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INVESTIGATING THE WATERS FLUSHING OF THE INNER BASIN OF NEA MOUDANIA HARBOUR (NORTHERN GREECE)

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Abstract. The harbour of Nea Moudania lies at the southeastern coasts of the external Thermaikos gulf and constitutes one of the most important harbours of the Northern Greece. The great importance of the harbour in combination with its imminent extension raises the need of a thorough investigation of its hydrodynamics. The study of the waters' flushing between the inner and outer basin of the harbour constitutes the objective of this work. For this purpose, field research was realised, including current measurements in the port entrance as well as pressure – water level data recordings. Meteorological data have been also collected and studied. The analysis of the collected data led to flushing flow rates of a few m^3/sec, with mean annual value approx. 5.5 m^3/s and corresponding residence times of one order of one day, with mean annual value of 0.7 days. These values were taken into account for the estimation of the self-purification capacity of the harbour inner basin.

Keywords: flushing time, flushing flow rate, harbour, current velocity, Nea Moudania.

AIMS AND BACKGROUND

The waters flushing of a harbour or a coastal basin represents the waters' substitution with fresh water from the open sea through an entrance. It is obvious that the time needed for such a process to be achieved is closely related with the basin's water quality. This time period has been computed for several cases of different harbours in the world; for example the Carberas harbour in Spain, where waters flushing is achieved in 6 days[1] while for the case of the inner basin of the Boston Harbour (United States of America) the time needed for waters flushing is achieved between 2 to 10 days[2]. Also the flushing (renewal) time in a private marina in eastern Thermaikos gulf was estimated to be achieved in 2.9 days[3], while the time needed for the waters of the Port of Thessaloniki to be renewed (flushed) was of the order of one day since the flushing time due to wind was estimated between 1 and 2 days and the flushing time due tide was 11 days[4].

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The above times of waters flushing have been estimated with field measurements or the application of mathematical models. In the present study a research based on field measurements is realised, aiming to the estimation of the waters flushing times and flow rates of the inner basin of Nea Moudanias' harbour in Northern Greece. The harbour of Nea Moudania lies at the west coasts of Chalkidiki and at the southeastern coasts of outer basin of Thermaikos gulf, and constitutes one of the most important harbours in the northwest Aegean sea. The harbour and the whole area of the northwest Aegean sea is given in Fig. 1 (Ref. 5).

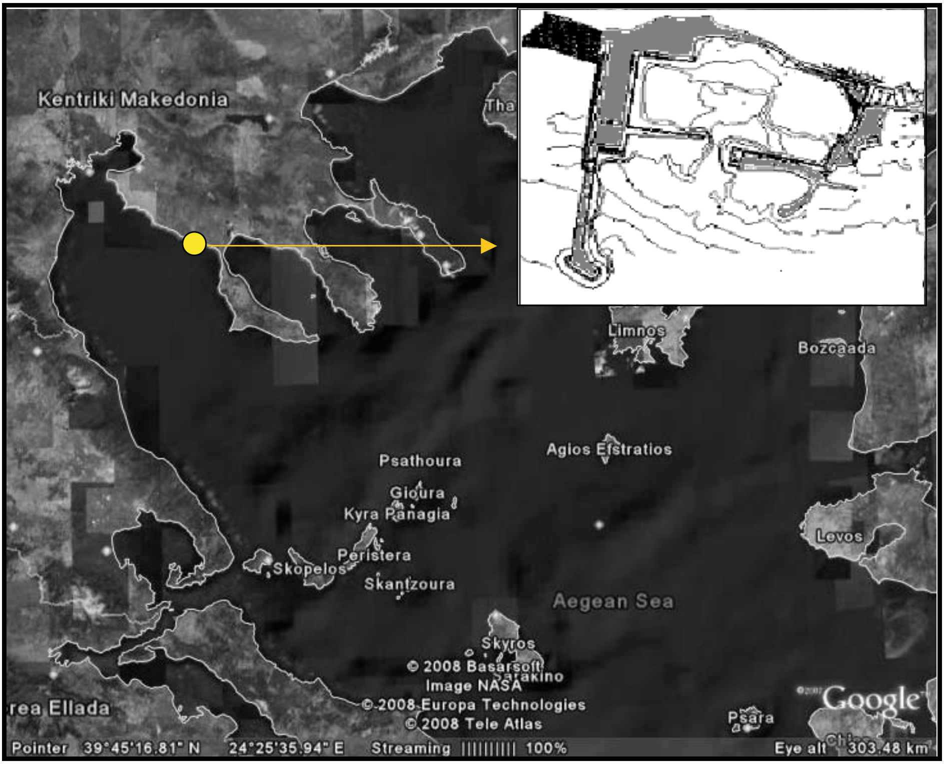

Fig. 1. North Aegean sea and Nea Moudania harbour topography (composition of the N. Aegean map from Google Earth[5] and the topographical drawing of the harbour)

Recent studies for the harbours expansion through dredging and constructing new port facilities and structures in relation with an environmental approach of constructing large structures raise the need of a thorough investigation of harbours hydrodynamics.

Concerning the topography of the particular harbor, the inner basin lies to an area of 70000 m^3, with a volume of 270000 m^3 and a mean depth of about 3.5-4 m. The opening length of the entrance, in the inner basin, is about 50 m with a mean sea depth about 4 m. The water column of the harbour, can be realistically considered as homogenous due to the minor depths, therefore, wind and tide constitute the basic factors of waters circulation. The aim of this work is the study of waters flushing of the inner basin of the harbour, and estimation of the maximum polluting load that the basin of the harbour can undertake according to the calculated flushing time. In this way the self-purification capacity of the harbour can then be estimated.

EXPERIMENTAL

For this study, field research was realised including 10 twelve-hour measurements, from July to December 2007. Submerged currentmeters were used in the entrance of the harbour for the recording of the sea currents velocity and the estimation of flow rates and the water mass exchange between the inner and outer part of the harbour.

In particular, four currentmeters (of the Valeport Company) were submerged in the entrance of the inner harbour. Two couples of currentmeters were installed at the two ends of the harbour breakwaters. Each couple of currentmeters, which was submerged at the same end, was constituted of a currentmeter submerged close to the surface and another one close to the seafloor (with distance of 1-1.5 m between them). Current measurements were also realised in front of a channel at the eastern breakwater, which connects the outer coastal basin with the inner basin of the harbour. These currentmeters were recently used for similar measurements in other areas of Thermaikos gulf[6,7]. At the same time with the currentmeters submersion, a self-recording instrument (CTD Diver) that measures pressure and sea surface level variations, was also submerged. Furthermore, the effect of the wind was taken into account by the collection of meteorological measurements from an adjacent station of the Institute of Forestry Research, and also from the website of POSEIDON system of the Hellenic Center of Marine Sea Research[8]. The computational approximation of waters flushing of a basin was based on the below relation:

$$T = \Omega/Q \tag{1}$$

where Ω is the volume of the harbour inner basin (m^3), Q – waters flushing flow rate (m^3/s) which results from the half of the sum of the entering (positive) and the leaving (negative) flow rates Q_+ and Q_- respectively, T – the waters flushing time of the inner basin of the harbour (in seconds or days). The flows rates Q_+ and Q_- are calculated from the currents velocity data using the following relationships:

$$Q_+ = \sum_i (V_{i\,(+)} A_i) \text{ and } V_{i\,(+)} = \frac{1}{z_2 - z_1} \int_{z_1}^{z_2} v_{i\,(+)} \, \mathrm{d}z \tag{2a}$$

$$Q_- = \sum_i (V_{i(-)} A_i) \text{ and } V_{i(-)} = \frac{1}{z_2 - z_1} \int_{z_1}^{z_2} v_{i(-)} \mathrm{d}z \quad (2b)$$

where $V_{i(+)}$ and $V_{i(-)}$ are the mean depth current speed velocity, which enters or leaves the inner harbour basin, respectively from the entrance surface A_i, which corresponds to the i currentmeter (where i =1 to 4), $v_{i(+)}$ and $v_{i(-)}$ – local velocities, A_i = $[(z_2-z_1)(b/2)]$ and $\Sigma A_i = A$ (where A is the entrance surface area, b is the entrance length, and z_1 and z_2 are determined form the currentmeter vertical position and the depth profile of the flow.

From the above relation, an issue that requires special attention concerns the profile of currents velocity over the depth and the calculation of the flow rates via the approximation of the velocity distribution along the water column. In this study a wind and tidal current profile is adopted as shown in Fig. 2 (Ref. 9).

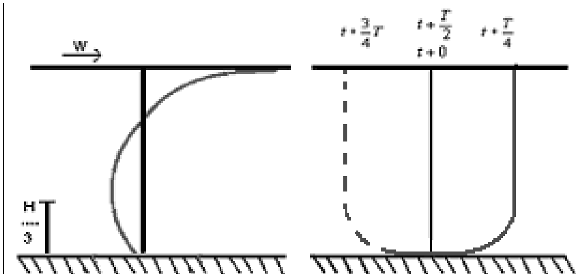

Fig. 2 . Vertical profile of wind (left) and tidal (right) current velocity

It is obvious that current data recorded concerned the resultant current velocity, caused by many different forces, the most important from which are the wind and the tidal action. Through the calculation of the tidal prism and the data level variation, the tidal current component was estimated. Then, abstracting the tidal component from the resultant velocity, the wind component of the current was computed.

RESULTS AND DISCUSSION

Process and resolution of the measurements. Measurements of the sea surface level recorded a variability of approximately ±0.15 m from the mean sea level, with a period of twelve-hours, concluding that waters' flushing based on tidal action is 6.5 days. In Fig. 3 is suggestively given the variation of sea level surface on 14.09.2007.

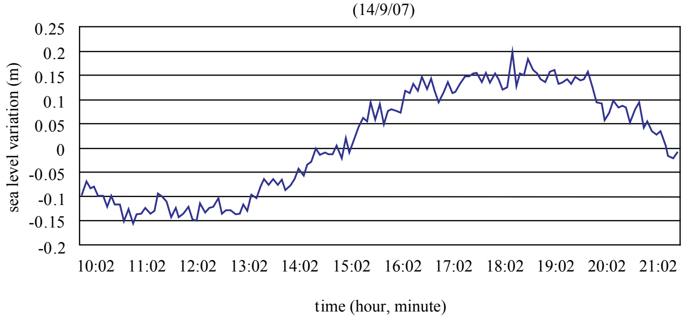

Fig. 3. Variability of sea level during the measurement on 14.09.2007

In Fig. 3, the appearance of common semidiurnal tide with height approx. 0.30 m that agrees with biographical references[10,11]. The figures below show the flow entrance and flow exit in the same measurement period

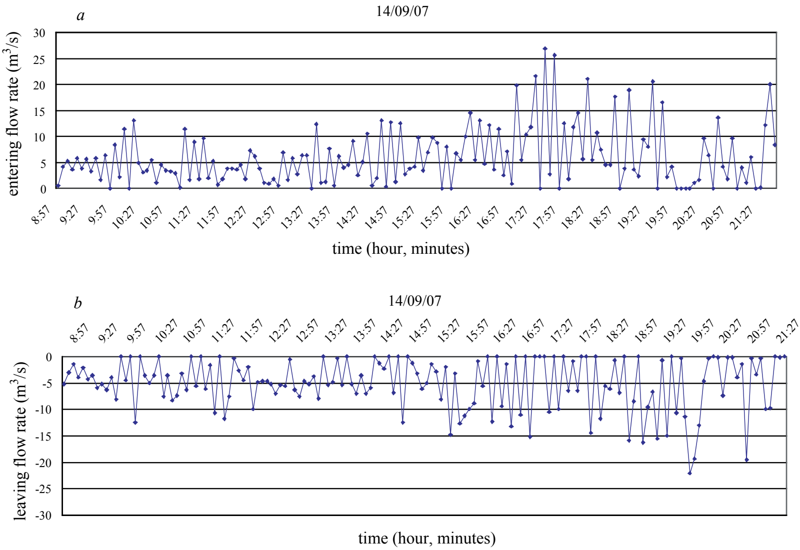

Fig. 4. Entering flow (*a*) and leaving flow (*b*) during the measurements on 14.09.2007

In Fig. 4 flow rates at the entrance of the inner basin are given. They reach 25 m^3/s with a mean rate of 5.5 m^3/s. Flow rates (for the flushing process) recorded at the channel in the eastern part of the harbour, were about two to three orders of magnitude smaller. This fact indicates the negligible influence of the channel in waters' flushing of the inner basin. Figure 5 depicts the flow rates and flushing times of each period of the field measurements.

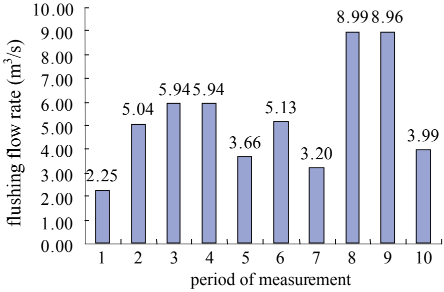

Fig. 5. Flow rates during the measurement periods

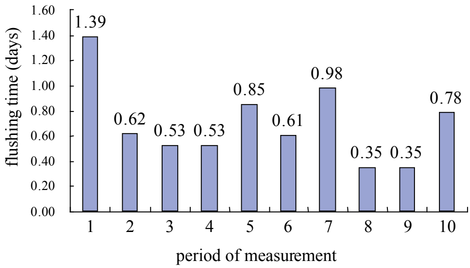

Fig. 6. Flushing times during the measurement periods

Table 1. Data of the field measurements

Meas-urement period	Date	Hour	Wind direction (prevailing)	Flushing flow rate from wind (m^3/s)	Flushing time from wind (days)	Flow flushing (m^3/s)	Flushing time (days)
1	23/7/07	4:00-16:00	NW	1.77	1.76	2.25	1.39
2	31/7/07	16:00-4:00	S	4.56	0.68	5.04	0.62
3	10/9/07	8:00-20:00	SW	5.46	0.57	5.94	0.53
4	14/9/07	10:00-22:00	SE	5.46	0.57	5.94	0.53
5	21/9/07	8:00-20:00	NE	3.17	0.98	3.66	0.85
6	25/9/07	8:00-20:00	SE	4.65	0.67	5.13	0.61
7	13/11/07	5:00-17:00	SW	2.72	1.15	3.20	0.98
8	17/11/07	14.00-2.00	SE	8.51	0.37	9.00	0.35
9	18/11/07	2.30-14.30	NW	8.48	0.37	8.96	0.35
10	2/12/07	5.00-17.00	NE	3.51	0.89	4.00	0.78

In Table 1 the periods of measurements, the time of each period (date and hour), the prevailing wind direction, the flow rate, and the flushing time due to wind as well as the flow rate and the overall (total) flushing time for each period (due to the combined action of tide and wind) are given. Concerning the wind velocity, the meteorological data in all the periods of measurements show mild and mean winds with rare episodes of strong wind, and with the prevailing conditions according to published reports[12,13].

In order to extract representative flushing times for the meteorological conditions through the year, the weighted mean value of flushing flow rate Q_{wind} due to wind is initially calculated from the above wind flushing flow rates (Fig. 1) and the statistical data (during 1950-1968) given in Table 2 (Ref. 14).

Table 2. Statistics of wind data (over a period of 18 years)

Magnitude/direction	N	NE	E	SE	S	SW	W	NW	Calm
Light/mild	6.64	4.20	0.88	6.11	7.18	1.88	3.40	10.77	12.74
Moderate	9.91	1.58	0.90	5.30	6.10	1.55	2.84	6.26	
Strong	3.66	0.15	0.16	0.44	0.55	0.28	0.54	1.17	
Very strong/strong	2.76	0.04	0.06	0.12	0.19	0.44	0.55	0.67	
Sum	22.97	5.97	2.00	11.97	14.02	4.15	7.33	18.87	

More analytically, two main prevailing wind directions were distinguished, based on available periods from measurements; the first one with the north main component, and the second one with the south main component. The main north direction corresponded to the data sets of four measurement periods and the south at six data sets of measurement periods. For a statistically valid information corresponded to meteorological conditions throughout the year, the following approach was adopted: For each one of the two main prevailing directions, mean flushing flow rate has been calculated. Table 2 was used to take into account winds' direction frequency. According to Table 2, north winds appear in a percentage of 47.81%, while south winds appear in a percentage of 30.14%. Frequency of east (2%) and west winds (7.33%), given in Table 2, have been normally distributed (in percentage) to the north and the south winds, as there were no prevailing east or west winds during the periods of measurements. So a percentage of 52.5% of north component and a percentage of 34.8% of north component were taken into account. The rest amount of 12.7% corresponds to calm conditions. This analysis is given from relationship (3) as follows:

$$Q_{wind} = (f_{north}\,Q_{north} + f_{south}\,Q_{south} + f_{calm}\,Q_{calm}) / \Sigma f_I \qquad (3)$$

where f_i is the wind frequency in a particular direction (f_{north} for the case of a north wind, f_{south} for the case of a south wind and f_{calm} for the of calm conditions), Q_{north} – the water flushing flow by mainly north wind direction effect, Q_{south} – the water flushing flow by main south wind direction effect and Q_{calm} – zero water flushing flow.

Following, the flushing time T_{flush} has been calculated from the respective Q_{wind} using the following relation:

$$T_{wind} = \Omega / Q_{wind} \qquad (4)$$

Flushing time T_{tide} and flushing flow Q_{tide} caused from tide have been calculated as it was mentioned before from tide prism through sea surface fluctuation measurements. T_{tide} and Q_{tide} are related as given below:

$$T_{tide} = \Omega / Q_{tide} \tag{5}$$

Total mean flushing time $T_{total,}$ caused by tide and wind has been calculated from relation (6) as follows:

$$T_{total} = \frac{1}{\dfrac{1}{T_{tide}} + \dfrac{1}{T_{wind}}} \tag{6}$$

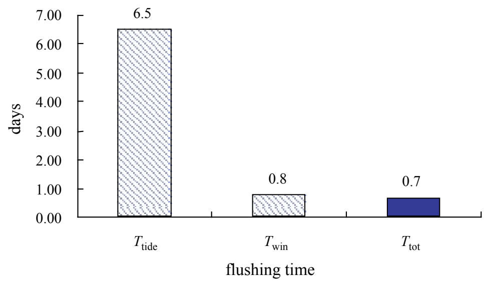

Fig. 7. Mean in the annually flushing times caused by tide (*a*), wind (*b*) and the combined action of tide and wind (*c*)

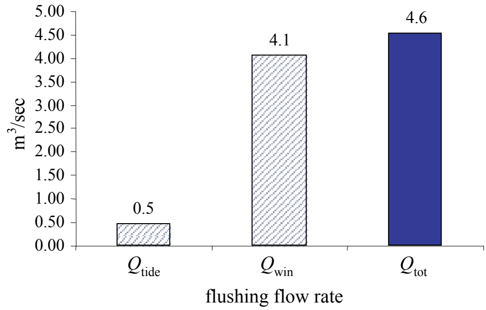

Fig. 8. Mean in the annually flushing flow rates caused by tide (*a*), wind (*b*) and the combined action of tide and wind (*c*)

From the above investigation it is clear that waters flushing is caused mainly from wind action rather than tide.

Control of harbours self-purification capacity. Based on flushing time that was calculated for the inner basin, an attempt to account harbours self-purification capacity follows. The investigation concerns the most unfavourable situation according to which the law provisions are not observed (applied) although the existed law provides measures so that pollution can be avoided. In more detail, the calculation of the harbours self-purification capacity can be based on the flushing time and flow values and also from polluting load q whish corresponds to sewage waters of a maximum number of all the passengers of the boats in the harbour, which in total is estimated to 1000 people. If we take into account a mean value of sewage, 200 l per person per day, then for 1000 people, a load of $q = 0.2 \times 1000 = 200$ m^3/day is used for our computational approximation. To estimate harbours self-purification capacity, so that no eutrophic problems will appear, biological demand oxygen (BOD) parameter was used. BOD is one of the most commonly used parameters for estimation of the organic pollution of surface water and waste waters, respectively. The biological demand oxygen is defined as the quantity needed for the oxidation of an organic component of waste materials from microbes in aerobic conditions[15]. A maximum value C_{er} of BOD in the basin, of the order of 5 mg/l is considered as acceptable[16] . The mean concentration in the basin is given by the following relation[3]:

$$C = \frac{q\,C_0}{q + \Omega/T + \Omega\lambda} \qquad (7)$$

where q is the entering flow discharge (with polluted load), C_0 – the concentration of BOD of untreated sewage (220-400 mg/l), T – the mean flushing time, Ω – harbours volume and λ – the biodegradation coefficient which for urban sewage is of the order of 0.1 (Ref. 17).

The solution of equation (7) gives the concentration of BOD in the harbour inner basin, which is about 0.2 mg/l (<<5 mg/l).

If we consider the case at which no wind blows over the basin (i.e. considering calm conditions) tide constitutes the only basic factor that controls the waters flushing of the port basin and this is obviously the most unfavourable condition for the self-purification process. Thus, taking into account the flushing time caused only from tide 4, i.e. 6.5 days, the solution of equation (7) gives the BOD concentration $C = 1.16$ mg/l in the harbour which is again less than 5 mg/l.

CONCLUSIONS

In this study, the method and the results from a research based on field measurements in Nea Moudania harbours, in east Chalkidiki (Northern Greece) were presented. The aim of this study was focused on the waters flushing of the harbour inner basin. From this study the following conclusions arise:

- The minimum flushing time during the field measurments was 0.35 days (8.4 h) with corresponded flow rate 9 m^3/s (maximum value). The maximum flushing time during the periods of field measurements was 1.39 days (33.4 h) with corresponding flow rate 2.25 m^3/s (minimum value).

● The mean, in the year, waters flushing time of the inner basin of the harbour was calculated to 0.7 days (approx. 17 h) with corresponding mean flushing flow rate 4.6 m^3/s.

● Flushing time caused only by the tide is 6.5 days with corresponding flushing flow rate 0.5 m^3/s while the mean in the year flushing time caused only by the wind was found to be 0.8 days with corresponding flushing flow rate 4.1 m^3/s, i.e. higher than the tidal one (almost an order of magnitude). It is obvious that for calm conditions the flushing time is equal to the tidal one.

● The variability of sea surface level because of tide is approx. 0.30 m.

● Harbours waters self-purification seems to be quite satisfactory, however, under the condition that harbours sea environment will be not overloaded with any other kind of polluting load (such as discharged fish).

It is obvious that the methodology, which was applied in the present research, can be also used diagnostically as well as prognosticallly in other harbours for the forecast or the control of the environmental situation which may be resulted from different solutions or technical changes of the harbour such reconstruction or expanding works.

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