water depth at the coast
d_o	mean low water level
f	angular rate of rotation of the earth (7.29×10^{-5} radians per second)
-fV and fU	the Coriolis or geostrophic acceleration terms arising from the earth rotation
g	acceleration due to gravity
h	water depth
H_b	is the breaking wave height
K	a coefficient of friction with atypical value of 2×10^{-3}
k_s	coefficient equal to 3×10^{-6}
L_c	distance of the East African Coastal Current from the coast
p_a	atmospheric pressure
P_n	average monthly atmospheric pressure at a given locality
P_o	identical atmospheric pressure given in Lisitsin (1974)
S	$S_x + S_y$ is the storm surge height due to wind above mean water le
S_o	initial rise in tide caused by the storm approaching the continental shelf prior to the arrival of the winds.
S_p	that component of a storm surge due to atmospheric pressure reduction from normal.
S_x	wind tide due to the direct wind stress component perpendicular to the coast
S_y	storm surge due to wind driven current parallel to the coastline caused by the wind
U,V	velocity components parallel to the x and y axes
U_b	bottom current
V_c	current speed
W	the wind speed measured at a given height
W_{10}	wind speed measured at 10 meters above the sea
W_z	the observed wind speed at elevation z
W_z	observed wind speed at elevation z.

Greek symbols

$\Delta\zeta$	change of surface elevation over a finite horizontal distance Δx
ΔP_a	change of atmospheric pressure over a finite horizontal distance Δx
α	coefficient 0.1 to 0.24
αH_b	approximate wave set-up due to breaking waves in the surf zone
φ	geographical latitude of a location, positive to the north of the equator.
ρ	density of water.
ρ_a	the density of the air ($\cong 1.25$ kg/m^3)
τ_{bx} and τ_{by}	the components of the stress at the bottom in the x- and y- axes stress component parallel to the coastline.
τ_s	stress of the wind on the surface
τ_{sx} and τ_{sy}	components of the stress on the surface in the x- and y- axes
ω	the angular rate of rotation of the earth (7.29×10^{-5} radians per second)
ζ	elevation of the sea surface above its undisturbed value

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