Available online at www.sciencedirect.com

SCIENCE DIRECT®

Marine Geology 201 (2003) 253–267

MARINE GEOLOGY
INTERNATIONAL JOURNAL OF MARINE GEOLOGY, GEOCHEMISTRY AND GEOPHYSICS

www.elsevier.com/locate/margeo

Hydraulic calculations of postglacial connections between the Mediterranean and the Black Sea

Paul G. Myers [a,*], Chris Wielki [a], Shoshana B. Goldstein [a], Eelco J. Rohling [b,**]

[a] *Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, AB, Canada T6G 2E3*
[b] *School of Ocean and Earth Science, Southampton University, Southampton Oceanography Centre, Waterfront Campus, European Way, Southampton, Hampshire SO14 3ZH, UK*

Received 15 November 2002; accepted 17 July 2003

Abstract

A series of simple hydraulic calculations has been performed to examine some of the questions associated with the reconnection of the Black Sea to the Mediterranean through the Turkish Strait System during the Holocene. Ryan et al.'s catastrophic flood scenario, whereby the erosive power of the marine in-fluxes, initiated after eustatic sea level reached the sill depth, opened up the Bosphorus, allowing saline water to pour into the Black Sea and filling it on a short time scale, is examined. The calculations show that although it *might* be possible to fill the palaeo-Black Sea within the order of a decade, a 1–2 year filling time scale is not physically possible. A hydraulic model is also used to examine the more traditional connection hypothesis of (near-)continuous freshwater outflow from the Black Sea, with a slowly increasing saline inflow from the Mediterranean beginning around 8–9 kyr BP. The model considers two forms for the structure of the Bosphorus: a shallow sill as seen today and a deep sill associated with no sediments filling the 100 m gorge above the bedrock in the strait. Sensitivity experiments with the hydraulic model show what possible strait geometric configurations may lead to the Black Sea reaching its present-day salinity of 18 psu. Salinity transients within the Black Sea are shown as a function of time, providing for values that can be validated against estimates from cores. To consider a deep, non-sediment-filled Bosphorus (100 m deep), the entry of Mediterranean water into the Sea of Marmara after 12.0 kyr BP is examined. A rapid entry of marine water into the Sea of Marmara is only consistent with small freshwater fluxes flowing through the Turkish Strait System, smaller than those of the present day by a factor of at least 4. Such a small freshwater flux would lead to the salinification of the Black Sea being complete by an early date of 10.2–9.6 kyr BP. Thus the possibility of a deep Bosphorus sill should be discounted.

Keywords: Black Sea; Bosphorus; Sea of Marmara; Mediterranean; Palaeoceanography; Hydraulic modelling

1. Introduction

The Black Sea and the Mediterranean are two marginal, nearly enclosed basins connected to each other by the Turkish Straits System (TSS)

* Corresponding author. Fax: +1-780-492-2030.
** Fax: +44-23-80-593059.
E-mail addresses: pmyers@ualberta.ca (P.G. Myers), e.rohling@soc.soton.ac.uk (E.J. Rohling).

0025-3227/03/$ – see front matter © 2003 Elsevier B.V. All rights reserved.
doi:10.1016/S0025-3227(03)00225-1

(Fig. 1a). At the centre of the TSS is the Sea of Marmara, a small body of water about 210 km long and 75 km wide (Cagatay et al., 2000). Connecting the Sea of Marmara to the Aegean (a part of the Mediterranean) is the Dardanelles, a 62 km long strait that varies in width between 1.2 and 7 km (Ergin et al., 1997). The connection between the Sea of Marmara and the Black Sea is the short (31 km long) and narrow (0.5–3.5 km wide) Bosphorus Strait (Oguz et al., 1990). The sill for the Bosphorus, at 35 m, is also much shallower than the 80 ± 5 m of the Dardanelles (Ryan et al., 1997). The flow regime throughout the entire TSS is one of two-layer flow, hydraulically controlled in the narrow, shallow straits (Lane-Serff et al., 1997). Dense, salty Mediterranean water enters from the Aegean and flows at depth through the system to empty into the Black Sea while fresher, lighter Black Sea water outflows through the system into the Aegean. The interface

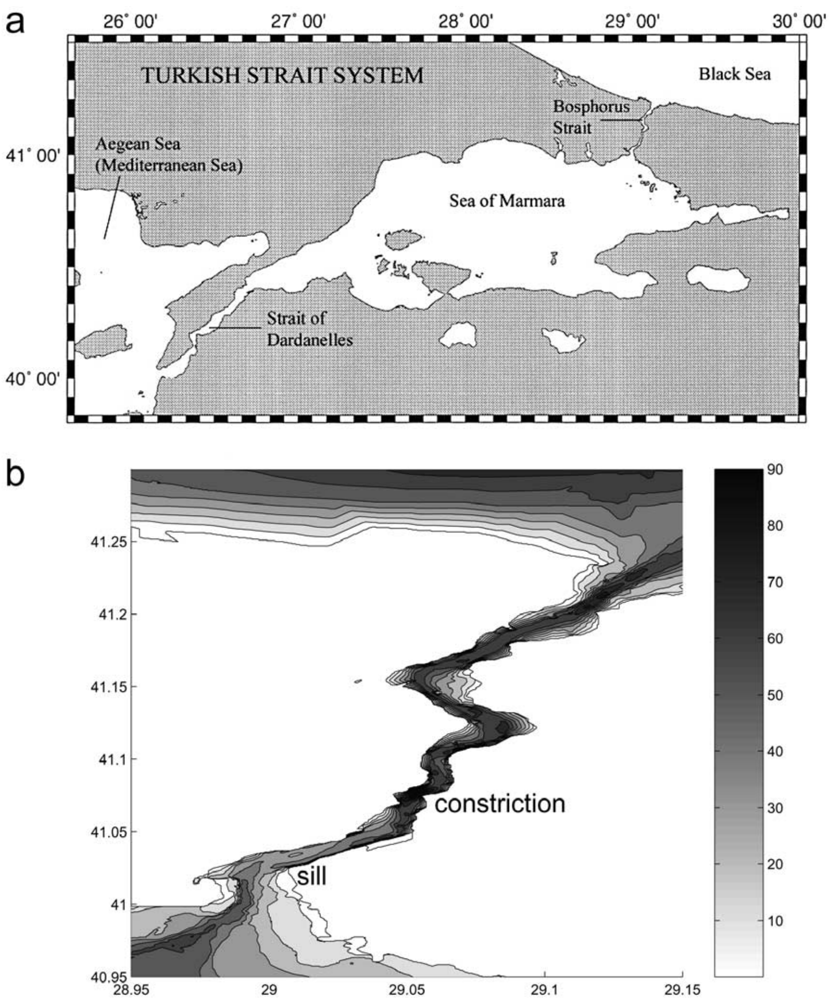

Fig. 1. (a) Map of the Turkish Strait System (TSS). (b) Bathymetric map of the Bosphorus, indicating the position of the sill and the constriction. (c) Cartoon showing the geological constraints associated with the TSS. The present-day sea level is shown, as well as the estimated sea level at two dates in the past (7150 and 12 000 yr BP). Sill depths are shown for the Dardanelles and Bosphorus (based on its present-day configuration as well as the deep-sill model of Major et al., 2002). Note that the water depths in the three basins (Aegean Sea, Sea of Marmara and the Black Sea) are not shown to scale.

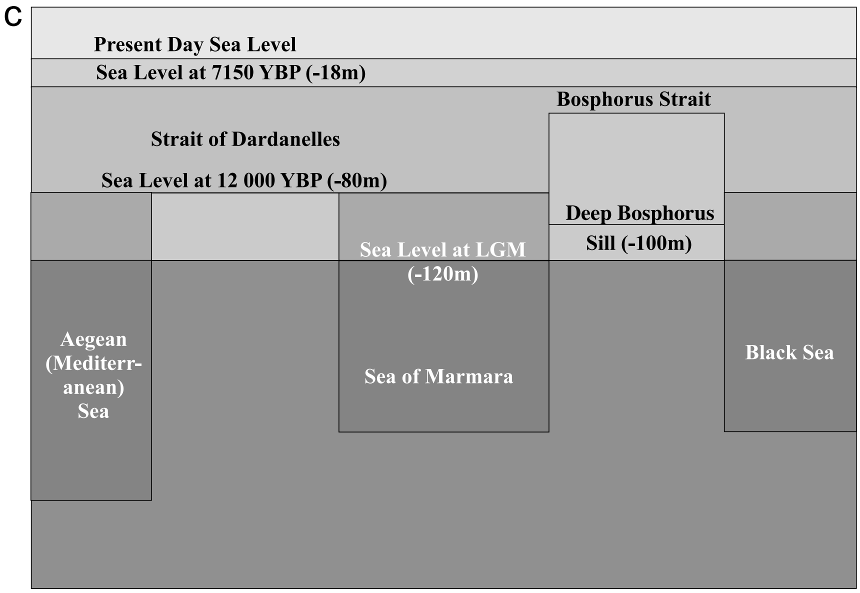

Fig. 1 (*Continued*).

depth between the two water masses varies from 15 to 40 m (Staschuk and Hutter, 2001), and there can be significant mixing of waters between the two layers in the straits (Ozsoy et al., 1994).

During the last glacial maximum, the global sea level was about 120 m below its present level (Fairbanks, 1989), and, as a result, this connection between the Black Sea and the Mediterranean was not present. The segregation of the water masses allowed each basin to develop different water properties. Evidence suggests that both the Sea of Marmara and the Black Sea were freshwater lakes at this time (Emery and Hunt, 1974). With the rise of sea level after the end of glaciation, the global sea level reached the 80 m sill depth of the Dardanelles around 12 000 yr BP (Fairbanks, 1989; see also Lambeck, 1995, for further discussion of local sea-level changes in the Aegean region). At some time after this date, salty Mediterranean water inundated the Sea of Marmara, leading to the formation of a sapropel between 10.6 and 6.4 kyr BP (Cagatay et al., 2000).

There is more uncertainty in the date upon which saline water first entered the Black Sea during the Holocene, leading to its switch from a freshwater ecosystem to its modern brackish state (18 psu). Ryan et al. (1997) showed the presence of Mediterranean water at 7.15 kyr BP using ^{14}C datings on the northern Black Sea shelf. Ballard et al. (2000) revealed the transition took place between 7460 ± 55 and 6820 ± 55 yr BP, based on the last and first datings, respectively, of freshwater and marine mollusks. Recently, Major et al. (2002) postulated a possible early entry of saline water into the Black Sea, as early as 12.8 kyr BP, based on the increase of $\delta^{18}O$ of mollusk shells and the appearance of inorganic calcite with low $\delta^{18}O$ associated with periodic weak stratification.

Traditional thought holds that the level of the freshwater Black 'Lake' was always above the Bosphorus (and hence also the Dardanelles) sill and thus there was freshwater export to the Mediterranean. Evidence for this includes the presence of a sapropel in the Sea of Marmara (Cagatay et al., 2000), studies of shelf sediments in the Black Sea (Gorur et al., 2001), west-directed bedforms in the Sea of Marmara (Aksu et al., 1999) and the analysis of planktonic and benthic foraminifera (Yanko et al., 1999; Kaminski et al., 2002).

Previously, Olausson (1961) had speculated that the discharge of freshwater from the Black Sea played a role in the formation of sapropel S1 in the eastern Mediterranean. Reduced surface water

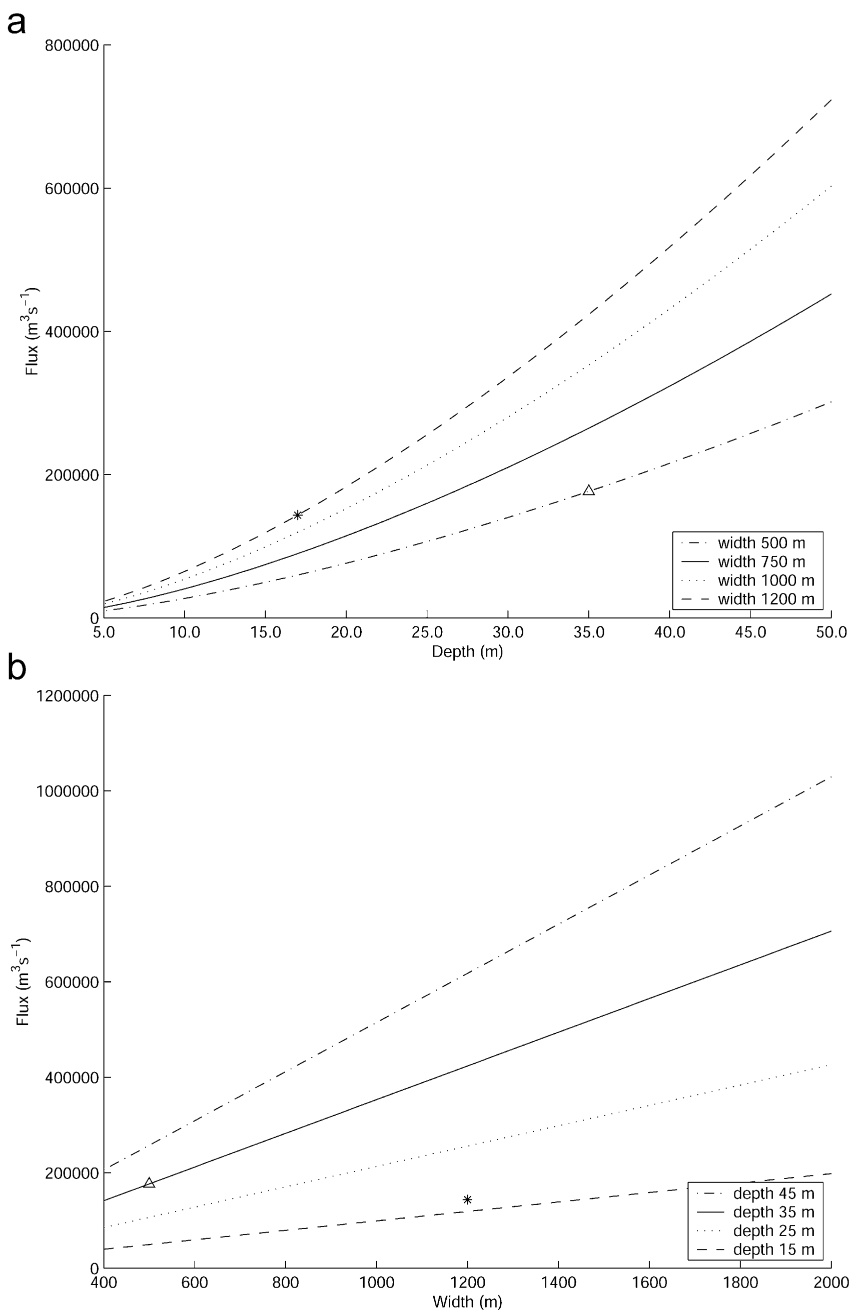

Fig. 2. Plot of the flux through the Bosphorus for (a) specific widths and (b) specific sill depths (at 7.15 kyr BP). The star indicates the estimated configurations of depth and width for the sill and the triangle indicates the same for the narrows.

salinities at the time of eastern Mediterranean sapropel formation, which may in part reflect Black Sea outflow and in part the discharge of excess freshwater by enhanced monsoon floods (Rossignol-Strick, 1985), are widely represented by low oxygen isotope values in surface-dwelling foraminifera (see overviews in Rohling and Gieskes, 1989; Rohling, 1994, 1999). Modelling studies showed the importance of freshwater in capping convection and shutting down ventilation (Myers et al., 1998). Differences in timing between the global sea level reaching the sill of the Bosphorus and the onset of sapropel formation in the Mediterranean and Black Sea were shown to be consistent with calculations based on simple hydraulic arguments for the opening of the Black Sea (Lane-Serff et al., 1997). Not all are in agreement, however, and from a study of palaeo-sea surface temperature and palaeo-sea surface salinity in the Sea of Marmara, Sperling et al. (2003) concluded that the Black Sea was not a major freshwater source contributing to the formation of S1.

Recently, Ryan et al. (1997) proposed, based on evidence that salinification in the Black Sea did not start until 7150 yr BP, that the post-glacial connection between the Mediterranean and the Black Sea occurred as a catastrophic flood of saline water into the Black Sea that rapidly inundated the basin within several years. They then went on to speculate that this might have had a significant effect on the migration of early Neolithic peoples from the region. Ballard et al. (2000) used evidence from a survey of the continental shelf off the north Turkish coast to suggest that the Black Sea could not have had persistent outflow during its isolation. Ryan et al. (2003) refined the hypothesis by considering large amounts of additional data from numerous studies in the Black Sea region. They (Ryan et al., 2003) also discussed how the arid climate present in the region after the Younger Dryas would have supported the evaporative drawdown of the level of the Black Sea to well below the Bosphorus sill, preconditioning the system for the flood hypothesis.

Major et al. (2002) noted that, although the sill of the Bosphorus is presently 35 m deep, the bedrock of the Bosphorus gorge is 100 m below the present sea level, with the majority of the gorge filled in with sediments. Thus, they explored the possibility of a deep Black Sea outlet such that the Black Sea became connected in tandem with the Sea of Marmara. Although Major et al. (2002) discuss reasons why connection over a deep sill is improbable, including the incompatibility with the timing of salinity increase in the Black Sea and the presence of freshwater faunal assemblages on the mid-inner continental shelves of Russia and Ukraine, they do leave open the possibility.

In this paper we will examine the feasibility of some of the suggested connection scenarios for the Black Sea using simple hydraulic theory, expanding on some of the calculations of Lane-Serff et al. (1997). Section 2 will examine the catastrophic flooding scenario of Ryan et al. (1997), while Section 3 will consider additions to the work of Lane-Serff et al. (1997), examining the outflow over a shallow sill, concentrating on the transient salinity signal in the Black Sea. Section 4 examines the possibility of a deep 100 m Bosphorus sill, as recently suggested by Major et al. (2002).

2. Hydraulics of a Black Sea catastrophic flood

At 7.15 kyr BP, global sea level was around 18 m below that of today (Fairbanks, 1989). In the hypothesis of Ryan et al. (1997), the erosive power of the marine influx led to the opening of a dam in the Bosphorus, and the salty Mediterranean water poured into the Black Sea, whose sea level was far below (120 m). Since the time scale for this flooding is long compared to the dynamical adjustment time scale for the strait and yet short compared to the time scale of sea-level rise (i.e. sea level can be considered constant over the course of the flooding), steady hydraulic theory for flow over a weir (e.g. Batchelor, 1967) can be used to study the flux into the Black Sea.

Given that flow over the sill will be uni-directional in this scenario and is hydraulically critical, a relationship between the height of the inflowing Mediterranean water above the sill and volume flux can be obtained:

$$H = 1.5\left(\frac{Q^2}{gW^2}\right)^{1/3} \tag{1}$$

$$Q = \sqrt{\frac{H^3 g W^2}{(1.5)^3}} \tag{2}$$

Here H is the height (depth) of the water above the Bosphorus seabed, Q is the flux of water into

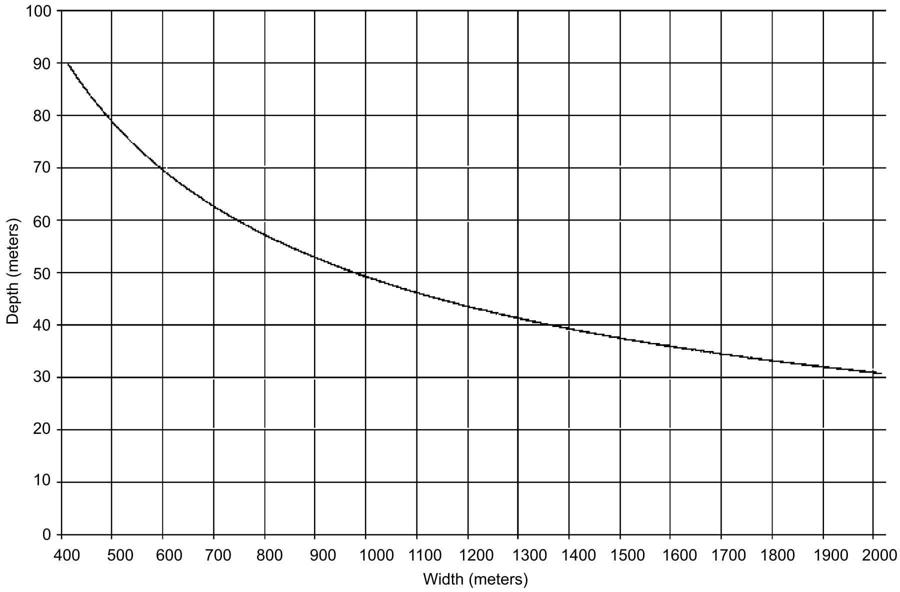

Fig. 3. The Bosphorus dimensions required in order to have a 50 km^3 day^{-1} flux.

the Black Sea, g is the gravitational constant and W is the width of the Bosphorus Strait. The time to fill the Black Sea is purely a function of the influx and the volume difference between the Black Sea pre- and post-flood. Estimates of the present-day Black Sea volume vary from 534 000 km^3 (Ross et al., 1974) to 547 000 km^3 (North Atlantic Treaty Organization (NATO) Committee on the Challenges of Modern Society, 2000), with a surface area of 423 000 km^2. A rapid depth change from −120 to −18 m, associated with the flood, would lead to a maximum volume change of 43 146 km^3. Even if one assumes that 100 m of water will not end up over the entire shelf, and instead assumes an average depth change of 50 m over the 100 000 km^2 of shelf area in the Black Sea, the volume change is still 38 000 km^3. For simplicity, we assume the maximum volume change in the paper.

Fig. 2a shows the maximum flux (in m^3 s^{-1}) as a function of the water depth (i.e. height of the water head above the seafloor) for a number of possible widths. Fig. 2b shows the flux as a function of width for different potential depths (assuming potential uncertainty in the height of the water at the time of a potential flood). These figures show the sensitivity of the system to the different uncertain parameters of strait depth and width. There is assumed to be more uncertainty in the sill depth at this time, and this term is raised to a higher power in Eq. 2. Thus, small changes in the depth of water over the sill will have a greater influence on the flux than an equal change in the strait width would.

What configuration of depth and width is most consistent with the Ryan et al. (1997) hypothesis? Given a present-day sill depth of 35 m and a Holocene (7.15 kyr BP) sea level of −18 m, 17 m of water would be on the sill at the time of the Bosphorus' opening. At present, the strait is 1200 m wide at this point. This width is an overestimate for the opening scenario since the strait would be narrower when the sea level was lower, but we can still use this width to give us an upper bound on the possible flux. The other choke-point for the flux through the strait is the constriction where the strait width is a minimum. And this is not co-located with the sill. At the constriction, the strait narrows to 500 m, with a present-day depth of at least 50 m (Fig. 1b). Thus, the narrows is the location of the minimum cross-sectional area.

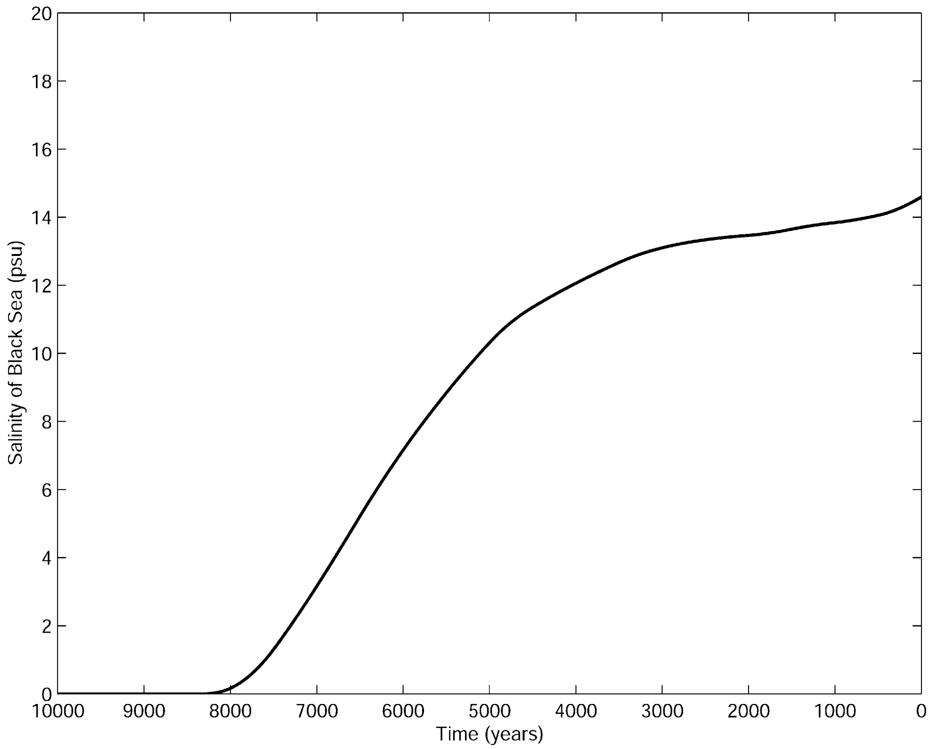

Fig. 4. Black Sea salinity for our base experiment (reproducing Lane-Serff et al., 1997). Note that for this and subsequent figures, dates are given in years BP.

Fig. 2 shows the maximum possible flux through the strait is no more than 175 000 m^3 s^{-1} (15 km^3 day^{-1}). Such a flux could fill a drawn-down Black Sea in around 8 years. Important to note is that the maximum flux is associated with the narrows and not the sill, as is often assumed. Thus, the narrows is the important physical barrier to the influx of water to the Black Sea at high flow rates.

Fig. 3 shows the Bosphorus dimensions required in order to have a flux of 50 km^3 day^{-1}, the minimum flow rate suggested by Ryan et al. (1997) for the catastrophic flood. Given the dimensions of the narrows (or even the sill), the necessary flux cannot be driven through the system. However, as shown from the above calculations, it would still be possible to fill the Black Sea very quickly (especially with respect to geologic, or even anthropologic, time scales), just not within 1–2 years. Additionally, the Ryan et al. (1997) scenario assumes that the cross-sectional area of the strait increases over time due to flow-induced erosion. Since our calculation above for the minimum filling time assumes the maximum cross-sectional area from the start, the actual time needed to fill the basin in this scenario might be much longer than the 8 years calculated above.

3. Black Sea outflow with a shallow sill

Lane-Serff et al. (1997) calculated the exchange between the Mediterranean and Black Sea, assuming a sill depth of 40 or 60 m and a net freshwater export from the Black Sea (precipitation+runoff −evaporation) varying between zero and 20 000 m^3 s^{-1}. They examined the decay of the Black Sea freshwater reservoir, but did not explicitly report on the salinity within the Black Sea, other than mentioning that when they ran their simulation to the present day with complete mixing in the Black Sea, their Black Sea salinity only reached 14 psu,

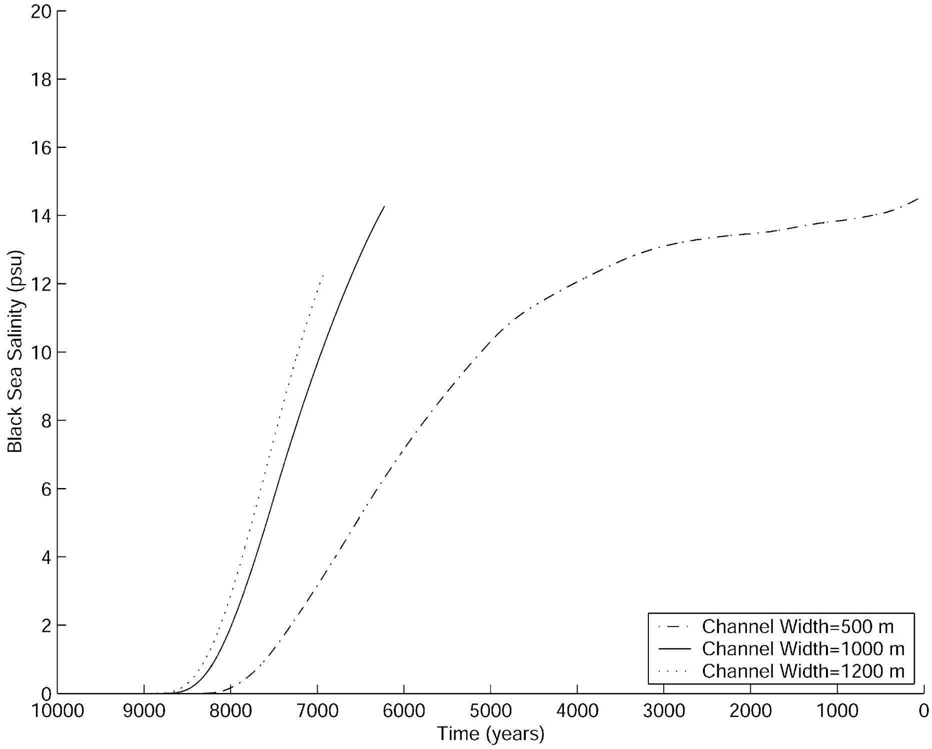

Fig. 5. Sensitivity of the Black Sea salinity to changes in Bosphorus width.

below the 18 psu observed today. Using the same hydraulic calculations as Lane-Serff et al. (1997), and assuming the same strait conditions (40 m deep sill, the sea-level increase curve of Fairbanks, 1989, $Q_o = 10\,000$ m^3 s^{-1}, a channel width of 500 m), we can reproduce their calculations and show the change of the Black Sea salinity in Fig. 4. Note that for this calculation, we assume complete and rapid mixing within the Black Sea, unlike Lane-Serff et al. (1997), who assumed no interaction between the salty Mediterranean inflow and the Black Sea's freshwater reservoir (until that reservoir was exhausted) for the bulk of their calculations, except for the single complete mixing case described above. In Section 5, we will discuss the significance, limitations and implications of our assumption of complete mixing.

Estimates of the actual width at the sill vary from 1000 to 1200 m. Assuming these much larger widths, the time scale for the Black Sea's flushing is shorter (around 2000 years) and the basin does reach the present-day salinity of 18 psu, in fact quite early, around 6–7 kyr BP (Fig. 5). However, the sill does not limit the exchange, as it is not the part of the strait with the minimum cross-sectional area. This occurs at the narrows, where the width is 500 m. With a depth of 40 m, we get the curve shown previously, based on the calculations of Lane-Serff et al. (1997). Considering any uncertainty in the depths, we plot the different salinity profiles for a range of possible depths at the constriction in Fig. 6. As long as the present-day depth is at least 50 m, the salinity reaches 18 psu by the present day. In fact, if we plot the combination of depths and widths (for a combination of different freshwater influxes) needed for the present-day Black Sea salinity to reach 18 psu (Fig. 7), we find that for a 500 m wide constriction and $Q_o = 10\,000$ m^3 s^{-1}, a depth of near 50 m is needed, consistent with the results from Fig. 6.

There is also a large sensitivity to the fresh-

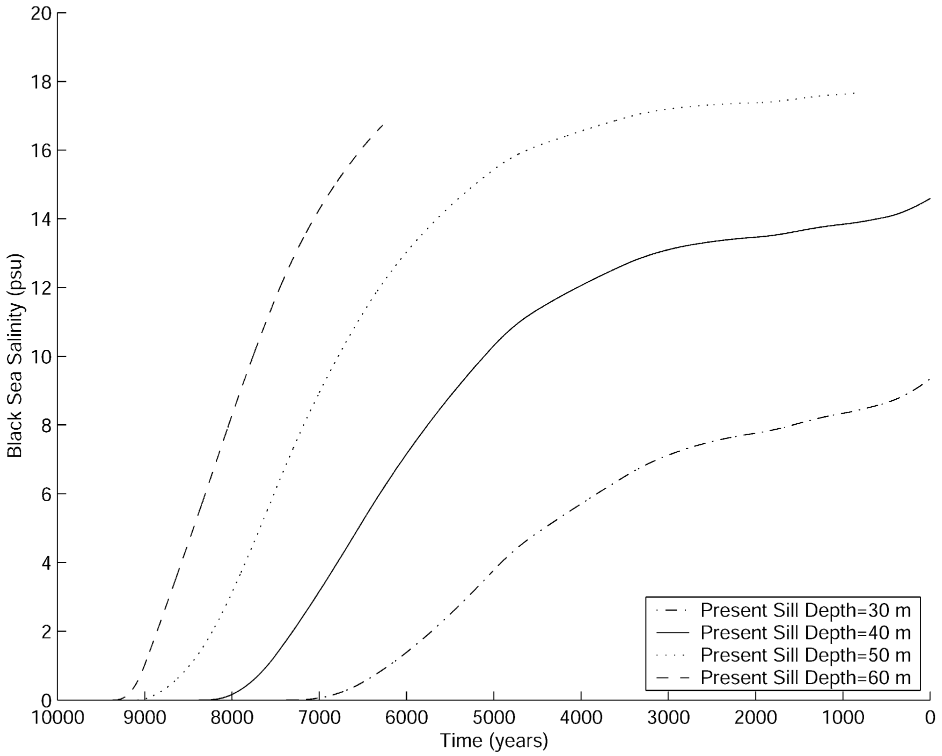

Fig. 6. Sensitivity of the Black Sea salinity to changes in Bosphorus sill depth.

water budget of the Black Sea (Fig. 8). As more freshwater (presumably as runoff) enters the Black Sea, our assumption of mass continuity within the Black Sea requires a greater transport to be forced through the Bosphorus (assumed to be 500 m wide, with a present-day depth of 50 m, in these experiments). Note for simplicity (and the lack of a good time series of the Black Sea freshwater balance), the assumption has been made that the freshwater flux is constant through time. Although the Black Sea is too far north to be affected by the humid period of the last monsoonal maximum, 9–6 kyr ago (Rohling and Hilgen, 1991), pollen records suggest the Black Sea area remained arid until the onset of sapropel deposition (Ryan et al., 2003). Thus, beyond providing sensitivity experiments for the modern hydrological balance of the Black Sea, this figure gives upper and lower bounds for the effect of changes in the freshwater balance of the Black Sea.

We have also looked at any dependence on the initial salinity. It is zero for the basic outflow scenario that assumes the Black Sea was the freshwater 'Black Lake', but varies from 2.9 to 9.3 psu after the Ryan flood scenario (and depending on the salinity before such a flood, if the Black Sea was not completely fresh at that time). In the long term, any initial salinity variations are averaged out (Fig. 9). It is interesting to note the initial salinity drop for higher pre-connection salinities. The reason for this is that initially the hydrological balance of the basin (Q_o) is bringing in more freshwater than the limited amount of salt water that can inflow through the shallow (at that time) Bosphorus exchange. Thus, a drop in the Black Sea's salinity can actually be associated with the opening of a connection to the saline Mediterranean. Additionally, a scenario with high salinity and strong outflow is probably unrealistic since the residence time of water in the basin (and time for evaporative concentration) would be low. This may also be an artefact of our complete

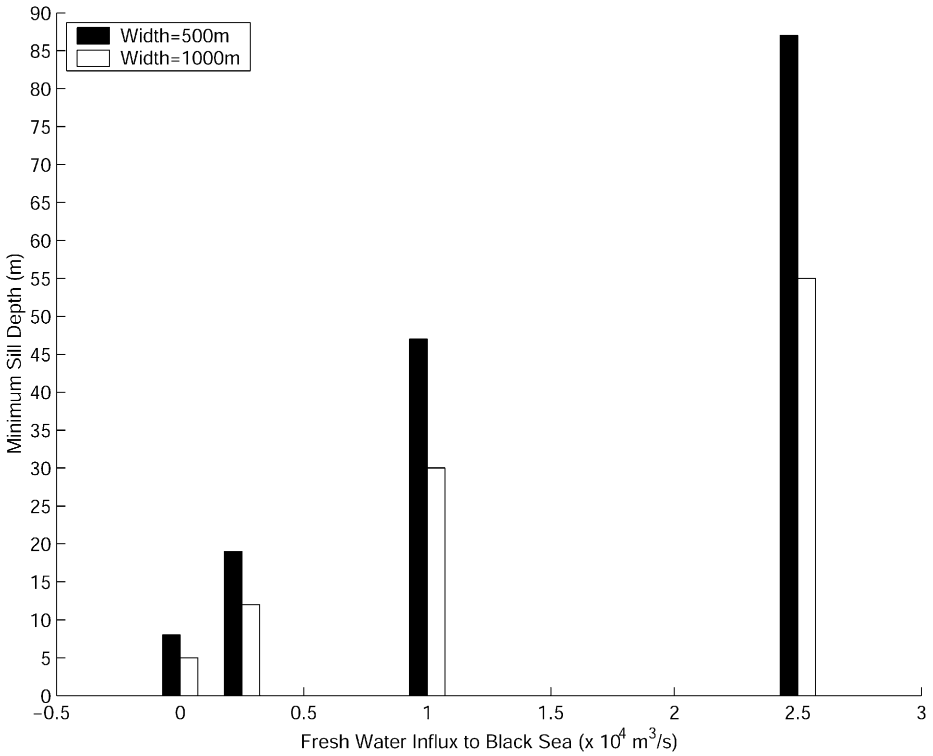

Fig. 7. Minimum sill depths needed for the Black Sea salinity to reach the present-day value of 18 psu, given different Bosphorus widths and Black Sea freshwater inputs.

mixing assumption, discussed in more detail in Section 5.

4. Black Sea outflow with a deep sill

Here we consider the behaviour of the TSS and Black Sea under the assumption of a deep Bosphorus channel that is only filled with sediments in recent times (Major et al., 2002). In this scenario, two-way flow between the Black Sea will be established once sufficient saline water enters the Sea of Marmara, initiated by the commencement of two-layer exchange through the Dardanelles, to raise the sea level in that basin above the critical height for the Bosphorus. Under the assumption that the hydraulic equations are also valid in the Dardanelles, and that the outflow from the Black Sea remains constant at 10 000 m^3 s^{-1}, a series of calculations shows that Marmara salinities will reach 24 psu (a threshold for the survival of planktonic foraminifera within the basin) within 2650 years (assuming a Dardanelles sill that is presently 85 m deep and 1000 m wide – note additional experiments not presented in this paper showed that these results are not strongly sensitive to the choice of the parameters), with the salinity reaching 12 psu by 10.6 kyr BP, the starting date for the Marmara sapropel (Fig. 10). This date is late, as Cagatay et al. (2000) and Kaminski et al. (2002) find the first appearance of Mediterranean marine fauna shortly after 12.0 kyr BP, the date global sea level reached the Dardanelles sill.

As Lane-Serff et al. (1997) found with the Bosphorus, the date that the global sea-level curve reaches the sill depth of the Dardanelles will not be the date for the entry of saline waters into the Sea of Marmara if there is significant freshwater discharge through the system, since the flow in the Dardanelles will remain uni-directional until the sea level reaches a critical height over the sill. For

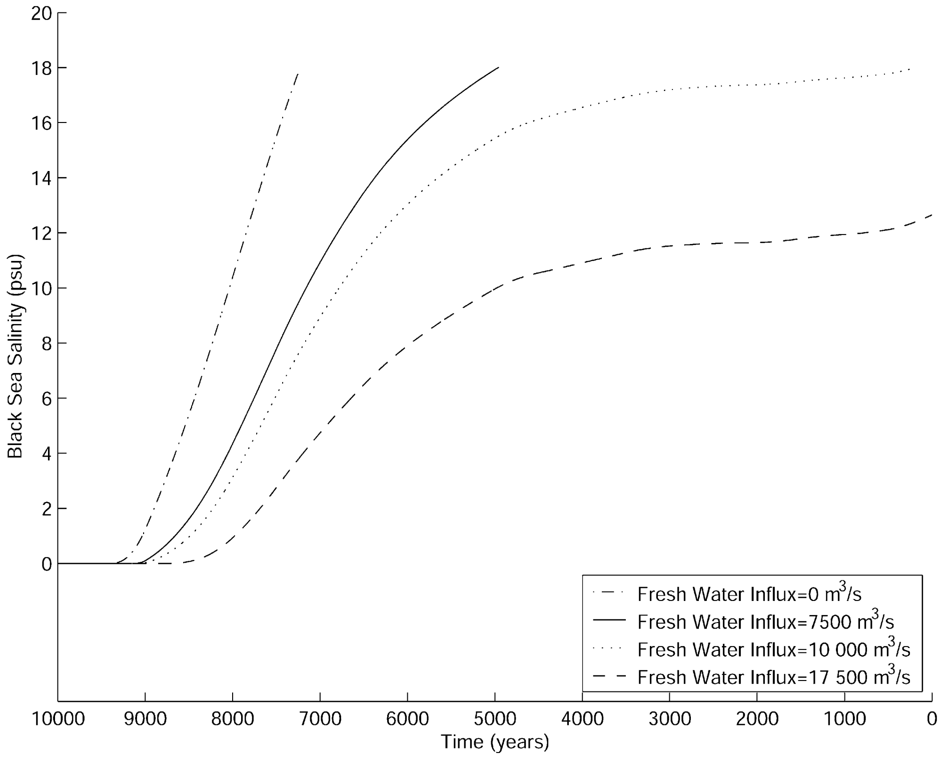

Fig. 8. Sensitivity of the Black Sea salinity to changes in the freshwater influx rate.

the palaeo-Dardanelles such a critical height is around 15.0 m. If the 12.0 kyr BP date for entry of Mediterranean water into the Sea of Marmara is correct, this would suggest that the freshwater outflow from the Black Sea is either very weak or possibly seasonal at this time. Table 1 lists the time it would take for the salinity within the Sea of Marmara to reach the 24 psu threshold for planktonic foraminifera survival given different amounts of freshwater discharge through the system from the Black Sea. Note that for simplicity we have not assumed any seasonality in the outflow in this calculation. The flow rate of freshwater through the system would then have to be under 2000 m^3 s^{-1} (and potentially significantly under) to be consistent with the rapid appearance of marine fauna in the Sea of Marmara shortly after 12.0 kyr BP (Cagatay et al., 2000; Kaminski et al., 2002). Such a freshwater flow rate is significantly smaller than for the present day, by a factor of at least 4.

Table 1
A summary of the time needed for the salinity in the Sea of Marmara to reach the 24 psu necessary to support marine foraminifera

Flow rate (m^3 s^{-1})	Time (years)
500	77
1 000	135
1 500	283
2 000	637
2 500	964
5 000	2076
10 000	2642

The times are given in years needed after the global sea level reaches the sill of the Dardanelles, for a number of different flow rates of freshwater through the TSS.

We can then use the salinity profiles calculated for the Sea of Marmara as the input salinity for the inflow to the Black Sea, in the hydraulic calculations, given the deep sill. If we were to use our base freshwater flux of 10 000 m^3 s^{-1} (which would imply that the entry of Mediterranean

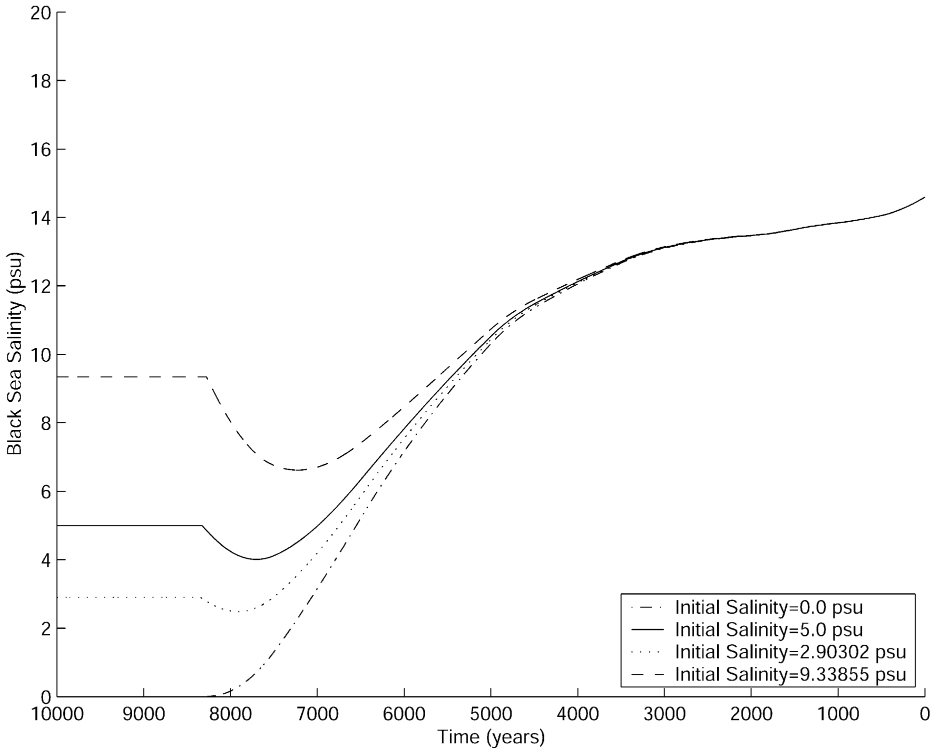

Fig. 9. Sensitivity of the Black Sea salinity to changes in the initial Black Sea salinity before reconnection.

water into the Sea of Marmara was significantly delayed), we would find that the salinity in the Black Sea would have a slow period of initial growth, and then begin to rise quickly, as the salinity of the Sea of Marmara rises. The present-day salinity of 18 psu would be reached by 6.4 kyr BP. If, however, we assume that the findings of a rapid salinification of the Sea of Marmara are correct and thus the freshwater flux is initially small (≤ 2000 m^3 s^{-1}), we find a much earlier date for Black Sea salinification. Here, we find a rapid, and basically linear, rise of salinity within the Black Sea with time, with the present-day value of 18 psu reached by 10.2–9.6 kyr BP. The oldest of these dates assumes that the freshwater flux remains constant at 2000 m^3 s^{-1} during this time period, while the younger date of 9.6 kyr BP assumes a rapid rise of the freshwater flux back towards a standard value of 10 000 m^3 s^{-1} after the initial entry of saline water into the Sea of Marmara is completed.

5. Summary and discussion

A series of simple hydraulic calculations has been performed to examine some of the questions associated with the connection of the Black Sea to the Mediterranean through the TSS. The equations for flow over a weir are used to examine the catastrophic flooding scenario of Ryan et al. (1997). The results show that although it might be possible to fill the Black Sea within the order of a decade(s) (assuming a realistic range of parameters for the Bosphorus), to fill it within a single year (or even two) would be physically impossible, without significant change in the geology and geography of the connection.

We then expand upon the calculations of Lane-Serff et al. (1997), examining the transient salinity behaviour in the Black Sea associated with the connection of a freshwater ‘Black Lake’ over a shallow Bosphorus sill to the Mediterranean. We conduct a large range of sensitivity experiments

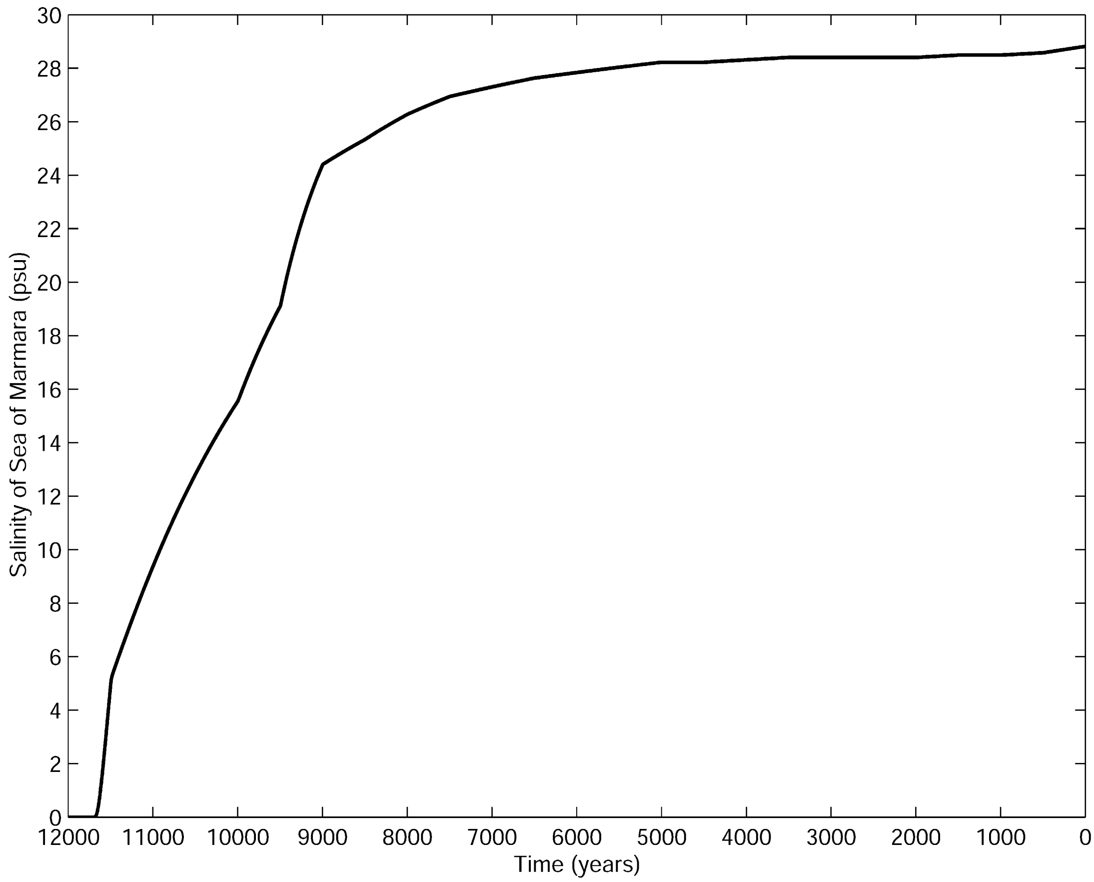

Fig. 10. Sea of Marmara salinity based on the connection to the Mediterranean through the Dardanelles.

considering different strait geometries. With the choke-point for the strait being the constriction (not the sill), the results show that a present-day depth of just less than 50 m is needed for the Black Sea salinity to reach the present-day value of 18 psu, assuming a freshwater budget similar to today. As might be expected, the larger the freshwater input to the Black Sea, the larger the strait needs to be for the salinity in the Black Sea to reach present-day values. However, interestingly, if the salinity of the Black Sea was not zero before the reconnection (potentially associated with some previous connection), the salinity within the basin will actually drop for a period after the opening of the TSS, even though salty Mediterranean water is entering the basin. The reason for this is the small size of the inflow with respect to the large freshwater flux entering the strait system. Another possible advantage of calculating the salinity transients is that salinity changes are a quantity that can be more reliably validated from palaeo-proxies than potential freshwater fluxes.

A final series of calculations considers the recent hypothesis of Major et al. (2002) of a deep Bosphorus sill (100 m bedrock depth) that is only filled in recent times with sediment. Two-way flow over such a deep sill would begin once the Sea of Marmara became sufficiently saline to allow two-layer flow to develop, within 500 years of its inundation around 12.0 kyr BP (Cagatay et al., 2000) and potentially before the initiation of sapropel formation in that smaller basin. Hydraulic calculations for the Dardanelles show that if the entry of saline water into the Sea of Marmara was indeed rapid (Cagatay et al., 2000; Kaminski et al., 2002), then the freshwater outflux from the Black Sea must have been much smaller at this time, under 2000 m^3 s^{-1}. Such a flux would have been at least four times smaller than the present-day outflux through the system.

The resulting salinification of the Black Sea in the deep-sill model would occur quickly. For all combinations of freshwater flux considered, the Black Sea would reach its present-day salinity of 18 psu at an early date. Assuming a large freshwater flux (and thus a late date for the entry of Mediterranean water into the Sea of Marmara, which may not be justified), the present-day salinity of 18 psu would be reached by 6.4 kyr BP. If the smaller freshwater flux suggested by the hydraulic calculations to be consistent with presence of marine fauna in the Sea of Marmara shortly after 12.0 kyr BP is valid, then the salinification of the Black Sea would be complete, in the deep-sill model, by the very early dates of 10.2–9.6 kyr BP. Thus, these results support the supposition of Major et al. (2002) that the delay in the Black Sea salinification in the case of a deep sill can only be explained by a large Black Sea outflow. Yet, the clear evidence of Mediterranean water entry into the Sea of Marmara at 12 kyr BP cannot be reconciled with vigourous outflow from the Black Sea at that time. Thus, the possibility of a deep sill should be discounted.

In all the salinity calculations discussed in this paper one important caveat needs to be considered: namely, what is the level of mixing that occurs within the basins in question. For simplicity, we are assuming that each basin is well mixed and that all new sources of fresh and/or salty water are mixed into the existing water masses within a 1 year time scale. The present-day 2000 year residence time for present-day Black Sea deep waters may argue against our assumption of complete mixing within the Black Sea. However, our experiments examine the transient salinity behaviour in the Black Sea prior to sapropel onset around 7160 year BP (Jones and Gagnon, 1994). Prior to sapropel onset, the Black Sea would be much less stratified than today, suggesting that exchange of surface and deep waters (through both mixing and deep wintertime convection) would be much more prevalent than today. Also, when the salty Mediterranean water enters the Black Sea, it does so at the shallow depth associated with the Bosphorus sill, and then sinks to the depths associated with its high salinity. The sinking of such plumes normally includes significant entrainment, mixing the inflowing saline water with the fresher outflow and providing salt to the upper levels of the Black Sea (Siddall et al., 2003). Finally, the presence of a second hydraulic control point near the northern sill in the Bosphorus leads to much mixing between the outflow and inflow upstream of the control point, reaching well into the Black Sea itself (Cetin, 1999). All of these factors suggest that assuming a well-mixed Black Sea is a reasonable modelling assumption during the time of the reconnection of the Black Sea to the Mediterranean. A more rigorous approach would be to partition the Black Sea into a number of vertical boxes and compute the salinity transient within each box, connecting them with vertical mixing processes. However, such a model is beyond the scope of the present work.

Acknowledgements

We would like to thank Greg Lane-Serff and Candace Major for constructive reviews for this paper, Michael Sperling for discussions that led to thinking about this problem, Nilgun Cetin for discussions about the Bosphorus and Black Sea and Frank Gerdes for providing us with topographic data for the Bosphorus. This work was funded by a NSERC grant awarded to P.G.M. and an NSERC USRA awarded to S.G.

References

Aksu, A.E., Hiscott, R.N., Yasar, D., 1999. Oscillating Quaternary water levels of the Marmara Sea and vigourous outflow into the Aegean Sea from the Marmara Sea-Black Sea drainage corridor. Mar. Geol. 153, 275–302.

Ballard, R.D., Coleman, D.F., Rosenberg, G.D., 2000. Further evidence of abrupt Holocene drowning of the Black Sea shelf. Mar. Geol. 170, 253–261.

Batchelor, G.K., 1967. An Introduction to Fluid Dynamics. Cambridge University Press, p. 15.

Cagatay, M.N., Gorur, N., Algan, O., Eastoe, C., Tchapalyga, A., Ongan, D., Kuhn, T., Kuscu, I., 2000. Late Glacial-Holocene palaeoceanography of the Sea of Marmara: timing of connections with the Mediterranan and the Black Sea. Mar. Geol. 167, 191–206.

Cetin, N., 1999. Analysis of the exchange flow through the Bosphorus Strait. Master's Thesis, Middle East Technical University, Institute of Marine Sciences.

Emery, K.O., Hunt, J.M., 1974. Summary of Black Sea investigations. In: Degens, E.T., Ross, D.A. (Eds.), The Black Sea - Geology, Chemistry and Biology. Am. Assoc. Pet. Geol., Tulsa, OK, pp. 575–590.

Ergin, M., Kazanci, N., Varol, B., Ileri, O., Karadenizli, L., 1997. Sea-level changes and related depositional environments on the southern Marmara shelf. Mar. Geol. 140, 391–403.

Fairbanks, R.G., 1989. A 17000-year glacio-eustatic sea level record: influence of glacial melting an the Younger Dryas event and deep-ocean circulation. Nature 342, 637–642.

Gorur, N., Cagatay, M.N., Emre, O., Alpar, B., Sakinc, M., Islamoglu, Y., Algan, O., Erkal, T., Kecer, M., Akkok, R., Karlik, G., 2001. Is the abrupt drowning of the Black Sea shelf at 7150 yr BP a myth? Mar. Geol. 176, 65–73.

Jones, G.A., Gagnon, A.R., 1994. Radiocarbon chronology of Black Sea sediments. Deep-Sea Res. 41, 531–557.

Kaminski, M.A., Aksu, A., Box, M., Hiscott, R.N., Filipescu, S., Al-Salameen, M., 2002. Late Glacial to Holocene benthic foraminifera in the Marmara Sea: implications for Black Sea-Mediterranean Sea connections following the last deglaciation. Mar. Geol. 190, 165–202.

Lambeck, K., 1995. Late Pleistocene and Holocene sea-level change in Greece and southwestern Turkey: a separation of eustatic, isostatic and tectonic contributions. Geophys. J. Int. 122, 1022–1044.

Lane-Serff, G., Rohling, E.J., Bryden, H.L., Charnock, H., 1997. Postglacial connections of the Black Sea to the Mediterranean and its relation to the timing of sapropel formation. Paleoceanography 12, 169–174.

Major, C., Ryan, W., Lericolais, G., Hajdas, I., 2002. Constraints on Black Sea outflow to the Sea of Marmara during the last glacial-interglacial transition. Mar. Geol. 190, 19–34.

Myers, P.G., Haines, K., Rohling, E.J., 1998. Modelling the paeo-circulation of the Mediterranean: The Last Glacial Maximum and the Holocene with emphasis on the formation of sapropel S_1. Paleoceanography 13, 586–606.

North Atlantic Treaty Organization (NATO) Committee on the Challenges of Modern Society, 2000. Black Sea integrated coastal and shelf zone monitoring and modeling (incom) program. NATO Tech. Rep. No. 248, p. 49.

Oguz, T., Ozsoy, E., Latif, M.A., Sur, H.I., Unluata, U., 1990. Modelling of hydraulically controlled exchange flow in the Bosphorur Strait. J. Phys. Oceanogr. 20, 945–965.

Olausson, E., 1961. Studies of deep-sea cores. Tech. rep., Rep. Swed. Deep Sea Exped. 1947-1948.

Ozsoy, E., Latif, M.A., Besiktepe, S., Oguz, T., Gungor, H., Unluata, U., Gaines, A.F., Tugrul, S., Basturk, O., Yilmax, A., Yemenicioglu, S., Saydam, C., Salihoglu, I., 1994. Monitoring via direct measurements of the modes of mixing and transport of wastewater discharges into the Bosphorus underflow: Hydrography, sea-level, current and flux measurements in the Bosphorus Strait and acoustical, chemical and Rhodarmine-B dye tracer studies of the Ahirkapi Waste Discharge. Tech. Rep. Volumes 1, 2, 3. METU, Institute of Marine Sciences, Erdemli, Icel.

Rohling, E.J., Hilgen, F.J., 1991. The eastern Mediterranean climate at times of sapropel formation: a review. Geol. Mijnb. 70, 253–264.

Rohling, E.J., 1994. Review and new aspects concerning the formation of eastern Mediterranean sapropels. Mar. Geol. 122, 1–28.

Rohling, E.J., 1999. Environmental control of Mediterranean salinity and $\delta^{18}O$. Paleoceanography 14, 706–715.

Rohling, E.J., Gieskes, W.W.C., 1989. Late Quaternary changes in Mediterraean intermediate water density and formation rate. Paleoceanography 4, 531–545.

Ross, D.A., Uchupi, E., Prada, K.E., MacIlvaine, J.C., 1974. Bathymetry and Microtopography of Black Sea. In: Degens, E.T., Ross, D.A. (Eds.), The Black Sea - Geology, Chemistry and Biology. Am. Assoc. Pet. Geol., Tulsa, OK, pp. 1–10.

Rossignol-Strick, M., 1985. Mediterranean quaternary sapropels, an immediate response of the African monsoon to variation in insolation. Palaeogeogr. Palaeoclimatol. Palaeoecol. 49, 237–263.

Ryan, W.B.F., Major, C.O., Lericolais, G., Goldstein, S.L., 2003. Catastrophic flooding of the Black Sea. Annu. Rev. Earth Planet. Sci. 31, 525–554.

Ryan, W.B.F., Pitman, W.C., III, Major, C.O., Shimkus, K., Moskalenko, V., Jones, G.A., Dimitrov, P., Gorur, N., Sakinc, M., Yuce, H., 1997. An abrupt drowning of the Black Sea shelf. Mar. Geol. 138, 119–126.

Siddall, M., Pratt, L.J., Helfich, K.R., Giosan, L., 2003. Towards understanding the physical oceanography of a sudden Black Sea in-fill 8400 years ago. Paleoceanography, submitted.

Sperling, M., Schmiedl, G., Hemleben, C., Emeis, K.C., Erlenkeuser, H., Grootes, P.M., 2003. Black Sea impact on the formation of eastern Mediterranean sapropel S1? Evidence from the Marmara Sea. Palaeogr. Palaeoclimatol. Palaeoecol. 190, 9–21.

Staschuk, N., Hutter, K., 2001. Modelling of water exchange through the Strait of the Dardanelles. Cont. Shelf Res. 21, 1361–1382.

Yanko, V., Kennett, J., Koral, H., Kronfield, J., 1999. Stable isotope evidence from the Holocene Sea of Marmara sediments for two-way watermass interchange between the Black Sea and the Mediterranean Sea. S. Afr. J. Sci. 95, 201–204.