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# Tidal Power Potential in the Submerged Channels of Dar es Salaam Coastal Waters

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***Abstract***—This is a study conducted in the coastal waters off Dar es Salaam between three reef islands, Mbudya, Pangavini and Bongoyo, to assess the characteristics of tidal currents and their potential for tidal power in submerged channels. The study entailed detailed bathymetric surveying of the area, measurement of currents and data analysis. Tidal currents were measured on the tidal plateau, shallow water area on the sand banks and in the submerged channels, using self-recording multi-sensor current meters. A self-recording current meter type RCM9 (www.aadi.no) was deployed on the tidal plateau. Two South African PUV-type of current meters (Sea Pac and MCM), both of which were manufactured by CSIR (www.csir.co.za), were deployed in shallow water and in the submerged channels respectively.

Results from in-situ measurements show that currents on the sandbank and the tidal flat, in water depths from 0.5 m to 3.0 m, are directed opposite the main tidal current in the deeper waters. Current velocities vary during a tidal cycle and are strongest in the middle of the cycle. Generally, velocities on the tidal flat are around 0.1m/s during the SE monsoon winds and only half that during the NE monsoon winds. In the submerged channels, below 6 m, velocities are more than 0.5 m/s. In the deepest part of the test area, velocities reach 1.5 m/s. Flood and ebb current velocities were comparable. The mass flux reached 20 $m^3/s$ in the submerged channels and decreased with decreasing depth. The potential for use of tidal power is discussed.

## INTRODUCTION

In coastal areas with large tidal ranges, flowing tidal waters contain large amounts of potential and kinetic energies. The principal of harnessing the energy of the tides dates back to the eleventh century. Tide mills were in use on the coasts of Spain, France and the UK before 1100 AD and in tidal estuaries (e.g. in Scheide in Belgium) around 1800 AD. The tides were used to turn waterwheels, producing mechanical power.

More recently, rising and falling tides have been used to generate electricity, in much the same manner as hydroelectric power plants. The first requirement is a dam or "barrage" across a tidal bay or estuary. At certain points along the dam, gates and turbines are installed. When there is an adequate difference in the elevation of the water on the different sides of the barrage, the gates are opened. This "hydrostatic head" that is created, causes water to flow through the turbines, turning an electric generator to produce electricity.

Although the technology required to harness tidal energy is currently well established, tidal power is still expensive, and there is only one major tidal generating station in operation. This is a 240-megawatt at the mouth of the La Rance river estuary on the northern coast of France (in comparison a large coal or nuclear power plant generates about 1,000 MW of electricity). The La Rance generating station has been in operation since 1966 and has been a very reliable source of

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electricity. La Rance was supposed to be one of the many tidal power plants in France, until their nuclear program was greatly expanded in the late 1960's. Elsewhere there is a 20 MW experimental facility at Annapolis Royal in Nova Scotia, and a 0.4 MW tidal power plant near Murmansk in Russia.

The coastal waters of Tanzania experience a semi-diurnal tide with two almost equal maxima and two minima during a lunar day (24.8 solar hours) (Lwiza and Bigendako, 1988). There is a considerable rise and fall of water against the coast of Tanzania (of about 3.5 m during spring tides) [e.g. Dubi, 2002], which has important geomorphologic and hydrodynamic repercussions when combined with the inter-tidal profile and the prevailing winds. While the ebb and flood tidal movements tend to be self-balancing on the open coast, individual features will influence the extent of fluctuations. Tidal currents in estuaries and areas in between islands and sand spits such as those found between the shoreline and the Islands of Mbudya, Bongoyo are localised and may be important in their effect on coastal processes and harnessing tidal energy.

Several studies have been undertaken in or close to the study area. Harvey (1977) studied hydrographic conditions in the Zanzibar Channel and in the Kunduchi coastal waters and reported that flood and ebb streams enter the Zanzibar Channel from both the north and south. On measuring tidal currents for about 30 days, about 800 metres from the shore, Lwiza (1987) reported that during north-east monsoon season the current speed, averaged over one tidal cycle, was 0.25 m/s and the maximum was 0.5 m/s. There was, however, no big change in current speeds and direction during the south-east monsoon season. Ebbing speeds in the Kunduchi-Manyema creek reached as much as 3.5 m/s.

However, there has been no comprehensive study to determine the tidal energy potential in this area. The objective of the study is, therefore, to assess characteristics of tidal currents and the potential for tidal power in the submerged channels of coastal waters off Dar es Salaam.

## THE STUDY AREA

The continental shelf off Tanzania includes the three large offshore islands of Unguja, Pemba and Mafia. Off Dar es Salaam, there are three reef islands, Mbudya, Pangavini and Bongoyo, which are composed of a core of raised coral reef (Figure 1). The raised reef rock and the surrounding inter-tidal reef have an interesting relationship in terms of location relative to each other (Temple, 1970). The raised coral reef is located on the northwestern sector of the inter-tidal flat. The asymmetrical disposition can be related to some physical control, which is probably the dominant south-east trade winds, the waves generated by them and the tidal currents. The study area is a 2.5 km x 4.0 km segment of the coastal water area situated in between Mbudya and Pangavini Islands and the shoreline (Figure 1). The mean neap and spring tidal ranges at the test area are 1.1 m and 3.3 m, respectively.

## MATERIALS AND METHODS

### Field measurements

With a small boat, an echo sounder and a GPS, the 2.5 km x 4.0 km area was surveyed with a grid spacing of 50 m. Positioning and navigation were facilitated by using the waypoint facility in the GPS. The tidal plateau ranging from 100 m to 500 m from the shoreline was not measured due to difficulties in navigating the boat in shallow water. The error in the water depths measured with a simple echo sounder was approximately 0.1 m and the error of the GPS in plane coordinates was around 20 m.

For measuring currents, different current meters were used, including the RCM9 (www.aadi.no), Seapac and Marine Current Meter (MCM) instruments (www.csir.co.za) which utilize the Doppler principle. The RCM9 is a unique self-contained instrument that can be moored in the sea for long periods of time. It measures the horizontal current speed and direction, temperature, conductivity and turbidity as well as pressure from which the instrument's

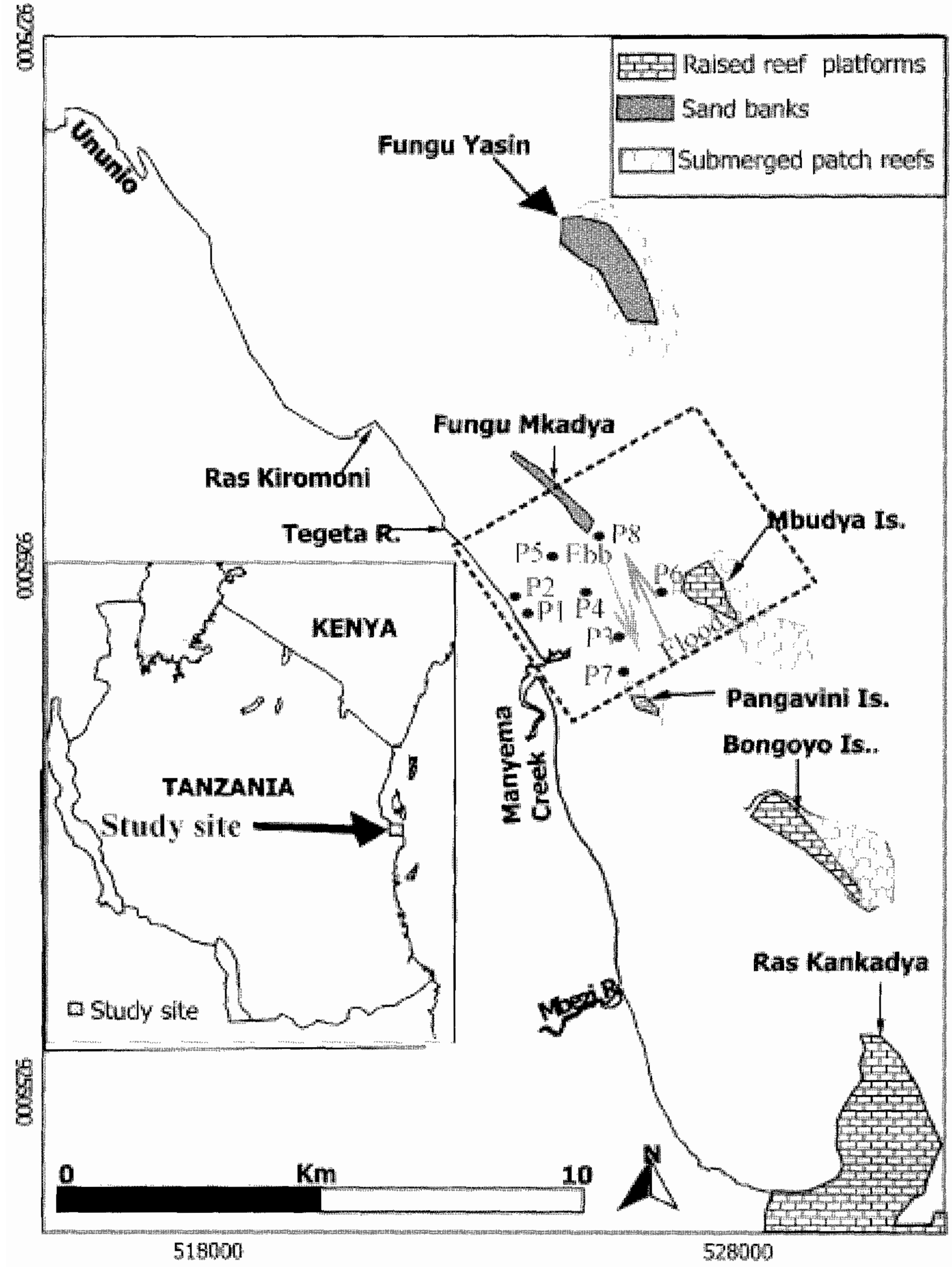


Fig. 1. Location of the study area and positions of measurements

depth is determined. The Seapac and MCM are PUV instruments that measure the pressure, u and v velocities in the x- and y-directions respectively. The data set was collected in the SE monsoon and NE monsoon over three years beginning 1998. The duration of sampling varied from minutes to months and sampling frequencies ranged from one to eight Hz for the Seapac and MCM and 10 minutes for the RCM9. The collection of data was concentrated in the period of the SE monsoon period where the currents are strongest, but also measurements in the NE monsoon were taken. Tides were measured in seven positions (Figure 1), namely P1 and P2 on the tidal plateau, P4 and P5 in shallow waters and P3, P6 and P7 in the submerged channels.

## Data analysis

The data set was analysed to find tidal characteristics and power potential of the tidal elevation and currents in the submerged channels basing on the following theoretical background:

### Characteristics of the tidal wave and currents

If it is assumed that a tidal current runs horizontally in a Cartesian frame where iz is directed towards the vertical, ix points eastwards and iy points north, the current measured at a point (x,y,z) in the interior of the fluid can be represented by a vector V in the xy plane as:

$$V \cong \mathbf{w}(t) = u(t)\mathbf{i}_x + v(t)\mathbf{i}_y \quad \text{.................................(1)}$$

The vector V has components u and v along the x- and y- directions given as:

$$\left.\begin{array}{l} u = a_u \cos(\omega t - \varphi_u)) \\ v = a_v \cos(\omega t - \varphi_v) \end{array}\right\} \quad \text{....................................(2)}$$

where $a_u$ and $\varphi_u$ are spectral amplitudes and phase lags for the *u*-components and likewise for $a_v$ and $\varphi_v$, and $\omega$ is the tidal angular frequency. We can form a complex tidal current *w* as:

$$w = u + iv \quad \text{........................................................ (3)}$$

where i = $\sqrt{-1}$. If the tidal current on a complex plane is traced as time goes by a period, $T = 2\pi/\omega$, an ellipse will be formed. The following ellipse parameters are important for the evaluation of a tidal current:

- Maximum current velocity or semi-major axis;
- Eccentricity: the ratio of semi-minor to semi major axis, negative values indicating that the ellipse is traversed in a clockwise rotation;
- Inclination or angle between east (x-) and semi-major axis;
- Phase angle, i.e. the time of maximum velocity with respect to a chosen origin of time.

Substituting Equation 2 into Equation 3 and using Euler's relation given as

$$\cos\theta = {}^1/_2\,(e^{i\theta} + e^{-i\theta}) \quad \text{.......................................(4)}$$

and rearranging, the following is obtained:

$$w = \frac{a_u e^{-i\phi_u} + i a_v e^{-i\phi_v}}{2}\, e^{i\omega t}\;\; \frac{a_u e^{i\phi_u} + i a_v e^{i\phi_v}}{2}\, e^{-\omega t} \quad \text{.........................(5)}$$

Equation 5 represents a decomposed ellipse with two circular components: the term with $e^{i\omega t}$ describes an anti-clockwise circle with a radius of $W_p$ and the term with $e^{-i\omega t}$ describes a clockwise circle with a radius of $W_m$. Depending on whether $W_p$ is greater than, equal to or less than $W_m$ the ellipse will traverse anti-clockwise, rectilinear, or clockwise. The maximum current, or semi-major axis (M) is given as

$$M = W_p + W_m \quad \text{................................................(6)}$$

And the minimum speed of the tidal current, or semi-minor axis (m) is

$$m = W_p - W_m \quad \text{................................................(7)}$$

and the eccentricity is

$$ECC = \frac{m}{M} = \frac{W_P - W_m}{W_P + W_M} \quad \text{.......................................(8)}$$

When $W_m > W_p$ the eccentricity is negative and the ellipse rotates clock-wisely.

### Tidal power

From the fundamental equations of hydrodynamics on a rotating Earth, the power contained in a tidal wave is given as (e.g. Godin, 1988) as:

$$\nabla p.\mathbf{V} = -\frac{d}{dt}\left[\frac{\rho|\mathbf{V}|^2}{2} + \rho g z\right] + \rho(\mathbf{T} + \mathbf{F}).\mathbf{V} \quad \text{.......................(9)}$$

The first term on the RHS of Equation 9 represents the change in kinetic energy and the second term is the change in potential energy. The third and fourth terms are the rate of work done by the tidal force **T** and friction **F** respectively. Thus, the vector **p.V** is equal to changes in mechanical energy (kinetic and potential) of the fluid and to the power contributed by the tidal force and friction.

The potential energy is the energy due to position. Potential energy as it occurs in water waves is the result of displacing a mass from a position of equilibrium against a gravitation field. The potential energy of a small column of fluid with mass $dm$ in a mean water depth $h$ and surface elevation $\eta$ relative to the mean water level (MWL) is

$$d(PE) = dmg\,\bar{z} \quad \text{.......(9)}$$

where $g$ is the gravitational acceleration and $\bar{z}$ is the height to the center of gravity of the mass, which can be written as (e.g. Dean and Dalrymple, 1984)

$$\bar{z} = \frac{h+\eta}{2} \quad \text{.......(10)}$$

and the surface elevation can be expressed as

$$\eta = \frac{H}{2}\cos(\omega t - kx) \quad \text{.......(11)}$$

in which $H$ is the wave height, $k = 2\pi/L$ is the wave number and L is the wavelength. The differential mass per unit width is then

$$dm = \rho(h+\eta)dx \quad \text{.......(12)}$$

At a given time, say at $t = 0$, the potential energy averaged over one wave length for a tidal wave of height $H$ is then

$$\overline{PE_L} = \frac{1}{L}\int_x^{x+L} d(PE) = \frac{1}{L}\int_x^{x+L} \rho g\frac{(h+\eta)^2}{2}dx \quad \text{.......(13)}$$

Similarly at a given location, say at $x = 0$, the potential energy of a tidal wave averaged over one wave period can be shown to be

$$\begin{aligned}\overline{PE_T} &= \frac{1}{T}\int_t^{t+T} d(PE) = \frac{1}{T}\int_t^{t+T}\rho g\frac{(h+\eta)^2}{2}dt \\ &= \frac{\rho g}{T}\left(\frac{1}{2}h^2T + h\int_t^{t+T}\eta dt + \frac{1}{2}\int_t^{t+T}\eta^2 dt\right)\end{aligned} \quad \text{.......(14)}$$

However, if the potential energy from the high water level (HWL) to low water level (LW) is considered, the limits of the integral are accordingly changed from t to $t + T/2$. Substituting Equation 11 into Equation 14, the second integral becomes identically equal to zero and for one-half wave period the last integral is one-half, giving (see also Dean and Dalrymple, 1984)

$$\overline{PE_{T/2}} = \rho g\frac{h^2}{2} + \rho g\frac{H^2}{16} \quad \text{.......(15)}$$

The last term in Equation 15 is the potential energy due to the tidal wave falling from HW to LW. Kinetic energy is due to the moving water particles; the kinetic energy associated with a small parcel of fluid with mass $dm$ is

$$d(KE) = dm\frac{V^2}{2} \quad \text{.......(16)}$$

where $V$ is the current velocity as given in Equation 1. If a tide is considered as a long progressive wave, the current can be expressed as

$$V = U\cos(at - kx) \quad \text{.......(17)}$$

where $U$ is the amplitude of the current. For a long wave the current amplitude is related to the tidal wave height and water depth (Bowden, 1983) as

$$U = \frac{H}{2}\left(\frac{g}{h}\right)^{\frac{1}{2}} \quad \text{.......(18)}$$

where $H$ is the tidal wave height and $h$ is the water depth. Substituting Equation 18 into Equation 17 and thereafter inserting into Equation 16 and integrating, at a given location, the averaged kinetic energy over a wave period can be shown to be

$$\begin{aligned}\overline{KE} &= \frac{\rho g}{2T}\frac{H^2}{4h}\int_{-h}^{\eta=0}dz\int_t^{t+T}\cos^2(\omega t)dt \\ &= \frac{1}{16}\rho g H^2\end{aligned} \quad \text{.......(19)}$$

The rate of transmission of energy across a vertical strip of unit width and extending from surface to bottom is given by (Bowden, 1983)

$$E_{TR} = \rho g h A U\cos^2(\omega t - kx) \quad \text{.......(20)}$$

where $A$ is the amplitude of the surface elevation equal to $H/2$. Taking the average value over a tidal period, the mean rate of transmission of energy per unit width perpendicular to the direction of propagation is

$$\overline{E_{TR}} = \frac{1}{2}\rho g h A U \text{ (W/m)} \quad \text{.......(21)}$$

After inserting Equation 18 into Equation 21, the following is obtained:

$$\overline{E_{TR}} = \frac{1}{2}\rho g^{3/2}h^{1/2}A^2 \text{ (W/m)} \quad \text{.......(22)}$$

When dividing Equation 22 by $\rho g$, the following equation is derived:

$$E/\rho g = 0.5\sqrt{gh}A^2 \text{.......................................(23)}$$

which has units (m$^3$ /s). This Equation gives us an indication of the kinetic energy flux, since $\sqrt{gh}$ is stream velocity in a tidal wave.

If the surface area of the basin covering the submerged channels is taken to be S(z), when the surface is at elevation z and the tidal range is 2A, the potential energy created between LW and HW and back to HW can be shown to be

$$E_s = 2\rho g\int_0^{2A} S(z)zdz \approx \rho g S_o(2A)^2 \text{ ............................(24)}$$

where $S(z)$ has been approximated as $S(z) = S_o + \varepsilon(z)$. So which denotes the surface area during low tide is assumed to have a small deviation ((z) caused by the change in water level from LW to HW. Equation 24 gives the upper limit of the energy that can be extracted from the basin over a tidal cycle, since exploitation of energy is never totally efficient.

## RESULTS AND DISCUSSION

### Bathymetry and general characteristics of the tidal wave and currents

Detailed bathymetry of the study area is shown in Figure 2, which reveals two submerged channels off the coast of Dar es Salaam. The first channel is the main shipping approach to Dar es Salaam with depths of almost 40 m. Beginning south of Bongoyo, there is a 15 m deep channel that passes west of Bongoyo, running almost parallel to the coastline and passing between Pangavini and Mbudya islands. A shallower channel, with a depth of 10 metres, branches off the main channel to pass between the coastline and Pangavini. Both channels have steep banks on their western sides.

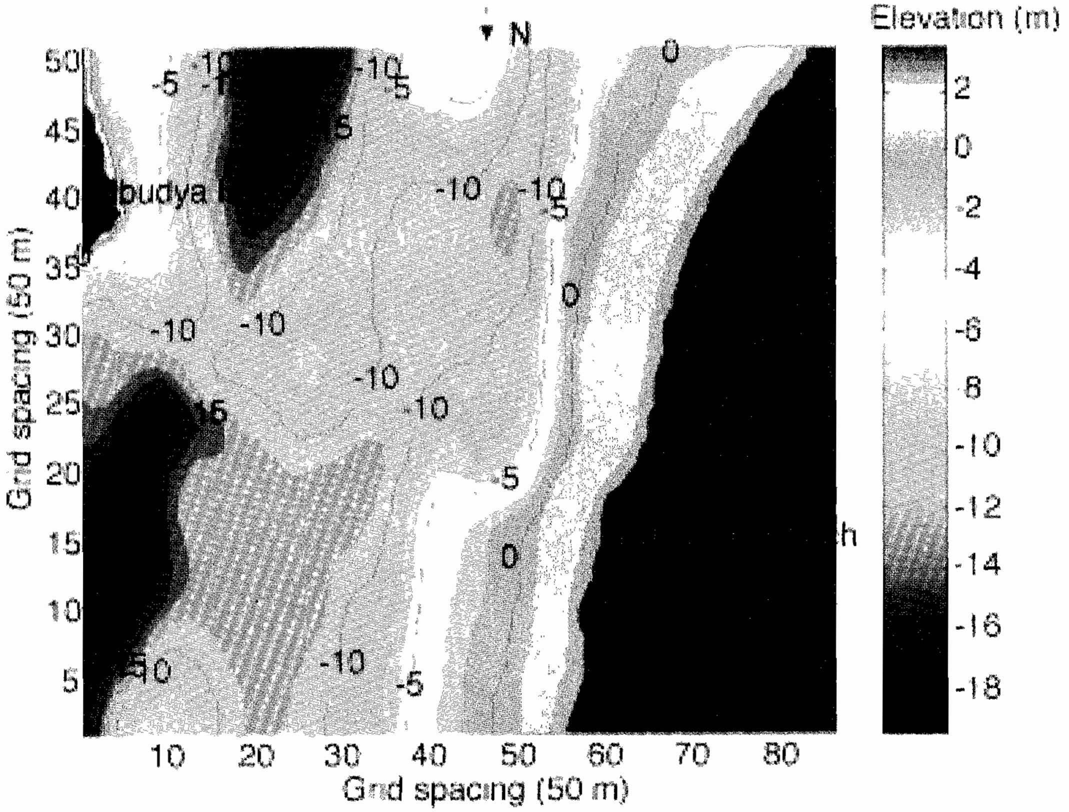


**Fig. 2. Bathymetric features of the study area**

In the submerged channels, the tide enters from direction SE and ebbs from the NW direction. The tidal current is cyclic. The current velocity builds up during flooding until it reverses in ebbing. Then the velocity rebuilds and another cycle starts. Figure 3 shows that at position P3 the maximum current velocity is 0.8 m/s and the average current velocity is 0.56 m/s. The direction holds a steady value of 340 degrees, measured clockwise from the North. In the submerged channels, where water depths exceed 14 m, the maximum current speed reaches 1.5 m/s. The amplitude of the surface elevation exceeds 1.5 m depending on meteorological conditions and the rate of transmission of energy per unit width, as per Equation 21, is 132 kW/m.

Figure 4 shows that in shallow waters, at positions P4 and P5 with depth ranging from 0.5 and 3.0 m, the average current velocity is 0.25 m/s and direction is 37 degrees, measured clockwise from the North. In assessing the tidal ellipse (Equation 6), the semi-major axis, which represents the maximum current velocity, is 0.67 m/s and the semi-minor axis is 0.5 m/s. Figure 5 shows the density spectrum of measured current velocities at position P4. The peak frequencies are found to be 0.094 Hz for u (x-direction current velocities), 0.098 Hz for both v (y-direction) and w (resultant) velocities. The velocity amplitudes are found to be 0.75 m/s for u velocities, 0.96 m/s for v velocities and 0.92 m/s for w current velocity.

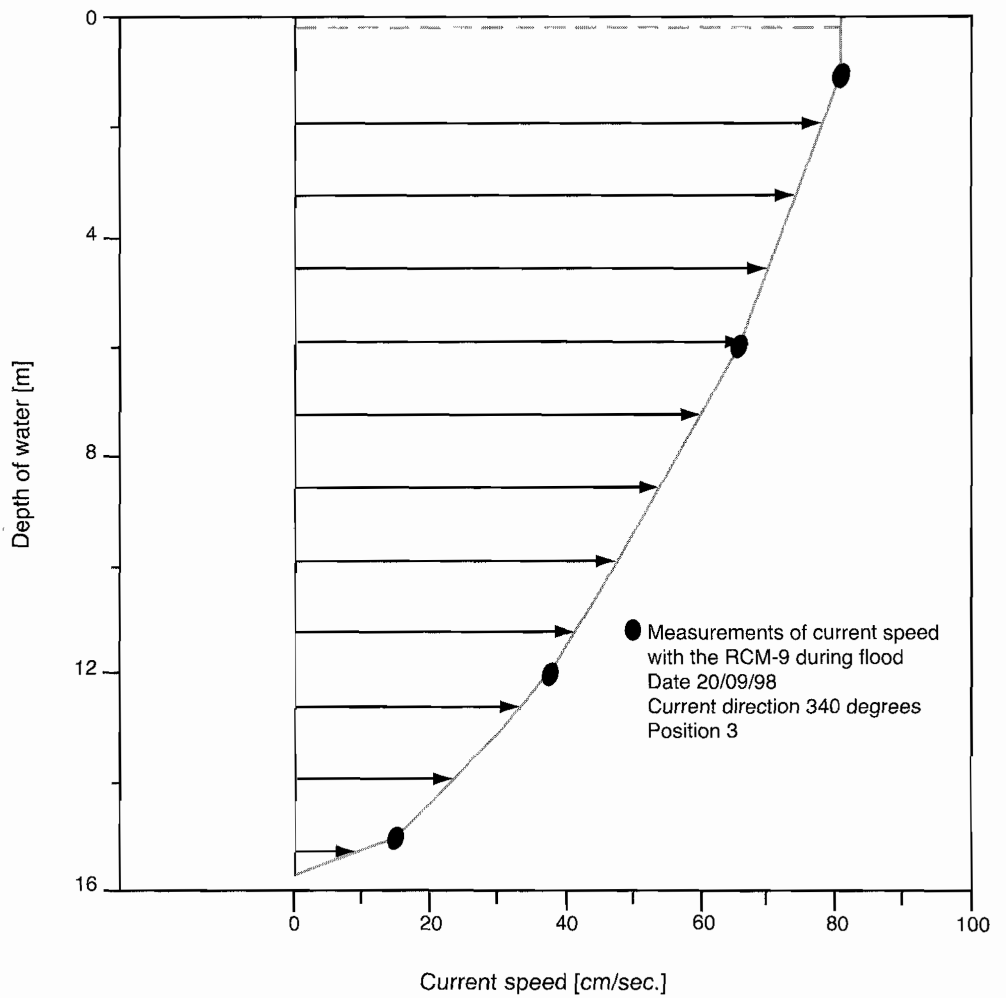


**Fig. 3. A profile of current velocity measured at position P3**

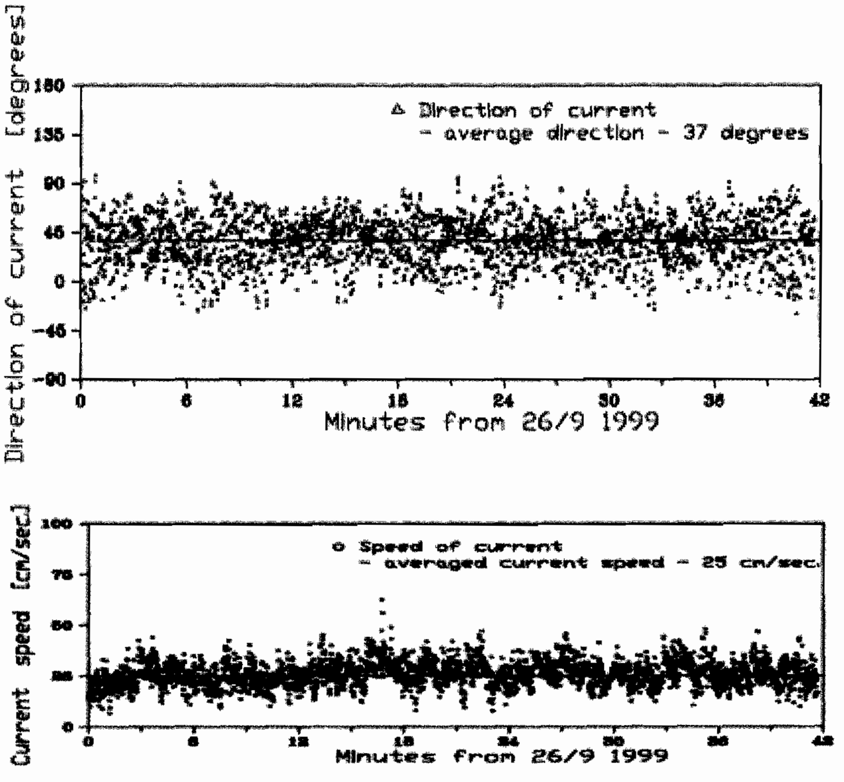


**Fig. 4. Typical current speed and direction at position P4**

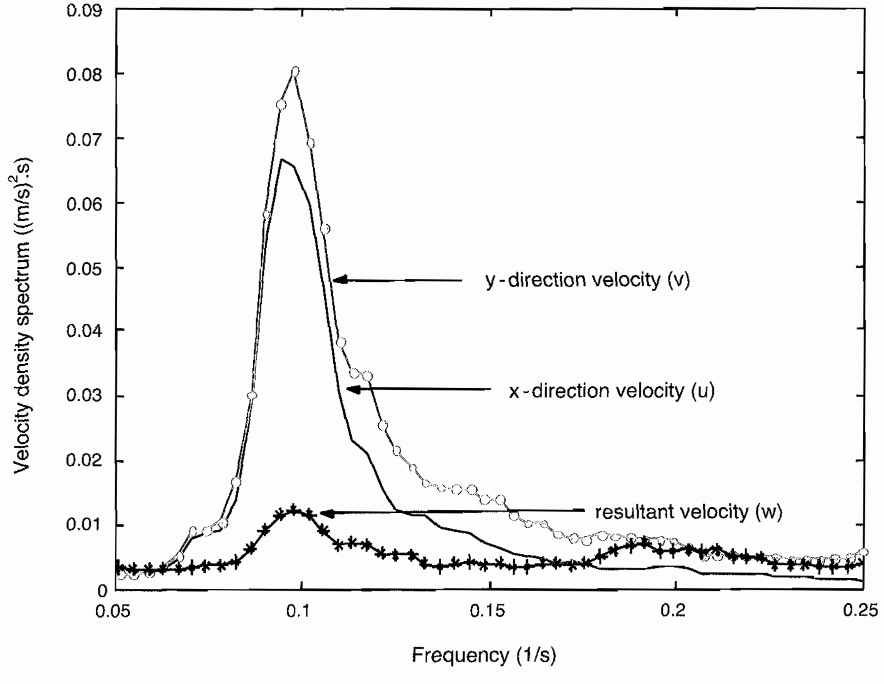


**Fig. 5. Density spectrum of measured current velocities at position 4 with Seapac**

Figures 6 and 7 show spatial distribution of energy flux during flood tide and ebb tide respectively in the SE-monsoon winds. The mass flux reaches 20 m3/s in the deepest parts of the channels and is nearly zero on the tidal flat.

On the tidal plateau, the strength of the current is in the order of 0.10 m/s during the SE monsoon and only half the strength during the NE monsoon.

## CONCLUSION AND RECOMMENDATION

The exploitation of tidal energy normally consists of constructing a dam separating a basin from the rest of the ocean and installing a set of turbines, which will generate the power from the level difference between the two sides. The construction

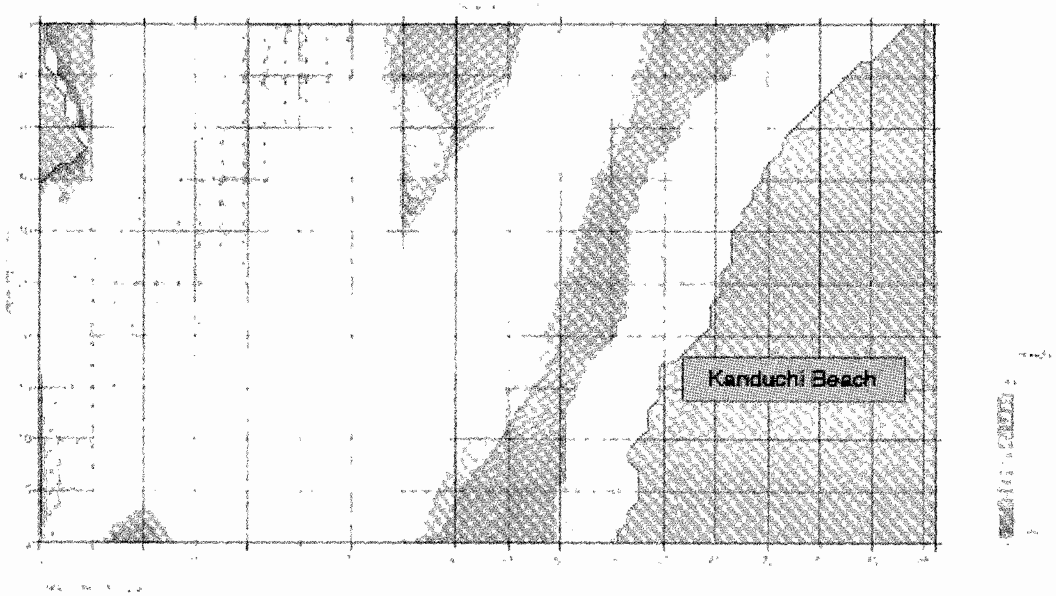


**Fig. 6. Energy flux during flood tide in SE-monsoon**

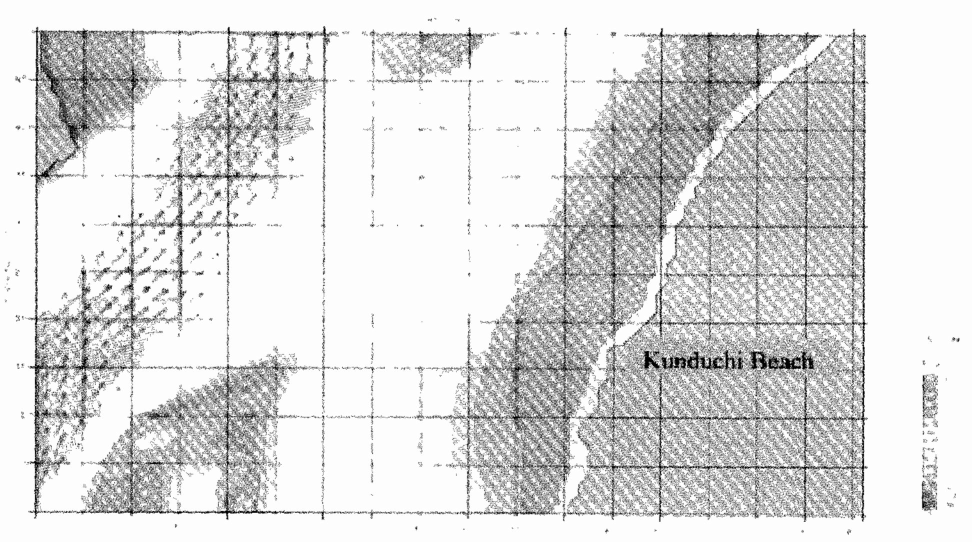


**Fig. 7. Energy flux during ebb tide in SE-monsoon**

of the dam will affect the tidal flow and consequently the local tidal energy budget. This implies that the tidal regime in the area will somehow be modified. It is therefore necessary to evaluate such possible changes before deciding on the construction of a tidal power plant in the area.

The challenges ahead of utilizing the estimated tidal power potential in the area include a comprehensive and accurate velocity measurement in the submerged channels. This is necessitated by the fact that the energy flux is proportional to the stream velocity raised to the third power. Another challenge is to map the energy market in the vicinity of the source, that is, the energy consumption and price. At thus stage, pre-feasibility study on local economics, local products and their costs are crucial to the market study.

As a tidal wave propagates in shallow water, it will lose some of its energy due to bottom friction. It is therefore important to consider such energy losses when evaluating the amount of energy that can be extracted from the tides.

The studied area is a waterway for ferries that ply between Dar es Salaam and Zanzibar and is also sometimes used as fishing ground by the local communities. Therefore, it is also necessary to assess the impact of constructing a power plant on the livelihood of the local communities and the impact on the physical environment.

However, the above observations notwithstanding, the study shows that there is a potential of tidal power in the submerged channels of the Dar es Salaam coastal waters. The author is not aware of a similar study that has been conducted in Tanzania. It is recommended that such a study be replicated in other areas in Tanzania and also in the Western Indian Ocean region.

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