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Effects of Discharge Characteristics on Aqueous Pollutant Concentration at Jebel Ali Harbor, Dubai-UAE

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1. Introduction

The Arabian Gulf is an important geographical location. The Gulf has been extensively used for transport purposes. Meanwhile, countries in the region benefit from the Gulf's diverse marine habitats and utilize its water for desalination or some industrial needs. Several pollutants are induced into the Gulf including those resulting from oil spill accidents, offshore exploration processes, ballast water discharge, reject brine discharge, dredging activities, and coastal construction projects. Meanwhile, some of the Gulf countries are developing new coastal industrial facilities or expanding existing ones. These facilities are not without an adverse impact on the marine environment.

Most of the work related to the quality of Arabian Gulf water has focused on understanding the flow dynamics and the impact of oil spills. A number of researchers, for example, used numerical modeling to investigate residual circulation and flow pattern of the Arabian Gulf (Hughes and Hunter, 1979; Lardner et al. 1987, 1993; Chao et al. 1992; Horton et al., 1994; Elshorbagy et al., 2006; Azam et al., 2006a, 2006b; Thoppil & Hogan, 2010). Other researchers assessed the Gulf water quality as affected by oil spills (El Samra et al., 1986; Lardner et al., 1988; Al-Rabeh et al., 1992; Spaulding et al., 1993).

Little attention, however, has been directed to investigate the impact of discharges from coastal industrial facilities on water quality in the Arabian Gulf. In this study, we will consider the case of Jebel Ali Harbor to numerically assess the harbor's water quality as affected by discharges from industrial facilities located at Jebel Ali Free Zone (JAFZ) area in Dubai, United Arab Emirates (UAE). The harbor at JAFZ area (Fig. 1) is one of the largest man-made ports in the world. The harbor receives discharge consisting of several treated industrial effluents. Water discharged into the harbor must adhere to the effluent quality criteria set forth in the Environmental Requirements established by the Ports, Customs and Free Zone Corporation (PCFC, 2003) at JAFZ area. PCFC has also established harbor water quality objective limits (PCFC, 2003) in order to protect marine life and to minimize the

impact of industrial activities on the surrounding ecosystem. Regular monitoring of discharged treated wastewater as well as harbor water and sediments is conducted by the PCFC to assure adherence to effluent standard and quality objective limits.
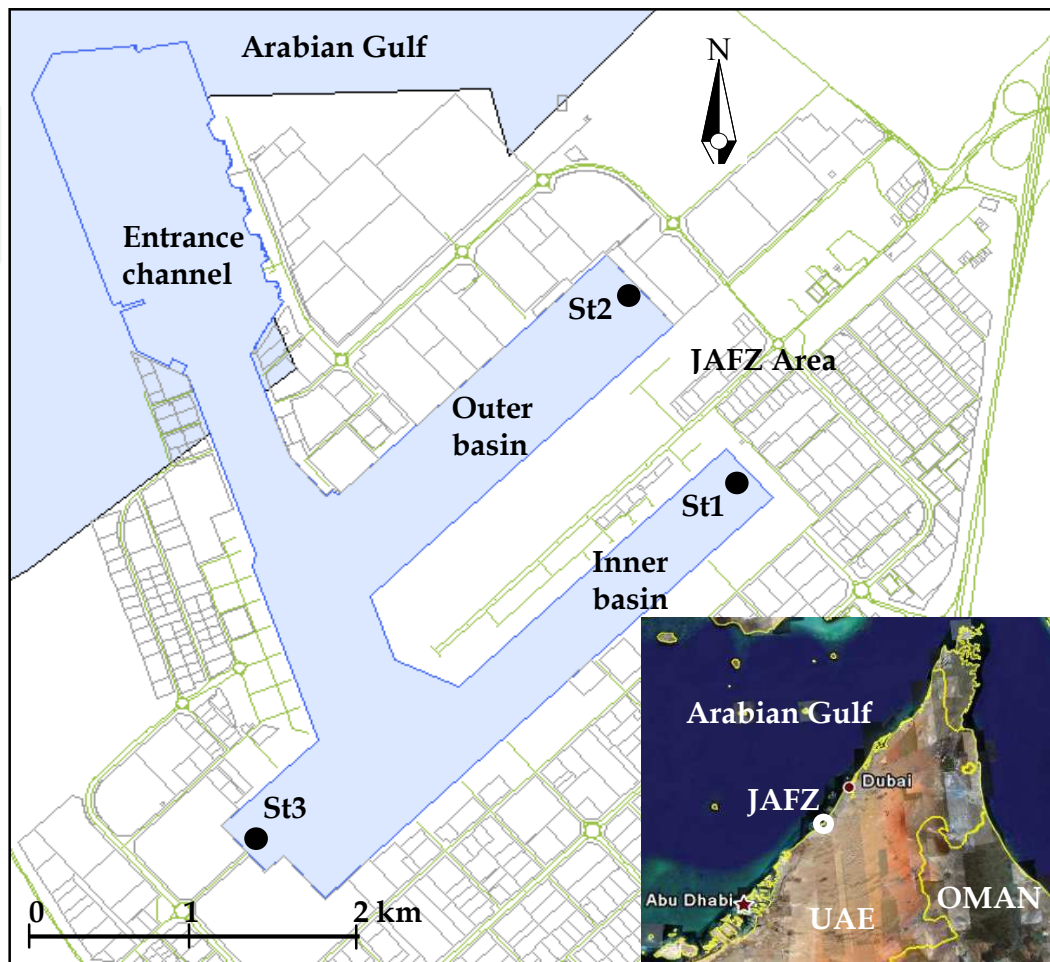

Fig. 1. Map of Jebel Ali Harbor. The circle in the bottom map is the location of JAFZ area.

Future expansion of industrial activities at JAFZ area, in addition to port activities and on-going as well as planned coastal construction projects in the vicinity of the harbor, may increase pollutant loading to the receiving water body. Limited work, however, has been conducted to assess the water quality of Jebel Ali Harbor. Maraqa et al. (2007) studied the fate of selected pollutants in the harbor and concluded that induced pollutants tend to accumulate in the harbor due to its limited flushing capacity. Furthermore, Maraqa et al. (2008) found that the main flow regime in the harbor follows alternate paths during flooding and ebbing, which creates eddy-like circulations in net flow distribution (see Fig. 2). Maraqa et al. (2008) also showed that dead-end locations at Jebel Ali Harbor have low water circulation and that flushing of a conservative pollutant discharged into the harbor takes a few months to several years depending on the discharge location.

This study expands on the work of Maraqa et al. (2008) to investigate variations in the concentration of pollutants induced into the harbor due to variations in the loading rate, discharge location and discharge concentration. A similar approach was used by Kashefipour et al. (2002; 2006) to assess the impact of various bacterial input rates on the

receiving water in coastal basins in the UK. This study further explores the relationship between a continuous pollutant loading rate and average pollutant concentration in Jebel Ali Harbor water. As such, the study is of importance to modeling experts and managers interested in the hydrodynamic and transport properties of this harbor. The outcome of this study could further assist managers of the harbor decide on proper input rates and discharge locations so that water quality objective limits are not exceeded. Meanwhile, the general approach presented here may be of value in application to other systems.
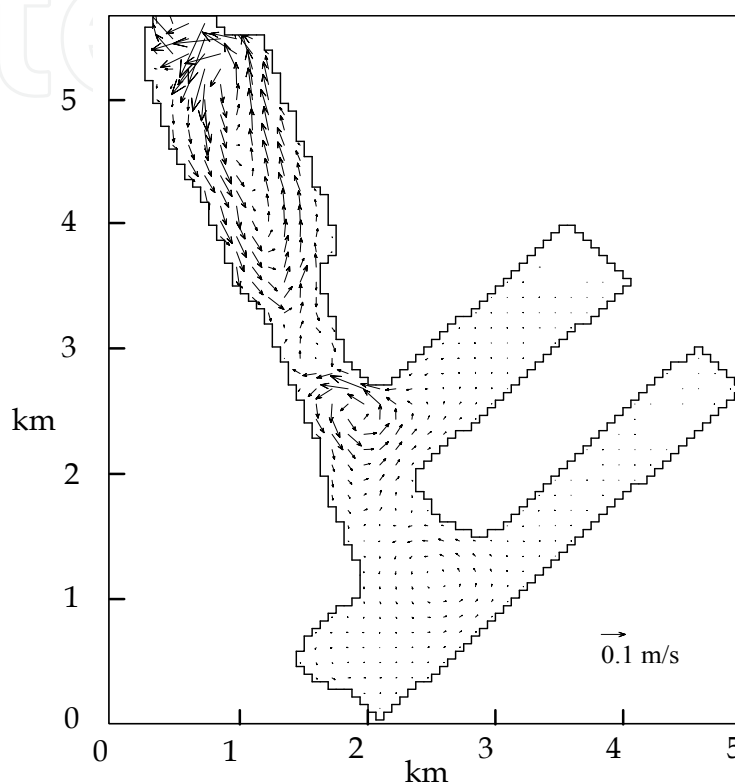

Fig. 2. Net flow over a tidal cycle of Jebel Ali Harbor (adopted from Maraqa et al., 2008)

2. Governing equations

Numerical modeling can be used to help achieve discharge conditions that meet pre-set environmental limits. Numerical modeling has been extensively applied to simulate water circulation and contaminant transport in harbors and semi-enclosed coastal areas. For example, efforts were made to better understand the hydrodynamic regimes (Estacio et al., 1997; Vethamnoy et al., 2005; Azam et al., 2006a; Dias and Lopes, 2006a,b; Maraqa et al., 2008; Montano-Ley et al., 2008), to investigate pollutant dispersion (Gesteira-Gomez et al., 1999; Das et al. 2000), and to assess water quality (Tao et al., 2001; Copeland et al., 2003; Fiandrino et al., 2003; Lopes et al., 2005; Cerejo and Dias, 2007). Other efforts were made to establish surveillance procedures (Lopes et al., 2005) and to quantify the impact of effluent discharge (Ganoulis, 1991; Kashefipour et al., 2002; Gupta et al., 2004, Kashefipour et al., 2006; Rucinski et al., 2007; Brewer et al., 2008).

Modeling of fluid flow is based on the principles of continuity of mass and conservation of momentum. For flows, which show little variation in the vertical dimension, it is acceptable

to integrate these equations over the depth of water, resulting in two-dimensional (2D) equations of motion. In a 2D hydrodynamic (HD) model, the continuity equation is:

$$\frac{\partial \zeta}{\partial t} + \frac{\partial p}{\partial x} + \frac{\partial q}{dy} = 0 \tag{1}$$

where, ζ is the water level (m); p and q are flux densities in x and y directions (m³/s/m); t is time (s); x and y are space coordinates (m). The x-and y-momentum are given by Eq. (2) and (3), respectively:

$$\frac{\partial p}{\partial t} + \frac{\partial}{\partial x}\left(\frac{p^2}{h}\right) + \frac{\partial}{dy}\left(\frac{pq}{h}\right) + gh\frac{\partial \zeta}{\partial x} +$$
$$\frac{gp\sqrt{p^2+q^2}}{C^2 h^2} - \frac{1}{\rho_w}\left[\frac{\partial}{\partial x}\left(h\tau_{xx}\right) + \frac{\partial}{\partial y}\left(h\tau_{xy}\right)\right] - \tag{2}$$
$$\Omega q - fVV_x \frac{h}{\rho_w}\frac{\partial}{\partial x}\left(p_a\right) = 0$$

$$\frac{\partial q}{\partial t} + \frac{\partial}{\partial y}\left(\frac{q^2}{h}\right) + \frac{\partial}{dx}\left(\frac{pq}{h}\right) + gh\frac{\partial \zeta}{\partial y} +$$
$$\frac{gq\sqrt{p^2+q^2}}{C^2 h^2} - \frac{1}{\rho_w}\left[\frac{\partial}{\partial x}\left(h\tau_{yy}\right) + \frac{\partial}{\partial x}\left(h\tau_{xy}\right)\right] - \tag{3}$$
$$\Omega p - fVV_y \frac{h}{\rho_w}\frac{\partial}{\partial y}\left(p_a\right) = 0$$

where, h is water depth (m); C is Chezy resistance (m$^{1/2}$/s); f is the wind friction factor (dimensionless), V, V_x, and V_y are wind speed and components in x and y directions (m/s), respectively; Ω is Coriolis parameter (s^{-1}); p_a is atmospheric pressure (kg/m/s²); ρ_w is the density of water (kg/m³); and τ_{xx}, τ_{xy} and τ_{yy} are components of effective shear stress (N/m²).

The advection-dispersion (AD) model simulates the spreading of a substance in an aquatic environment under the influence of fluid transport and dispersion processes. The substance may be treated conservatively or with decay. The governing equation for a 2D AD model is given as (Adams and Baptista, 1986):

$$\frac{\partial}{\partial t}\left(hc\right) + \frac{\partial}{\partial x}\left(uhc\right) + \frac{\partial}{\partial y}\left(vhc\right) = \frac{\partial}{\partial x}\left(hD_x \frac{\partial c}{\partial x}\right)$$
$$+ \frac{\partial}{\partial y}\left(hD_y \frac{\partial c}{\partial y}\right) - khC + Q_s\left(c_s - c\right) \tag{4}$$

where, c is substance concentration (mg/l); u and v are horizontal velocity components in x and y directions (m/s), respectively; D_x and D_y are dispersion coefficients in x and y directions (m²/s), respectively; k is the linear decay rate coefficient (s^{-1}); Q_s is the source/sink discharge per unit horizontal area (m³/s/m²); c_s is substance concentration in the source/sink discharge (mg/l).

3. Methodology

3.1 Model description

Jebel Ali Harbor has an approach channel that starts 15 km offshore. The approach channel has a depth of 14-15 m and a width of 280 m reducing to 235 m. It bends after 10 km and becomes the entrance channel. It widens to 300 m at the bend and to 340 m at the entrance channel. There are two basins within the port. The outer 14-m deep basin is 2.3 km long and 600 m wide. The inner basin is 3.7 km long and 425 m wide, with a depth of 11.5 m. All channel and basin bottoms are sandstone. The surface area of the harbor is about 5.3 million m^2 and the total water volume is about 75 million m^3.

Maraqa et al. (2008) developed a 2D model using the MIKE21 modeling system of the Danish Hydraulic Institute (DHI, 2003a; 2003b) to simulate the HD and the AD processes within the Jebel Ali Harbor. Justification of the use of a depth-integrated 2D model was based on the nearly uniform temperature and salinity profiles found at different locations in the harbor (Maraqa et al., 2008). Since the AD model developed by Maraqa et al. (2008) was used in this study, a brief description of the model setup is presented below. For more details about the model setup the readers are referred to Maraqa et al. (2008).

The HD model of Jebel Ali Harbor is the basis for the AD model. The model was constructed with a rectangular grid system of 60×60 m^2. The dimensions of the grid were selected as a compromise between resolution and computational time. The origin of the model was 24°58'03″ latitude and 55°01′28″ longitude, taking east-west and north-south directions as the x and y directions, respectively. The entrance to the harbor was selected as the open boundary and the flow direction was considered perpendicular to the boundary. The closed side and bottom boundaries were considered as no flow boundaries. A constant water level and zero velocities were used as initial conditions at all grid points. Tide level was used as the boundary condition and the flow direction was considered perpendicular to the boundary. Latest topographical description of the harbor area was incorporated in the model (Jan de Nul Dredging Ltd., 2004). Although, the hydraulic regime of Jebel Ali Harbor is mainly dependent on the tide (Maraqa et al., 2008), meteorological forces were incorporated to improve the accuracy of the model. Observed meteorological conditions during January to December 2004 at the site were applied to the model in the first simulation year and similar meteorological conditions were used for a simulation period of 12 successive years.

The predicted tide level at the entrance of the harbor was used as the boundary condition for the HD model. The prediction was carried out using the Admiralty method (DHI, 2003a) facilitated in MIKE21 tools using major tidal constituents (see Table 1) with necessary seasonal corrections of -0.1 during February, March and April and +0.1 during July and August (ATT, 2003). Predicted tide levels were referenced to mean sea level datum and converted to local chart datum (CD) adding 1.02 m (ATT, 2003). The HD model was calibrated against tide level and flow data measured in December 2004. Through a rigorous calibration process, constant Chezy number and eddy viscosity were selected as 40 and 1.0 m^2/s, respectively. Simulated tide levels compared quite well with measured levels at three locations within the harbor. Also, simulated flow values through the entrance channel matched quite well with the measured ones at the same location (Maraqa et al., 2008).

In the development of the AD model of Jebel Ali Harbor, Maraqa et al. (2008) used a spatially varied dispersion coefficient determined by a formula suggested by Fischer et al. (1979):

$$D = 0.011 \frac{\bar{u}^2 W^2}{d u^*}$$ (5)

where, D is the dispersion coefficient (m²/s); $\bar{u}$ is the average velocity (m/s); W is the width of the channel (m); d is the depth of the channel (m); u^* is the shear velocity (m/s) which is expressed as $(ghS)^{0.5}$; g is the gravitational acceleration = 9.81 (m/s²); h is the hydraulic radius ≈ depth of the channel (m); and S is the water surface slope.

Constituent name	Amplitude (m)	Phase (°)
Principal lunar semidiurnal (M_2)	0.43	359
Principal solar semidiurnal (S_2)	0.17	49
Luni-solar declinational diurnal (K_1)	0.25	155
Lunar declinational diurnal (O_1)	0.17	100
First overtide of M_2 (F_4)	0.0	0
Second overtide of M_2 (F_6)	0.0	0

Table 1. Tidal constituents at Jebel Ali Harbor (ATT, 2003).

Values of the dispersion coefficient in the x and y directions were calculated using Eq. (5) based on a channel width of 300 m, an estimated average water surface slope of 2×10^{-5} m/m, and a hydraulic radius (considered as the average depth of flow) of 12.0 m (Maraqa et al., 2008). Furthermore, the mean velocity at each grid point during an ebb tide in spring was calculated from the HD model and was used as an average velocity for calculating the dispersion coefficient. Estimated dispersion coefficients at the dead-end locations within the inner and outer basins were found to be much lower (<0.0001 m²/s) than those in the main channel (>0.01 m²/s).

3.2 Model applications

In this study, the effect of variation in the loading rate on the average pollutant concentration in the harbor (C_{avg}) was numerically investigated by simulating pollutant concentration in harbor water subject to different continuous loading rates at specified locations. Three discharge points were selected (Fig. 1); one in the corner of the inner basin (St1), another in the corner of the outer basin (St2), and a third point at the west corner of the inner basin (St3). These locations are currently used to discharge treated industrial wastewater into the harbor (Maraqa et al., 2007). Conservative and degradable pollutants were considered with a loading rate (LR) that varied from 0.01-1.0 g/s. The lower limit of loading rates nearly corresponds to the current total rate of discharge of phosphate, while the upper limit is close to the rate of discharge of nitrate or BOD_5 (Maraqa et al., 2007). It should be noted that conservative pollutants discharged into Jebel Ali Harbor could include

reject brine from desalination plants or any pollutant that does not undergo transfer and transform reactions. On the other hand, degradable pollutants could include BOD, coliform bacteria, or any other pollutant that undergoes transformation, not transfer, reactions.

Three different sets of simulations were conducted in this study. In the first set, the loading rate of a conservative pollutant varied while fixing the discharge concentration at 20 mg/l. This discharge concentration was chosen based on the current discharge concentration of some contaminants (Maraqa et al., 2007). Since the concentration at the source was fixed in this set of simulations, variations in the loading rates are due to variations in the discharge flow rates. The second set of simulations was carried out to investigate the impact of changing the discharge concentration, with fixed loading rates, on the value of C_{avg}. Discharge concentrations of 10, 20, and 40 mg/l at St1 were simulated for discharge rates of 0.01, 0.1 and 1.0 g/s of a conservative pollutant. The third set of simulations was conducted to study the impact of pollutant degradation on C_{avg}. Simulations of the latter cases were accomplished using the ECO Lab module of MIKE21 (DHI, 2003c) along with the AD model. A decay rate constant of 0.1, 0.2 and 0.5/yr were used with pollutant input rates of 0.01, 0.1 and 1.0 g/s at St1.

All simulated cases in this study are summarized in Table 2. In all simulated cases, a pollutant concentration background value of zero in harbor water was used as the initial and boundary conditions. For each simulated case, the concentration level at different locations and the total mass of the pollutant within the harbor were numerically estimated using the developed model by Maraqa et al. (2008) to find out C_{avg}. For a continuous and constant loading rate, steady-state conditions were assumed to be reached when the mean pollutant concentration over a tidal cycle at any point in the harbor did not change over time. This definition of steady-state concentration is similar to the definition of stationary-state concentration used by Edinger et al. (1998).

The value of C_{avg} at steady-state conditions was calculated by averaging the spatial concentration values over the entire harbor-modeling area when steady-state conditions prevailed. As indicated by the California Regional Water Quality Control Board (CRWQCB, 2007), an average concentration value of the main water mass is typically used when comparison with a water quality objective limit is intended. The CRWQCB (2007) also indicated that objective limits cannot be applied at or immediately adjacent to zones of initial dilution within which higher concentration can be tolerated.

4. Results and discussion

4.1 Time of steady-state conditions

The time to reach steady-state conditions due to a continuous discharge was almost the same for a certain discharge location independent of the loading rate. However, the time to reach steady-state was dependent on the discharge location with a value of about 12 yrs for discharge at St1, 7 yrs for discharge at St2, and 4 yrs for discharge at St3 (Table 2). It should be noted that the time to reach steady-state is not directly comparable to flushing time or residence time. Generally, flushing time is defined as "the ratio of the scalar in a reservoir to the rate of renewal of the scalar" (Geyer et al., 2000). Flushing time describes the exchange characteristics of a waterbody without identifying the underlying physical processes or their spatial distribution (Monsen et al., 2002). Residence time, on the other hand, is the time it

takes a waterparcel to leave a semi-enclosed waterbody through its outlet (Monsen et al., 2002). Residence time is measured from an arbitrary start location within the waterbody, whereas the time to reach steady-state concentration used in this study depends primarily on the mixing characteristics of the entire waterbody. However, steady-state times were found quite similar to residence times simulated by Maraqa et al. (2008) for these stations since both of these time scales depend on the same physical processes.

Case	Location	Concentration (mg/l)	Discharge flow (m³/s)	Loading rate (g/s)	Degradation rate constant (yr⁻¹)	Time to reach steady-state (yr)
1	St1	20	0.0005	0.01	0	12
2	St1	20	0.0025	0.05	0	12
3	St1	20	0.0050	0.10	0	12
4	St1	20	0.0250	0.50	0	12
5	St1	20	0.0500	1.00	0	12
6	St2	20	0.0005	0.01	0	7
7	St2	20	0.0050	0.10	0	7
8	St2	20	0.0500	1.00	0	7
9	St3	20	0.0005	0.01	0	4
10	St3	20	0.0050	0.10	0	4
11	St3	20	0.0500	1.00	0	4
12	St1	10	0.0010	0.01	0	12
13	St1	10	0.0100	0.10	0	12
14	St1	10	0.1000	1.00	0	12
15	St1	40	0.00025	0.01	0	12
16	St1	40	0.0025	0.10	0	12
17	St1	40	0.0250	1.00	0	12
18	St1	20	0.0005	0.01	0.1	12
19	St1	20	0.0050	0.10	0.2	12
20	St1	20	0.0500	1.00	0.5	12
21	St1	20	0.0005	0.01	0.1	12
22	St1	20	0.0050	0.10	0.2	12
23	St1	20	0.0500	1.00	0.5	12
24	St1	20	0.0005	0.01	0.1	12
25	St1	20	0.0050	0.10	0.2	12
26	St1	20	0.0500	1.00	0.5	12

Table 2. Description of the simulated cases.

4.2 Spatial variations

Spatial variations of pollutant concentration in harbor water due to a loading rate of 1.0 g/s at St1 is shown in Fig. 3. Simulation shows that the concentration distribution changes significantly from year 2 to year 8, whereas it increases slightly after year 8 until it reaches steady-state conditions. From the circulation pattern of the harbor, as presented by Maraqa et al. (2008), pollutant distribution in the inner and outer basin is dominated by diffusion while that in the entrance channel is greatly affected by advection.

To examine the effect of pollutant source location, the simulations were repeated relocating the point source at St2 (Fig. 1). It was found (Fig. 4) that the concentration distributions in the inner and outer basins are different than the distribution with the source location at St1. But, the concentration distributions in the entrance channel were almost similar for the two cases (see Fig. 3 and Fig. 4). The concentration in the entrance channel is mostly influenced by the Gulf water rather than the inside basins because of the dominant advection processes. In any case, the highest concentration occurs at the source location, while the lowest concentration generally occurs at the west side of the entrance channel due to the inward net flow conditions (Maraqa et al., 2008). For a loading rate of 1.0 g/s, the average pollutant concentration in the harbor water reached 0.35 mg/l with the discharge point located at St2 and 1.3 mg/l with the discharge point located at St1. The reasons behind reaching steady-state conditions with lower concentration at St2 are faster transport due to advection and more dilution with Gulf water. Thus, it is necessary to examine the impact of pollutant loading using modeling technique before selecting the discharge location.
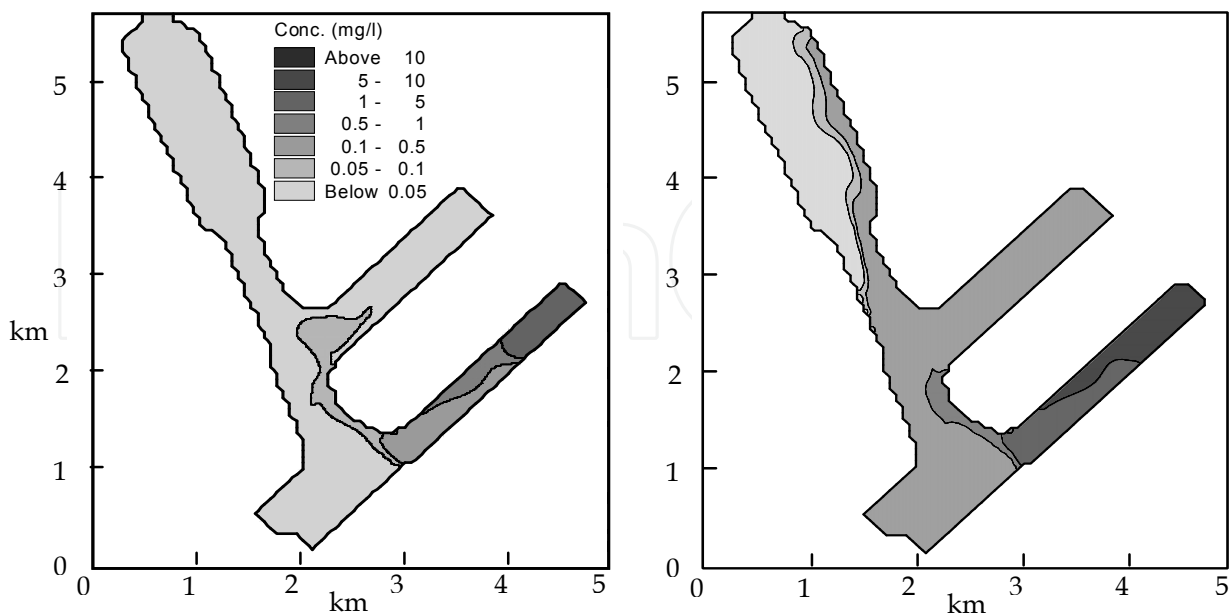

Fig. 3. Concentration map after 4 yrs (left) and 12 yrs (right) from start of simulation with a continuous loading rate of a conservative pollutant of 1.0 g/s at St1.
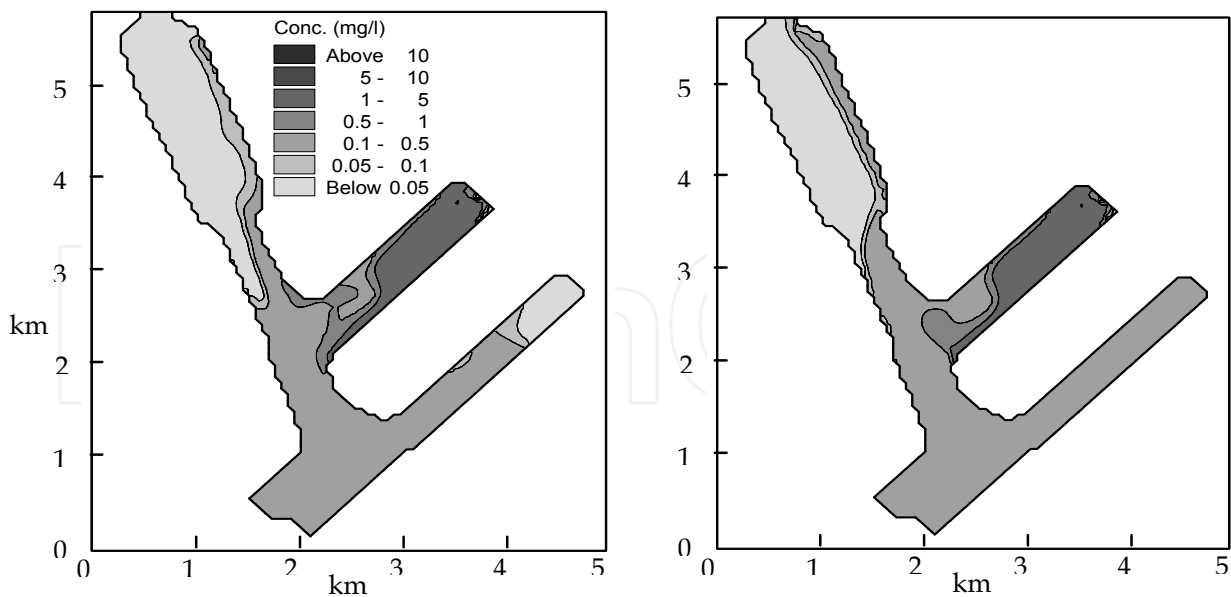
Fig. 4. Concentration map after 2 yrs (left), and 7 yrs (right) from start of simulation with a continuous loading rate of 1.0 g/s at St2.

4.3 Temporal variations

Temporal variation of pollutant concentration at St3 due to pollutant loading of 1.0 and 0.1 g/s at St1 is shown in Fig. 5. The figure shows that the concentration at St3 increases sharply at initial times and levels of at later times until it reaches a plateau value. For a conservative pollutant, the mechanisms of solute transport within the harbor are associated with the advection-dispersion processes. Advection driven by the tide was the principal transporting process within Jebel Ali Harbor. Winds and waves play a minor role in mixing and transport of pollutants because of the bottle-neck shape of the harbor.
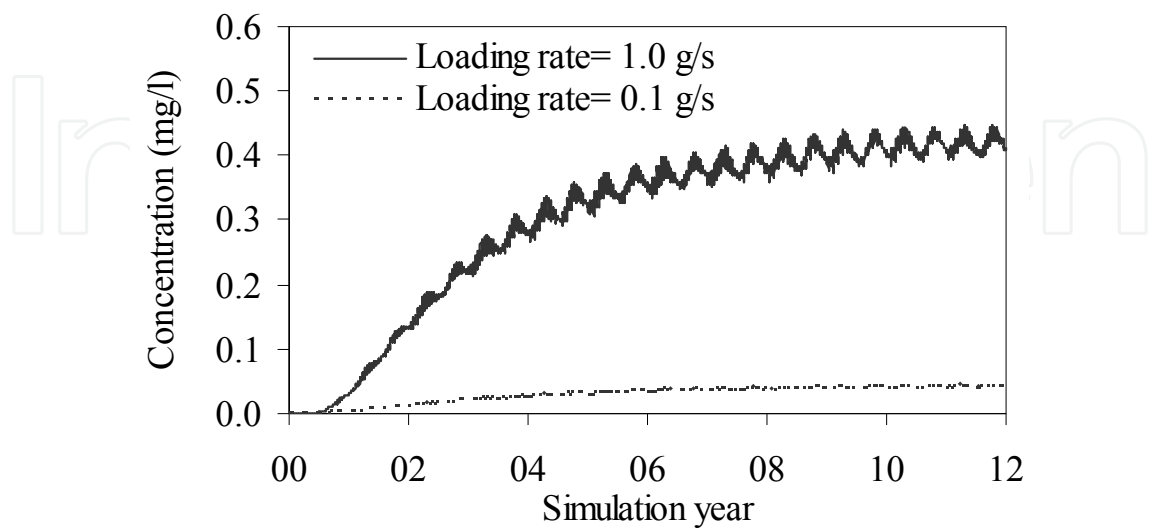
Fig. 5. Long-term variation of concentration at St3 subject to a loading rate of a conservative pollutant of 0.1 and 1.0 g/s at St1.

Further inspection of Fig. 5 shows that there are seasonal fluctuations in the concentration level. Such fluctuation occurs at hourly levels due to variations of tidal levels as demonstrated in Fig. 6. In general, the average concentration reduces during summer season when the tide levels are high and the concentration increases during winter season when the tide levels are low. Also, the concentration reduces during high water and increases during low water because of hourly tide level changes. This indicates that short-term monitoring of water quality in the harbor may not reflect on the long-term changes. For example, the concentration of a conservative pollutant at St3 reaches 0.46 mg/l in April of year 11 as a result of a loading rate of 1.0 g/s at St1. The concentration drops in July (of that year) to about 0.41 mg/l for the same loading rate at St1.
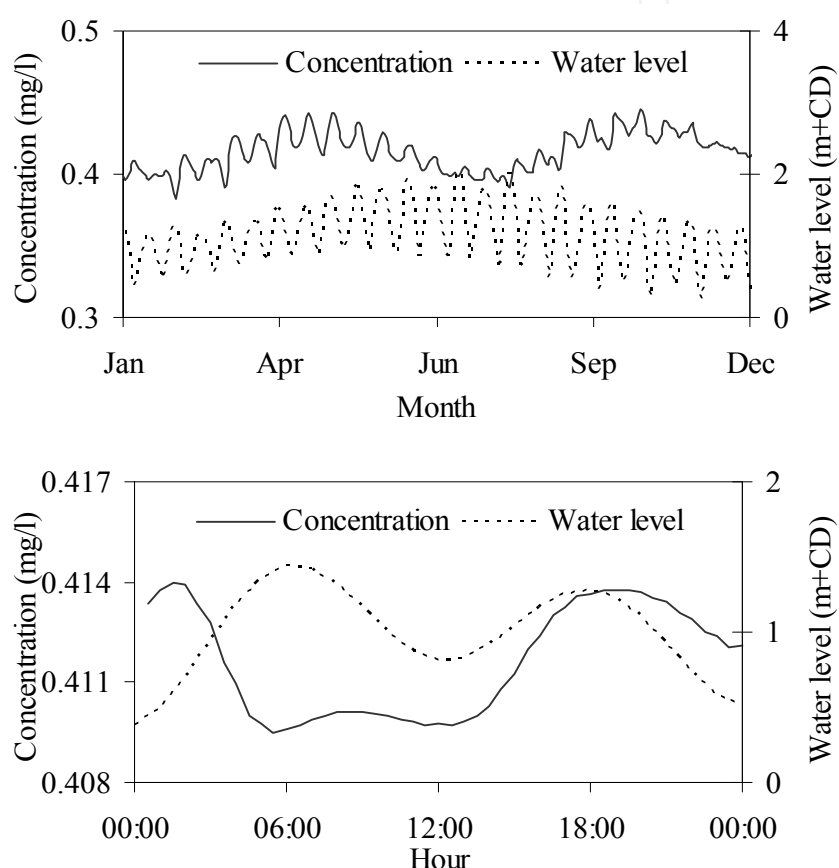
Fig. 6. Concentration at St3 due to a loading rate of 1.0 g/s at St1 showing seasonal variations (top) and daily variations (bottom) at the end of the 10th yr along with the tide levels.

4.4 Steady-state concentration of conservative pollutants

For conservative pollutants, the values of C_{avg} resulting from different loading rates at St1, St2, and St3 are presented in Fig. 7. As the figure shows, C_{avg} varies with both the loading rate and the discharge location. Higher concentration was observed when the source was located at St1. On the other hand, relatively lower concentrations were observed when the source was located at St2 or St3. Discharging at St2 and St3 produces almost the same average concentration in harbor water for similar loading rates. Similar concentration

distributions were also observed in the entrance channel whether the source was located at St2 or St3, but different concentration distributions were observed in the inner and outer basins.
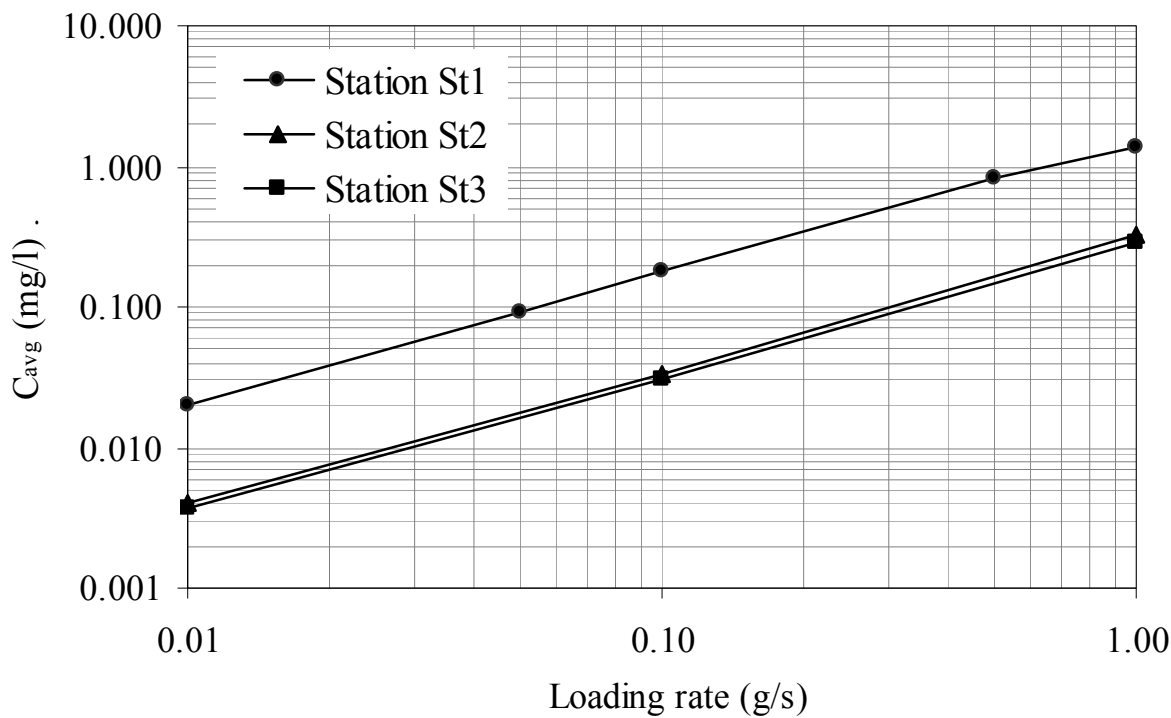

Fig. 7. Average concentration in harbor water for different discharge locations and loading rates of a conservative pollutant.

Based on the data presented in Fig. 7, the following best fit equations were produced relating the average concentration (mg/l) in harbor water to the loading rate (g/s):

$$\text{Discharge at St1: } C_{avg} = 1.468 \, (LR)^{0.926} \tag{6}$$

$$\text{Discharge at St2: } C_{avg} = 0.322 \, (LR)^{0.956} \tag{7}$$

$$\text{Discharge at St3: } C_{avg} = 0.286 \, (LR)^{0.953} \tag{8}$$

Equations 6-8 have a coefficient of determination (r^2) of 0.999. From Eqs. (6)-(8), C_{avg} correlates almost linearly with the pollutant loading rate. At a given loading rate, discharge at St1 results in values of C_{avg} that are 4-5 times higher that those due to discharge at either St2 or St3. However, the maximum concentration in the harbor always occurred close to the discharge location. This is consistent with the findings of Kumar et al. (2000) who reported higher bacterial pollution near diffuser locations (discharge points). Also, the maximum concentration in this work was almost an order of magnitude higher than the average concentration in the harbor. For example, the maximum concentration due to a discharge of 1.0 g/s at St1 was 13.26 mg/l compared to an average concentration of 1.31 mg/l for this case.

The effect of changes in the discharge concentration on the value of C_{avg} is shown in Fig. 8. The figure shows that C_{avg} is more dependent on the loading rate and less dependent on the discharge concentration. In other words, it is the mass input rate, rather than the discharge concentration itself, that influences the concentration of the pollutant in the harbor. Thus, Fig. 7 (or Eqs. 6-8) can be used to determine the allowable discharge rate of a pollutant such that C_{avg} does not exceed a pre-set harbor objective limit. Further inspection of Fig. 8 shows that C_{avg} increases with the increase in the input concentration at a loading rate of 1 g/s, while it maintains nearly the same value regardless of the input concentration at lower loading rates. Such observation could be due to the high volume of discharge water associated with a high loading rate and a relatively low input concentration.
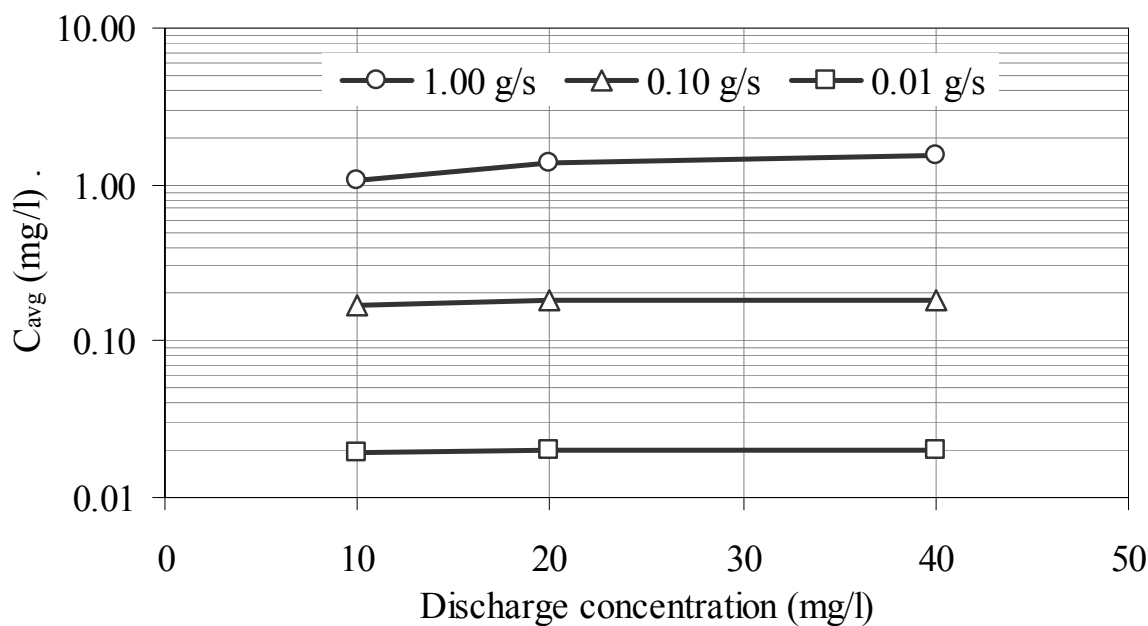
Fig. 8. Average concentration in harbor water for different discharge concentrations and loading rates of a conservative pollutant at St1.

4.5 Steady-state concentration of degradable pollutants

The simulations carried out under the previous cases were limited to pollutants that are conservative. The effect of degradation on the average concentration in harbor water is presented in Fig. 9 for degradable pollutants discharged at St1. As expected, an increase in the decay rate constant (k) results in a reduction in C_{avg}. This reduction is almost independent of the loading rate and averages 18%, 36% and 62% with a decay rate of 0.1, 0.2 and 0.5/yr, respectively. Meanwhile, the average concentration of a degrading pollutant introduced at St1 could be well predicted from that of a conservative pollutant using a decreasing exponential function with an average time (t) of 2 yrs as shown in Eq. (9):

$$(C_{avg})_k = (C_{avg})_{k=0} \, e^{-2k} \tag{9}$$

where, $(C_{avg})_k$ is the average concentration of a degrading pollutant in harbor water and $(C_{avg})_{k=0}$ is the average concentration of a conservative pollutant and k is in units of yr^{-1}.
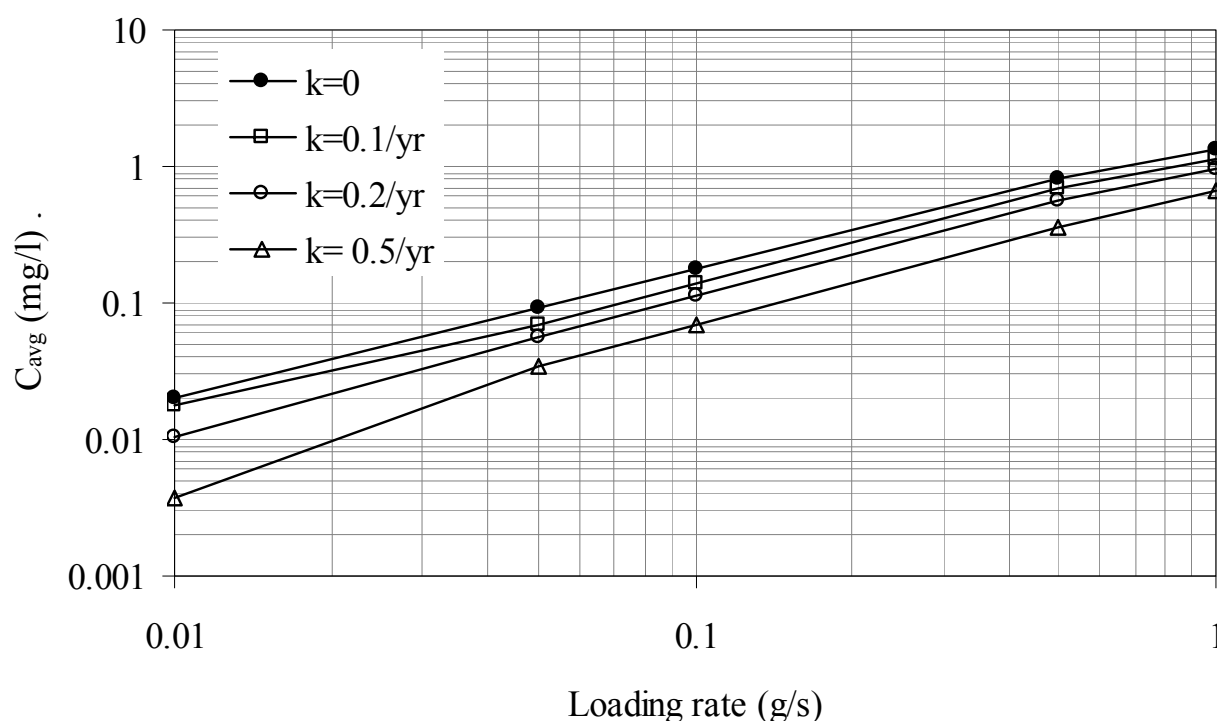
Fig. 9. Average concentration of pollutants with different degradation rates as a result of discharge at St1.

5. Conclusion

With a continuous pollutant discharge, the aqueous concentration at any point in Jebel Ali Harbor reaches steady-state conditions with duration that depends on the discharge location. The longest duration (about 12 yrs) occurs with discharge in the east corner of the inner basin. Results of this study show that the average steady-state pollutant concentration in harbor water varies with both the loading rate and the discharge location, but is independent of the discharge concentration. For a conservative pollutant discharged in Jebel Ali Harbor, developed relationships of average pollutant concentration in harbor water were found to correlate almost linearly with the discharge loading rate. It was also observed that discharging in the east corner of the inner basin results in an average steady-state concentration of about 4-5 times higher than values associated with discharge at the east corner of the outer basin or the west corner of the inner basin. For a degrading pollutant, the reduction in the steady-state average concentration is almost independent of the loading rate, but could be adequately predicted from that of a conservative pollutant using a decreasing exponential time function. Derived relationships of average aqueous pollutant concentration in the harbor versus the discharge loading rate will be useful for better management of harbor water quality.

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7. References

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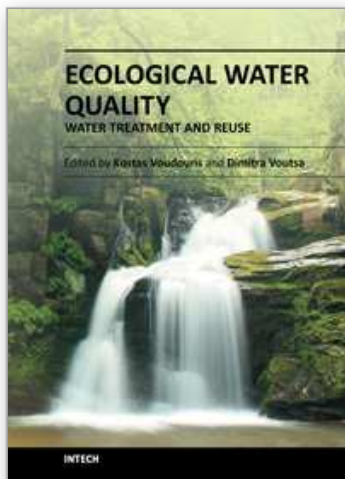
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