OIL SPILL ALONG THE TURKISH STRAITS SEA AREA; ACCIDENTS, ENVIRONMENTAL POLLUTION, SOCIO-ECONOMIC IMPACTS AND PROTECTION

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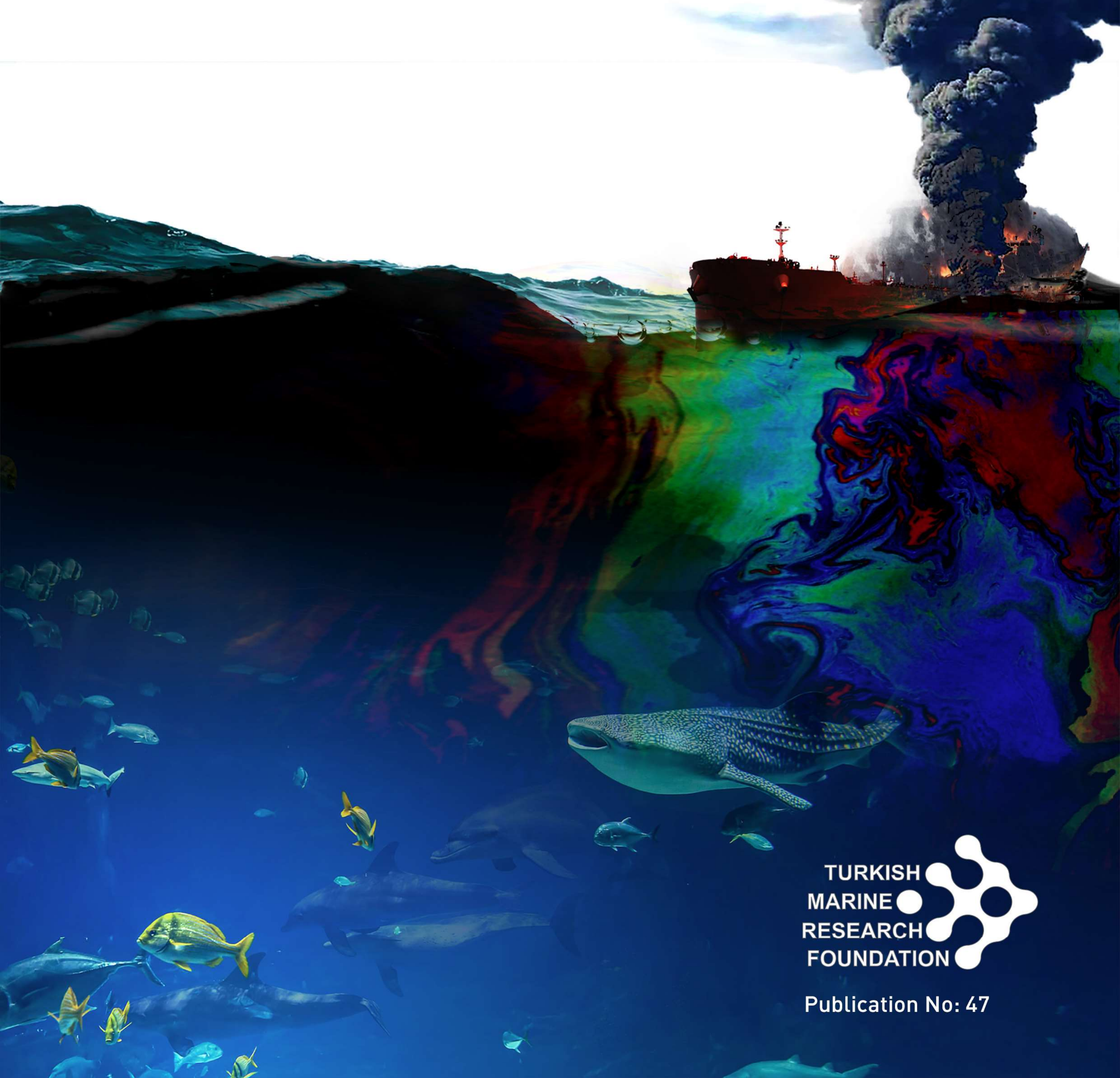

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HYDRODYNAMICS AND MODELLING OF TURKISH STRAITS

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1. Introduction

The beginning of scientific oceanographic research may be traced back to the in situ measurements of Count Luigi Ferdinando Marsili in the Adriatic Sea, Aegean Sea, and more importantly in the Sea of Marmara and the İstanbul Strait between 1679 and 1680. Marsili's measurements are termed scientific because they were accurately described by referring to specific geographical locations and time. Marsili collected surface and deep-water samples and determined the seawater densities of samples, which were found to agree with present-day values within 10% to 20% uncertainty. Marsili also measured the current speeds and the depth of the current direction reversal in the İstanbul Strait, which are again in agreement with the present-day measurements. Furthermore, based on the experimental data collected in the İstanbul Strait, Marsili put forward a theory on the cause of the two-layer flow at the strait and demonstrated its validity by laboratory experiments (Pinardi et al., 2018).

Virtually centuries passed until oceanographic measurements were done again in the region between 1918 and 1921 by the German oceanographer Alfred Merz. Merz's measurements of flow velocity and salinity in the İstanbul Strait was reported later by Möller (1928). In the 1940's and 1950's, nearly two decades after the establishment of the Turkish Republic, the Turkish researchers began stepping in to the field of oceanography. Ulyott and Ilgaz (1944) and almost a decade later Pektaş (1953) carried out some rather limited measurements in the İstanbul Strait with scanty means available at the time. In a related work, Pektaş (1956) interpreted the effect of Mediterranean water to the Black Sea.

In the early 1980's Çeçen et al. (1981) and Sümer and Bakioğlu (1981) made quite important contributions from theoretical and computational point of view by mathematically describing the hydraulics of two-layer flows and applying the equations to the İstanbul Strait.

The 1990's saw an outburst in studies concerning the Turkish Straits System. Ünlüata et al. (1990) presented an in-depth review of the subject besides giving assessments of fluxes. Oğuz et al. (1990) made numerical computations of exchange flows in the İstanbul Strait. Latif et al. (1991) reported observations of the Mediterranean inflow into the Black Sea while the role of the Sea of Marmara in coupling these two water bodies were treated in Beşiktepe et al. (1994). Özsoy et al. (1995) investigated fluxes and mixing processes in the Black Sea and a review of exchange flow characteristics and mixing in the İstanbul Strait was given by Özsoy et al. (1996). Effects of the Turkish Strait System on the Black Sea can be found in the reviews by Özsoy and Ünlüata (1997, 1998).

Altıok (2001) carried out a comprehensive study of current measurements in the İstanbul Strait and later re-examined the findings in Altıok, Sur and Yüce (2005). Özsoy, Latif, and Beşiktepe (2002) analyzed the currents using the measurements in the İstanbul Strait. Gregg and Özsoy (2002) considered the flow, water mass changes, and hydraulics of the İstanbul Strait. Güler et al. (2006) carried out a field study in the İstanbul Strait for measuring short-term and long-term current profiles at selected locations. In-depth reviews of the hydrography and water fluxes of the Turkish Straits System can be found in Özsoy and Altıok (2016a, b). Finally, Jordà et al. (2017) give a very extensive review of the Mediterranean Sea heat and mass budgets with special emphasis on the Turkish Straits System and the Strait of Gibraltar. Numerical modelling issues of the straits are also treated with actual simulations.

2. Turkish Straits

The Turkish Straits System is composed of the İstanbul Strait (Bosphorus) and the Çanakkale Strait (Dardanelles). The system comprises a region extending from Aegean Sea to Black Sea with the Sea of Marmara encompassed as shown in Figure 1. Thus, the Turkish Straits System connects essentially Mediterranean and Black Sea through two narrow and long straits.

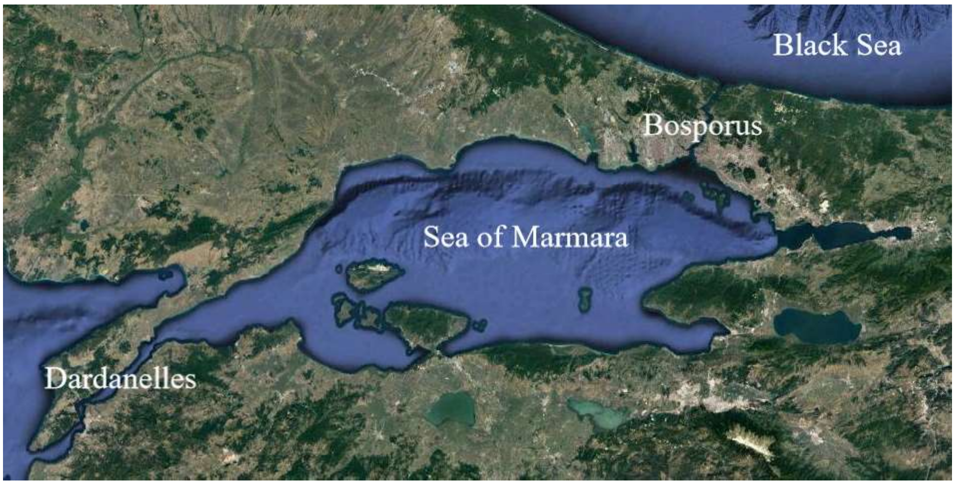

Figure 1. Sea of Marmara connecting Mediterranean and Black Sea via Çanakkale and İstanbul straits.

The İstanbul and Çanakkale Straits have unique features of two-layer flows, which may be compared only with the Gibraltar Strait. The İstanbul Strait is approximately 35 km in length and only 700 m wide in its narrowest pass. The Çanakkale Strait is relatively longer, 75 km, and wider, 1300 m in the narrowest (Figures 2a, b).

Figures 2a, b. İstanbul Strait (left) and Çanakkale Strait (right).

The southern exit of the İstanbul Strait opens to the Sea of Marmara while a deep channel continues north where it meets with the complex southern sill of 30 m depth flanked by deeper channels of 40 m depth on either sides. The water depth throughout the strait ranges from 30 m to 100 m with a mean depth of approximately 60 m while the width varies within 700 m to 3500 m. The Çanakkale Strait, on the other hand, connects the Aegean Sea to the Marmara Sea, with two near right-angle turns at the narrows of the Nara Pass. The depth ranges between 60 m to 80 m with a mean of approximately 70 m.

Both the İstanbul Strait and the Çanakkale Strait have two-layer stratified flow system. The upper-layer currents carry the lighter Black Sea water southwards while the lower-layer currents carry the Mediterranean water northwards. Thus, a system of two-layer opposing currents is maintained. Thicknesses and velocities of both layers show appreciable spatial and temporal variations. Geography of the straits, the wind conditions, and hydraulic controls dictated primarily by local depths all contribute to the overall flow characteristics and variations.

The two-layer system of the straits is principally established by two mechanisms. In the upper layer, the currents are driven by water level differences such as the 20-40 cm higher Black Sea versus the Sea of Marmara; hence, the flow arises from the pressure difference and termed barotropic. In the lower layer, on the other hand, the basic driving mechanism is the density difference of the two layers and the flow is said to be baroclinic. These two different mechanisms are elucidated below in a separate part by a simple hydrostatic model. It must also be indicated that strong shear between the opposing currents generates a turbulent mixing layer. In realistic modeling, the effect of this mixing layer must definitely be included.

In the southern part of the İstanbul Strait, following the narrowest section, the surface currents generally exceed 1 m s^{-1} and reach 2-3 m s^{-1} at the southern exit. Similarly, surface currents of around 1 m s^{-1} occur past the narrow sections of the Çanakkale Strait such as Nara Pass (Özsoy and Altıok, 2016a).

A rather well known occurrence in the İstanbul Strait is the short-duration blocking of the flows in the upper or lower-layer due to extreme values of sea-level differences. For instance, it is argued that a sea-level difference of less than 10 cm would block the upper-layer while a level difference of 50 cm would block the lower-layer. Naturally, not only sea-level differences but also barometric pressure, winds, and net water fluxes all contribute to dynamical forces creating blocking conditions (Oğuz et al. 1990). Accordingly, the lower layer is now and then blocked in spring and summer, with increased Black Sea influx, which is primarily due to the northerly winds. On such occasions, the southerly currents of the Black Sea virtually overwhelm and flush out the Mediterranean water. On the other hand, the upper-layer blocking events, called *Orkoz*, coincide with the reversal of the net flow in response to the southerly winds, called *Lodos*, in the fall and winter (Özsoy and Altıok, 2016a).

The exchange flow rate in the İstanbul Strait may be estimated by considering the water budget of the Black Sea. In other words, the net water flux through the İstanbul Strait is dictated by the rate of mean sea-level change and the water masses flowing in and out of the Black Sea. The annual average fluxes are computed from the Knudsen relations expressing a steady-state mass and salt budget. For the İstanbul Strait the annual average upper- and lower-layer fluxes are estimated as 650 km^3 $year^{-1}$ (20,600 m^3 s^{-1}) and 325 km^3 $year^{-1}$ (10,300 m^3s^{-1}), respectively. These values are quite in agreement with the calculation based on the long-term salt budget of the Black Sea, which gives a ratio of 2 between the outgoing and incoming mass fluxes. Thus, the mean net water flux leaving the Black Sea may be approximately estimated as 650 - 325 = 325 km^3 $year^{-1}$ (10,300 m^3s^{-1}) (Özsoy and Ünlüata 1997).

A 10-year monthly-measurements campaign of direct measurements of water fluxes in the İstanbul Strait at the two ends of the Strait were carried out by Altıok and Kayışoğlu (2015). The results of the measurements produced mean fluxes for the upper layer 12,540 m^3s^{-1} and the lower layer 8100 m^3s^{-1} hence a net flux of 12,540-8100=4440 m^3s^{-1} at the northern exit of the İstanbul Strait. The corresponding values at the southern exit are 13,320, 7900, 5420 m^3s^{-1}, respectively. Increase in the upper-layer flux and decrease in the lower-layer flux as we move from the north to the south reveal a net flux injection into the upper layer from the lower layer. On the average, the net flux must be conserved between the two ends of the Strait. This expectation is however only approximately fulfilled as the upper, lower layer and net flux differences are respectively found to be 13,320-12,540=780 m^3s^{-1}, 7900-8100 = -200 m^3s^{-1} and 780-(-200) = 5420-4440 = 980 m^3s^{-1}, a net increase in the southern exit flux. This relatively small violation of conservation of mass is of course due to instrumental and methodological inaccuracies involved in the measurements. Finally, if we calculate the upper and lower-layer averages of the two ends we have 12,930 m^3s^{-1} for the upper layer and 8000 m^3s^{-1} for the lower layer hence giving the ratio as 12,930/8000=1.6, somewhat less than expected value 2.

Relatively recent flux measurements for the İstanbul Strait (Jarosz et al., 2011) and for the Çanakkale Strait (Jarosz et al., 2012) have been reported. Tables 1 and 2, adapted from Özsoy and Altıok (2016b), show the measured values for the İstanbul and

Çanakkale Straits, respectively. Note that positive values indicate flow in the southward direction while negative values indicate the flow in the northward direction.

Table 1. Flux values for the İstanbul Strait.

Layer	South (m^3s^{-1})	North (m^3s^{-1})	Difference South-North
Upper	+14,071	+11,875	+2217
Lower	-10,564	-8018	-2559
Net	+3508	+3857	-342

Table 2. Flux values for the Çanakkale Strait.

Layer	South (m^3s^{-1})	North (m^3s^{-1})	Difference South-North
Upper	+36,329	+25,560	+10,844
Lower	-32,129	-14,473	-17,673
Net	+4200	+11,087	-6829

When Tables 1 and 2 are compared, it is first noted that the net flux difference for the Çanakkale Strait is approximately 20 times greater than that of the İstanbul Strait. Indeed, the difference of -6829 m^3/s is such a large value that it is comparable in magnitude with the layer fluxes. Such great variation between two ends raises questions concerning measurement accuracies and crosswise flow variations for the Çanakkale Strait. The relatively wider cross-sectional areas of the Çanakkale Strait is probably responsible for this big discrepancy, which must ideally be zero, when the net effect of precipitation and evaporation is dismissed.

On the other hand, the net flux difference for the İstanbul Strait is relatively small hence establishes confidence for the measured flux values. Considering the mean values of the north-south fluxes of the upper and lower layers for the İstanbul Strait, we have +12,973 m^3s^{-1} and -9291 m^3s^{-1}, respectively. Using these mean values gives for the upper to lower flux ratio as 1.4, which is even less than the ratio 1.6 calculated from the measurements of Altıok and Kayışoğlu (2015).

3. A Simplified Hydrostatic Model of Two-Layer Flow

Çeçen et al. (1981), besides presenting a very comprehensive in depth treatment of hydraulics of two-layer flow in the İstanbul Strait, suggested a very simplified hydrostatic model to understand the physical mechanism laying behind. Although drastically simplified in many aspects this hydrostatic model offers good insight into the physics of any such two-layer systems. Generalizing for arbitrary canal length and water level heights this idea is mathematically formulated here. A simple one-dimensional two-layer model of the İstanbul Strait is considered in Figure 3.

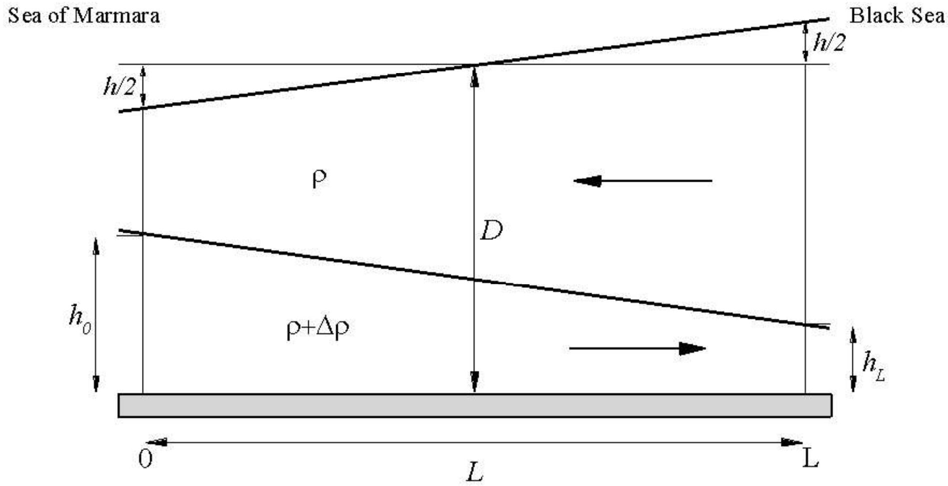

Figure 3. A one-dimensional two-layer idealization of the İstanbul Strait.

Here, the total length of the canal is denoted by L, the depth in the mid-canal is D, the total water level difference between the Sea of Marmara and Black Sea is h, the lower layer height at the side of the Marmara Sea is h_0 and at the side of Black Sea is h_L. Finally, upper and lower layer densities are denoted by ρ and $\rho + \Delta\rho$, respectively. Considering the upper and lower layers separately in terms of the hydrostatic pressure distributions one gets the sketches below.

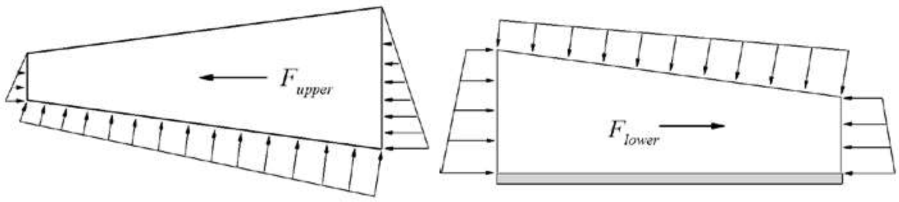

Figure 4a, b. Pressure distributions for the upper (left) and lower (right) layers.

Using the notation given in Figure 3 the net horizontal hydrostatic forces for the upper F_u (to the left) and lower F_l (to the right) layers for a unit canal width (into the paper) are formulated as given in Beji (2008).

$$F_u = \rho g h \left[D - \tfrac{1}{2}(h_0 + h_L)\right]$$

$$F_l = \rho g \tfrac{1}{2}(h_0 + h_L)\left[\frac{\Delta\rho}{\rho}(h_0 - h_L) - h\right]$$

Note that the net pressure force F_u is calculated by taking the left direction positive while F_l is calculated by taking the right direction positive.

Let us examine the above expressions with reference to the physics they imply. Considering F_u first, it is obvious from Figure 3 that $D > \frac{1}{2}(h_0 + h_L)$ always. Therefore, as long as the water level is higher on the Black Sea side compared to the Marmara side as shown in Figure 3 and denoted by the positive quantity h, the upper layer force $F_u > 0$ hence there is a net hydrostatic force acting to the left, namely from the Black Sea side to the Marmara side. It is crucial however that there is a positive water level difference $h > 0$ to have a positive F_u; that is, the flow is essentially driven by the water level difference h and there is no force when $h = 0$. This kind of flow, which is driven by the pressure difference due to water level difference, is called barotropic flow. Thus, the upper layer flow is barotropic.

For the lower layer on the other hand, to have a positive F_l, the terms inside the square brackets must be positive or non-zero as the other multiplier $\frac{1}{2}(h_0 + h_L)$ is always positive. To make the terms inside the square brackets positive it is necessary that;

$$\frac{\Delta\rho}{\rho} > \frac{h}{(h_0 - h_L)}$$

indicating that the density difference $\Delta\rho$ must be above a certain ratio in order to maintain a positive force hence a flow in the lower layer. Thus, in the lower layer, the density plays a decisive role in driving the flow and such flows are called broclinic.

This simplified hydrostatic model then has revealed the most important physical aspects of the two-layer flow observed in the İstanbul Strait or alike straits. The upper layer flow is driven by surface water level difference and is called barotropic while the lower layer flow is driven by density difference and is called baroclinic.

The above treatment may be carried out further to estimate the flow speed ratio of the layers. Newton's second law of motion states that $F = ma$. For the present case the mass values for the upper and lower layers for unit width can be computed easily as

$$m_u = \rho L\left[D - \tfrac{1}{2}(h_0 + h_L)\right]$$

$$m_l = \rho L\frac{1}{2}(h_0 + h_L)\left(1 + \frac{\Delta\rho}{\rho}\right)$$

Since $a = F/m$ the ratio of the upper layer acceleration to the lower layer acceleration is

$$\frac{a_u}{a_l} = \frac{F_u/m_u}{F_l/m_l} = \frac{h}{\left[\frac{\Delta\rho}{\rho}(h_0 - h_L) - h\right] / \left(1 + \frac{\Delta\rho}{\rho}\right)}$$

Note that for the upper layer acceleration is solely dictated by the surface level difference h while for the lower layer the positive acceleration is only possible for large enough $\Delta\rho/\rho$ ratio as indicated before. For constant acceleration the velocity is simply $v = at$ therefore, the accelerations ratio may be taken as velocities ratio $a_u/a_l = v_u/v_l$. Taking the typical values from the measurements used for a typical computation in Çeçen et al. (1981) of Figure 5.5 for the İstanbul Strait, we set $h = 0.33$ m, $h_0 - h_L = 35$ m, $\Delta\rho/\rho = 0.014$ and use the above expression for a_u/a_l to obtain

$$\frac{v_u}{v_l} = 2.09$$

which is in nearly perfect agreement with the well-known theoretical ratio of 2 stated based on mass conservation estimates (Ünlüata et al., 1990). It must however be emphasized that the above excellent agreement is essentially fortunate for two reasons. First, due to the term in the denominator the ratio of accelerations is quite sensitive to the values substituted. Second, this simple hydrostatic model does not contain any mechanism of shear stresses in the mid-layer and bottom to slow down the system and does not account for velocity heads (dynamic effects). Nevertheless, despite these missing parts, the hydrostatic approach clearly reveals the parameters controlling physical mechanisms of flow for the different layers and produces acceptable, even good results for the ratio of flow velocities. Finally, in this connection the ratios obtained from actual measurements as 1.6 (Altıok and Kayışoğlu, 2015) and 1.4 (Jaresz et al., 2011) must also be discussed. These ratios are smaller than the theoretical value of 2 by around 25%. The above formulation, when interpreted from a different view, may shed some light into this somewhat large difference. As noted before the denominator of a_u/a_l is sensitive to small changes in h, $\Delta\rho$, h_0, and h_L. Then, small variations in these terms may cause relatively big variations in the ratio a_u/a_l hence in the ratio of fluxes. In other words, small variations of basic parameters driving the flow amplify the ratio. This sensitivity, together with other factors unaccounted, may well be the main source of differences between the theoretical estimate and the measured values.

4. Numerical Modeling of Currents

Two-layer opposing-current structure of the İstanbul and Çanakkale Straits has always been a source of interest for oceanographers, hydraulic engineers, and more recently computational fluid dynamists. As indicated above the upper layer flow is maintained by water level difference whereas the lower layer flow is due to the density difference between two layers. The simple hydrostatic model has clarified these points by developing mathematical formulations capturing the essence of physics involved. To take the modeling further not only the hydrostatics but also hydrodynamics must be taken into account. Apparently, the first step in this direction was taken by Çeçen et al. (1981) who clarified the two-layer mechanism from hydraulic point of view and presented a mathematical model with a computer algorithm numerically solving it. Oğuz and Sur (1989) gave a two-layer numerical treatment of the Çanakkale Strait. Oğuz et al. (1990) applied the shallow-water equations to the modeling of two-layer-flow in the İstanbul Strait. This model takes into account the variations in canal width but is essentially one-dimensional and the solution proceeds only along the canal length, which is taken straight. Beji, Dikili and Barlas (2008) expressed the two-layer shallow-water equations in curvilinear boundary-fitted coordinate system and solved numerically by finite-difference approximations for simulating currents in the İstanbul Strait. Figure 5 shows a sample computation of one-dimensional two-layer opposing flows over a ridge on the bottom.

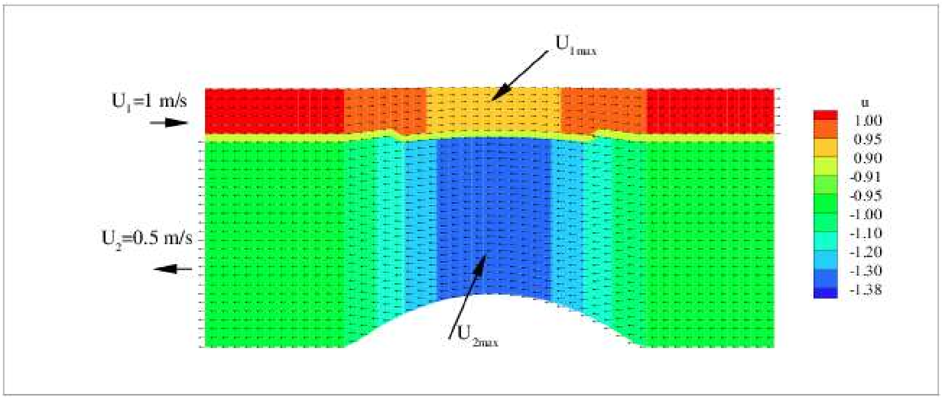

Figure 5. Velocity variations over a ridge for two-layer steady opposing currents.

Actual geographic representation of the İstanbul Strait used for numerical simulations in Beji, Dikili and Barlas (2008) is shown in Figure 6.

Sannino, Sözer and Özsoy (2015) presented results of the numerical modeling of currents in the Turkish Straits System. In the study, the MITgcm (MIT General Circulation Model) is employed with a high-resolution non-uniform grid system. The ability of MITgcm to capture the two-layer exchange dynamics both in the Straits and in the Marmara Sea is found to be quite satisfactory. Further, Sözer and Özsoy (2017) verified numerically the existence of the hydraulic controls responsible in establishing maximal exchange regimes as theoretically predicted by Farmer and Armi (1986).

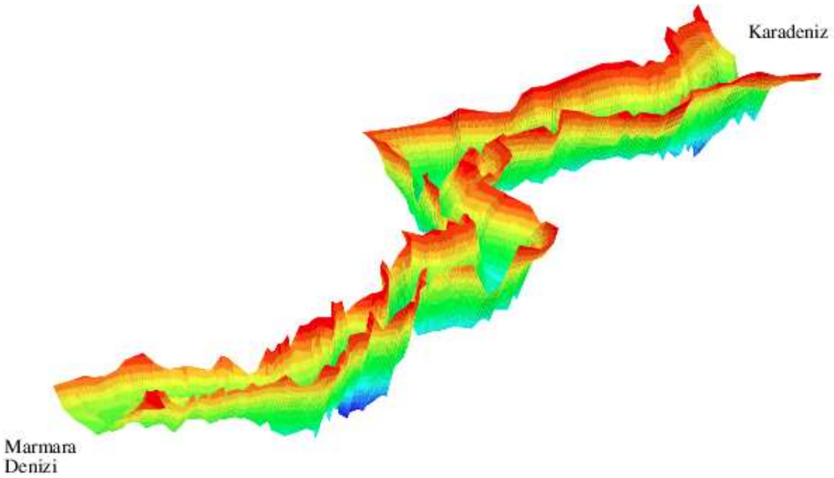

Figure 6. Perspective view of the İstanbul Strait bathymetry as used in simulations.

5. Conclusions

Hydrodynamics and modeling of the Turkish Straits have been reviewed with particular emphasis on the physical mechanisms driving the two-layer flow. Volume flux measurements in the Straits are recapitulated and discussed with reference to theoretical considerations based on conservation laws. A simple hydrostatic model, based on the suggestion made in Çeçen et al. (1981), is formulated for mathematically elucidating the physics laying behind two-layer flows. The formula derived for the ratio of the layer velocities produces meaningful values despite the extremely simplified approach adopted.

Numerical modeling of the currents in the internationally important seaways of the Turkish Straits is necessary especially for predicting the paths of the oil spills or pollutants in case of a sea accident. From the point of view of hydraulic engineering, the Turkish Straits are rare natural phenomena of two-layer flow with opposing currents. The usual approach of modelling such currents is to use the vertically integrated continuity and momentum equations with shallow-water approximations. However, as the effects of cross flows are realized more as a result of measurements, more sophisticated simulation tools such as the MIT General Circulation Model come into use (Sannino, Sözer and Özsoy, 2015).

References

Altıok, H., 2001. Monitoring seasonal changes of water bodies in the İstanbul Strait at the Black Sea Entrance. Ph.D. Thesis, Istanbul University Institute of Marine Sciences and Management (in Turkish).

Altıok, H. and M. Kayışoğlu, 2015. Seasonal and interannual variability of water exchange in the Strait of Istanbul. Mediterranean Marine Sciences, 16(3), 636-647.

Altıok, H., H.İ. Sur, and H. Yüce, 2005. Flow variations in the Strait of Istanbul (Bosphorus). European Geosciences Union, Second General Assembly. Wien, Austria.

Beji, S., 2008. Physical oceanography lecture notes. Istanbul Technical University, Faculty of Naval Architecture and Ocean Engineering, Unpublished documentation (in Turkish).

Beji, S., A.C. Dikili, and B. Barlas, 2008. Numerical modeling of currents in the Strait of Istanbul. TÜBİTAK Project no. 105Y127, Final Report, pp. 67 (in Turkish).

Beşiktepe, Ş., H.İ. Sur, E. Özsoy, M.A. Latif, T. Oğuz, and Ü. Ünlüata, 1994. The Circulation and Hydrography of the Marmara Sea. Progress in Oceanography, 34, 285-334.

Çeçen, K., M. Bayazıt, N.M., Sümer, Ş. Güçlüer, M. Doğusal, and H. Yüce, 1981. Hydraulic and oceanographic investigation of the İstanbul Strait. Istanbul Technical University, Faculty of Civil Engineering, TÜBİTAK Final Report No. 24 (in Turkish).

Farmer, D. M. and L. Armi, 1986. Maximal two-layer exchange over a sill and through the combination of a sill and contraction with barotropic flow. Journal of Fluid Mechanics, 164, 53-76.

Gregg, M.C. and E. Özsoy, 2002. Flow, water mass changes and hydraulics in the Bosphorus. Journal of Geophysical Research, 107, C3.

Güler, I., Y. Yüksel, A.C. Yalçıner, E. Çevik, and C. Ingerslev, 2006. Measurement and evaluation of the hydrodynamics and secondary currents in and near a strait connecting large water bodies - A field study. Journal of Ocean Engineering 33, 1718-1748.

Jarosz, E., W.J. Teague, J. Book, and Ş. Beşiktepe, 2011. Observed volume fluxes in the Bosphorus Strait. Geophysical Research Letters, 38, L21608, 1-6.

Jarosz, E., W.J. Teague, J.W. Book, and Ş. Beşiktepe, 2012. Observations on the characteristics of the exchange flow in the Dardanelles Strait. Journal of Geophysical Research, 117, C11012, 1-18.

Jordà, G., K. Von Schuckmann, S.A. Josey, G. Caniaux, J. García-Lafuente, S. Sammartino, E. Özsoy, J. Polcher, G. Notarstefano, P.-M. Poulain, F. Adloff, J. Salat, C. Naranjo, K. Schroeder, J. Chiggiato, G. Sannino and D. Macías, 2017. The Mediterranean Sea heat and mass budgets: Estimates, uncertainties and perspectives. Progress in Oceanography, 156, 174-208.

Latif, M.A., E. Özsoy, T. Oğuz, and Ü. Ünlüata, 1991. Observations of the Mediterranean inflow into the Black Sea. Deep-Sea Research, 38(2), 711–723.

Möller, L. 1928. Alfred Merz hydrographische Untersuchungen im Bosphorus und Dardanellen. Veröffentlichungen des Instituts für Meereskunde an der Universität Berlin, 18(A), 284.

Oğuz, T., E. Özsoy, M.A. Latif, H.İ. Sur, and Ü. Ünlüata, 1990. Modeling of Hydraulically Controlled Exchange Flow in the Bosphorus Strait. Journal of Physical Oceanography, 20(7), 945-965.

Oğuz, T. and H.İ. Sur, 1989. A two-layer model of water exchange through the Dardanelles Strait. Oceanologica ACTA, 12(1), 23-31.

Özsoy, E. and H. Altıok, 2016a. A review of hydrography of the Turkish Straits System. In: The Sea of Marmara (Eds: E. Özsoy, M.N. Çağatay, N. Balkıs, N. Balkıs, and B. Öztürk), İstanbul, Turkey: Turkish Marine Research Foundation, 13-41.
Özsoy, E. and H. Altıok, 2016b. A review of water fluxes across the Turkish Straits System. In: The Sea of Marmara (Eds: E. Özsoy, M. N. Çağatay, N. Balkıs, N. Balkıs, and B. Öztürk), İstanbul, Turkey: Turkish Marine Research Foundation, 42-61.
Özsoy, E., M.A. Latif, S. Tuğrul, and Ü. Ünlüata, 1995. Exchanges with the Mediterranean, fluxes and boundary mixing processes in the Black Sea. In: Mediterranean Tributary Seas, Bulletin de l'Institut Oceéanographique, (Ed: F. Briand), Monaco, CIESM Science Series No. 1, 1-25.
Özsoy, E., M.A. Latif, H.İ. Sur, and Y. Goryachkin, 1996. A review of the exchange flow regimes and mixing in the Bosphorus Strait, In: Mediterranean Tributary Seas (Ed. F. Briand), Bulletin de l'Institut Oceéanographique, Monaco, CIESM Science Series No. 2.
Özsoy, E., M.A. Latif, and Ş. Beşiktepe, 2002. The current system of the Bosphorus Strait based on recent measurements. 2nd Meeting on the Physical Oceanography of Sea Straits, Villefranche, 177-180.
Özsoy, E. and Ü. Ünlüata, 1997. Oceanography of the Black Sea: A review of some recent results. Earth Science Review, 42(4), 231-272.
Özsoy, E. and Ü. Ünlüata, 1998. The Black Sea, In: A. R. Robinson and K. Brink (Eds.) The Sea: The Global Coastal Ocean: Regional Studies and Syntheses, pp. 889-914, New York, USA, Wiley and Sons.
Pektaş, H., 1953. Surface currents in the Bosphorus and the Sea of Marmara. Hydrobiology Research Institute, Faculty of Science, University of Istanbul, Hydrobiology Series A, 1(4), 154-169 (in Turkish).
Pektaş, H., 1956. The influence of the Mediterranean water on the hydrography of the Black Sea. GFC Tech. Papers, V4. Rome.
Pinardi, N., E. Özsoy, M.A. Latif, F. Moroni, A. Grandi, G. Manzella, F. De Strobel and V. Lyubartsev, 2018. Measuring the Sea: Marsili's Oceanographic Cruise (1679–80) and the Roots of Oceanography. Journal of Physical Oceanography, 48, 845-860.
Sannino, G., A. Sözer, and E. Özsoy, 2015. Recent advancements on modelling the exchange flow dynamics through the Turkish Straits System. Journal of Black Sea/Mediterranean Environment Special Issue, 110-116.
Sözer, A. and E. Özsoy, 2017. Modeling of the Bosphorus exchange flow dynamics. Ocean Dynamics, 67(3/4), 321-343.
Sümer, B.M., and M. Bakioğlu, 1981. Sea-strait flow with special reference to Bosphorus. ITU Faculty of Civil Engineering, Technical report.
Ulyott, P.H. and O. Ilgaz, 1944. Research in the Strait of Istanbul. A new hypothesis on water movements in the throat. Journal of the Turkish Geography, 6-7.
Ünlüata, Ü., T. Oğuz, M.A. Latif, and E. Özsoy, 1990. On the physical oceanography of Turkish Straits. In: The Physical Oceanography of Sea Straits (Ed: L.J. Pratt) Dordrecht, the Netherlands. Kluwer, 25-60.