CONSIDERATIONS ON THE BLACK SEA SALINITY PALAEO-BUDGET DURING THE LATE PLEISTOCENE

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Abstract. The present study attempts to estimate the time of infilling of the Black Sea with Mediterranean water during the Late Pleistocene, using a hydraulic evaluation of saline water inflow through the Bosporus strait. This approach differs from previous research on the palaeo-hydrologic evolution of the Black Sea, research mainly confined to the salinity and water volume conservation. The author analyses two instances when the Black Sea level was low. For these two instances, the time necessary for filling of the Black Sea with Mediterranean water and the changes of salinity and of water-level compared to the Marmara Sea level are computed. The computation takes into consideration the present-day morphometry of the Black Sea and of the Bosporus strait, as well as similar to present-day climatic conditions (fresh water river discharge, precipitations and evaporations). The proposed model simulates the Black Sea infilling process and the changes of the average salinity. According to this model, the present sea-level and water salinity have been reached in thousands of years.

Key words: water palaeo-budget, water level, salinity, strait, sill

1. GENERAL SETTING

1.1. The morphometry of the Bosporus strait

For computing the time of the Black Sea infilling with Mediterranean water from the moment when the water in the Black Sea was fresh/brackish and its level was lower than the Bosporus sill until reaching the present-day salinity and level, the following simplified morphology data have been used (Fig.1):

- The reference level *Zm0* is the Marmara Sea level at the beginning of Mediterranean water inflow;
- The length of the strait $L = 30$km;
- The average depth of the strait $h \approx 45$m;
- The average depth of the strait at the Sea of Marmara mouth $hm \approx 30$m;
- The average depth at the Black Sea mouth $hn \approx 40$m;
- The difference between the average marks at the Sea of Marmara mouth and at the Black Sea mouth $dhf = 10$m;
- The average width of the strait, $B \approx 1300$m;
- The width of the strait at the Marmara mouth, $Bm \approx 950$m;
- The width of the strait at the Black Sea mouth, $Bn \approx 1680$m;
- The average slope of the strait bottom $pf \approx 33.3$ cm/km, dipping towards the Black Sea;
- The average area of the cross-section of the strait $F \approx 59{,}000$ m^2;
- The area of the cross-section at the Marmara mouth, $Fm \approx 39{,}000$ m^2;
- The area of the cross-section at the Black Sea mouth, $Fn \approx 80{,}000$ m^2.

1.2. The morphometry of the Black Sea

The computation of the area and volume of the Black Sea between the level of -200m and the Sea of Marmara level was performed using the following empirical functions:

- Water surface area

$$A = 423000 + (1343 + 3.15 \times Z) \times Z \qquad (1)$$

where A is the area (in km^2) at the level Z (in m) of the water free surface;

- Water volume

$$W = 538124 + (236.9 - 0.644 \times Z) \times Z \qquad (2)$$

where W is the volume (in km^3) at the level Z (in m) of the water free surface.

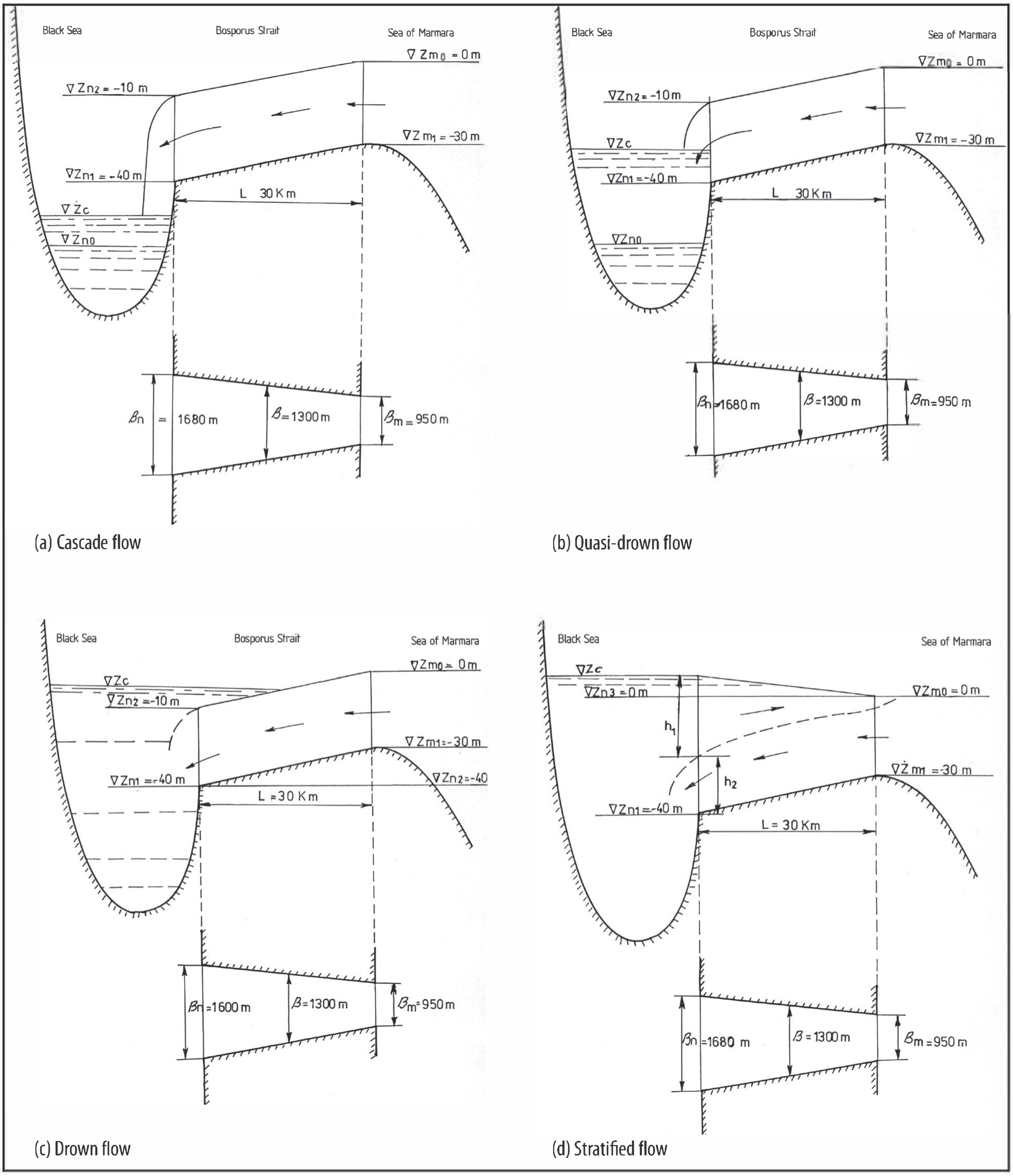

Fig. 1 Phases of the Mediterranean water inflow through the Bosporus during the filling up of the Black Sea

1.3. The Black Sea water budget components

The components considered in the computation were:

- Average yearly freshwater river discharge,

$$WR = 353\ \text{km}^3 \times \text{yr}^{1} \quad (3)$$

- Average yearly freshwater input from precipitations,

$$WP = 3.8533 \times 10^{-4} \times A \quad (4)$$

- Average loss of water due to evaporation,

$$WE = 7.9333 \times 10^{-4} \times A \quad (5)$$

- Water budget:

$$WBH = WR + WP - WE = 352 - 4.08 \times 10^{-4} \times A \quad (6)$$

where A is the area in km²

The present-day water budget of the Black Sea is evaluated at about 180 km^3 and it corresponds to an average value of exceeding water discharge of about 5700 $m^3.s^{-1}$

2. FINITE DIFFERENCES EQUATIONS USED

The computing of the Black Sea filling up process with consequent changes of water level and salinity was performed using the following finite differential equations:

2.1. Differential equations for water budget

$$A \times dZ = 1000 \times (Q + WBH) \times dt \tag{7}$$

$$Q = f(Z) \tag{8}$$

$$dZ = 1000 \times \frac{(Q + WBH)}{A} \times dt \tag{9}$$

where,

Z, is the water level in the Black Sea, in meters;
Zm, the water level in the Marmara Sea, considered at 0 m;
Q, the water inflow from the Marmara to the Black Sea and vice-versa, in $km^3.yr^{-1}$, a function depending of the level Z;
B, the average width of the Bosporus strait, of about 1300 m;
h, the average depth of the Bosporus strait, of about 45 m
dZ (in m) and dt (in yr), finite differences of water level in the Black Sea and of time, respectively.

2.2. Salinity budget differential equation

The salinity budget differential equation is expressed as follows:

$$W \times dS = Q \times Sm \times dt \tag{10}$$

$$dS = Q \times Sm \times \frac{dt}{W} \tag{11}$$

where,

Q is the Mediterranean water discharge through the strait,
W is the Black Sea water volume (in km^3) at a level Z (in m), from the equation (2),
Sm, the salinity of the Marmara Sea, of about 34 ‰,
dS, the increase of salinity in the Black Sea in the time interval dt, expressed in ‰.

The equation (11) allows to compute the change of the Black Sea water average salinity caused by the inflow of the Mediterranean water.

3. THE MATHEMATICAL MODEL OF THE BLACK SEA PALAEO-HYDROLOGICAL EVOLUTION

The model is based on the software called "Pontus.bas", which is designed using the following algorithm.

3.1. The filling of the Black Sea, the water exchange through the Bosporus strait and the salinisation of the Pontic water

The analysis of phenomena showed that one can distinguish four phases of the Black Sea infilling generating different hydraulic conditions of flow through the strait. To determine the water average velocity of the flow under these different conditions, the global equations of hydrodynamic equilibrium of the water movement were used.

Phase 1, when the water level in the Black Sea was below the average level of the bottom of the Bosporus strait at the Black Sea mouth. The strait is considered as a natural channel of known slope. In these conditions, the flow is uniform along the strait. This hydraulic situation is maintained until the rising level of the Black Sea reaches the level of the strait sill at the Black Sea embouchure.

Considering the average morphometric characteristics of the channel and the hydrodynamic equilibrium equation of water movement within the strait, the function expressing the average flow velocity along the strait is:

$$v = \left[2 \times \frac{g}{f} \times \frac{\left(\frac{hm^2}{2} + hm \times hpf\right)}{L}\right]^{0.5} \tag{12}$$

where:

g, is the acceleration of gravity;
f, friction coefficient between water and the walls or the bottom of the strait;
hm, the mean depth of the strait;
L, the length of the strait;
hpf, the difference between the level of sills at the Marmara and Black Sea mouths.

Consequently, the water flow from the Marmara to the Black Sea has the following characteristics:

- The mean *hydraulic radius* of the wet cross-section Rm = 42.45 m;
- The average slope of the bottom pf = 33.3 $cm.km^{-1}$;
- The *rugosity coefficient* n = 0.04;
- The *Chezy coefficient* Cm = 46.7;
- The average water velocity in the wet cross-section v_{1m} = 5.554 $m.s^{-1}$;
- The water discharge is Q = 327,686 $m^3.s^{-1}$ that corresponds to an annual water volume of 10,341 km^3;
- *Froude number* corresponding to the average velocity of the flow and mean depth of the strait is about 0.0699 for a uniform water movement in the strait.

Phase 2 represents the phase when the flow through the strait is semi-drown, as the Black Sea level is higher than the Bosporus sill at the Pontic mouth. In these conditions the water flow is slowed down by the counter-pressure of the Black Sea water.

The following function shows the flow velocity along the strait under the new conditions,

$$v = \left[2 \times \frac{g}{f} \times \frac{\left(\frac{hm^2}{2} + \frac{hm}{2} \times hpf - \frac{\gamma_n}{\gamma_m} \times \frac{(z_c - z_{n1})^2}{2}\right)}{L}\right]^{0.5} \tag{13}$$

where,

g, is the acceleration of gravity;

f, friction coefficient between water and the walls or the bottom of the strait;

hm, the mean depth of the strait;

L, the length of the strait;

hpf, the difference between the level of sills at the Marmara and Black Sea mouths;

γ_n, the specific weight of the Black Sea water;

γ_m, the specific weight of the Marmara Sea water;

z_c, the water level in the Black Sea;

z_{n1}, the level of the strait sill at the Black Sea mouth;

b, the average width of the strait.

The function (13) shows that the mean water velocity in the strait decreases with the rise of the Black Sea water level. The decrease of the water velocity in the strait creates the conditions for drowning of the Mediterranean water inflow and for superficial penetration of the Black Sea water into the strait. This hydraulic situation appears when the water level in the Black Sea rises above the upper level of the uniform flow of the Mediterranean water through the strait, at its Pontic mouth.

Phase 3, is the phase of filling when the Mediterranean inflow is drown within the strait and when the Black Sea water level is above the upper level of the uniform flow at the Pontic mouth of the strait. In this phase, the Black Sea level is not higher than the Marmara level: $z_{n2} \leq z_c \leq z_{m0}$.

The penetration of the Black Sea water into the strait is due to the hydrostatic pressure excess when this water is floating on top of the Mediterranean water without entering the Marmara Sea.

At the Pontic entry into the strait, the water depth will be $hn = z_c - z_{n1}$ and the thickness of the Black Sea water layer $z_c - z_{n2}$.

$$v_1 = \frac{2}{3} \times \left(2 \times g \times \frac{d\gamma_{mn}}{\gamma_n} \times (z_c - z_{n1})\right)^{0.5} \times \left(1 + \frac{d\gamma_{mn}}{\gamma_n}\right) \quad (14)$$

The following function expresses the velocity of the Mediterranean water under-current:

$$v_2 = \left\{2 \times \frac{g}{f} \times \frac{\left[\frac{hm^2}{2} + \frac{(z_c - z_{n1} + hm)}{2} \times hpf - \frac{\frac{\gamma_n}{\gamma_m}}{2} \times (z_c - z_{n1})^2\right]}{L}\right\}^{0.5} \quad (15)$$

where the terms have the same significance as in the previous functions.

Phase 4, is the filling phase when the Black Sea water level is higher than the Marmara water level ($z_c > z_{n3} = z_{m0}$) and the flow through the strait is stratified: the Mediterranean water inflow into the Black Sea forms an under-current, while the Black Sea water enters the Marmara Sea as a surface current. The limit condition when the under-current is hindered to enter the strait is expressed by the functions:

$$v_{mn} \Rightarrow \left(\frac{g \times h \times d\gamma_{nm}}{\gamma_m}\right)^{0.5} \quad (16)$$

$$d\gamma_{nm} = \gamma_m - \gamma_n \quad (17)$$

where, γ_m and γ_n are the specific weights of the Marmara and Black Sea water, respectively in kg/m³ ($\gamma_m = 1.0253$ and $\gamma_n = 1.0128$), $\Delta\gamma_{nm}$ is the difference between them and h_m the average depth of the strait at the Marmara entrance ($h_m = 46$m).

Under these conditions, the critical value of the upper Black Sea water current velocity at the Marmara entrance that can block the Mediterranean under-current is of 3.98 $m.s^{-1}$. At this mean velocity the water discharge of the Black Sea water into the Marmara Sea is of 155,298 $m^3.s^{-1}$. At a smaller velocity, and correspondingly discharge, the stratified water circulation through the strait exists and can be expressed by the following functions:

- for the upper current, flowing towards the Marmara Sea, the velocity is v_1, expressed by the function (14);
- for the under-current, flowing towards the Black Sea, the velocity is v_2, expressed by the function (18):

$$v_2 = \left[g \times \frac{(h_2 \times d\gamma_{nm} - 2 \times \gamma_n \times z_c)}{\gamma_m}\right]^{0.5} \quad (18)$$

The expression of the velocity v_2 was computed based on the resultant of the hydrostatic pressure forces within the bottom layer at the Black Sea entrance, where, γ_m and γ_n are, as mentioned above, the specific weights of the Marmara and Black Sea water, respectively in kg/m³ ($\gamma_m = 1.0253$ and $\gamma_n = 1.0128$), while $\Delta\gamma_{nm}$ is the difference between them.

The computation of the time needed for the Black Sea filling up and its water level rising was performed through the numerical integration of the finite differential equations of water budget (9) and of water salinity (11). For this numerical integration the author has proposed a model, the results of which are exposed bellow.

3.2. Results of the proposed model

The proposed model showed that the process of the Black Sea filling with Mediterranean water and the consequent water level rise and increase of water salinity occurred as follows:

The filling of the Black Sea with Mediterranean water was very fast until the stratified water flow through the strait was established (phases 1 - 3). The water level in the Black Sea reached the level of the Sea of Marmara (Fig. 2) and the salinity rose from almost 0 to about 7.2 ‰ (Fig. 3). The time interval that was necessary for these changes is of about 35 years (Fig. 2).

After the water level in the Black Sea exceeded the initial Marmara level, the filling of the Black Sea with Mediterranean water continued but at a much slower rate. The process of reaching the present-day situation took about 2 500 years. In this time interval, the salinity of the Black Sea water increased slowly to the limit of about 19.3 ‰ (Fig.3).

Computations based on a different algorithm are reported in specialised literature (4) and give for the increase of the Black Sea water salinity a much longer time interval, up to 6 000 years.

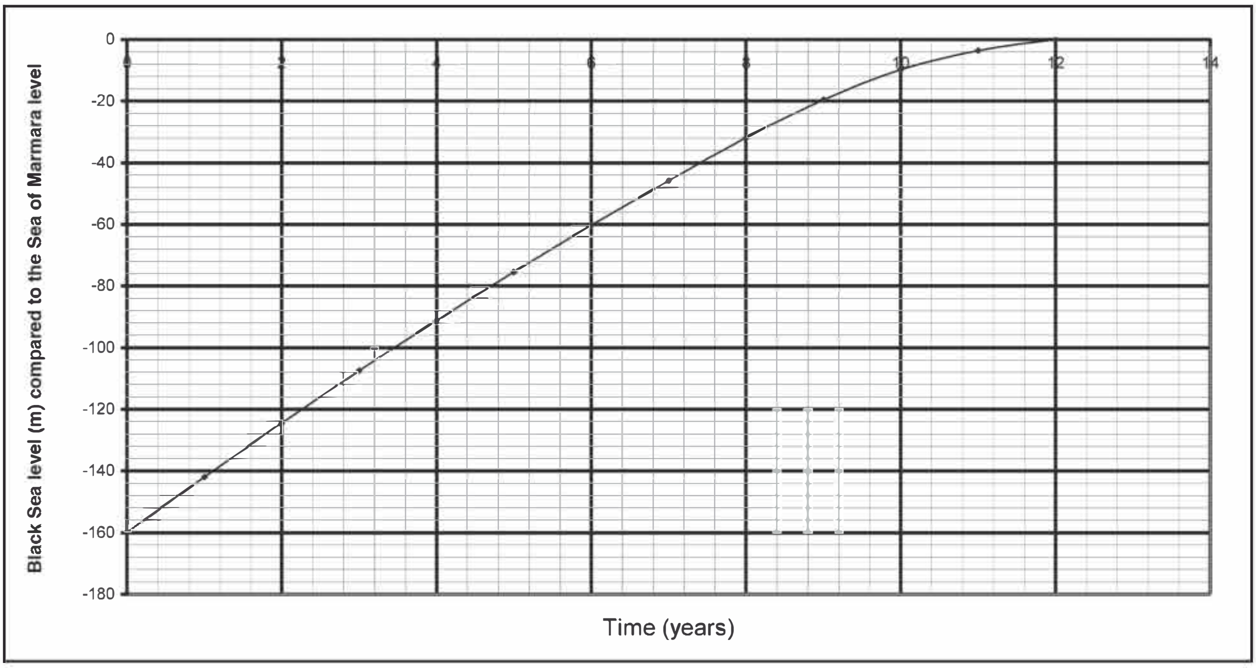

Fig. 2 The rise of the Black Sea water level due to the infilling of the sea with Mediterranean water *versus* time

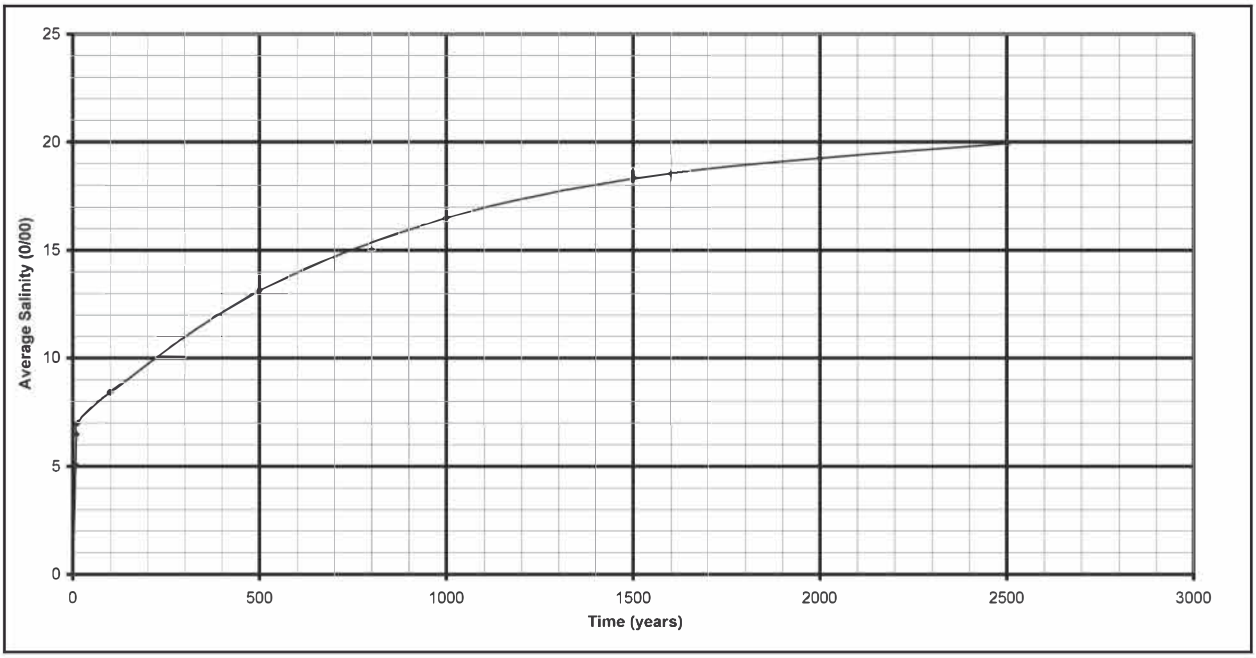

Fig. 3 The change of the Black Sea water salinity due to the infilling of the sea with Mediterranean water *versus* time

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