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Numerical Modeling and Site Investigation on Water Body Movements in Ayvalık Bay, Turkey

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ABSTRACT

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Water body movements in bays and seas should also be determined for the solution of many engineering problems. This study aims to determine the hydrodynamic characteristics of the movements of the water body in Ayvalık Bay, one of the most important touristic coastal zones of Turkey with a great number of islands. Ayvalık Bay is located in the Ayvalık county of the province of Balıkesir in the northern part of the Aegean Sea in Turkey. For this aim site measurements and numerical model studies have been carried out. In order to determine the hydrodynamic characteristics of Ayvalık Bay, AQUASEA model was used. Model verification and various scenarios tests were carried out. The output of this project will be basis of pollution studies in Ayvalık Bay. The effects of landfill road (between Ayvalık and Dolap Island) on water circulation could be seen and necessary suggestions were presented. The results of this study would be an important input in the contamination prevention efforts for the sustainable use of the Ayvalık Bay. Knowledge about the interaction between the water body movements and the environmental conditions is crucial for future planning and solution of engineering problems.

ADDITIONAL INDEX WORDS: *Numerical modeling, bay circulation, pollution*

INTRODUCTION

In the past, very limited coastal areas were used by a small amount of population. Nowadays, because of increasing population density, as well as developments in technology and means of transportation, coastal regions are being used more intensively. About 50% of the world's population lives within 60 km of the shorelines. Also, more than half of the Turkey's population lives in coastal regions. The aforementioned population increase in the coastal regions causes pollution in these areas. Therefore, coastal regions and seas should be protected for sustainability. To achieve this aim, one of the milestones is to understand the characteristics of hydrodynamic properties of coastal regions.

A great deal of research has been conducted by scientists to understand the water body movements in bays and coastal waters by using numerical modeling techniques. One of these studies was made by Ivanov *et.al.* (1997) who studied water circulation in the Gulf of İzmir by using a 3D numerical modeling. For this purpose, a multilevel model was applied based on the basic hydrodynamic equations and the components of circulation were reported under various wind conditions. By this study, stratification in Izmir Bay was presented and it is found that this stratification was closely dependent on the direction of wind force. In another study, Sinha *et al.* (2000) analysed tidal circulation and currents in the Gulf of Kachchh along the west coast of India by a vertically integrated numerical model. By using this model, changes at tidal flow were examined due to a dam on Hansthal Creek. They indicated that there was a considerable change in the tidal flow properties as a result of dam. Balas and Özhan (2000) developed a three dimensional baroclinic numerical model, which consists of hydrodynamic, transport and turbulence model components, to compute water levels and water particle velocity distributions in coastal waters. At this study, the developed numerical predictions are compared with the analytical solutions of the steady wind driven circulatory flow in a closed basin and the uni-nodal standing oscillation. The other modeling studies of the same researchers are also available, for example Balas and Ozhan (2001), Balas and Ozhan (2002). In a different study, Inkala and Myrberg (2002) compared two different 3D hydrodynamic model of the Gulf of Finland in the light of field measurements of salinity, sea temperature, water level and current made in 1995. They stated that these two models gave results with similar accuracy. In another study, Kjaran *et al.* (2004) calculated lake circulation and sediment transport in Lake Myvatn using AQUASEA numerical modeling software. In their study, a hydrodynamic numerical model of Lake Myvatn was established and the impact of the mining on sediment transport mechanism was studied. Also, it was revealed that the sediment deposition increased with increasing mining depth in study areas. At a different study, Cucco *et al.*, (2006) investigated water circulation in the Gulf of Oristano by using a 2D hydrodynamic model. They considered the wind as the main process influencing the water circulation of the basin. At the end of their study they deduced that the basin renewal efficiency was generally high under each forcing condition. Wang *et.al.*,(2010), developed a 3D hydrodynamic model and verified their numerical results by using

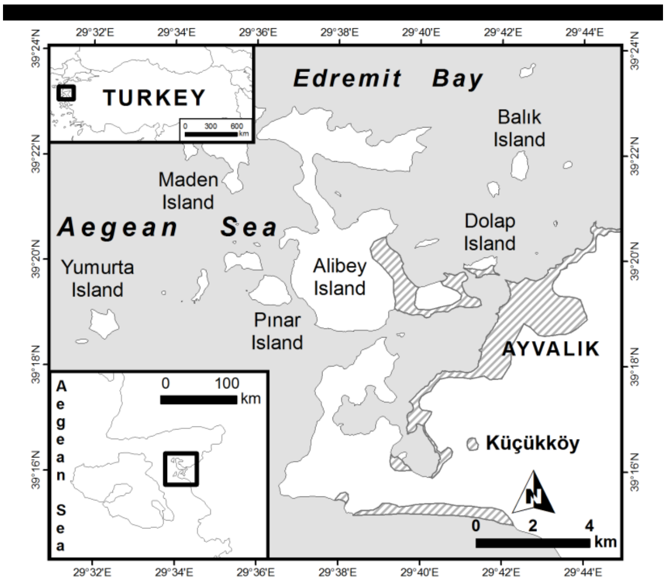

Figure 1. Study area

Figure 2. Measurement points in Ayvalık

in situ measurements at the Changjiang Estuary. The model result demonstrated that both estuarine circulation and long-term transport time-scale exhibit a strong seasonal variation. Freshwater discharge plays a key role in controlling the long-term transport time. The tidal mixing and density-driven flow also affect the transport structure significantly. The estuarine circulation is altered significantly as a result of waterway constructions.

This study aimed to determine the hydrodynamic characteristics of the water body movements for enhancing the solutions of contamination problem of the Ayvalık Bay, one of the most important touristic coastal zones of Turkey with a great number of islands. Ayvalık Bay is located in the Ayvalık County of the province of Balıkesir, in the northern part of the Aegean Sea in Turkey (Figure 1). Ayvalık Bay has a length of nearly 4.5 km and widths varying from 1.6 to 7 km with an area of 24 km^2. It has two mouths; one is at the west side of bay and it connects the bay to the Aegean Sea with a width of 330 m and the second mouth is between Dolap Island and Ali Bey Island and it connects the bay with Edremit Bay with a width of 60 m. Also, there was a third mouth connecting the mainland and Ayvalık Bay with a width of 460 m. This mouth was filled and a landfill road was constructed in 1960's. Thus, the biggest connection between Ayvalık Bay and Edremit Bay was cut and water body movement in Ayvalık Bay was changed. It is believed that the landfill road is preventing the circulation of the Ayvalık Bay, and at the end of this study, the main aim of researchers is to exhibit the effect of this road.

The county of Ayvalık, which also gives its name to the bay, is surrounded by the counties of Burhaniye from the north, Dikili from the south, and Bergama from the east. Ayvalık Bay includes 22 islands. Ayvalık is also called the "City of Islands". A nature park covers 19 of the islands around Ayvalık. Its area is 179 km^2 and it includes 752 kinds of plant. Seventeen of these are found only in Turkey and four plants are endemic-they can only be found in and around Ayvalık.

The Ayvalık Bay is a unique tourism destination with its natural attractions, beaches, recreational sites, rich undersea biota and islands. However, like other bays, this bay also faces the threat of contamination. In summer, with the increasing population, the sewage system becomes insufficient and sewage water is also discharged directly to the sea and contaminates water. It is believed that the mentioned landfill road (about 500 m long, 20 m wide) is blocking the circulation of the Ayvalık Bay. Under this landfill road, two culverts 2.60 m. x 1.60 m. in size were placed side by side to the deepest point on the landfill, and a partial circulation was achieved. However, this achievement is not at a level of required amount for sustainable water quality in the bay. For this reason, a bridge with four spans is planned between Ayvalık and the Dolap Island (Irtem and Soykan, 2008). With this study, this efficiency of this alternative is investigated by using a numerical modeling techniques accompanied by field study for calibrating and validating the numerical model.

METHODS

The study consists of two parts; the first part is field measurement which includes velocity, seawater temperature, pressure, conductivity and turbidity measurements over depth and the second part is numerical modeling with AQUASEA software for obtaining the circulation pattern of Ayvalık Bay for various scenarios.

Site Measurements

For determining the water body movements of the area, a field study was done at 20/11/2009 in Ayvalık Bay. During this study, Aanderaa Instruments ADCP-9 was used for velocity measurements at the points shown in Figure 2. In this measurement, velocity readings were done in 1 meter intervals to get velocity profiles for that measurement points. Additionally, velocity direction, sea water temperature, pressure, conductivity and turbidity measurements were made. Furthermore, a tide measurement was made along the coast of Ayvalık Bay simultaneously with velocity measurements.

In addition to measurements, visual observation of marine environment around the project area gave opinion about general water quality. In the light of these observations, it can be clearly said that the coastal areas around the Ayvalık province face with large scale contamination. Around the measurement point 4 (Figure 2), the colour of seawater unnatural (brown) with high turbidity and there was bad odour because of high organic pollution depending on sewage discharge. Furthermore, there was pollution inside the bay not as high as at the measurement point 4. As an exception, the only sea water with normal physical appearance was observed around the Aegean Sea mouth of the bay (around point 1). However, outside the bay, clear sea water was observed, especially around the measurement points 5 and 6 (Figure 2). Furthermore, in these areas *Posidonia Oceanica* seagrasses, one of the main indicator of high quality sea water (Elginoz, 2010), were observed which supports our conclusion about the water quality of said region.

Numerical Modeling

Hence the numerical modeling tools are cheaper, easier and faster than physical modeling, they are the most widely used tools by scientists for modeling the hydrodynamics of larger water bodies. In numerical modeling, a prototype of a water body is simulated with all forces, and at the end of this process, hydrodynamic properties of water body are obtained. Generally, numerical modeling concept in hydraulics includes two main processes which are surface flow model and transport model. In the scope of this study, only the surface flow model process was dealt with. In order to determine the hydrodynamic characteristics of Ayvalık Bay, the AQUASEA model, which is widely used in engineering applications to model coastal zones, estuaries, lakes and rivers was used. The surface flow model was based on conversation of mass and momentum equations (Equations 1, 2 and 3) in two coordinate directions. For conversation of momentum Saint-Venant equations were used (Equations 2 and 3) which were obtained from Navier-Stokes equations by averaging the horizontal velocities in the depths of the water body (Vatnaskil. 1998).

$$\frac{\partial(uH)}{\partial x}+\frac{\partial(vH)}{\partial y}+\frac{\partial\eta}{\partial t}=Q \qquad (1)$$

$$\frac{\partial u}{\partial t}+\left(\frac{\partial u}{\partial x}\right)u+\left(\frac{\partial u}{\partial y}\right)v=(-g)\left(\frac{\partial H}{\partial x}\right)+fv-gu\left(\frac{\sqrt{(u^2+v^2)}}{HC^2}\right)+kW_x|W|+\frac{Q(u-u_0)}{H} \qquad (2)$$

$$\frac{\partial v}{\partial t}+\left(\frac{\partial v}{\partial x}\right)u+\left(\frac{\partial v}{\partial y}\right)v=(-g)\left(\frac{\partial H}{\partial y}\right)+fu-gv\left(\frac{\sqrt{(u^2+v^2)}}{HC^2}\right)+kW_y|W|+\frac{Q(v-v_0)}{H} \qquad (3)$$

The variables in these equations are:

- u: water velocity components in x direction, m/s
- v: water velocity components in y direction, m/s
- t: time, s
- g: acceleration due to gravity, m^2/s
- H: total water depth, m
- η: change in water level, m
- f: Coriolis parameter
- C: Chezy friction coefficient, $m^{1/2}/s$
- k: wind stress parameter
- W: horizontal wind velocity, m/s
- W_x: wind velocity component in x direction, m/s
- W_y: wind velocity component in y direction, m/s
- Q: injected water, m^3/s
- u_0: injected water velocity component in x direction, m/s
- v_0: injected water velocity component in y direction, m/s

The model solves the differential equations of flow and transport using the finite element method. Finite element method includes the generation of a mesh structure with predefined nodes on and in the model boundary. The mesh is composed of triangles, the edges of which are defined by model nodes. Each triangle is an element, and calculations are carried out for each element. If the model is run in unsteady conditions (as in this study) calculations are done by making iterations with very small values of differential parameters. When the predefined time step is reached, the calculation is concluded and calculations for next time step begin.

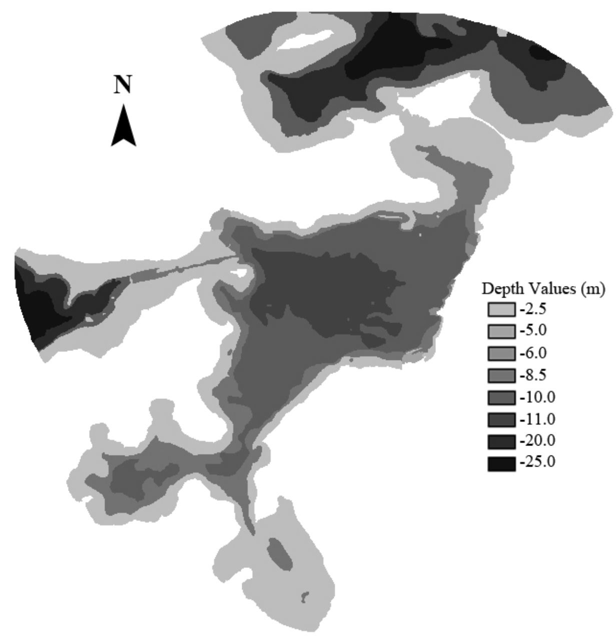

Figure 3. Bathymetry used in numerical models.

Two numerical models were set up for an area of approximately 24.35 km^2 and the bathymetry used in these models is shown in Figure 3. In the first model, existing conditions of the area was setup using current bathymetry and topography of the region. For the second model, landfill road which is seen as the main reason for blocked circulation in the bay was removed from topography to compare two situations. In these two models, the mesh density was increased around the project area. The time step was set to 6 seconds, near to real-time. A 20 cm tide was added to the model as an input that creates the flow. Additionally, a 2 hours shift phase of tide was added between Aegean Sea and Edremit Bay entrances of Ayvalık Bay. Finally, a total running of 48 hours was set aside for the runs.

RESULTS

In the context of this study, two numerical models were solved for understanding the effect of the landfill road on the main water body motion of the Ayvalık Bay. In the first numerical model (Alternative 1), the existing bathymetrical and topographical conditions were simulated. By running this model, an attempt was made to exhibit the existing water body motions in Ayvalık Bay. Furthermore, the flow characteristics obtained by the numerical model were confirmed with field study data (Table 1). Tide measurements which were made simultaneously with velocity measurements were also taken into consideration consistent with tide phase at this confirmation process. Thus the relationship between the velocity and tide phase were deduced. After that step, the velocity values corresponding to this tide phase were read from numerical model. It can be clearly seen from Table 1 that the field measurements and numerical model match in respect to their velocities and directions at the points 1 and 3. Nevertheless, measurement points 2 and 4 have same velocity values but different directions when the same comparison was made. The main reason of this situation is the different velocity sources acting on the water body in the numerical model. In this study, only the effect of tide was considered when establishing the numerical model depending on that being the main force driving the circulation pattern in the bay. However, field measurements

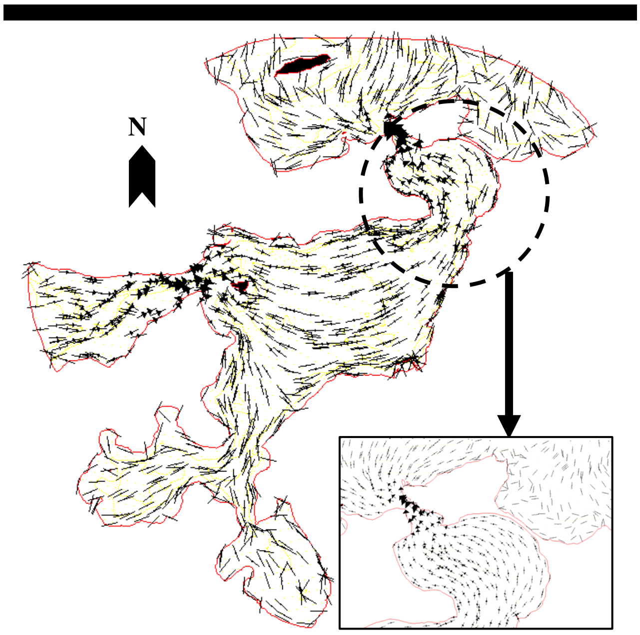

Figure 4. Flow vectors at a typical flood phase of Alternative 1.

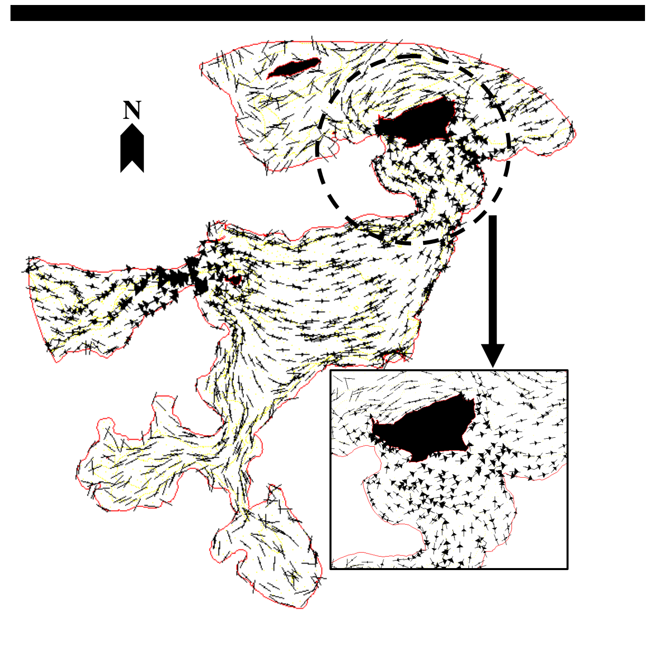

Figure 6. Flow vectors at a typical flood phase of Alternative 2.

were including other effects such as wind drift in addition to the tidal effects and this is the reason of mentioned direction difference obtained especially at the low velocity values.

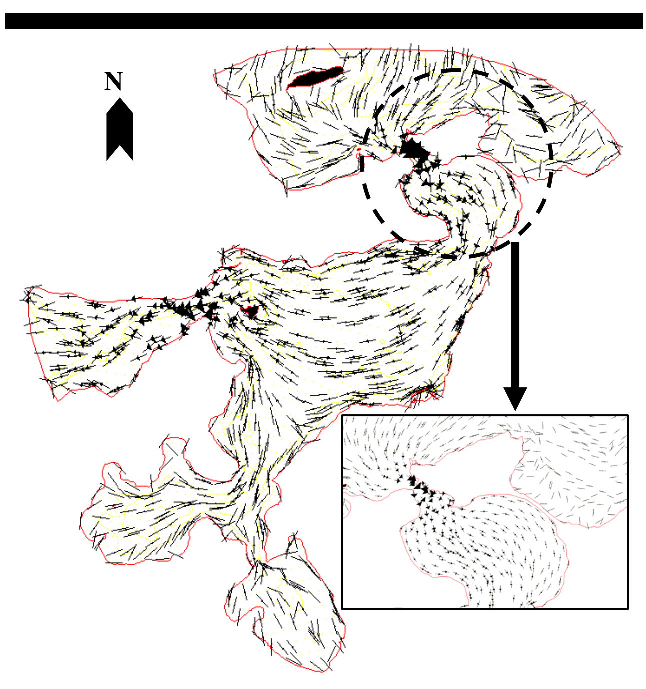

Figure 5. Flow vectors at a typical flood ebb of Alternative 1.

The typical flow vector outputs of Alternative 1 are shown in Figure 4 and 5 for both flood and ebb phases, respectively. Also some depth average velocity values gained from numerical models at the field measurements points are summarized in Table 1. The tidal phases were taken into account and the phases matched the field measurements and numerical model.

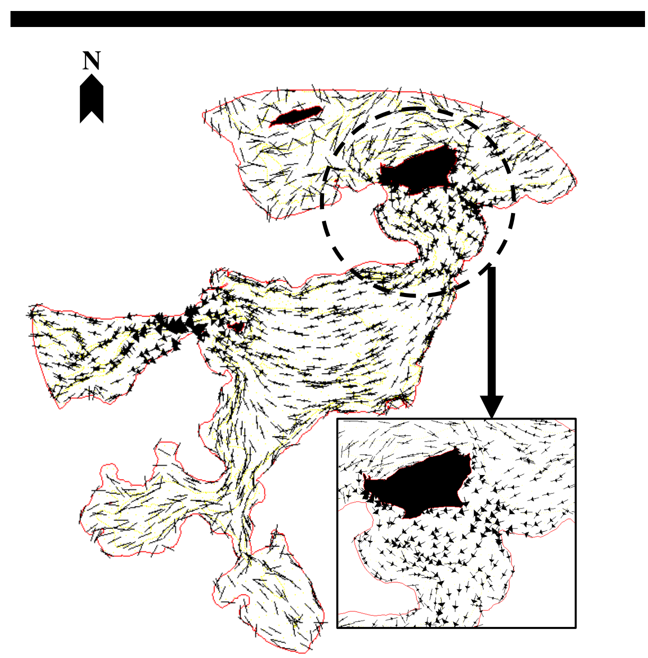

Figure 7. Flow vectors at a typical ebb phase of Alternative 2.

As we examine the site measurements and numerical model outputs belonging to Alternative 1, it is clearly seen that both values are significantly close to each other (Table 1).

Removal of existing landfill road is thought to be a solution for providing better circulation of water body of Ayvalık Bay and by this aim, an alternative numerical model scenario (Alternative 2) without road was built and run. In summary, the only difference between existing conditions (Alternative 1) and scenario (Alternative 2) was the existence of landfill road. Results of this model test are presented in Figures 6 and 7 for the typical ebb and flood phase of tidal current in Ayvalık Bay.

Table 1: Velociy values and directions of numerical model validation points.

	Field Measurements			Numerical Model Outputs		
Point No	Velocity (cm/s)	Direction (degrees)	Direction	Velocity (cm/s)	Direction (degrees)	Direction
1	9.45	59.95	NE	8.13	48.10	NE
2	3.42	239.00	SW	2.16	95.52	E
3	12.47	318.98	NW	15.80	320.20	NW
4	6.57	36.53	NE	6.87	106.50	E

Table 2: Maximum velocity values of tidal phases belongs to numerical models

	Alternative 1		Alternative 2	
Point No	Ebb (cm/s)	Flood (cm/s)	Ebb (cm/s)	Flood (cm/s)
1	8.22	8.22	16.3	16.4
2	2.62	2.6	5.33	5.41
3	37.8	36.7	18	17.4
4	14.7	15	9.75	9.93
5	0.29	0.34	0.44	0.44
6	0.2	0.27	8.64	8.62

Also depth averaged maximum tidal velocity values at the same points as the field measurements points were summarized in Table 2. In light of the data in Table 2, it can be clearly said that removing the road has a significant positive effect on the circulation of the Ayvalık Bay. In particular, it was predicted that the velocity increment at point 6 improves circulation in polluted areas. At this point, velocity values increased approximately 40 times compared to the existing conditions. This increment will provide a sufficient circulation in Ayvalık Bay if the landfill road is turned into a four span bridge road which allows water circulation.

CONCLUSIONS

In this study, the water body movements in the Ayvalık Bay and the effect of the landfill road on these movements were investigated. For this aim, site measurements and numerical model studies have been carried out. Two different numerical model alternatives were prepared depending on if they were including the existing landfill road or not to give opportunity for comparison of two cases. Existing conditions were obtained with first numerical model test which gave compatible results with field measurements. Higher velocity values in the polluted areas obtained by the second model which simulates water body movements without existing landfill road. According to these results, it can be clearly said that this increment will have a positive effect on the water circulation of Ayvalık Bay. For this reason, authors of this paper are suggesting to removal of the landfill road and constructing a four span bridge instead of it in order to gain better circulation for preventing contamination problem in Ayvalık Bay. The results of this study would be an important input in the contamination prevention efforts for the sustainable use of the Ayvalık Bay.

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