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Water Exchange in the Golden Horn

Haliç'de Su Değişimi

Bedri Alpar[(1)], Hüseyin Yüce[(2)], Ahmet Türker[(3)]

[(1)] Istanbul University, Institute of Marine Sciences and Management, Marine Geology and Geophysics Dept., Vefa, İstanbul

[(2)] Gemi Sanayi A.Ş. Tophane, İstanbul

[(3)] Department. of Navigation, Hydrography and Oceanography, Çubuklu, İstanbul, Turkey

Abstract

The water circulation in the Golden Horn estuary is mainly dominated by coupling with the flow in the Strait of İstanbul, which is subject, depending on the atmospheric factors and the water budget, to many nonlinear transient variances such as temporary blocking of the flows in either direction. The present paper describes observations of the water mass structure and circulation in the Golden Horn on the basis of recent oceanographic data.

Keywords: Golden Horn, current, sea level, water exchange

Introduction

The Golden Horn is a 7-km-long estuary located at the southern end of the Strait of İstanbul (Figure 1). Alibey and Kağıthane creeks discharge into the estuary with water inputs of 100 and 106 m^3/year, respectively. The sediments transported by these creeks cause a seaward extension of the sedimentation with an increasing speed. The width of the estuary averages out 370 m; ranging between 293 (Galata) and 685 (Kasımpaşa) metres. Its NE coastline is longer (7,934 m) than the SE one (6,684 m). Its surface area is about 2,565 km^2. The maximum depth is about 40 m at the mouth. A small portion (2%) of the area is deeper than 30 m. More than one third (38%) of the area is shallower than 10 m (Figure 1). Even there are 4 bridges on the estuary, only two of them, the Unkapanı (Atatürk) and Valide Sultan floating bridges which were mounted on the barges as high as 4 m, have an important influence on the water circulation. Both were open to the traffic, that is preventing water circulation, during our measurement period.

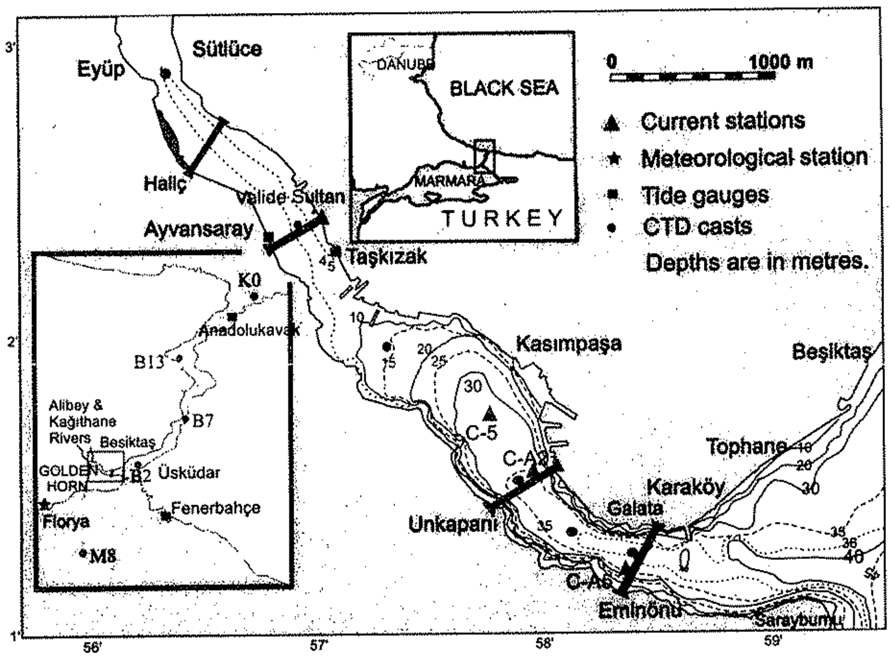

Figure 1. Bathymetry and location of the stations in the Golden Horn. Insets show its location and some localities mentioned in the manuscript.

Physical characteristics of the water column

Its physical oceanographic characteristics, mainly relevant to its pollution, have been investigated in the past (DAMOC, 1971; Doğusal and Güçlüer, 1977; Saydam et al., 1988; Ergin et al., 1990; Saydam and Salihoğlu, 1991; IMC, 1997). The water circulation in the Golden Horn is governed by the volume and rate of flow of the water masses and the meteorological conditions. The topmost of the water masses is the fluvial and brackish water (runoff-rainfall) with a salinity as low as 10 [using the Practical Salinity Scale]. This quasi-fresh water zone is generally 2-3 m thick and is commonly depleted in dissolved oxygen content (0.5-3 mg/l) as a result of increased pollution. Below the quasi-fresh near surface water, a two-layer stratification exists in the Golden Horn; the brackish water of the Black Sea overlying the highly saline (38-39) waters of the Mediterranean Sea, similar to those observed at the southern entrance of the Strait of İstanbul (Yüce, 1986, 1990). The Mediterranean waters in the estuary shows dissolved oxygen contents in the range between 2 and 6 mg/l. The salinity of intermediate layers range between 10 and 38, while they have a relatively high content (3-8 mg/l) of dissolved oxygen. Depending on the seasonal climatic and meteorological conditions, the depth (30 m in normal) and thickness of the transient zone between the intermediate and bottom layers changes (Doğan et al., 1998).

Water Circulation in General

The inflow of the Mediterranean and Black Sea waters into the Golden Horn has a profound effect on the water structures in the estuary and their temporal physical behaviours. The Sarayburnu headland (Figure 1) and its underwater prolongation, which cause an anticyclonic eddy in front of Beşiktaş (Möller, 1928), are the most important geomorphic factors on the water flowing. In normal conditions, the southern sill at 38 m depth between Üsküdar and Beşiktaş (Figure 1) does not prevent the Mediterranean inflow into the strait. However, a little is known if it may help the Mediterranean water to steer towards the Golden Horn, particularly during lower-layer blockage. However, it may help the Mediterranean water to steer towards the Golden Horn in case of a lower-layer blockage. In addition, the southern sill seems to have no steering role on the Mediterranean water towards the Golden Horn during lower-layer blockage events (Alpar et al., 1999).

In recent years, the Mediterranean water intrusion into the Golden Horn has been studied for different weather conditions. In normal or moderate northerly wind conditions the Mediterranean water extends up to Kasımpaşa. This structure varies as a response to changes in prevailing winds and sea-level difference between the Black Sea and the Marmara Sea (Doğan et al., 1998).

The Golden Horn area is affected by two distinct seasonal climatic regimes. During the winter, the weather is dominated by an almost continuous passage of cyclonic systems. During the summer, NE winds coming from the Black Sea are dominant. When not blowing from the NE direction, winds are most often from SW. Northerly winds are dominant from May to October with a frequency of 60%, while the southerly winds (SW-SE sector) occur 20% of the time, mainly in winter months.

Depending mainly on the wind direction and magnitude of the flow from the Black Sea, less-saline, fluvial, drainage and sewer inflows of surface water may leave the Golden Horn in two directions. It may either flow northward entering into the Beşiktaş eddy or eastward the main surface flow of the strait entering into the Marmara Sea.

Data and Results

Oceanography

Using a SBE SeaCat 19 Profiler, temperature, salinity and density measurements were taken on a monthly basis (December, 1997 to December 1998) at the Galata Bridge (Doğan et al., 1998). The distance between the sampling points varies between 0.5 to 2 m. On the basis of the temperature and salinity profiles (Figure 2), two distinct boundaries located at 20-30 m and 25-35 m water depths are evident. The average depth for 20 psu salinity is 22±6 m, it is 27±4 m for 30 psu salinity. Density profiles are very similar to the salinity profiles and will not be given here. These figures indicate a three-layer system in the Golden Horn as an extension of the characteristic two-layer water system observed in the Strait of İstanbul.

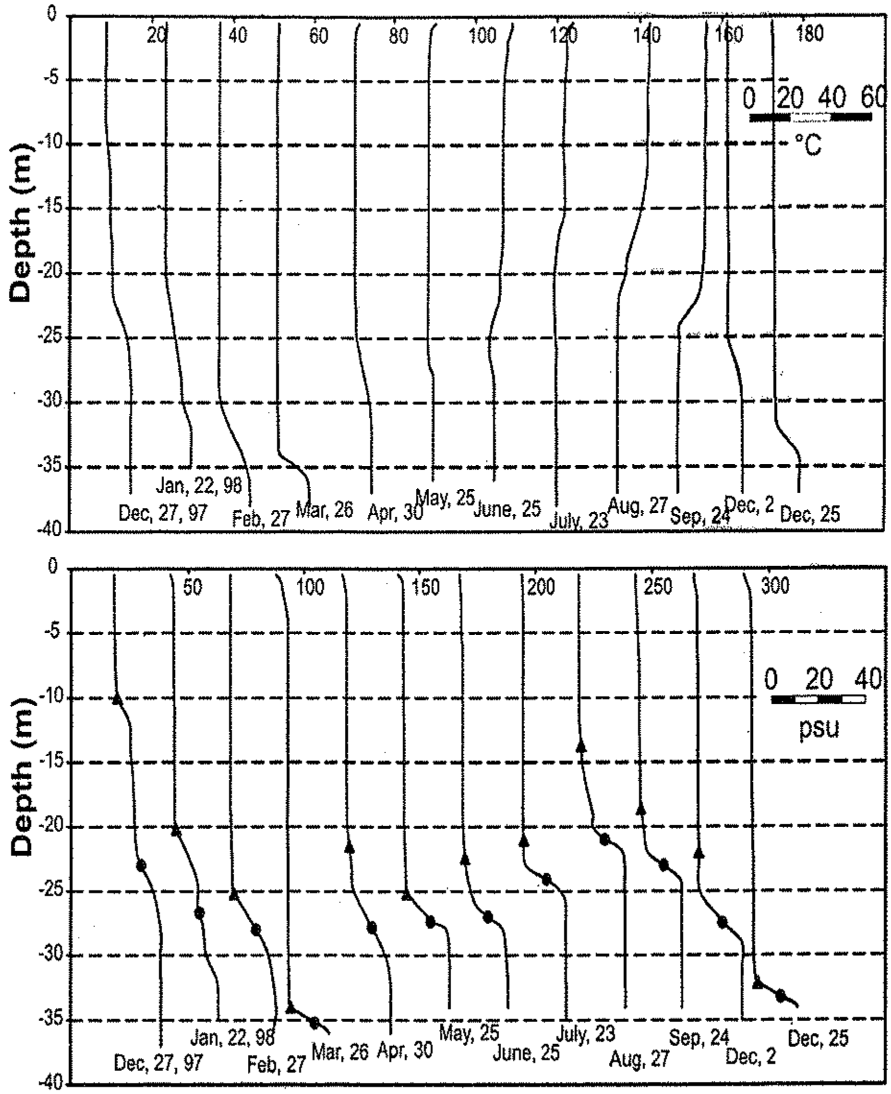

Figure 2. Seasonal changes of the temperature (top) and salinity (bottom) profiles at the exit of the Golden Horn (Galata Bridge). The salinity values of 20 and 30 psu have been defined on the profiles.

Sea Level

Characteristics of the sea-level variations in the Golden Horn and its environments have only been partially studied in the past. At the south end of the Strait of İstanbul, tides are mainly diurnal with a spring range of 2.5 cm (Yüce, 1986; Yüce and Alpar, 1994).

Within the scope of this study, short-term sea level variations were observed at Ayvansaray and Taşkızak (Figure 1). All tidal stations were equipped with OTT Float type tide- gauges. Vertical datum is arbitrary at each station. Water levels were digitised hourly from analogue records. Data shows small amplitude tidal and non-tidal oscillations superimposed upon higher amplitude long-period oscillations (Figure 3). Long–period oscillations are due to both long–period tidal constituents and meteorological influences. Sea levels in the estuary may differ 30-40 cm.

The sea-level variations in the estuary were also compared with those recorded at Anadolukavak, the northern end of the Strait and İstanbul (Figure 3). It was the only available data close to the estuary. The difference between sea levels was variable and may be as much as 30 cm. The long period and tidal oscillations of the Black Sea dissipate along the strait. Therefore the small-amplitude sea level oscillations in the Golden Horn are predominantly under the influence of the oscillations of the Marmara Sea.

The power spectra of the sea-level records for Taşkızak and Ayvansaray were calculated. Spectral estimates were computed for the hourly sea-level records, utilising the Seaspect Software (Lascaratos et al., 1990). The spectral computations were made using 7 segments over the simultaneous data. The energy spectra of the sea levels are almost red, showing some tidal oscillations at semidiurnal and diurnal bands, and long-period oscillations of non-tidal origin (Figure 4).

A linear least squares tidal analysis (Caldwell, 1991) was applied in order to calculate the harmonic constants of the tidal constituents. The amplitude and phases of the M_2, S_2, K_1 and O_1 principal components (semi-diurnal lunar, semi-diurnal solar, soli-lunar diurnal and main lunar diurnal), form numbers, mean spring ranges and mean neap ranges (Defant, 1961) have been calculated (Table 1). The amplitudes and phases were calculated by applying the nodal corrections to the outputs from the linear least squares tidal analysis. Applying nodal corrections allows the fitted components to be used further from the actual time period used to fit the components.

Tidal amplitudes are small. Tides are mixed but mainly diurnal at Anadolukavak, and mixed but mainly semi-diurnal in the Golden Horn. Semidiurnal tides with a marked inequality have a maximum range of 4 cm. This indicates that the atmospheric effects on the sea level are more obvious. Especially, short-term effects of wind on sea level are evident.

Cyclones coming from the Aegean Sea to the Black Sea in winter may pull up water at the southern end of the strait, destroy layer structure at surface, and often cause upper-layer blocking. The influence of southerly winds is pronounced with a sea-level increase in the southern part of the strait; which may also be effective on the water masses in the Golden Horn. In addition, the transient changes in the water budget of the Black Sea or setup by persistent northerly winds can temporarily cause the lower layer flow to be blocked (Oğuz et al., 1990; Özsoy et al., 1998; Alpar et al., 1999). All these events may directly affect the Golden Horn estuary which is coupled to the Strait of İstanbul.

Currents and Circulation

A series of ADCP measurements were taken at the Galata Bridge (Figure 1). The bottom depth is 38 m at the measurement locality. First data set begins on August 25th and ceases on October 6th, 1998. The measurement depths change between surface and -28.4 m. In order to provide a visual comparison with the sea-level variations, the current speeds measured at surface and near bottom at the Galata Bridge are given together (Figure 3). The current speeds are small; with an average of 6.2 cm/s for all measurements.

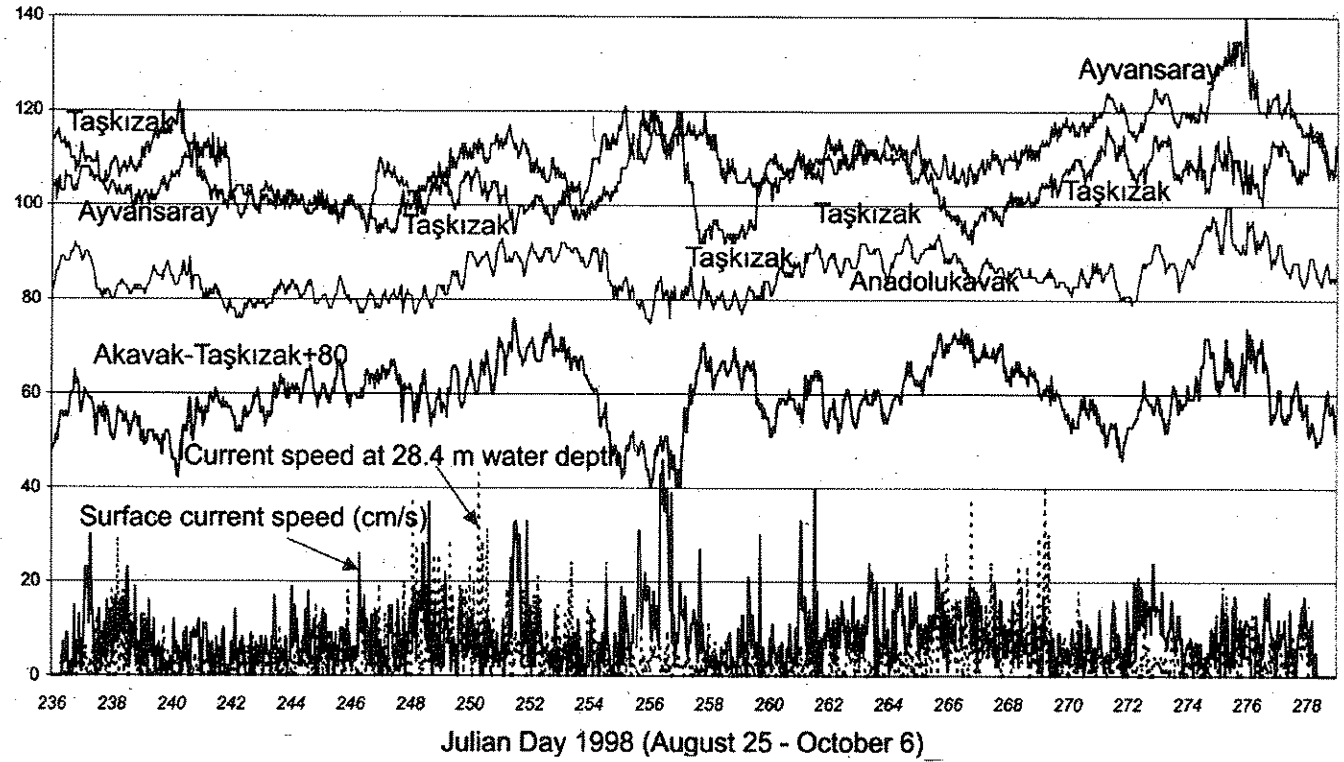

Figure 3. Sea level variations at Ayvansaray, Taşkızak and Anadolukavak. Current speeds at surface and near bottom at the Galata Bridge are given for a visual comparison.

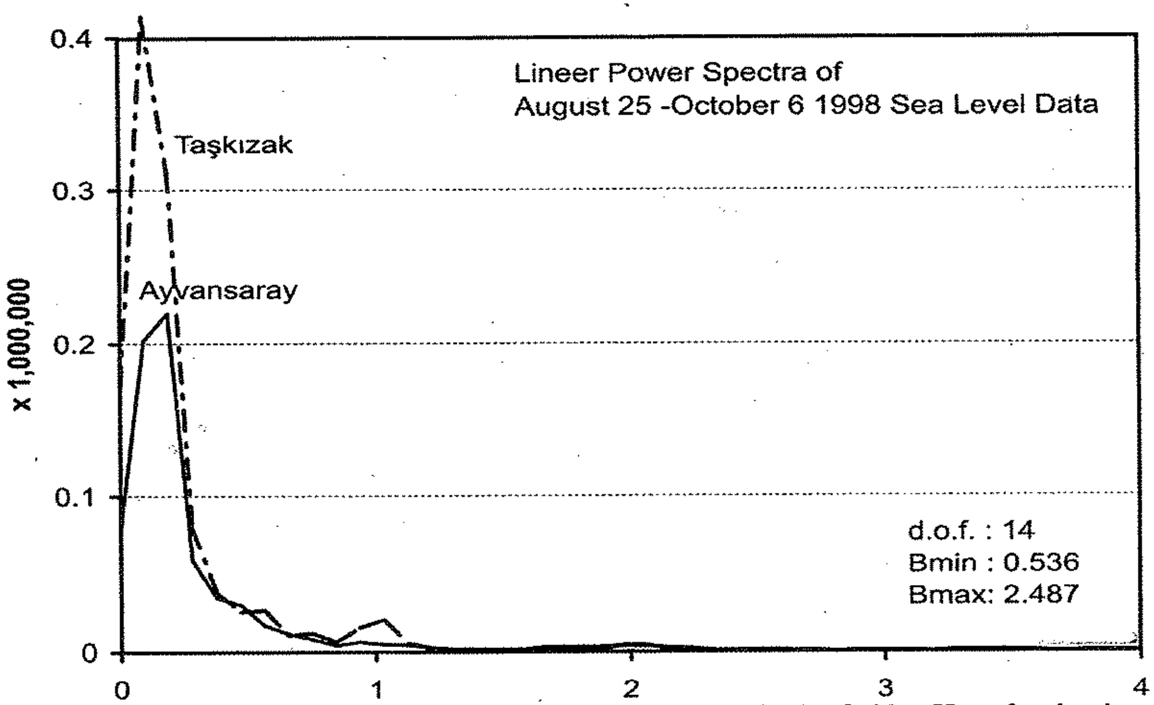

Figure 4. Lineer power spectra of Taşkızak and Ayvansaray sea-levels in the Golden Horn for the time series between August 25 and October 6, 1998; the 95% confidence factor, for 14 d.o.f., is (Bmin = 0.536, Bmax = 2.487) on 1032 points.

Table 1. Harmonic constants of some main tidal constituents at Anadolukavak and in the Golden Horn (Taşkızak) [amplitudes and ranges in cm; phase lags in degrees and relative to Eastern European time origin (30°E) at 00:00, 1 Jan 1976]. (* phase for 030° (EET), ** phase for Greenwich). Mean Spring and Neap ranges and Form Factor.

	M_2		S_2		K_1		O_1	
	H	G	H	G	H	G	H	G
Anadolukavak	0.70	217.4*	0.42	277.1	2.04	102.8	1.13	94.7
		6.9**		97.1		194.1		153.0
	MSR : 6.34 cm , MNR : 0.56 cm, Form Factor: 2.83							
Taşkızak	1.23	57.4	0.54	32.5	1.16	95.3	1.03	95.3
		207.0		212.5		186.5		186.5
	MSR : 3.54 cm , MNR : 1.38 cm, Form Factor: 1.237							

On average, it is 8.1 cm/s for surface with a maximum of 46 cm/s, and only 40% of surface measurements exceeds this mean. Second highest average is 7.3 cm/s for -17.1 m water depth. The average current speed for the deepest measurement point is 4.5 cm/s with a maximum of 43 cm/s, and only 35% of data exceeds this mean. Such slow-speed currents may not be so effective on deposition. In addition, the interaction with the Strait of İstanbul partially prevents the Golden Horn from filling.

On the basis of the progressive vector plots at the measurement depths (Figure 5), there are three distinct current directions. The current direction of the very surface layer is southeastwardly, but it may be reversed. This may be due to wind conditions. Between 5 and 12 m, the currents are directed northwestward. A partial direction diversion can be seen between 20 and 26 days for -11.5 m. However, between these days the current speed is very low. This may imply that this measurement depth is rather close to the water interface between this and overlaid layer. For -17.1 and -28.4 m water depths the dominant current direction is northeast. This direction is not consistent with that of the Mediterranean water. Meanwhile, the most striking feature for that group of currents is that the current speed becomes less and less downwards. The bottom mounted ADCP instrument was unable to record data in the very bottom of 10 metres. Therefore, there should be Mediterranean inflow at the bottom which can not be detected by ADCP measurements. Taking into account these results, we may define three boundaries located at the depths of about 4-5, 12-13 m and 30 m, respectively.

In order to find if some periodicities are existing, especially along the axis of the estuary, the power spectra of the current measurements (110° projected) for Galata Bridge (August 25 - October 6, 1998) were calculated (Figure 6). The spectral computations were made using 7 segments over the simultaneous data. Long period and diurnal fluctuations are dominant for surface currents. There are some periodicities at semidiurnal band especially between 15 and 25 m water depths.

Discussion and Conclusions

On the basis of the oceanographic data and the calculated progressive vector plots, we have separated 4 distinct water layers in the Golden Horn.

a. Surface Layer : The uppermost layer is very thin. It is characterised by downstream movements which are occasionally reversed to upstream, especially during the first half of the measurement period. Its salinity is measured less than 17.

The surficial distribution of this topmost layer can be estimated from the works of Doğan et al. (1998). On August 27th 1998, the surface layer with a salinity less than 16 psu can reach the Valide Sultan Bridge, a structure that impedes free movement of surface waters. On September 24th 1998, the salinity of this cool surface layer was less than that in August. The surface salinity increases seaward, but always less than that measured at the surface water of the Strait of İstanbul. It was measured as 17.5 psu at the inner part of the Galata Bridge. The surface salinity was 14.2 offshore part of the Valide Sultan Bridge. Behind this barrier structure, towards the creeks, the salinity is less than 9.

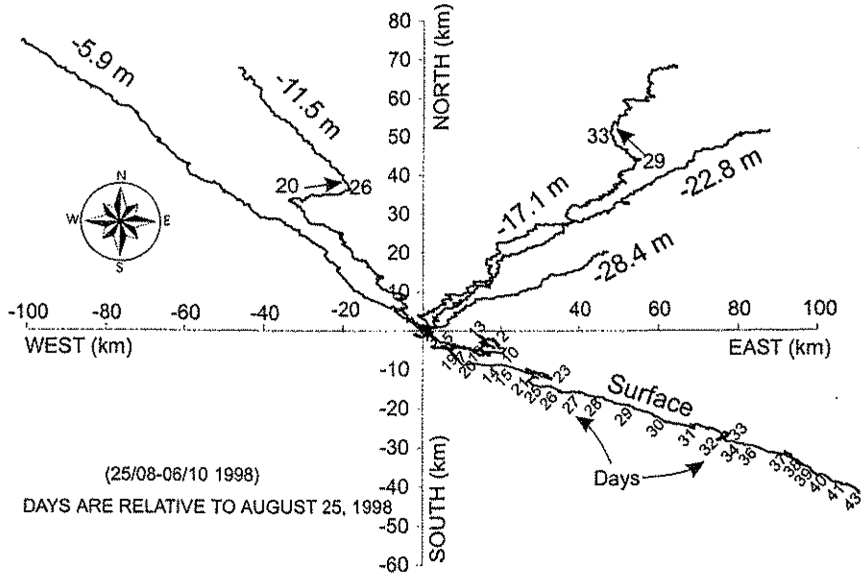

Figure 5. Progressive vector plots of the currents recorded at different depths at the Galata Bridge.

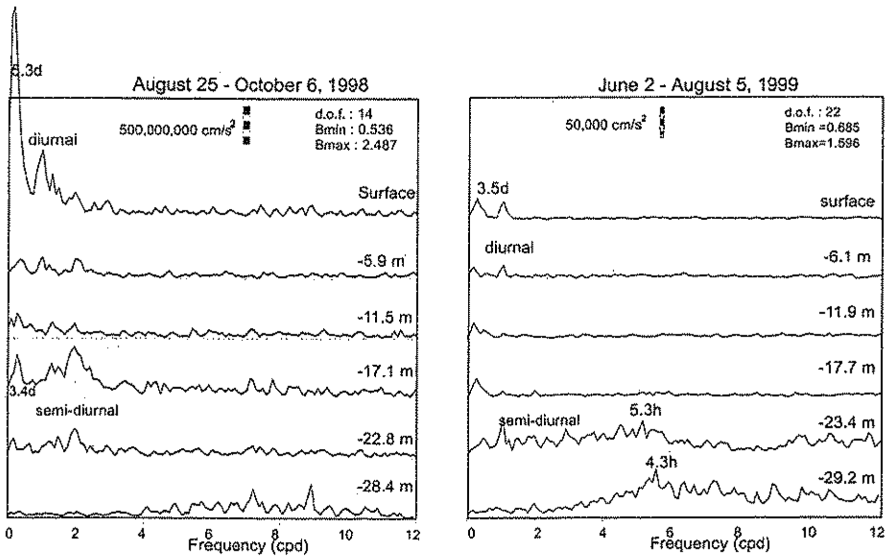

Figure 6. Linear power spectra of current components along-estuary (110° projected) for different depths at the Galata Bridge, Golden Horn. The 95% confidence factor were given in the drawings.

Without considering the current reversals in the surface layer (Figure 5), a simple arithmetical mean of surface current speed is low. If we consider these reversals, an average speed can be calculated as 9.7 cm/s for the direction span of 110±30°. On the other hand, an average speed of the currents entering into the Golden Horn (driven by the surface waters of the SOI) can be calculated as 9.4 cm/s for the direction span of 290±30°.

b. Second (Intermediate) Layer : Under the thin surface layer, an intermediate layer flows upstream. The measurements at -5.9 and -11.5 m stay in that layer. However, within the period of 14-20 September, the current directions observed at the depth of –11.5 m show some reversals (Figure 5). In that specific portion of data set, except for the dates 17.5-18 September, the current directions are similar to those observed at the depth of –17.1 m. This event can be explained by the persistent southerly winds started in the morning on 13 September and dominated for the following 3 days (Kumköy meteorological data, Figure 1). The air pressure was between 1000 and 995 mb, the lowest measured during all data set. These persistent winds pushed the less saline Black Sea water northward along the SOI and the high saline Mediterranean water came upward. Possibly oceanographic conditions continue for a while and the Mediterranean water can be seen at 22-23 m on September 24^{th} (Figure 2). By discarding the effect of these current reversal events, the average current speeds at the depths of 5.9 and 11.5 m were calculated as 3.5 and 3.1 cm/s, respectively.

By the precise areal works of Doğan et al. (1998), this intermediate layer is well defined up to the Valide Sultan Bridge. Its salinity is similar to that of the strait's upper layer (17-20 psu). In summer, because of the seasonal effects such as less precipitation and less fresh water inputs, this layer becomes thinner and its salinity increases. The temperature of the Black Sea originated water in the estuary is higher than its normal because of the decreased circulation.

c. Third (Near-Bottom) Layer : The thickest water mass at the Galata Bridge stays below 13-14 m interface, where the salinity is greater than 20 psu. The current speed in this layer decreases with depth. The averages were calculated as 3.0, 3.1 and 1.4 cm/s at the depths of -17.1, -22.8 and -28.4 m, respectively. The possible effects of a current direction reversal observed at -17.1 m water depth during September 23-27, 1998 (Figure 4) have been eliminated in the average speed calculations. This event is possibly due to the persistent northwesterly winds dominated in the area on 23-24 September. The current directions observed in this layer indicate an outflow which is partly affected by the eddies occurred at the SOI junction of the estuary.

d. Mediterranean Water : We have no continuous current measurements available to represent the Mediterranean inflow at the bottom. Because, unfortunately, the ADCP instrument was unable to record data within the lowermost 10 m. However, a close examination of the data obtained from –28.4 m water depth may give some minor inflows representing the Mediterranean water; e.g. during August 31 – September 1 (Figure 5). This implies that, even the Mediterranean water with a salinity greater than 38 (Yüce, 1996) may be as thick as 15 m (Doğan et al., 1998), with a halocline placed at 22-23 m water depth, it hardly reached to –28.4 m water depth during our measurements between August 25th and October 6th, 1998. However, numerous CTD measurements in the estuary show that the upper boundary of the Mediterranean water varies between 22-35 m at the Galata Bridge. On September 24th 1998, for example, the thickness of the Mediterranean water (38.1 psu) is reported to be 13 m at the mouth which becomes 7 m at the inner part of the Unkapanı (Atatürk) Bridge (Doğan et al., 1998).

All these findings indicate that the circulation of estuarial waters is mainly caused by the intermediate Black Sea layer which carries the fresh water of the open sea into the estuary. On the basis of our obtained results, the flow discharges have been estimated at the mouth of the Golden Horn (Table 2).

Table 2. Estimated flows, based on August 25 - October 6, 1998 current measurements in the middle of the Galata Bridge. Geometric parameters across shores were calculated from the bathymetric maps. * The current speed of Mediterranean water is assumed on the basis of water balance. Negative values show inflow.

Layer	Surface Water	Intermediate Black Sea 1	Near Bottom Black Sea 2	Bottom Mediterranean
Depth Range (m)	0 - 5	5 - 14	14 - 30	30 - 40
Thickness (m)	5	9	16	10
Width (m)	425	400	310	200
Cross Area (m^2)	2125	3600	4960	2000
Current Speed (m/s)	0.032	-0.025	0.013	-0.019 *
Discharge				
m^3/s	+ 69	- 93	+ 64	- 39
m^3/d	+ 6.0E+06	- 8.0E+06	+ 5.5E+06	- 3.4E+06

These results may inherit some deficiencies. At first, since we have not current speed measured for the Mediterranean water, we have assumed a boundary at –30 m and a water balance is existed. In addition, these calculations are based on the average of current data measured at a specific point in the middle of the estuary. The position of the Galata Bridge may have also some unwanted disturbing effects on the measurements. Definitely, the current speed and directions will be changed in space due to the seabed topographical effects and the eddies occurred at the junction of the estuary with the Strait of İstanbul. In addition, seasonal and meteorological variations in the depth of the interface layers will alter our results.

It is evident that cross-section of Doppler current profiles across shores will give much more precise current data. A combination of long-term data series, such as our case, with those current profiles will evidently produce more precise results. Therefore, our results deserve further studies, especially current profiles measured during different seasonal conditions.

Özet

Haliç su sirkülasyonu genel hatları ile İstanbul Boğazındaki akış sistemi tarafından kontrol edilmektedir. İstanbul Boğazındaki durum ise, atmosferik faktörler, Karadeniz su bütçesi, alt ve üst su blokajları gibi birçok geçici fiziksel olay tarafından kontrol edilmektedir. Bu çalışmada haliç içi ve çıkışında yapılan son deniz düzeyi, oşinografi ve akıntı ölçümleri değerlendirilerek İstanbul Haliçi'nin su kütlesi yapısı, su sirkülasyonu ve bütçesi araştırılmıştır.

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