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WATER FLUX AND PHOSPHORUS TRANSPORT IN THE MIXED LAYER OF THE NORTHERN RED SEA AND GULF OF SUEZ

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ABSTRACT

The study presents an attempt to calculate water flux and phosphorus transportation in the upper 50m layer (mixed layer) of the northern Red Sea and Gulf of Suez using data collected during the joint Russian-Egyptian expedition onboard the Russian R/V "*Professor Bogorov*" which took place during March 1990. The hydrographic structure of the study area indicated the existence of an inflow of low salinity (40.10), warm (>22°C) and σ_t <28.3 surface water from the Red Sea into the Gulf of Suez and an outflow of a more saline (>40.40), colder (<22°C) and relatively high density (σ_t >28.3) subsurface water in the opposite direction. This water is forming in the entrance area of the Gulf, sinking as indicated by the down-sloping of the isotherms, isohalines and isopleths and entering the Red Sea as a mid-deep water. The distribution of phosphate in the investigated area showed that all the surface waters are nearly depleted in the phosphate and lie near 0.1 μ mole PO_4-P/l. An apparent first peak lies nearly between 50 and 100m depth. All the stations showed gradual increase of the phosphate with depth till 500m. Phosphorus transported to the area from the west accounts for 316.05 tons/day, while 1.34 tons/day are transported from the east. Phosphorus flux from the south plays the most important role, it reaches 1212.67 tons/day. From Gulf of Aqaba, 2.25 tons/day enters the area. Cumulatively about 1530 tons phosphorus/day enters the upper 50m layer, of which only 117.63 tons/day enters the Gulf of Suez. The rest may be exhausted in plant growth or through sinking to the lower layers. The calculated downward phosphorus transport amounts to 872.79 tons/day.

1. INTRODUCTION

The Red Sea is a narrow body of water, roughly NNW-SSE oriented, about 1930 km long and 270 km wide between 12° N and 28° N. North of 28° N the Northern Red Sea is bounded by the shallow Gulf of Suez to the west and the deep Gulf of Aqaba to the east.

The Red Sea is a fascinating part of the world's oceans in view of its unique physical and biogeochemical processes. These include the role of convective and subductive water mass formation in maintaining meridional thermohaline overturning, air-sea interactions leading to formation events, interactions with adjacent semi-enclosed basins, and the significance of small-scale mixing (Eshel and Naik, 1997). Other remarkable features of the Red Sea are that it has: 1) the highest surface salinities of the World Ocean caused by intense evaporation rate, and 2) atomic ratios between carbon, nitrogen, and phosphorus in the phytoplankton that differ strongly from the oceanic averages (C:N:P=188:21:1 in the

Red Sea against the Redfield ratios C:N:P=106:16:1) (Naqvi *et al*., 1986).

Morcos (1970) stated that, the problem of nutrient budget is vague in the Red Sea where no river inputs occur. He added that the most obvious agent in the nutrient budget supply is the intermittent inflow from the intermediate layer from the Gulf of Aden, which has a relatively higher content of nutrient salts. The Red Sea is characterized by prevailing low levels of nutrients and a relative deficiency in phosphate as compared to nitrate (Naqvi et al, 1986). Due to the latter condition, more nitrate relative to phosphate appears to escape the Red Sea with the outflowing high-salinity water than the quantity added by the inflowing current. Assuming that the conservation of phosphate is maintained by increased inputs from the Gulf of Aden in late summer, the excess flux of nitrate out of the sea is estimated as 0.74 x 10^6 tons of nitrogen per year The phytoplankton biomass and primary production in the southern Red Sea are markedly higher than in its northern part, where nutrient concentrations are lower as compared with the southern part of the sea. Fahmy (2003) concluded from the high N/P ratio in the Egyptian Red Sea coastal waters that the PO_4-P is the limiting factor for phytoplankton growth in the Red Sea coastal waters.

As evidenced by the foregoing, many features of the general circulation, nutrient budgets and biological productivity in the Red Sea are poorly understood. Accordingly, the aim of the present work is to present an attempt to calculate water flux and phosphorus transportation in the upper 50 m layer (mixed layer) of the northern Red Sea and Gulf of Suez, the water mass of which has different characteristics from that below.

2. MATERIALS AND METHODS

The data used in this study were collected during the joint Russian-Egyptian expedition onboard the Russian R/V "*Professor Bogorov*", which took place during March 1990. Fig.1 shows the study area and the locations of the hydrographic stations covered by the expedition. During the cruise water temperature, salinity and dissolved inorganic phosphate were observed from surface to bottom at each station. Dissolved inorganic phosphate was determined by the molybdate blue method according to Koroleff (1976).

Also the standard meteorological parameters such as; wind speed and direction, atmospheric pressure and air temperature were taken onboard every four hours using an automatic weather station.

3. RESULTS AND DISCUSSION

3.1. Water circulation in the study area

The circulation pattern in the Red Sea as outlined by Morcos (1970) is as follows: the inflowing water from the Gulf of Aden in the south, after passing the Strait of Bab el-Mandab, is deflected towards the eastern coast. This less dense water occupies the upper stratum, which as it penetrates to the north, undergoes a gradual increase of salinity and decrease of temperature. Arriving at the northern end of the Red Sea, it sends a branch in the Gulf of Aqaba, turns to the west, and sends another branch to the Gulf of Suez, but its main mass reaches the African coast where, becoming more saline through the influence of the Gulf of Suez, it sets southwards along this coast. The controlling factors in driving the circulation of the upper layer in the longitudinal direction along the main axis of the sea is the wind stress. While, in the transverse direction, the hydrostatic pressure gradient resulting from the water mass distribution is the most influential factor.

The horizontal circulation of the Red Sea appears to consist of a number of gyres distributed along the length of the sea, of which some may be semi-permanent (Quadfasel and Baudner, 1993). There is little detailed information on this circulation, as most studies have tended to treat the Red Sea as a two-dimensional basin.

Eshel and Naik (1997) studied the dynamics of winter intermediate water formation and the general circulation of the Red Sea using climatological data. The results obtained from their numerical model indicated that near the Strait of Bab El-Mandab, the inflow from the Gulf of Aden forms an intense, short western boundary current. Near 18°N another western boundary current originates, extending through 25°N. North of 22°N a third boundary current flows to the northwest along the eastern coast of the Red Sea proper, all the way to the north end of the basin. At the northern boundary, the eastern current follows the geometry, eventually turning back to the south at the western coast near 26°N.

3.2. Physical-Chemical characteristics

The horizontal distribution of water temperature at the sea surface of the study area (Fig.2) indicates the existence of inflowing warm water of temperature more than 22°C from the Red Sea proper to the Gulf of Suez. The temperature decreases northward to reach 17°C at the northern part of the Gulf. In the meantime, the salinity increases from 40.10-40.20 in the northern Red Sea to reach its maximum values (42.20) in the Gulf of Suez (Fig.2). This increase in salinity of the Gulf waters is due to the high evaporation which takes place particularly in the northern extremity of the Gulf of Suez (Morcos, 1970).

The surface density (σ_t) values varied between 27.9 and 28.2 in the northern Red sea. It increases northward in the Gulf of Suez to reach its maximum values (>31.0) in the northern part of the Gulf. This increase in density is due to the high salinity and low temperature of the Gulf waters. The surface distribution of phosphate (Fig.2) indicated that, the southern part of the study area had lower dissolved inorganic phosphorous than the other locations. The western part has higher concentration than the northern or the southern parts. This suggested the existence of some discharge of effluents originating from certain land-based activities in the neighboring coastal area to the surface waters.

Vertical profiles of temperature, salinity and σ_t at some stations are presented in Fig.3. The vertical distribution of water temperature in the upper layer down to about 200 m depth shows a great uniformity in temperature. Below that depth, the water temperature decreases with increasing depth to reach 21.60°C at 500 m depth. Salinity and σ_t values at these stations show also great variations in the upper 200 m layer. Below this layer, the salinity and σ_t increase with depth to reach 40.46 and 28.5 σ_t at 500 m depth respectively. Vertically, the distribution of phosphate in the investigated area showed that all the surface waters are nearly depleted in the phosphate the values of which lie near 0.1 μ mole PO_4-P/l. Apparent first peaks lie nearly between 50 and 100 m depth. All the stations showed gradual increase of the phosphate with depth till 500 m.

The hydrographic structure along the axis of the study area (Fig.4), indicates the existence of an inflow of low salinity (40.10), warm (>22°C) and σ_t <28.3 surface water from the Red Sea into the Gulf of Suez and an outflow of a more saline (>40.40), colder (<22°C) and relatively high density (σ_t >28.3) subsurface water in the opposite direction. This water is forming at the entrance area of the Gulf, sinking as indicated by the down-sloping of the isotherms, isohalines and isopleths and entering the Red Sea as a mid-deep water. This area may be one of the sources of formation of the mid-depth Red Sea waters. This new features was not found previously in the scientific literatures. Said & Averkiev (2004) found that this area is characterized by abnormally high loss of heat (98.90 Wm^{-2}) from the surface which amount to about 10 times more than its surroundings.

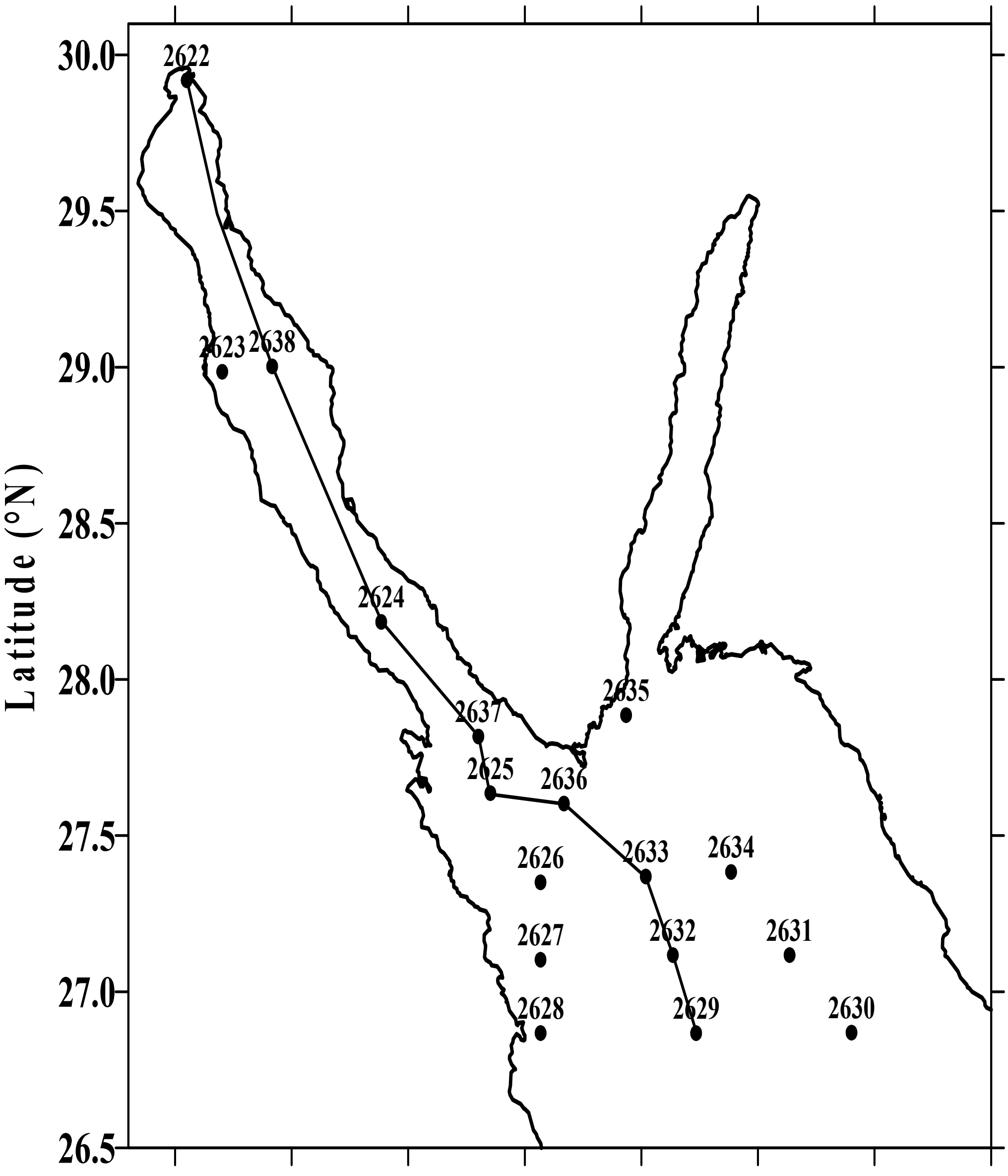

Fig. (1): Area of investigation and locations of the sampling stations

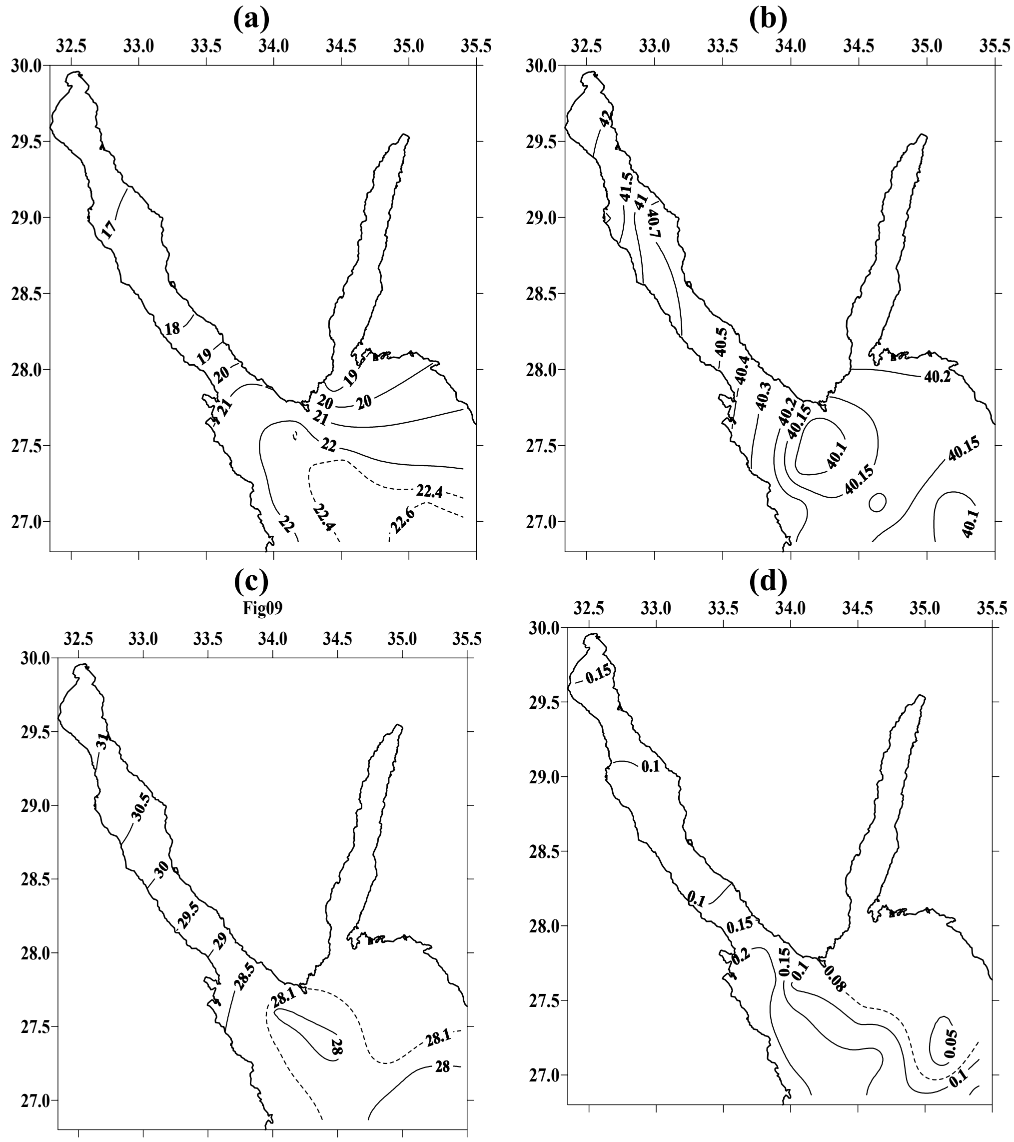

Fig. (2): Horizontal distribution of (a) temperature, (b) salinity, (c) density and (d) phosphorus at surface of the study area.

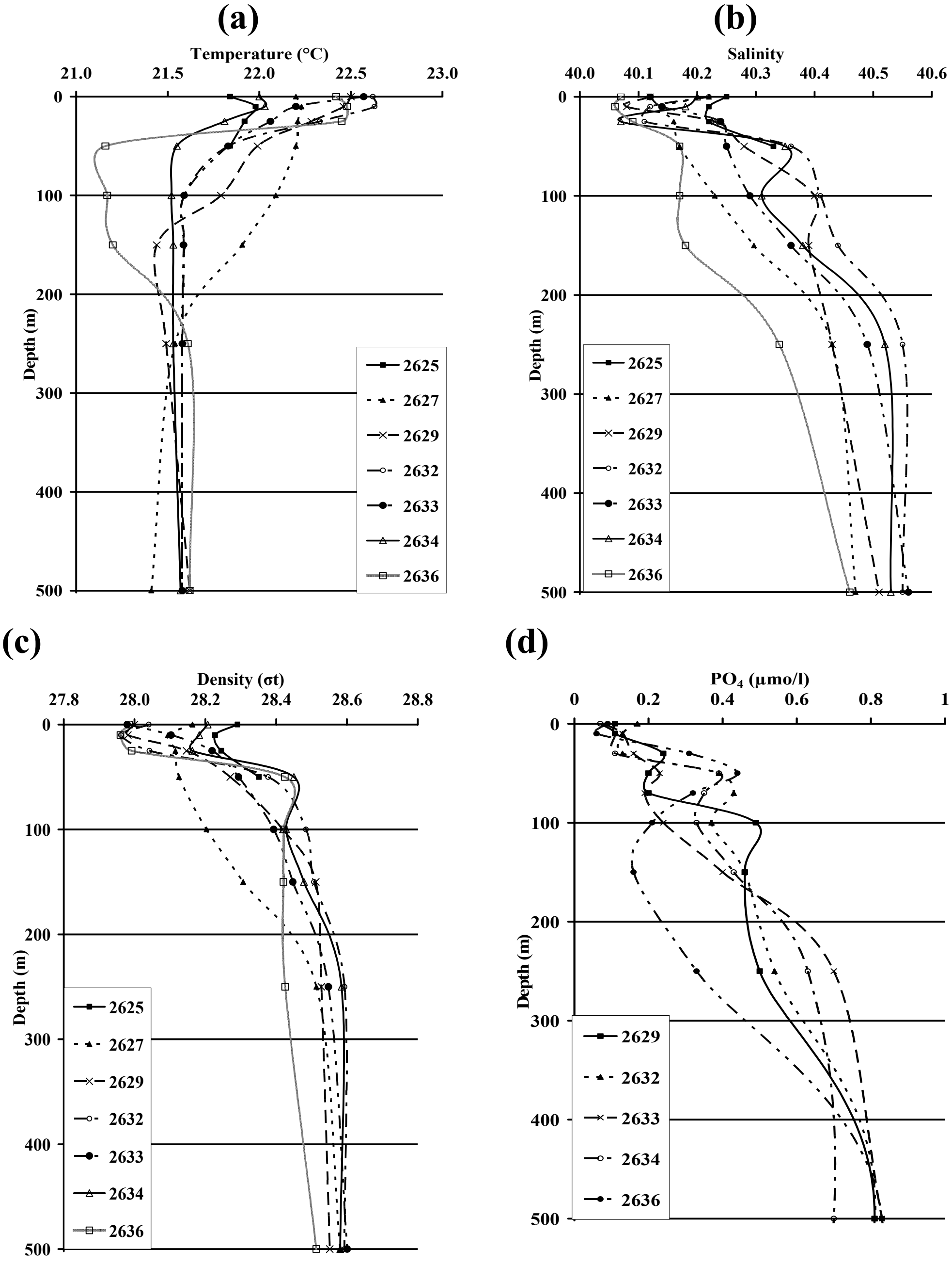

Fig. (3): Vertical Profiles of (a) temperature, (b) salinity, (c) density and (d) phosphorus at some stations in the study area.

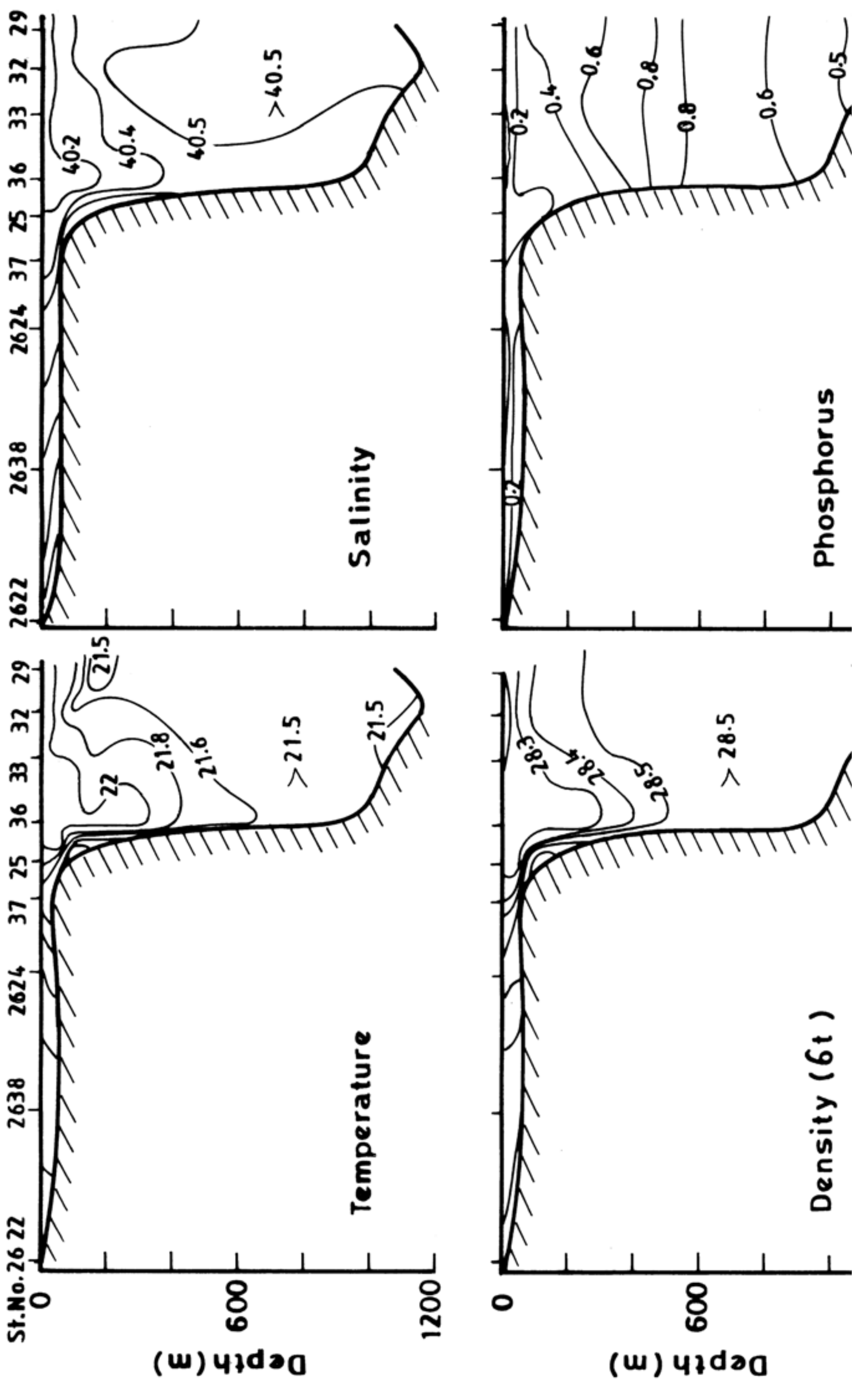

Fig. 4. Vertical structure of temperature, salinity, density and phosphorus along the main axis of the study area

3.3. Volume flux and transport in the upper 50m layer:

The density convection is clearly observed and the thickness of the mixed layer changes from station to another. It reaches about 50 m at most of the stations and increases to more than 100 m at some stations. In calculating the thickness of the Ekman layer using Ekman formula, we found that, at a wind velocity of 10 m/sec the thickness of the Ekman layer was 57 m. Consequently, the thickness of 50m is considered in the present work as an average depth of the upper mixed layer formed by wind stress.

Based on the wind stress components, zonal and meridional components of the Ekman fluxes are calculated for the upper 50 m layer. The formulas used in the calculations are:

$$U_e = \tau_y / \rho f \qquad V_e = -\tau_x / \rho f$$

where f is the Coriolis parameter, τ_x and τ_y are the zonal and meridional components of the wind stress. The surface wind stress was computed for each wind speed value observed during the present study using the bulk formula:

$$\tau_x = \rho_a C_D V_x V \qquad \tau_y = \rho_a C_D V_y V$$

Where V_x and V_y are the components of the wind, V the wind speed, ρ is the water density; ρ_a the air density (1.2 kgm^{-3}), and C_D the drag coefficient derived from Garratt (1977) is as follows:

$$C_D = (0.75 + 0.067V) \times 10^{-3}$$

The drag coefficient in the above bulk formulae depends upon wind speed and is the same as that used in the stress calculations over the world oceans by Hellerman and Rosentien (1983).

During the period of investigation, NW winds were prevailed over the study area with a velocity range of 3-17 m/sec. The calculated wind stress components indicated that the eastward wind stress is dominating. The high energy area was observed around 27^o 45' N and 33^o 45' E, where the highest values of wind stress were observed. For the meridional stress, the north component of wind stress dominated for the whole study area except for the northern part of the Gulf, where the south component has apparently dominated.

Fig.5, shows the Ekman water fluxes and volume transports through the boundaries of the study area during the period of investigation. The magnitude of the eastward transport through the Gulf of Suez is estimated at 2.0 S_V (S_V=10^6 m^3/sec), is larger than those through the northern Red Sea (0.59 S_V). The estimated water transport through the southern boundary of the study area is 1.47 S_V, of which 0.24 S_V occurs through the Gulf of Suez. The evaporation rate in the Red Sea is about 2m per year (Morcos, 1970), corresponding to the volume transport of about 0.001 S_V. Notably, the application of the volume conservation, during the winter season, to the northern Red Sea requires a large downward transport reaching about 1.822 S_V. This conclusion confirms the finding of Said (1998) that the area centered near 27°30'N and 34°10`E is a source of formation of the deep Red Sea waters enhanced by winter convection and high density of water.

Phosphorus transported to the area from the west accounts to 316.05 tons/day, while 1.34 tons/day are transported from the east. Phosphorus flux from the south plays the most important role, reaching 1212.67 tons/day. From Gulf of Aqaba 2.25 tons/day enters the area. Cumulatively about 1530 tons phosphorus/day enters the upper 50 m layer, of which only 117.63 tons/day enters the Gulf of Suez. The rest may be exhausted in the processes associated with plant growth or through sinking to the lower layers. The calculated downward phosphorus transport amounts to 872.79 tons/day.

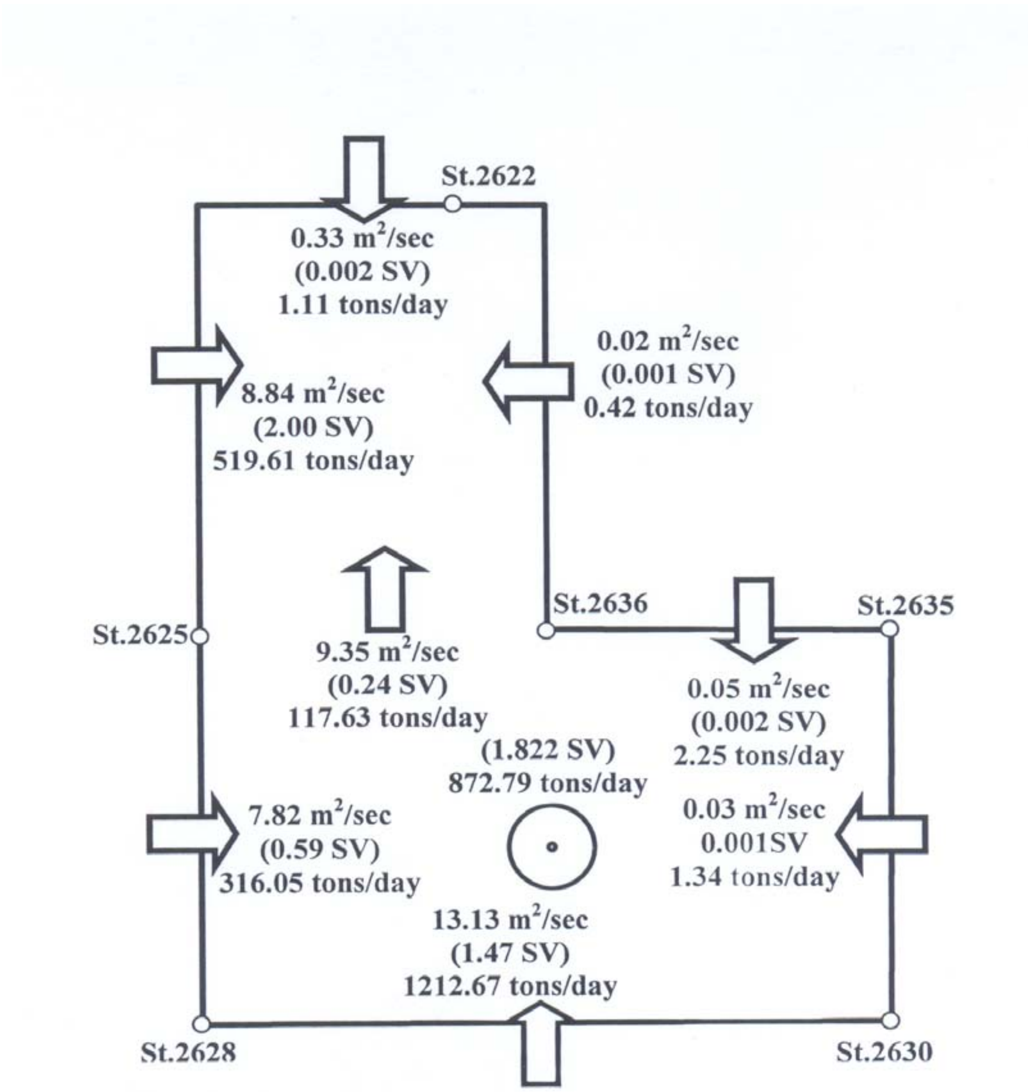

Fig. (5): Water fluxes and volume transports through zonal and meridional boundaries of the study area

4. CONCLUSIONS

The current pattern in the study area was such that surface waters from the northern Red Sea entered the Gulf of Suez is compensated by an opposite flux of deep waters, resembling the overall pattern throughout most of the year. This pattern is similar to that observed and discussed for the Gulf of Aqaba by Manasrah *et al*., 2004.

The sinking of water at the Gulf of Suez entrance is a logic phenomenon because most of the water transported northward in the Red Sea proper can not enter the Gulf. This means that, an expected turnover of water occurs at the entrance of the Gulf. Also the Gulf water will stay longer within the Gulf and the main anthropogenic activity in the Gulf of Suez, especially at the northwestern part, would lead to a permanent enrichment in phosphorus and higher phosphate concentration in the Gulf, more than in the surface waters of the proper northern Red Sea.

Hase *et al* (2006) supports the concept that phosphate is the ultimate limiting nutrient for primary production, which should not be neglected in the efforts that are undertaken for protecting the marine systems against eutrophication. In the Gulf of Aqaba, the industrial mining and subsequent shipping of phosphate obviously lead to episodic phosphorus enrichment of surface waters (Klinker *et al*., 1978), which on the long term might represent a threat to the adjacent coral reef communities in the area.

Due to the lack of data about the volume transport to the area the surface transport (50 m) layer was calculated. While the counter current due to the exchange was not calculated. As the concentration of dissolved inorganic phosphorous is increased with depth the counter deeper current may lead to phosphorus loss instead of the apparent gain interpreted by the available data. This lead to open an argument about the phosphorus problem in the Red Sea regarding sources and sinks especially of phosphorus in the Red Sea as a whole.

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