

Estimating water renewal time in semi-enclosed coastal areas of complicated geometry using a hydrodynamic model

A.I. Stamou†, C. Memos‡ and K. Spanoudaki§

†School of Civil Engineering
National Technical University of Athens
Iroon Polytechniou 5
15780 Athens, Greece
stamou@central.ntua.gr

‡School of Civil Engineering
National Technical University of Athens
Iroon Polytechniou 5
15780 Athens, Greece
memos@hydro.ntua.gr

§School of Civil Engineering
National Technical University of Athens
Iroon Polytechniou 5
15780 Athens, Greece
kspan@mail.ntua.gr



ABSTRACT

STAMOU, A.I., MEMOS, C. and SPANOUDAKI, K., 2007. Estimating water renewal time in semi-enclosed coastal areas of complicated geometry using a hydrodynamic model. *Journal of Coastal Research*, SI 50 (Proceedings of the 9th International Coastal Symposium), 282 – 286. Gold Coast, Australia, ISSN 0749.0208

A methodology is presented to determine water renewal time in semi-enclosed coastal areas with artificial peninsulas or islands of complicated geometry. The methodology is applied in Durrat Alkhobar development in Saudi Arabia. The coastal area consists of the inner and the outer region. The inner region will be dredged and a fingerlike alignment will emerge. A hydrodynamic model was applied to illustrate the future conditions of the Bay regarding water circulation and renewal due to wind and tidal forcing. The model employs the fundamental hydrodynamic equations of continuity and momentum. The inner region of the coastal area was divided into 21 compartments. The communication of the inner region with the outer region is performed via two openings. Calculations showed that average renewal times ranged from 2.3 to 10.1 days for the wind conditions tested; in 12 compartments renewal times were less than 10 days. Furthermore, tide contributed significantly to the renewal of waters. Renewal time decreased with increasing wind velocity; southerly winds were beneficial for water renewal, because they created flow fields with relatively high exchange of flow via the openings.

ADDITIONAL INDEX WORDS: *Tidal flows, Wind driven flows, Flushing time, Artificial islands*

INTRODUCTION

In the last years the development of coastal areas in various artistic arrangements has become very popular. Coastal areas are dredged and artificial peninsulas or islands of complicated geometry are constructed. In the future, the artificial peninsulas or islands may be common sights as many cities around the world, especially in Asia, face severe urban land shortages and congestion. The largest artificial islands in the world are the Palm Islands in the Persian Gulf, which have the shape of a palm tree, topped with a crescent. The World is another example, which was inspired by the Palm Islands; it is an archipelago of artificial islands, shaped like the continents of the Earth, being constructed off the coast of Dubai.

Renewal of waters is very crucial in such complicated arrangements for the supply of oxygen and the removal of pollution. The estimation of the expected water renewal time is performed during the design phase and it is usually included in the Environmental Impact Assessment study. When this investigation is underestimated or ignored, significant environmental problems may arise resulting in the need to perform alterations in the original geometry with significant cost expenditure. A typical example of such an underestimation is Jumeirah, one of the three Palm Islands, whose construction began in June 2001 and is expected to be completed in 2006. Due to design changes the expected completion date is now December 2007. After the Palm had been constructed, it was discovered that the tide did not reach all the way around the crescent with sufficient momentum to prevent stagnation of the water resulting thus in extremely high renewal times. The crescent was modified with two extra

channels, each about a quarter of the way from either end. These channels allow greater scope for the action of the tide and thus the water renewal time inside the Palm's boundary was reduced to approximately 15 days.

In the present work a methodology is presented to determine water renewal time in semi-enclosed coastal areas with artificial peninsulas or islands with complicated geometry. The methodology was applied in Durrat Alkhobar development area.

METHODS

The proposed methodology consists of the following 4 steps. (1) A hydrodynamic model is selected for the calculation of the typical flow fields associated with the prevailing or design environmental conditions. (2) The computational grid is constructed and the coastal area is segmented into compartments communicating among themselves via cross-sections, which are named internal boundaries. (3) The model is applied to calculate the flow field; calculated flow velocities are used to determine water flow exchanges across the internal boundaries. (4) Renewal times are calculated for the compartments; these values are used to identify those of the compartments with poor water renewal, for which modifications can be proposed prior to finalizing the layout.

The Hydrodynamic Model

The hydrodynamic model FLOW-3DL (STAMOU *et al.*, 1999a; STAMOU *et al.*, 1999b) was selected to perform the calculations. FLOW-3DL involves the 3-D non-steady state continuity and momentum equations, which are expressed in horizontal layer formulation. Using fixed permeable interfaces between layers, the

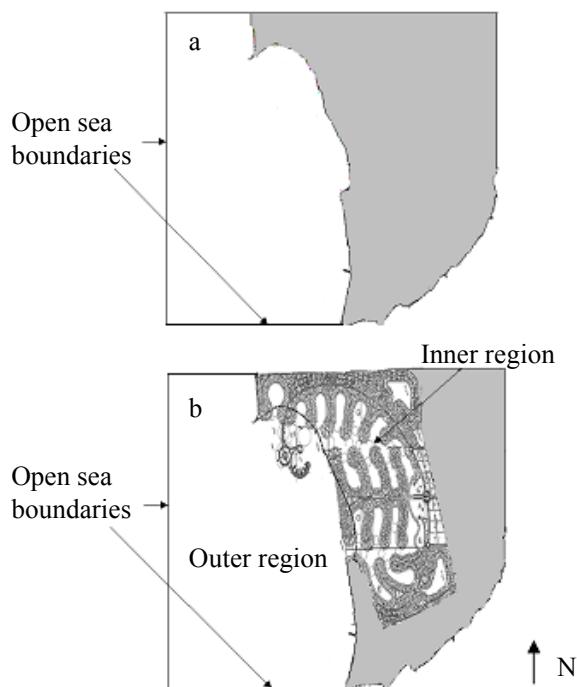


Figure 1. The study area (a) in its current state and (b) after the planned construction of artificial islands.

equations of the model are vertically integrated over a depth range, corresponding to a computational layer of that thickness. The variables of the equations are the layer averaged velocity components u , v and w , along the axes x , y and z , respectively of a Cartesian coordinate system and the free surface elevation ζ . More information on the model and its calibration in a coastal area with similar characteristics can be found in STAMOU and MEMOS (2006).

ANALYSIS

The Study Area

Durrat Alkhobar development area covers the southernmost tip of the Qurayyah Peninsula at some 18 km south of Al Khobar of Saudi Arabia. The bay waters outflow to the Saudi Arabia – Bahrain channel through an opening facing SE. It is planned to

Table 1: Water volume (m^3) of the compartments.

Compartment	Volume	Compartment	Volume
1	270000	12	326250
2	135000	13	258750
3	517500	14	281250
4	258750	15	236250
5	281250	16	618750
6	270000	17	405000
7	315000	18	258750
8	281250	19	292500
9	348750	20	1057500
10	247500	21	371250
11	303750	Total	7335000

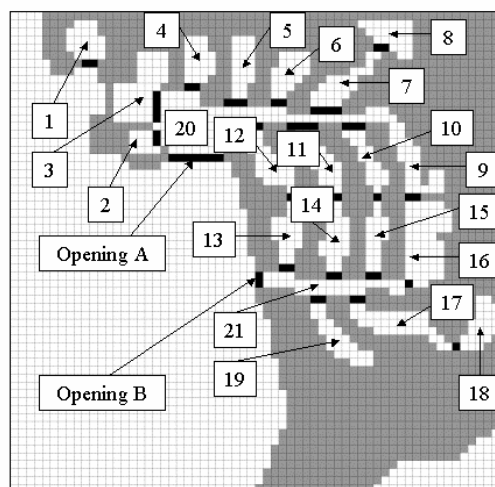


Figure 2. Computational grid of the study area. Numbers indicate the numbering of compartments. Dark bars indicate the internal boundaries.

dredge an area of about 5 km² to form a coast with a fingerlike alignment (inner region), as shown in Figure 1, while the rest of the coastal area will remain unaffected (outer region). The water depth after dredging will be uniformly 4.50 m at Mean Sea Level (MSL).

The Computational Grid

A relatively fine, space staggered, rectangular grid was used, which covers the inner and outer regions. The grid, which consists of 64x63 control volumes with constant resolution equal to 50 m and 4 layers in the z -direction, is shown in Figure 2. This grid was selected after performing grid independence tests. The thicknesses of the 4 layers starting from the surface are 0.5 m, 1.0 m, 1.5 m and 1.5 m.

Preliminary calculations were performed with a coarser grid covering the greater area of study and consisting of 86x110 control volumes with constant resolution equal to 200 m. The results of these computations were used for the verification of the approximate boundary conditions used in the computations with the fine grid.

The Compartments of the Inner Region

The inner region was divided into 21 compartments. As shown in Figure 2, compartments 1, 20 and 21 communicate directly with the outer region, while compartments 2 to 17 communicate with compartments 20 and 21 and the latter with the outer region via openings A and B. The communication among compartments is performed via internal boundaries, as shown in Figure 2 with dark bars. The water volumes of the compartments are quoted in Table 1.

Conditions and Series of Calculations

Six series of calculations were performed for the characteristics shown in Table 2. The first series was performed to determine typical tidal flow patterns and the rest to determine typical steady-state wind-driven flow patterns for the (design) wind characteristics, which are shown in Table 2.

Table 2: Series of calculations.

Series	Wind direction	Wind velocity (m/s)
S0	-	-
S1	0°, N	7.0
S2	90°, E	5.0
S3	135°, SE	8.0
S4	195°, SSW	4.6
S5	285°, WNW	4.1

From the calculated flow fields the following parameters were determined: (1) Magnitude and direction of flow velocities. (2) Exchange of flow between the inner and the outer region via the openings A and B. (3) Flushing times of the waters of the inner region and its individual compartments in order to identify the regions with reduced water renewal.

In this study the effect of wave induced circulation on the flushing time was not investigated. This effect could further improve the calculated flushing times, depending on wave direction, wave height etc.

Boundary Conditions

In all layers, the shoreline boundaries were treated as “solid walls”, at which the normal velocities were set equal to zero.

For the tidal calculations a periodic function of the water elevation was used to describe the effect of the tide along the open sea boundaries. Its expression has the following form

$$\zeta(t) = +0.12 \sin\left(\frac{2\pi t}{T}\right) \quad (1)$$

where $\zeta(t)$ is the elevation (m), t is the time (hours) and T is the

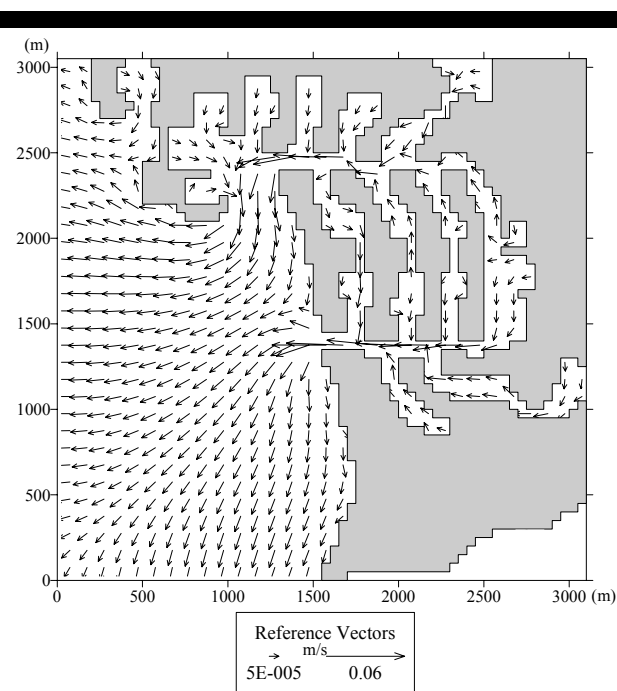


Figure 3. Tidal flow field (Series S0) – Top layer (0.0 – 0.5 m) – $t=T/2$ (ebb tide).

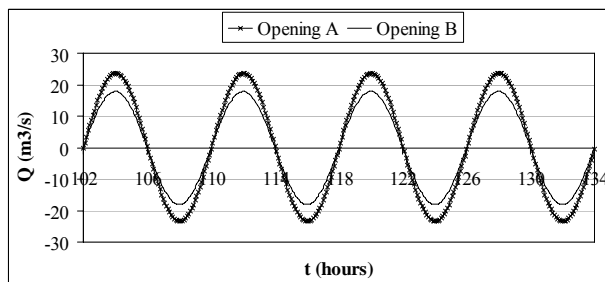


Figure 4. Variation of the flow rate across openings A and B.

period ($T=8$ hours). Equation (1) was applied at the two open sea boundaries, which are shown in Figure 1.

For the wind driven calculations a simplified boundary condition was adopted at these open sea boundaries, which assumes no variation of velocity along the boundary.

RESULTS AND DISCUSSION

Tidal Flow Calculations

In Figure 3 the velocity vectors of the top layer are shown for $t=T/2$. In Figure 4 the exchanges of flow via opening A (Q_A) and opening B (Q_B) are shown.

The calculations and Figure 3 show a tidal behaviour with maximum flow velocities at the top layer of the order of 0.06 m/s. The flow rates Q_A and Q_B varied approximately between -23.5 and $+23.5$ m^3/s and between -17.5 and $+17.5$ m^3/s , respectively. The absolute average flow rates were calculated equal to $(2/\pi) \times 23.5 = 15.0$ m^3/s and $(2/\pi) \times 17.5 = 11.1$ m^3/s for openings A and B, respectively.

Wind Driven Flow Calculations

A calculation period of 8-10 days was required to achieve steady-state conditions. In the outer region the flow field shows the general behavior of coastal wind driven flows. Two layers of flow are observed; a surface layer (depth $\approx 0-2.0$ m), which follows the direction of the wind and a bottom layer (depth >2.0 m) flowing in the opposite direction. Maximum flow velocities at the surface layer are of the order of 0.08-0.25 m/sec. These values, which correspond to approximately 2-2.5% of the wind velocity, are of the order of magnitude of values observed generally in coastal areas.

In the inner region the flow field is affected by the wind and the

Table 3: Flow exchanges (m^3/s) via the openings.

	$Q_A(+)$	$Q_A(-)$	$Q_B(+)$	$Q_B(-)$	Total In	Total Out
S0	15.1	-15.1	11.1	-11.1	26.1	26.1
S1	10.5	-20.0	9.5	0.0	20.0	20.0
S2	7.4	-4.8	2.1	-4.7	9.5	9.5
S3	37.0	-19.0	0.0	-18.0	37.0	37.0
S4	14.1	-7.8	0.0	-6.3	14.1	14.1
S5	2.2	-7.1	6.1	-1.2	8.3	8.3

Table 4: Average renewal times.

Series	Exit flow, Q_{ex} (m^3/s)	Θ (days)
S0	26.1	3.2
S1	20.0	4.2
S2	9.5	8.9
S3	37.0	2.3
S4	14.1	6.0
S5	8.3	10.2

flow exchange with the outer region via the openings. Generally, in the surface layer the flow follows the direction of the wind; thus the latter governs the direction of the generated exchange of flow with the outer region. For winds with a northerly velocity component (series S1 and S5, N and WNW winds, respectively) the flow of the surface layer enters the inner region via opening B into compartment 21, passes through the internal boundaries between compartments 13 and 12, 14 and 11, 15 and 10, 16 and 9, enters compartment 20 and exits via opening A, thus creating a counter clock-wise movement in the inner region. For winds with a southerly velocity component (series S3 and S4, SE and SSW winds, respectively) the flow of the surface layer enters via opening A and exits via opening B, thus creating a clock-wise movement in the inner region. For winds without a northerly or southerly velocity component (such as series S2), the generated “flow exchange” is relatively low; seawater enters the inner region via opening A and exits via opening B.

Flow Exchange

Exchange flow rates across the openings were calculated for all series and are shown in Table 3; these have been determined at the internal boundaries to formulate water mass balances in the compartments of the inner region. In Figure 5 the schematic diagram of the flow exchanges is shown indicatively for series S4. It is noted that flow rates are considered as “positive”, when they are directed to the northern or eastern direction.

Renewal Times

Average Renewal Time

The average renewal time (Θ) is calculated by the following equation (YIN *et al.*, 1998)

$$\Theta = \frac{V}{Q_{ex}} \quad (2)$$

where V is the water volume of the inner region and Q_{ex} is the flow rate leaving this region.

Average renewal times for series S1 to S5 were calculated on the basis of the average flow rates (see Table 3) and are shown in Table 4. Table 4 depicts that average renewal times ranged from 2.3 to 10.0 days for the wind conditions tested. Tide contributes significantly to the renewal of waters. Renewal times decrease with increasing wind velocity and southerly winds are beneficial to water renewal, because they create flow fields with relatively high exchange of flow via opening A.

Renewal Times of the Compartments

The renewal time of a compartment “i” (Θ_i), which communicates directly with the outer region, e.g. compartment 1, can be calculated by the following equation

$$\Theta_i = \frac{V_i}{Q_i} \quad (3)$$

where V_i is the water volume of the compartment and Q_i is the flow rate leaving the compartment.

In a compartment “i”, which does not communicate directly with the outer region, e.g. in compartment 9, the renewal time can be approximated by summing up the detention times in all of the compartments, which lie between this compartment and the outer region.

Renewal times for the 5 wind driven series are shown in Figure 6. Mean renewal times for all compartments were determined by averaging the renewal times for the 5 series and are shown in Table 5. For 12 compartments mean renewal times are less than 10 days. Compartment 1, which communicates directly with the outer region, has very short renewal times, i.e. less than 3 days, with the exception of purely easterly wind. In 11 out of 18 compartments,

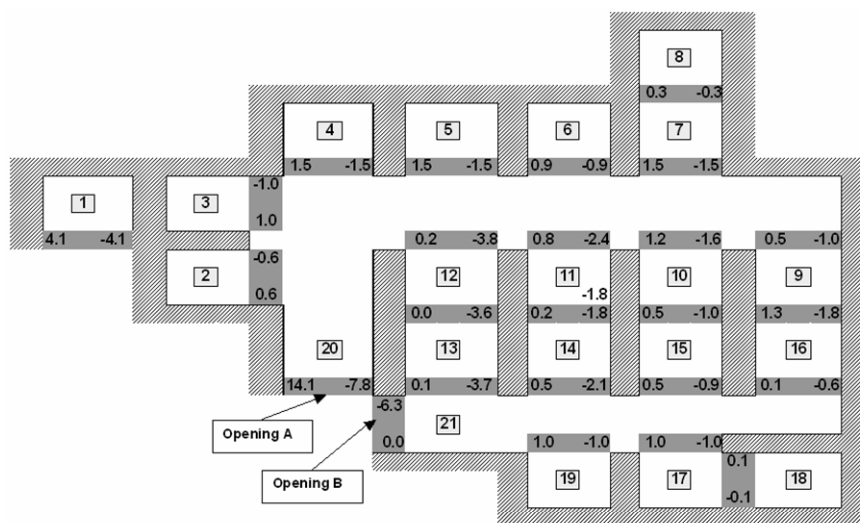


Figure 5. Schematic diagram of flow exchanges between compartments for Series S4. Gray bars indicate the internal boundaries, where flow rates (in m^3/s) are shown, shaded bars indicate land and numbers indicate the compartments.

Table 5: Series of calculations.

Compartment	Mean renewal time (days)	Compartment	Mean renewal time (days)
1	2.7	11	4.7
2	4.4	12	2.4
3	6.5	13	2.0
4	9.3	14	3.9
5	11.8	15	7.4
6	16.8	16	7.8
7	15.9	17	25.0
8	62.1	18	68.7
9	8.2	19	20.0
10	9.3		

which communicate directly with compartments 20 and 21, through which the main exchange of flow between the inner and the outer region of the study area is performed, mean renewal times are lower than 10 days, while 16 compartments out of 18 have mean renewal times lower than 25 days. Compartments 8 and 18, which do not communicate directly with compartments 20 and 21, have very high mean renewal times, which under certain wind conditions may rise up to several months. The compartments located in the southern part of the inner region (16, 17 and 18), have high mean renewal times. These values decrease significantly with winds having a southerly velocity component (series S4). Strong winds are beneficial for water renewal as expected; for series S1 and S3; renewal times are higher than 6 days only for compartments 3, 8 and 18, with the exception of purely easterly wind (series S2). The latter created flow conditions that do not permit the exchange of water via opening A, thus increasing significantly the renewal time to more than 20 days for 10 compartments.

CONCLUSION

A methodology was presented for the determination of water renewal time in semi-enclosed coastal areas with artificial peninsulas or islands of complicated geometry. The originality of

the methodology lies on the introduction of the concept of compartments. These are delineated based on the physical features of the configuration under examination and are enclosed by imaginary internal boundaries. This sub-division of the water body helps in identifying problematic areas of weak circulation, when the results of the hydrodynamic model are appropriately interpreted.

The methodology was applied in Durrat Alkhobar development in Saudi Arabia. The coastal area will be dredged and a fingerlike alignment will be shaped.

Calculations showed that average renewal times ranged from 2.3 to 10.1 days for the wind conditions tested; in 12 compartments renewal times were less than 10 days. Furthermore, tide contributed significantly to the renewal of waters. Renewal times decreased with increasing wind velocity, while southerly winds were beneficial to water renewal, because they created flow fields with relatively high exchange of flow via opening A.

LITERATURE CITED

- STAMOU, A.I. and MEMOS, C., 2006. Modelling water circulation and renewal in Salman Bay, S. Arabia. *Journal of Coastal Engineering* (submitted).
- STAMOU, A.I., MEMOS, K. and PIPILIS, K., 1999a. Mathematical modelling of thermal discharges in coastal regions. *28th IAHR Congress*, (Graz, Austria).
- STAMOU, A.I., NOUTSOPOULOS, C., PIPILIS, K.G., GAVALAKI, E. and ANDREADAKIS, A., 1999b. Hydrodynamic and water quality modelling of Southern Evoikos Gulf – Greece. *Global Nest the International Journal*, 1(2), 5-15.
- YIN, J., FALCONER, R.A., PIPILIS, K. and STAMOU, A.I., 1998. Flow characteristics and flushing processes in marinas and coastal embayments. *Proceedings of the 1st International conference on Maritime Engineering and Ports*, (Genoa, Italy), pp. 87-98.

ACKNOWLEDGEMENTS

Sincere thanks are expressed to Mr. S. Manes of ACE for his help during the course of this study.

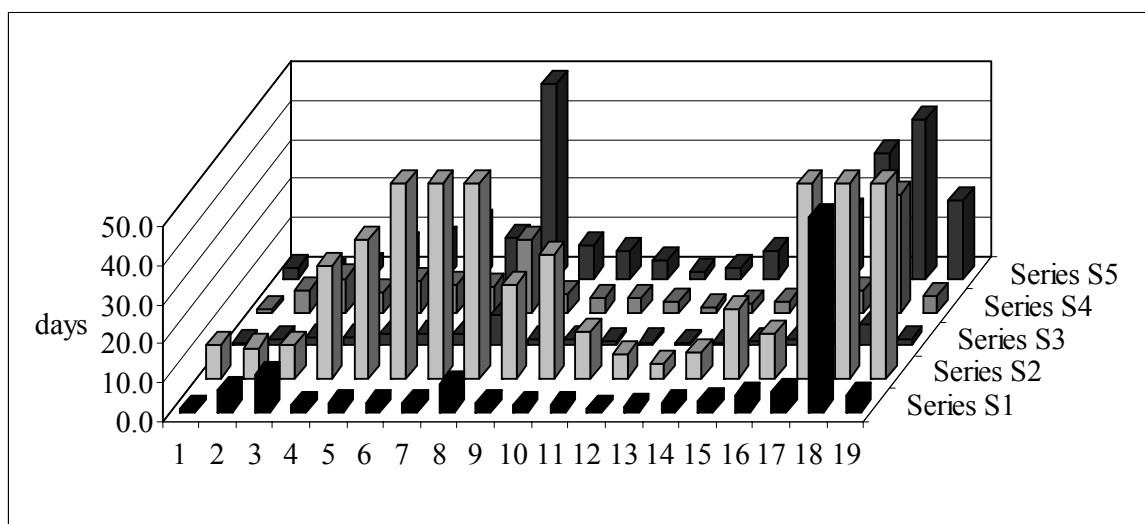


Figure 6. Renewal times of the compartments for wind-driven calculations.