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WATER QUALITY MODELING AND FIELD INVESTIGATIONS IN SOUTHEAST LAGOON OF CASPIAN SEA

Najafi-Jilani[1] M. Monshizadeh[2]

Abstract: *In this work, the water quality in a restricted lagoon at south-eastern coasts of Caspian Sea is investigated. Both numerical modeling and field investigations are used to study the effects of pollution which discharge into the lagoon by an adjacent industrial plant. The numerical model is a coupled hydrodynamic and advection-dispersion model which calibrated using field measurements. Various ratios of pollutant decay are considered in numerical modeling. The results are used to determine the flushing time of lagoon. It was concluded that the accumulation of pollution in lagoon will be occurred because of the long flushing time and low-order wind-induced water current. The effect of pollutants decay on the water quality of lagoon is also investigated.*

Keywords: Restricted lagoon, Water quality, Caspian Sea, Numerical modeling, Field investigations

1. Introduction

Lagoons, like other surface water bodies, can be used by adjacent industrial plants to supply the required water and to outfall the wastes. In restricted lagoons, water exchange with the sea can be restricted and circulation is mainly dominated by wind (Baltrame, et al., 2009). Especially in Caspian Sea, where there are not any tidal effects, the transportation of water into and out of the lagoon is mainly caused by wind (Kosarev, and Yablonskaya, 1994). The Gomishan lagoon located at the south-eastern coasts of Caspian Sea in Iran can be categorized as a restricted lagoon (Rodionov, 1994; Schwab, and Muhr, 1989). This shallow water body is going to be used by an adjacent industrial plant to supply the required water. The waste water of the plant will be discharged into it.

Water quality control of lagoons needs special technical concerns due to their restriction and water exchange pattern along the boundaries between lagoon and sea (Margarita, 2009). Pollution control in lagoon usually requires field investigation about wind pattern (Nicastro, et. al, 2009) and evaluation the flushing time of lagoon during the operational period of wastewater runoff (Dilorenzo, et. al., 1998; Frank, and Nancy, 2000; Gikas et al., 2006, and Denton et al., 2009). Studies on the environmental conditions and pollution source in south coasts of Caspian Sea are even more limited (Sovintervod, 1993).

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In numerical modeling of pollution spreading in surface water bodies such as lagoons, the effects of advection due to wind-forced water current are usually dominated (Murakami, et. al., 1985; Swail and Cox, 2000). Moreover, considering the effects of coastal structures and special geometry is in a major importance in real case study of restricted or chocked lagoons (Tufford and Mckellar, 1999; Tanaka and Lee, 2003). The effects of waves on the pollutant spreading pattern are usually in a lower order than the effects of water current induced by wind (Giordani et al, 2009; Najafi-Jilani and Ataie-Ashtiani, 2008).

In this work, the water quality of Gomishan lagoon in southeast of Caspian sea is numerically modeled considering the effects of discharged waste water. A six month period of field investigations carried out to measure the current velocity and wind data of study area. Model results calibrated with field measurements and applied to determine the flushing time and pollution spreading pattern in the lagoon. The numerical model is a coupled hydrodynamic and advection-dispersion module. The computational grid used was constructed from bathymetric soundings measured in 2002 and updated in 2007. The numerical modeling is made in several conditions considering different types of pollutant with various ratio of decay. The results are used to present some applicable experiences in integrated hydrodynamic and water quality modeling and also in field investigations in restricted lagoons. The water quality control of lagoon is also discussed considering the environmental criterion and safe water intake system.

2. Environmental Specifications

The Gomishan lagoon has an extension of about 110 km^2. Figure 1(a) shows an overview of the lagoon. The study area and the location of water intake and waste water outfall in lagoon are shown in Figure 1 (b). The distance between intake and outfall of plant is about 6 km. The water depth in the lagoon has a maximum value about 1.5m. The intake water and outfall wastewater discharge is time variable based on the plant operation. The maximum waste water discharge in about 23cms. The time variation of water intake and waste water discharge into the lagoon in each 6-month operation period of industrial plant is shown in Figure 2. This variation is considered in long-term numerical modeling of water quality in lagoon. The wastewater is released in an open channel and transferred into the seawater surface by gravity. Wind specifications including wind velocity and direction are the most important environmental data because the current pattern in the lagoon and water transferring into the sea is mainly caused by wind. To define the wind specifications in the numerical modeling, a process is made on the available wind data from study area. Firstly, the recorded data at the nearest climatology station is used to construct the wind rose of the studied area. In this climatology station the recorded wind data is available for 40-year period from 1968 to now.

The wind velocity and direction have been recorded in this station at 3-hour time interval. The recorded data are processed and the 40-year wind rose in two seasons of plant operation, spring and summer, is constructed. Figure 3 shows the wind rose of first 6-month of year based on 40 years recorded data at the nearest climatology station which is located about 15km far from study area. This figure shows the summarized occurrence of winds including wind strength or velocity in knot, direction and frequency.

Considering each branch of the rose in Figure 3 which represents wind coming from that direction, it is concluded that the prevailing directions of wind are west and south-west. The branches are divided into segments of different thickness and color, which represent wind speed ranges as 05-1.5, 1.5-3, 3-5, and 5-8 meter per second from that direction. The length of each segment within a branch is proportional to the frequency of winds blowing within the corresponding range of speeds from that direction and listed in Table 1. The frequency percentage of wind occurrence and velocity in each direction based on 40 years data for first 6 month of year are presented in this table.

The maximum frequency percentage of wind was blown from west and south-west, respectively. Based on the prevailing directions of wind, it is expected that the water transporting from lagoon into the sea can be mainly occurred from the northern boundary. The percentage of calm conditions is about 64.6%. It can be concluded that the study area is generally calm zone and it may be influenced on the flushing time of lagoon and accumulation of pollution in the lagoon in the operation period of plant.

3. Field Investigations

A six month period is assigned for field investigations and measuring important data which mainly govern the water current pattern and flushing time of lagoon (Maria et. al., 2009). Field investigations are also carried out to calibrate the hydrodynamic numerical model comparing the numerical and field measured data. The field data gathering began at April 10, 2007 and continued until September 20, 2007. During the field investigation period, main environmental parameters including wind direction as well as speed and water current specification in and out of the lagoon are measured. Because of the minor effects of water waves on the pollution transferring in the lagoon, the recorded wave data is not considered here (Ataie-Ashtiani and Najafi-Jilani, 2007, 2008)

A temporary wind measuring station (Figure 4) using SKYE MiniMet device was installed at the study area and the wind velocity and direction at a height of 8m from ground level have been measured in a 1-hour time interval. The field-gathered wind data during this period is interpreted in a 6-month wind rose as shown in Figure 5. The occurrence percentage of wind in each direction and the wind velocity range based on 180 days recorded data during field investigation are listed in Table 2.

The calm condition percentage during field investigation period was about 61.3%. Based on the field observation and recorded data during field investigation period, the prevailing wind direction was really from west and sometimes from south-west. The effect of west wind can be seen on the old buildings. The detail comparison can be made between 40-year recorded data at the nearest climatology station and measured 6-month wind rose. It can be concluded that the 40-year wind rose can be generally accepted as general climatology behavior of study area. Moreover, it seems that the measured data in 6-month period of field investigation is in a good agreement with long-term recorded wind data at the nearest climatology station. So, the detail data recorded at 1-hour time interval at the temporary wind station located at the study area is used in numerical modeling. The water current velocity and direction at the middle depth are measured at two stations during 6-month field investigations. One located at the lagoon (ST-C1) and another one located at sea (ST-C2). Because of the shallow water depth, a steel frame structure is used to install Valeport308 current meter made by AAnddera industrial company in the lagoon and in the sea. Figure 6 shows the construction of steel frame and installation of water current meter in the sea. The exact locations of the current meters are shown in Figure 7. The location of ST-C2 is selected near to the seaward boundaries of local model because of the major importance of the current speed and direction is in this area, where the hydrodynamic data are transferred from regional to local model.

The location of in-lagoon current meter is selected near to the outfall of plant because of the major importance of hydrodynamic specifications in this zone and the effects of them on the water quality and pollution spreading in the sea. The water current speed at the gauge points are captured from numerical model and compared with the field measured data recorded by the current meters.

3. Numerical Modeling

The numerical modeling was made using MIKE21 model. A coupled hydrodynamic (MIKE21-HD) and advection-dispersion (MIKE21-AD) modules are used to simulate the pollution spreading in the lagoon. This two-dimensional depth-averaged finite-difference model is completely applicable for shallow water restricted lagoons. Two regional and local models are developed and coupled. Coupling of models is an efficient and accurate means of calculating water level and current on local domain, at and around the intake and outfall of industrial plant (DHI Software, 2004). Figure 7 shows the selected area in both local and regional models and the bathymetry of study area in Caspian Sea and lagoon. The dimensions of regional model are 45 x 75km, along the X (east-west) and Y (south-north) directions, respectively. The grid spacing is accordingly selected as 150 and 200m. In local model, an 11 x 24km zone is selected around the study area and the grid spacing in both directions is selected as 50m. The time step in both numerical models is assumed as 20s. The selected grid spacing as well as time step in both numerical models is optimized due to minimize the effect of these computational parameters on the results. The boundary conditions in regional hydrodynamic model are assumed as the specified water level in both northern and western boundaries according to available data of Caspian Sea water level during the simulation period. At the east and south boundaries, the geometric boundary condition is assigned according to the available geometry of coasts. The hydrodynamic information provided by the regional model is applied as the boundary conditions at the seaward edges of local model. The effects of intake and outfalls of industrial plants are considered in the numerical modeling using sink-source module.

Calibration and verification of numerical model is done using the field measurements. Figure 8 shows the comparison of numerical results and measured data at ST-C1; in-lagoon current meter. To calibrate the numerical model, different values are selected for bed roughness and the agreement of numerical results with field data is checked. The resistance of the bed of lagoon and sea to the flow of water is defined by Manning coefficient in numerical model. A range of 0.05 to 0.1 (in SI system) is selected for value of n where n is the Manning coefficient. The comparison of numerical results and field data for water current speed at check point in the lagoon and sea is shown in Figure 8. As it can be seen, the duration of comparison which is shown in this figure is 24 hours. Although the field data and numerical results are available for six month but for better recognition and comparison, a 24-hour period in entire 6-month period is selected and shown in Figure 8. The maximum relative difference between numerical and field data is occurred in this duration.

It can be seen in Figure 8 that the water current velocity at the north boundaries of restricted lagoon is generally more than in-lagoon station. The average velocity in lagoon is about 20% less than northern boundaries. The low-order current velocity in lagoon with a range of 0.01 to 0.04m/s can increase the flushing time of lagoon and influence the transportation of pollution into the sea. The maximum agreement between measured data and numerical results in both measuring stations is happened when the roughness coefficient of bed is selected as $n = 0.07$. So the hydrodynamic model results assuming this value for Manning coefficient are used in water quality modeling. Besides, the specifications of the released waste water into the lagoon which was described in Figure 2 of Section 2 are considered. The computational parameters in water quality model are the same as hydrodynamic modeling.

4. Results and Discussion

The numerical results are used to investigate the pollution spreading pattern and water quality control in the lagoon. Firstly, the flushing time of lagoon is calculated based on the results of calibrated hydrodynamic model. In this regard, the average rate of water exchange between sea and lagoon are calculated (Villanoy et al, 1994). Using numerical results, the water discharge and direction along all of the boundaries between lagoon and sea in entire six month period of modeling is calculated. To determine the rate of water exchange between lagoon and sea, the time series of accumulated water volume which exchanges in lagoon boundaries are captured from numerical model and shown in Figure 9. The water volume exchange is assumed positive if it is transferred from sea into the lagoon and negative for water volume transfer from lagoon toward the sea.

Based on the accumulative values of water volume exchanges at the boundaries of lagoon within 6-month presented in Figure 9, the total water volume which transfer from sea into the lagoon (positive values) along the northern and southern edges are about 87.0 and 10.4, respectively. Similar values for water values exit from lagoon into the sea (negative values) are 46.0 and 33.3 million cubic meters, respectively. It can be concluded that the most flushing of lagoon is occurred along the northern boundaries. About 75% of flushing of lagoon water is occurred from northern boundaries. It mainly happened because of the wind pattern in the study area. Total water exchanges between lagoon and sea are about 176.7 million cubic meters per six month. So the rate of water exchange of lagoon is about 11.3 cubic meters per second. Considering the average water depth in the lagoon as 1.25m and the area of it as 110km^2, the flushing time of the lagoon is determined about 140 days. Considering that the duration of releasing wastewater is 180 days, it seems that this flushing time is too long to exchange the contaminated water of the lagoon with seawater. The detail investigations can be made based on the results of water quality modeling. In Figure 10, the numerical results of pollution spreading in the lagoon are shown at 2, 4, and 6 month after wastewater releasing into the lagoon. The no-decay pollutant with 100% concentration is released into the lagoon from outfall of adjacent plant. The pollutant concentration in the lagoon is shown on the figure.

According to Figure 10, the main transferring of pollution from lagoon into the sea is occurred from northern boundary. The pollutant concentration around the intake of the plant is about 55% and it cannot satisfy the environmental criterion and safe operation of plant. The accumulation of pollution in the lagoon means that the flushing of water is not properly occurred. It seems that the wind speed or wind durability at the study area is not sufficient to transport the contaminated water of lagoon into the sea. It can be concluded that the non-decay pollutant shall not be released into the lagoon because of the restricted conditions of it and weakly effects of wind.

More investigations are made for pollutant with a specified ratio of decay. In this complementary investigation, the hydrodynamic model and calibration procedure are the same as explained before. But in water quality modeling, the decay ratios of different types of pollutants are considered according to Table 3. The concentrations of pollution in the outfall of industrial plant are also listed in Table 3. The results of numerical model considering the decaying ratio of pollution are shown in Figure 11. As it can be seen in Figure 11, the general pattern of spreading of pollution is the same as shown in Figure 10 for non-decay pollution. But the maximum concentration of pollution in entire of the lagoon is about 0.1 to 0.25%.

The maximum concentration of pollution in worth case at the intake of plant is about 0.21% which completely satisfy the safe watering of plant. The environmental criterions are entirely satisfied considering the decay ratio of pollution in the lagoon. It can be concluded that for decaying pollutant as described in Table 3, the water quality of lagoon will be at a controlled status during the operation period of industrial plant.

5. CONCLUSION

The water quality modeling of a restricted lagoon at south-eastern coasts of Caspian Sea is investigated. Both numerical model and field measured data are used to study the spreading patter of pollution in the lagoon. The wind speed and direction as well as water current at two station in and out of the lagoon are measured during first six month of year which was the operational period of plant. Both regional and local numerical models are developed and calibrated using field measurements. The flushing time of lagoon is calculated along the boundaries between lagoon and sea. Based on the calibrated numerical model results, it is concluded that for non-decay pollutant, environmental problems will be occurred in the lagoon because of the long flushing time and weakly effects of wind-forced water current. But considering special rates for decay ratio of pollutant, the environmental criterions and safe watering of industrial plant can be satisfied.

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List of Tables and Figures

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Table 1.Occurrence percentage and velocity range of wind for each direction in spring and summer based on 40 years recorded data at the nearest climatology station

vel. (m/s) direction	**0.5 – 1.5**	**1.5 – 3.0**	**3.0 – 5.0**	**5.0 – 8.0**	**sum**
North	1.0	1.0	-	-	**2.0**
North- East	0.6	1	-	-	**1.6**
East	0.6	1.6	0.4	-	**2.6**
South-East	-	0.7	-	-	**0.7**
South	0.6	1.0	-	-	**1.6**
South-West	1.0	3.6	1.4	0.3	**6.3**
West	1.7	8.6	4.3	1.0	**15.6**
North-west	2.6	2.0	0.4		**5.0**
sum	**8.1**	**19.5**	**6.5**	**1.3**	**35.4**

Table 2.Occurrence percentage and velocity range of wind for each direction in spring and summer based on 6 month measured data at the study area

vel. (m/s) direction	**0.5 – 1.5**	**1.5 – 3.0**	**3.0 – 5.0**	**5.0 – 8.0**	**sum**
North	1.0	1.0	-	-	**2.0**
North- East	-	0.3	-	-	**0.3**
East	-	0.4	-	-	**0.4**
South-East	-	-	-	-	**-**
South	1.0	1.0	-	-	**2.0**
South-West	1.0	4.0	1.6	0.4	**7.0**
West	2.0	13.0	5.0	1.0	**21.0**
North-west	2.6	2.4	1.0	-	**6.0**
sum	**7.6**	**22.1**	**7.6**	**1.4**	**38.7**

Table 3.Decay ratio and concentration of pollutants in outfall of industrial plant

Pollutant	**Phosphor**	**Nitrogen**	**BOD**
Decay ratio per 24 hrs	59.2%	27.8%	55.8%
Concentration in firstly 120 days	0.15	2.2	4.55
Concentration in secondly 60 days	0.61	2.9	16.68

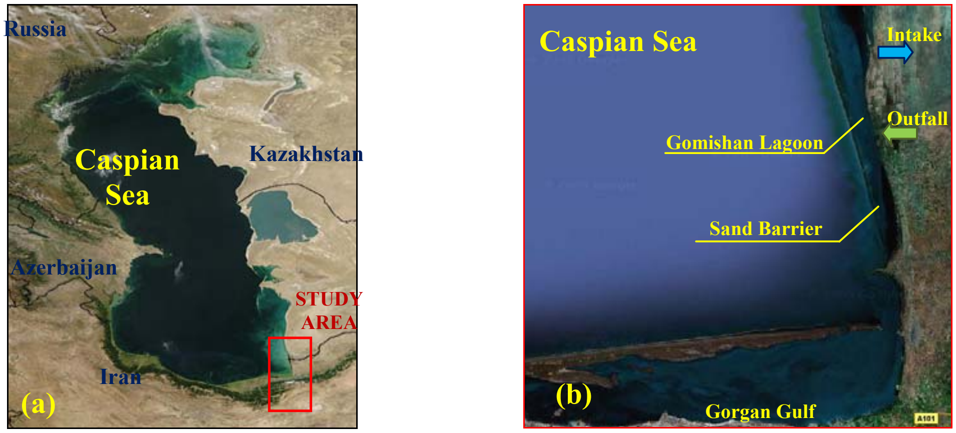

Figure 1.Location of Gomishan lagoon in south-east of Caspian Sea (a), and intake and outfall location of industrial plant in the study area (b)

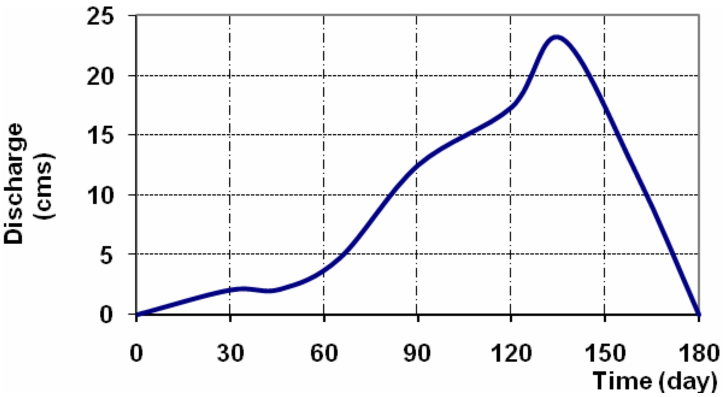

Fig 2.Variation of water intake and waste water discharge into the lagoon in 6-month operation period of industrial plant

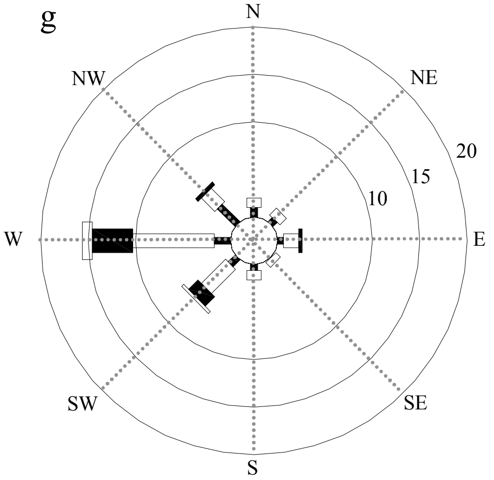

Fig 3.Spring-summer wind rose based on 40 years recorded data at the nearest climatology station to the study area

Fig 4.Temporary wind measuring station installed at the study area for 6 month

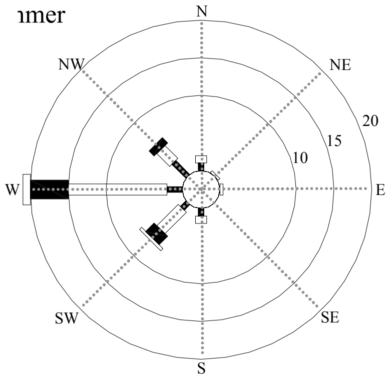

Fig 5.Spring-summer wind rose based on 6 month recorded data at the study area during the field investigations (Apr. 10 to Sep. 20, 2007)

Fig 6.Construction of steel frame structure in the shop (a) and installation of it in the sea (b) to measure the water current speed and direction

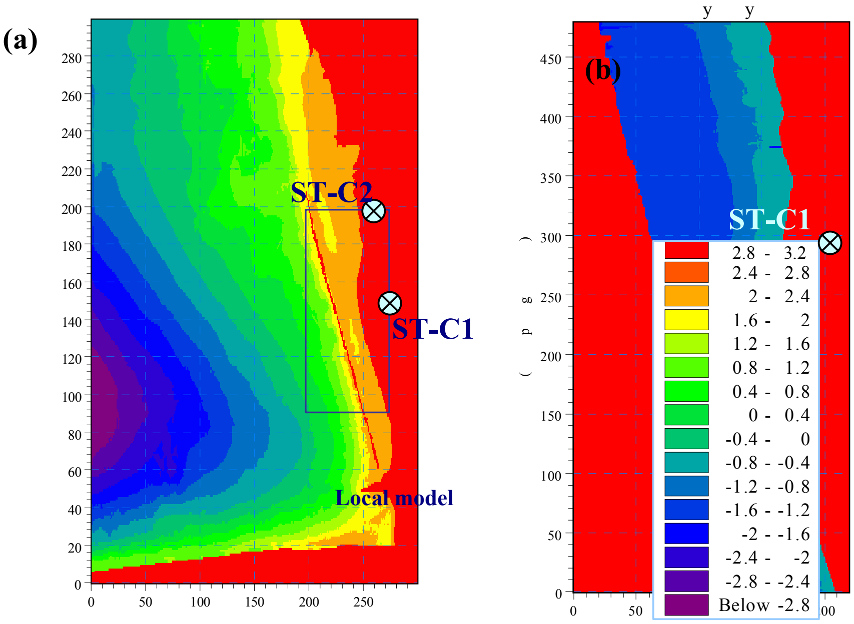

Fig 7.Bathymetry in regional (a) and local (b) models, the location of current meter stations during field measurements are also indicated

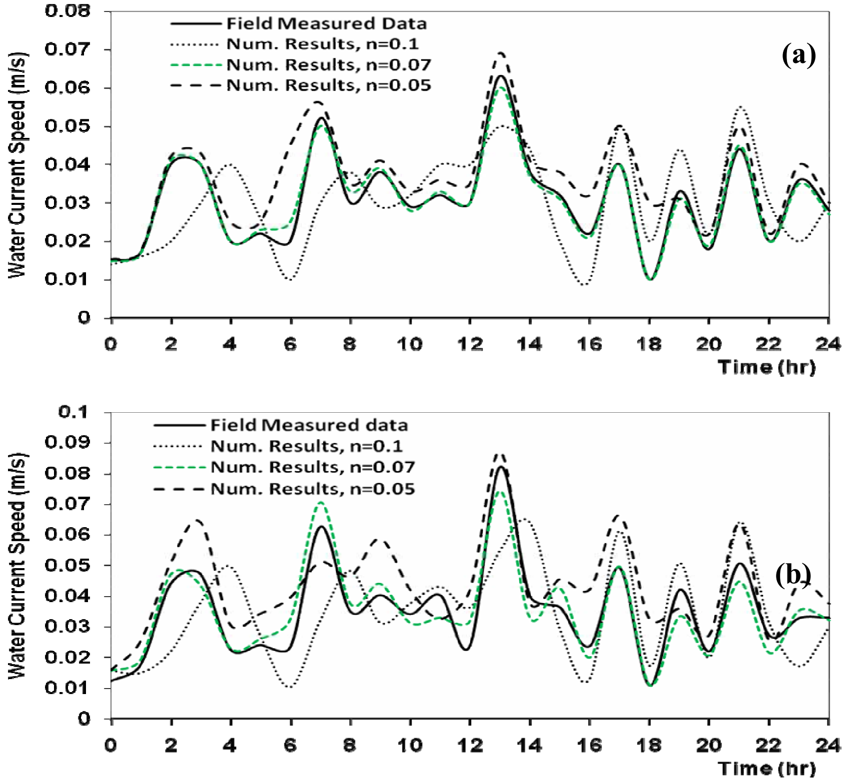

Fig 8.Calibration of numerical model comparing with field measurements at current gauges, (a) ST-C1 and (b) ST-C2

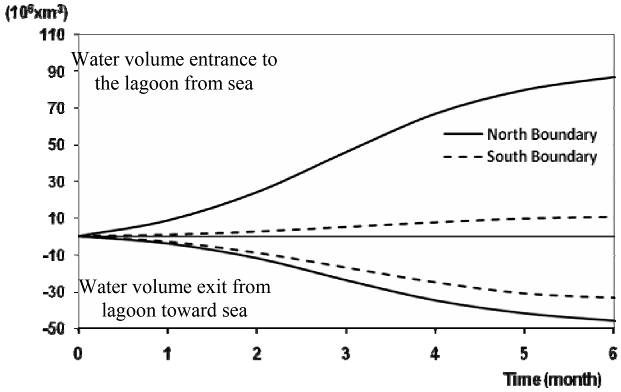

Fig 9.Accumulated water volume exchanges along the boundaries of lagoon during the period of waste water releasing into the lagoon

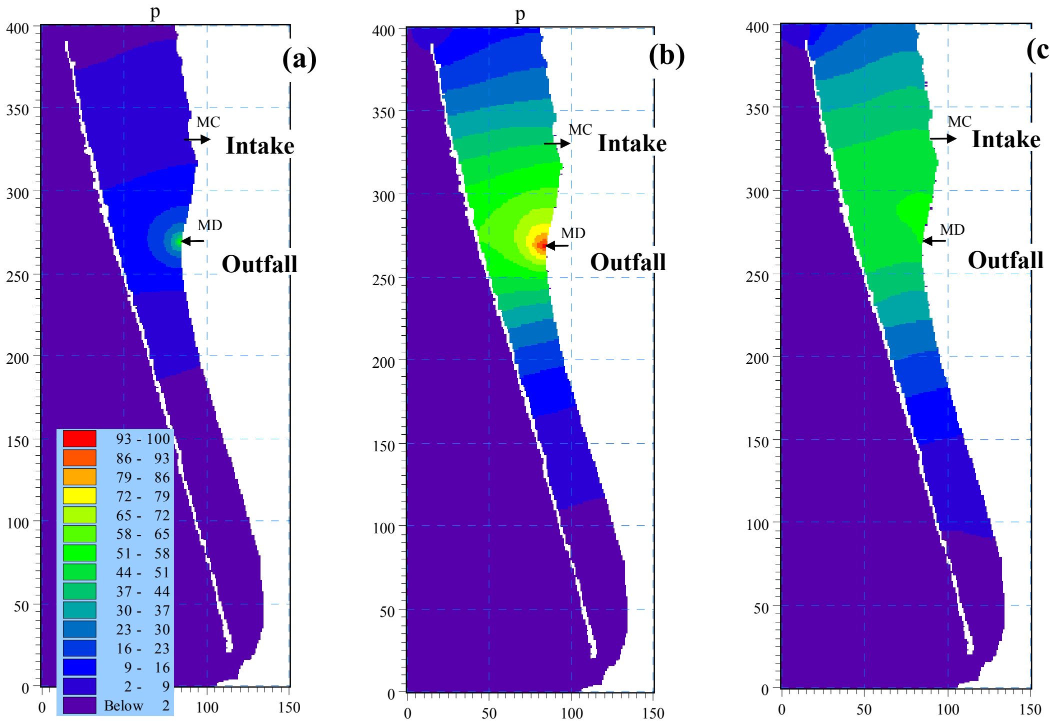

Fig 10.Numerical results of water quality modeling in lagoon, pollution spreading at a) 2, b) 4, and c) 6 month after waste water outfall, Grid spacing is 100m

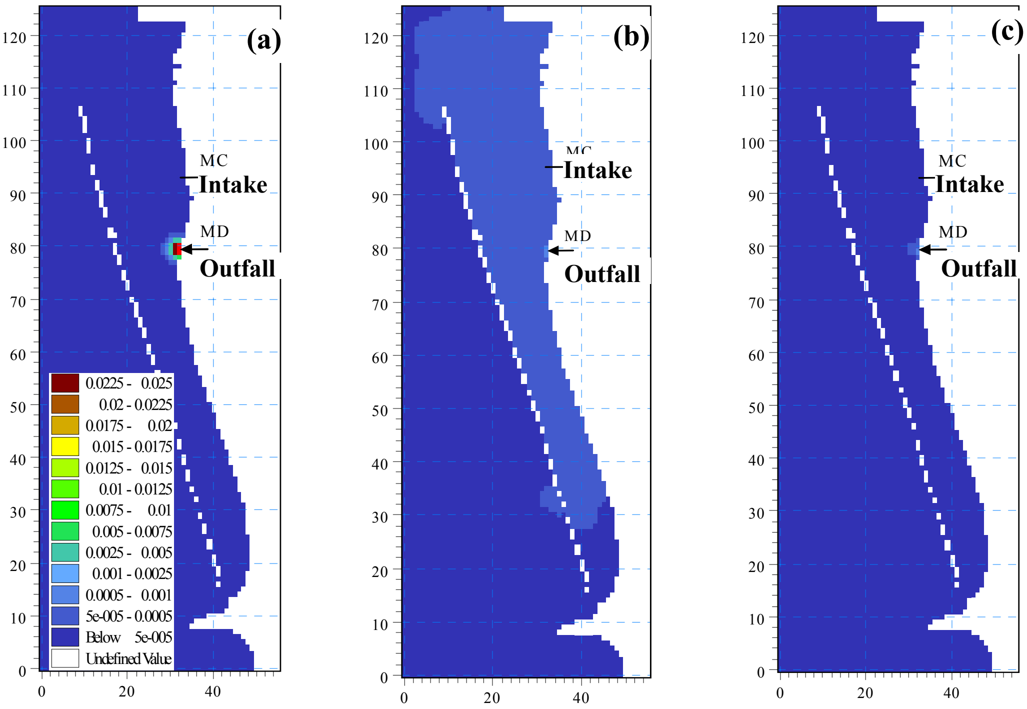

Fig 11.Numerical results of water quality modeling in lagoon, pollution spreading at the worth case during discharge of pollution for a) Phosphor, b) Nitrogen, and c) BOD, Grid spacing is 300m in *x* and 400m in *y* dir., decay ratio of pollutants are considered as Table 3.