Assessment of the Occurrence of Anoxic and Hypoxic Water Due to Coastal Construction in an Enclosed Water Area

Md. R. Karim, **M. Sekine and M. Ukita**

Department of Civil Engineering, Yamaguchi University, 2-16-1 Tokiwadai Ube City 755-8611, Japan (c5568@stu.cc.yamaguchi-u.ac.jp)

Abstract: A probabilistic calculation of the occurrence of hypoxic and anoxic conditions was carried out to assess the environmental impact of the ongoing construction of an artificial island in the shallow water zones of a coastal bay in Japan. For the purpose a combined hydrothermal and eutrophication model was used and long-term calculations under observed meteorological conditions for twenty years were carried out, with and without the artificial island, since the meteorology has a significant influence on the development of oxygen depleted waters. The results of the simulation show that the ongoing construction has insignificant impact on the formation and the progressive development of oxygen-depleted water mass in the bay, but it prolongs the duration of hypoxic and anoxic conditions of the bay. Both meteorology and hydrodynamics contribute to the development of oxygen-depleted bottom waters and the condition is most severe during August. In this period, a larger part of the inner bay is experienced by hypoxic water with high probability of occurrence, indicating potentially high damage and severity associated with hypoxia on ecology including mortality of fish and benthic community in this period. The model results agreed very well with the observed data in the stratified shallow bay and can be used in other bays and lakes, where knowledge of temperature and density stratification is important for assessing the water quality and formation of oxygen-depleted water.

Keyword: Hypoxia and anoxia; Probability of occurrence; Land reclamation work; Water quality modeling

1. INTRODUCTION

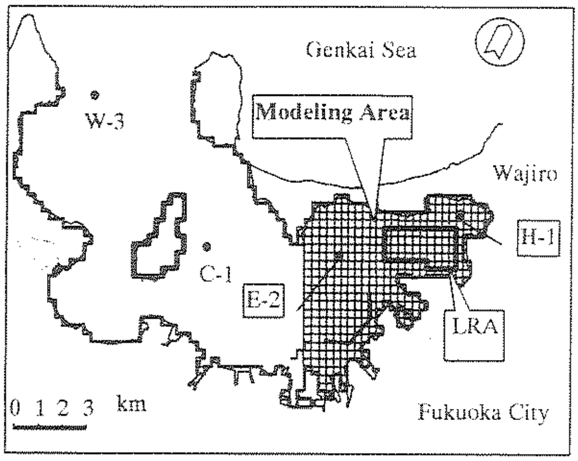
The importance of environmental impact assessment of the coastal construction works is widely recognized. Japan is an island nation comprised with a total land area of 378,000 km^2, but the habitable area is only 21% due to pre-dominance of rugged mountainous terrain. Habitable land is distributed mostly close to the coastline. Large-scale reclamation projects in urban coastal areas in Japan have recently increased to meet the great demand of urban housing, industrial expansion and relocation and port activities. About 170,000 ha have been reclaimed from the seas by 1985, which is about 2.1% of the habitable land area [Fujimori et al., 1989]. Land reclamation in coastal areas may cause drastic change in coastal ecosystem due to change in the current and mixing pattern of water. Moreover, high nutrients and organic loadings from land areas together with artificial construction may cause eutrophication and frequent appearance of algal bloom at water surface and hypoxic and anoxic condition at the bottom waters, which has adverse effect on the fisheries resources [Robert and Rutger, 1995]. Shallow coastal areas are of great importance for the nursery of fish and shellfish and land reclamation in this areas cause damage to fisheries [Nakatsuji et al., 1994].

There have been several definitions of the hypoxic and anoxic conditions depending on the degree of harmfulness to marine organisms. The number of species and abundance of benthic organisms and fishes are strongly associated with the dissolved oxygen concentration in the near bottom water [Imabayashi, 1983]. From the point of fisheries production, the number of fish species and their diversity decreases drastically, when DO falls below 3.0 mL/L (1 mL/L=1.45 mg/L) and almost all species of fish are influenced under DO less than 2.0 mL/L [Nagai and Ogawa, 1997]. When DO drops to less than 3.6 mg/L, the normal distribution of benthos begins to change and the mortality of yellowtail tuna is initiated [Yanagi, 1989]. Benthic infaunal and shellfish mortality will be initiated when DO drops below 2.0 mg/L [Yanagi, 1989; Robert and Rutger, 1995]. Water having DO in between 0.036 mg/L to 3.6 mg/L is termed as oxygen-deficient water mass and DO of 0.036 mg/L is the upper limit of anoxic water mass [Yanagi, 1989].

Although the tolerance of aquatic life to hypoxia is well known, evaluation of the probable spatial and temporal damage and severity caused by hypoxia and anoxia on an ecosystem remains difficult. However, this is directly related with the occurrence probability of these events. Since the physical and biological processes controlling water quality and DO in the ecosystem are inherently random [Tung and Hathhorn, 1988], probabilistic calculations of the occurrence of hypoxia and anoxia are more realistic and informative that represent also an indirect measure of the probable spatial and temporal damage and severity caused by hypoxia and anoxia on living resources in the ecosystem. If the occurrence probability of these events in a particular time interval is high, its subsequent adverse effects and severity will also be high. This paper presents a methodology of calculating the probability of occurrence of hypoxic and anoxic waters within a combined hydrothermal and eutrophication model. Using the method, an environmental impact assessment of the ongoing land reclamation work (Figure 1) in the shallow water zones of Hakata Bay was carried out in terms of the probability of occurrence of hypoxia and anoxia. Moreover, meteorology has a significant influence on the formation of oxygen-deficit waters, so long-term simulations with recorded daily meteorological data as input for 20 years (1980 to 1999) were also carried out to examine the influence of meteorology on the formation of hypoxic and anoxic waters and the succeeding probability of occurrence and duration of these events due to land reclamation work. The results of our findings are discussed in the following section.

2. DESCRIPTION OF STUDY AREA

Hakata Bay, a shallow semi-enclosed bay located in the western part of Japan, has been suffering from eutrophication and occurrence of red tides at water surface and the onset of hypoxic and anoxic conditions at bottom water of the inner bay in every summer due to excessive organic and nutrients loadings from Fukuoka City and its catchment. The longitudinal and latitudinal lengths of the bay are about 20 km and 10 km, respectively. The watershed area is about 690 km^2 and a population of about 1.9 million lives in this area. The bay has an average water depth of 10 m below the mean sea level. The average air temperature is as high as 28 ^{0}C in August and as low as 7 ^{0}C in January. Residence time of freshwater in the bay varies from 1 day in June to 24 days in March and the yearly averaged residence time of freshwater is about 8 days. The average freshwater inflow into the inner bay is about 15.43 m^3/sec and COD, TN and TP loadings from tributaries and land areas to the inner bay are 10350, 6661 and 474, respectively in kg/day. Moreover, high growth of algae and associated high primary production during winter is observed in spite of low water temperature, which is characterized especial phenomenon affecting water quality of the bay [Nakashima et al., 1999]. Land reclamation of about 401 ha areas is also going on in the Wajiro tidal flat zones at the head of the bay, which is very famous habitat for migratory birds and larvae and is planned as a wildlife special protection area by the Environmental Agency of Japan (Figure 1) and the project will be completed by the year 2004.



LRA – Land Reclamation Area • Monitoring Stations

Figure 1. Hakata Bay, modeling area, water quality monitoring stations and model grid.

3. METHODOLOGY

In order to evaluate the probability of occurrence of hypoxia and anoxia, DO of less than 3.6 mg/L and 0.036 mg/L were taken as the criterion for hypoxic and anoxic water, respectively [Yanagi, 1989; Sekine et al., 1995]. The probability of occurrence of hypoxia and anoxia that may occur in every 10 days at bottom water of a grid location is defined as:

$$P_{oh} = \frac{N_h}{N_T} \quad (1)$$

$$P_{oa} = \frac{N_a}{N_T} \quad (2)$$

in which, P_{oh} and P_{oa} are the occurrence probability of hypoxic and anoxic water, respectively, N_h and N_a are the number of occurrence of hypoxic and anoxic events in a computational time interval of 30 min within 10 days and N_T = 10 days/30 min = 480. In order to simulate the DO dynamics of the bay, a 3-Dimensinal combined hydrothermal and eutrophication model (CHEM) was used [Karim et al., 2001]. The hydrothermal model is the extension of the multi-level stratified flow model MK2 [Kishi et al., 1981; Fujihara et al., 1992] by including a heat transfer sub-module to calculate net hourly atmospheric heat exchanges and its distribution within the water body. The model calculates tidal currents, diffusion between layers, water surface elevation, salinity and water temperature considering density flow and wind-induced current in each time step. The eutrophication model is an integrated model of material circulation between water column and bottom sediment, which incorporated nine state variables such as organic and inorganic phosphorus, organic, ammonia and nitrates nitrogen, COD and DO and two biological components, phytoplankton and zooplankton. The structure of the model is based on a generally accepted framework [Thomann and Muller, 1987; Ambrose et al., 1988; Cerco and Cole, 1995; Karim et al., 2000] with the exception of the interaction between the layers via vertical advection and turbulent diffusion. The sediment model consists of three basic processes: deposition of particulate organic carbon, nitrogen and phosphorus (POM) from the water column to the bottom sediment; decay or diagenesis of POM within the sediment layer to produce inorganic substances (NH_4-N, NO_3-N and PO_4-P) and the released or flux of these substances to the water column and to the deep, inactive sediments. Nutrients undergo adsorption and desorption or precipitation and dissolving between the interstitial liquid phase and solid phase in mud. The released of phosphate from bottom sediment is markedly controlled by oxidation-reduction potential (ORP) condition, which depends on DO concentration in the bottom water. The mathematical formulations of the sediment water interactions processes are taken from the works of Nakanishi et al., [1986].

The layer-averaged water quality variables and transport equations of pollutants solved in the model are defined and derived in a similar way to those of MK2. The water quality algorithms are integrated directly into the hydrodynamic model, so that they shared the same computational grid and time steps and run simultaneously. Computational domain was divided into staggered meshes in the Cartesian coordinates with the horizontal grid of 300m x 300m (Figure 1) and the water depth into 5 layers with variable thickness. The thickness of the top water layer is 1m, while the second, third and forth layers are 3m, 3m and 4m, respectively and the rest is for the last layer. The number of layers at each grid depends on water depth and the thickness of the top layer varies with water level fluctuations. The sediment layer is divided into two layers, the top one is 1cm thick and the bottom layer is 5cm thick. Free surface elevation and depth-integrated currents were calculated with the finite difference schemes of forward difference in time, upwind difference for the advection and the central difference for the diffusion term. The model was developed with the collected data for the year 1996-97 [Port and Harbor Bureau of Fukuoka City; 1997].

4. RESULTS AND DISCUSSIONS

To evaluate the effect of the land reclamation project, the model was run with and without the artificial construction island for twenty years with observed meteorological data as input. Contours of the probability of occurrence and progressive development of hypoxia at the bottom waters under these two conditions are presented in Figure 2 and 3. These contours are the averaged results of our simulations under a wide range of meteorology from 1980 to 1999, thus represents the general trends and the most probable occurrence of hypoxic condition in a year. The cumulative occurrence of hypoxic and anoxic water at station H-1 (22,3) is presented in Figure 4. Seasonal hypoxia first appears at the end of June, and then gradually expanded and is most severe during August, when a larger portion of the bottom water in the inner bay is experienced by hypoxic condition having high probability of occurrence. These contours also point out the possible damage and severity associated with hypoxia on ecology including mortality of fishes and benthic communities are most intense in this period in the bay. In general, more hypoxic conditions are prevalent inshore. By the end of September, hypoxia disappears by the onset of cooling and subsequent breakdown in the strength of water column stratification. Water temperature in August is highest, which coincides with the highest probability of the occurrence of hypoxia. In summer, stratification caused by climate condition and excessive tributaries inflow isolates bottom waters from oxygen inputs and decomposition of settled organic matter produced by algal blooms in the sediment, exert high SOD and caused the development of oxygen deficit waters in the bay. The land reclamation work has no significant impact on the formation of oxygen-depleted bottom

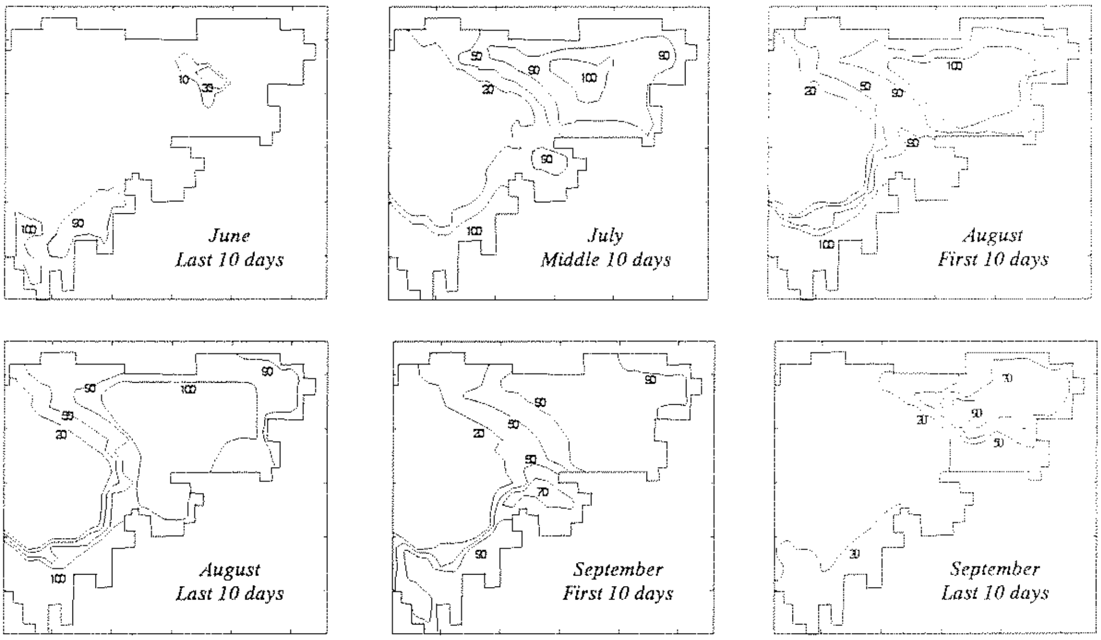


Figure 2. Contours of progressive development and probability of occurrence of hypoxic bottom water at the inner bay without artificial island averaged over 20 years' simulations from 1980 -1999.

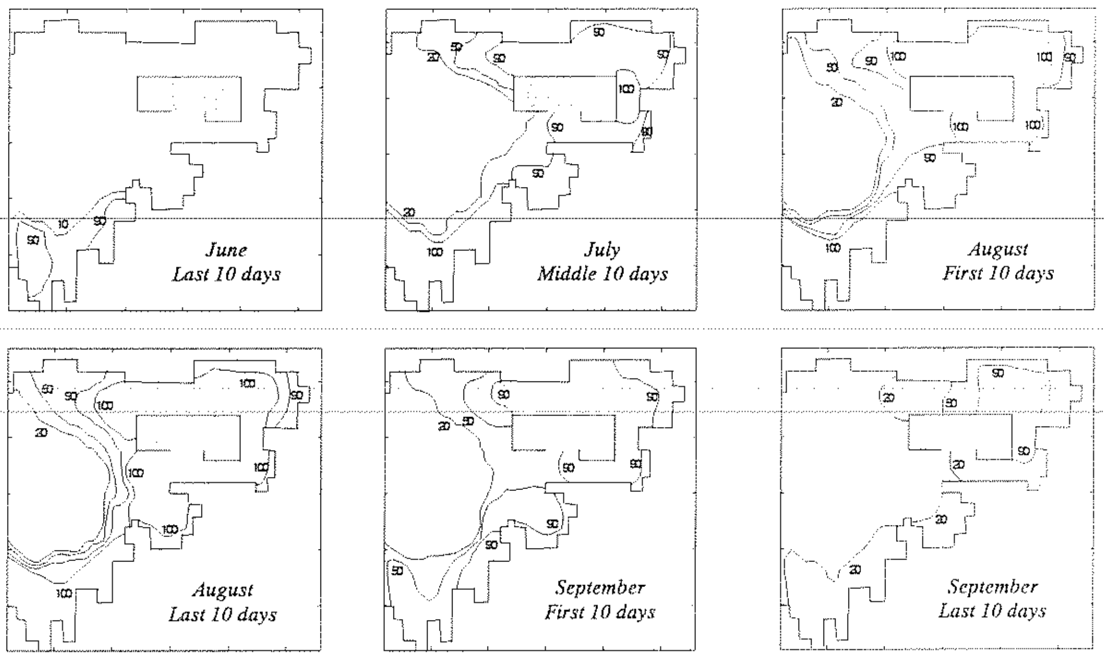


Figure 3. Contours of progressive development and probability of occurrence of hypoxic bottom water at the inner bay with artificial island averaged over 20 years' simulations from 1980 -1999.

water as shown in Figure 2 and 3. However, it shifted the highest oxygen-depleted water (area with low DO) towards the north edge of the artificial island, which agreed with the results of the previous simulation [Sekine et al., 1999]. The reason behind this is the change in circulation pattern in the area due to the construction of the artificial island.

4.1 Duration of Hypoxia and Anoxia

The bottom DO condition at the head of the bay from several measuring stations [Watanabe et al., 2000] during 1996-97 is shown in Figure 5. This survey results showed that oxygen depleted water mass occurred at the bottom water and hypoxia lasted for about 90 days. Anoxic condition also

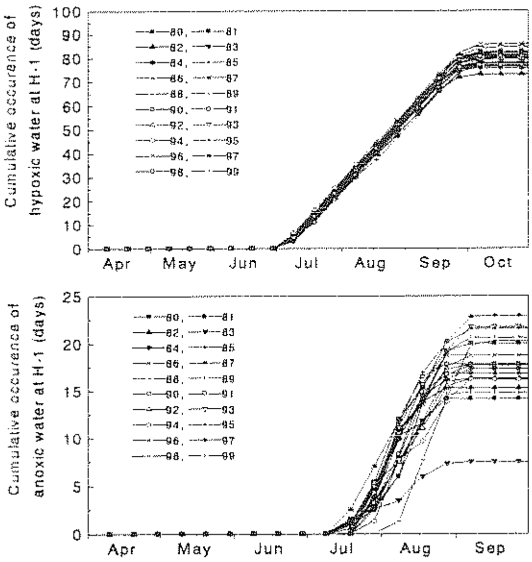


Figure 4. Cumulative occurrence of hypoxic and anoxic conditions at H-1 (22,3) for twenty years simulation.

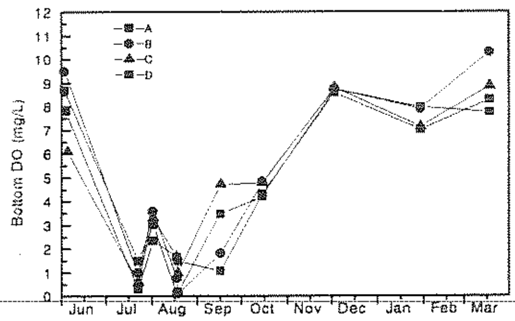


Figure 5. Bottom DO conditions at several stations in the inner bay in 1996-97.

occurred, however no information about its duration is available from this monthly-based survey. Model computation of the duration of hypoxic and anoxic conditions (in days) at the bottom water at (22,3) and the resulting effect of land reclamation work (LRW) is shown in Figure 6. The bar diagram represents the net increased of the duration of hypoxic and anoxic conditions. It clearly shows that the LRW prolongs the duration of hypoxic and anoxic conditions in the inner bay. Under prolonged hypoxia, fish and invertebrates die and energy are dissipated by micro-benthos. Strong wind can cause the upwelling of bottom oxygen-depleted water, causing the development of hypoxic condition to some extent at the surface. During the survey period in 1996-97, the project area for land reclamation was surrounded by thick polyester curtain down to the bottom, thus the effect of land reclamation was existed during the survey. Hypoxia that occurred in the bottom water in the inner bay in 1996 was about 90 days and the model computed duration of hypoxia for the

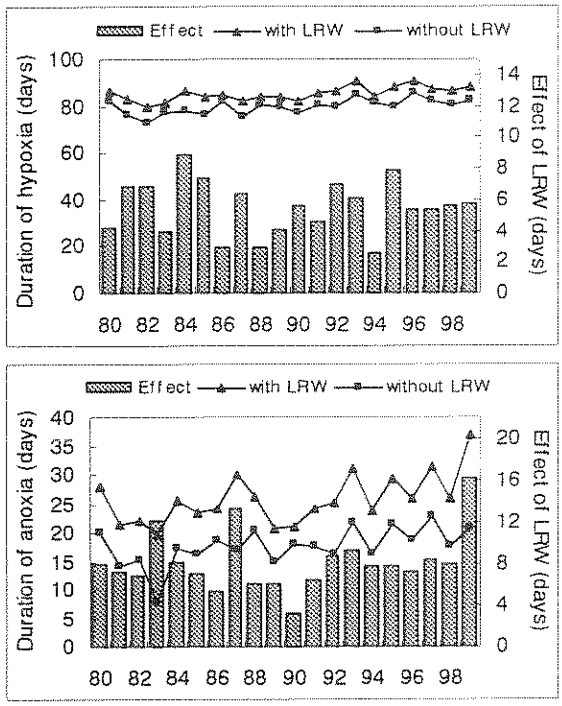


Figure 6. Effect of land reclamation work on the duration of hypoxia and anoxia in the inner bay.

same year is about 91 days with land reclamation work (Figure 6). This indicates that the present model could capture the processes controlling the development of oxygen-depleted water in the bay very accurately.

5. CONCLUSIONS

A methodology of assessing the probabilistic occurrence of hypoxic and anoxic conditions, that represent an indirect measure of the spatial and temporal damage and degree of harmfulness caused by these events on the ecosystem was presented in this paper. This method was used to evaluate the occurrence probability of hypoxia and anoxia due to the construction of an artificial island in the shallow water zone in Hakata Bay. The simulation results show that the ongoing artificial inland has insignificant impact in the formation and the progressive development of oxygen-deficit bottom waters. However, it prolongs the duration of hypoxic and anoxic conditions in the inner bay.

The presence of strong stratification caused by meteorology is the main reason of oxygen-depleted bottom waters appearing in the inner bay. The hydrodynamics of the bay has a significant role in transporting inputted organic materials as well as that produced by primary production to the inner bay. During August, a large part of bottom water is experienced by hypoxic condition with high probability of occurrence, which indicates that the possibility of the damage and severity caused by hypoxia on ecosystem including mortality of fish and benthos is also potentially high in this period. Model simulated duration of hypoxia in the year 1996 is almost equal to the observed duration in that year in the inner bay. Moreover, the model used in this study was capable of simulate reasonably the hydrodynamics, thermal structure and water quality processes of the bay, which are the key elements in the formation and analysis of oxygen depleted water mass. The model can be used for other lakes and bays, where knowledge of temperature and density stratification is important for assessing the water quality.

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