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COMPREHENSIVE CIRCULATION AND WATER QUALITY INVESTIGATION OF THE COASTAL LAGOON: PUERTO GALERA, THE PHILIPPINES

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ABSTRACT

Puerto Galera is a coastal lagoon connected to the Verde Island Passage through two channels. The lagoon and its vicinities are renowned for their attractive recreational and diving spots. However, this area has been adversely affected by anthropogenic loads from surrounding settlements. To minimize the irreversible and unfavorable effects on its ecosystem, this study endeavors to provide sufficient understanding of the lagoon's circulation and water quality characteristics. Various aspects were examined by field observations coupled with state-of-the-art numerical models. Results showed that the circulation of the lagoon is composed of two current regimes, i.e., strong currents at the outer sea and channels and weak currents in the lagoon. The lagoon appeared to be a source of phytoplankton biomass to the adjacent Verde Island Passage ecosystem. The water residence time was much higher at the lagoon interior where most of the pollutants are discharged from surrounding communities. This implies that the water body at Muelle cove, the innermost part of the lagoon, is vulnerable to eutrophication. In an attempt to improve the lagoon water quality condition, numerical model was used to evaluate the water quality condition after changing wastewater load as well as making additional connection between the lagoon and the outer sea. Based on modelling results, the most effective way to mitigate the water quality problem at Muelle cove is to reduce the amount of input pollution.

Keywords: coastal lagoon, hydrodynamic, biochemical, field survey, simulation

1. INTRODUCTION

Puerto Galera (PG) is a semi-enclosed coastal lagoon covering an area of 4.2 km^2. Three small coves are connected, forming the main lagoon, which connects to the Verde Island Passage (VIP) through two channels (Figure1). The passage links South China Sea and Sibuyan Sea. The lagoon is well known not only for its ideal condition as a natural harbor but also as one of the most renowned dive spots in the Philippines. The lagoon abounds with rich biodiversity in tropical marine flora and fauna including coral reefs, seagrasses and mangroves. In 1977, PG was designated as a Man and Biosphere (MAB) Reserve by UNESCO. This fact draws attention from both national and international tourists who frequently visit, thus, boosting up the tourism industry, replacing traditional fishing as a livelihood of the locals (Cola and Hapitan, 2004). Demands of growing population and influx of visitors in the recent years have compelled citizens to resort in unregulated development activities (Fortes, 1997). This area has been drastically contaminated generally due to poorly constructed sanitation and household facilities and runoff from the hillsides associated with the tourism development. To minimize the irreversible and unfavorable effects on these ecosystems due to these environmental stresses, this study aims to provide sufficient understanding of the lagoon's circulation and water quality characteristics to the local communities and governmental unit to promote the conservation and restoration of the coastal ecosystems. Hydrodynamic and bio-chemical aspects were examined by means of intensive field observations coupled with numerical models. Field observations were carried out to collect hydrographic data and water samples at many stations from February 22 to March 8, 2007. The water samples were subsequently analyzed for nutrients and phytoplankton content. State-of-the-art numerical simulations were performed to reproduce the 3D-flow structure as well as the bio-chemical properties of the lagoon.

Figure1. Location of Verde Island Passage and Puerto Galera, The Philippines.

2. FIELD OBSERVATION

The field survey was conducted based on three methodologies, i.e., 1) the monitoring at nine stations using bottom fixed deployment and taut-wire moorage system deployed with various kind of self-contained automatic data logging sensor; 2) the synoptic survey for water sampling and vertical profiling of water properties using a multi-parameter water quality sensor (AAQ1180: Alec, Japan) and a submersible fluorometer (Fluoroprobe: Moldenke, Germany) ; and 3) bathymetric survey using echo sounder. The first methodology established 9 fixed position stations (Figure2) and was conducted for 15 days to cover one lunar cycle from 22 February to 8 March, 2007. The survey with the second methodology was carried out once a day for 7 consecutive days between 25 February and 3 March, 2007. The bathymetric survey was performed on 4 March and 5 March, 2007. The schematic diagram showing the sensor deployment technique and synoptic survey is given in Figure3. List of sensors, setups and deployed locations are given in Table1. The weather station, on the hill adjacent to the lagoon indicated as W letter in Figure2, monitored time variation of wind, rainfall, air temperature, relative humidity, solar radition and atmospheric pressure. It was sunny with a few light showers during the survey with about 5m/s prevailing south-eastern wind. The water samples were collected from 0.5 meter below the sea surface, and 0.5 meter above the sea bottom using a 1 liter modified Niskin sampling bottle (Yoshino Keisoku Co.,Ltd., Japan). Samples for nutrients (ammonia, nitrate, nitrite, phosphate, silicate) were filtered using GFC glass fibre filters, frozen, and later analysed in Japan using methods based on Parson et al. (1984). Sample for chlorophyll-a analysis were filtered into GFC glass fibre filters, extracted to DMF solution using method based on Suzuki and Ishimaru (1990), frozen, and later analysed in Japan using methods based on Strikland and Parsons (1972).

Table1. Sensors and their set-up, locations

Parameters	Product name (manufacture)	Interval (min)	Locations	Depth of deployment
Water temperature	HOBO-water tem pro (onset computer)	10	B1, B2, B3, B4, C1, C2, C3, O2	Surface, 3m, 5m, and Bottom
Salinity, temperature	COMPACT-CT (Alec)	10	B2, C2, C3, O2	Surface& bottom
Water level	COMPACT-WH (Alec)	30	O2, C1, C2, C3, B2	Bottom
Velocity, temperature	COMPACT-EM (Alec)	30	C1, C2, C3, O2, O3	Surface& Bottom
Chlorophyll-a, turbidity	COMPACT-CLW (Alec)	10	B2, C2, B4, O2	Surface
Dissolved oxygen	OPTODE (Alec)	10	B2, O2	Bottom

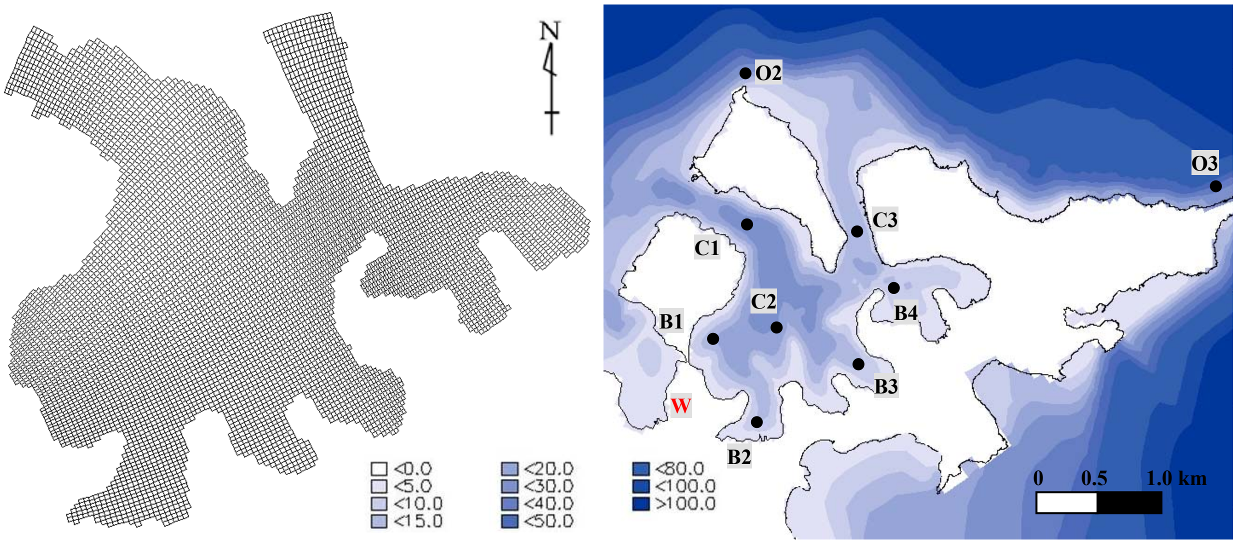

Figure2. Horizontal computational grid and bottom topography, locations of nine monitoring stations. Depth contours are in meters.

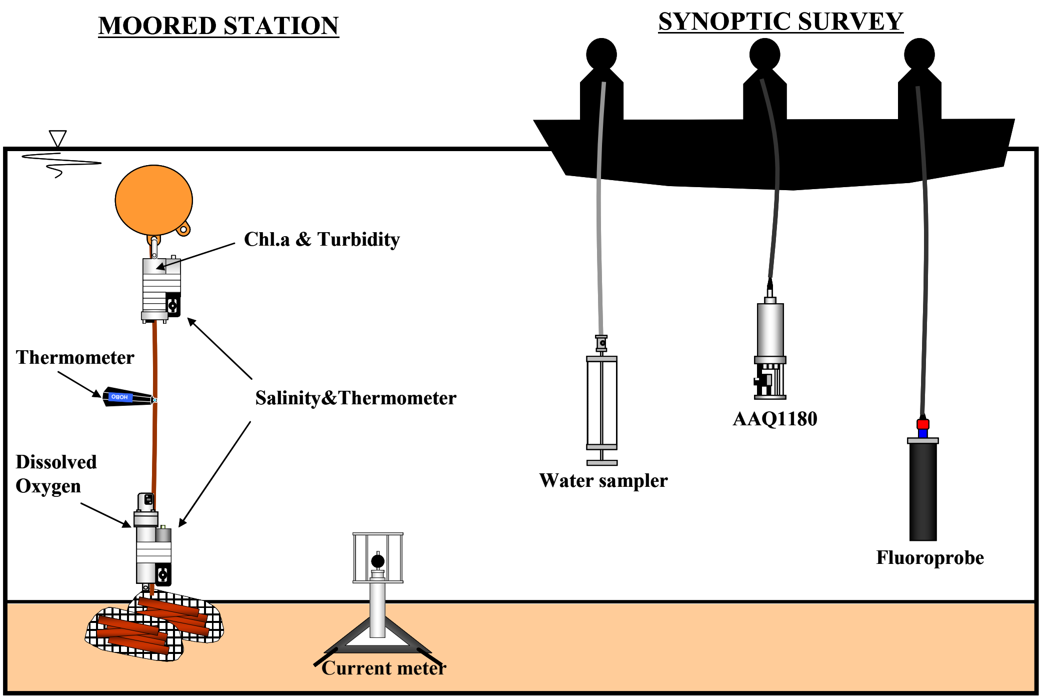

Figure3. Example illustration of a taut-wire moorage, bottom fixed deployment, water sampling and water properties profiling methodology.

3. NUMERICAL SIMULATION

Hydrodynamic model

The simulation was carried out using a sigma coordinate with horizontal orthogonal curvilinear grid. A well established three-dimensional density driven flow model, Delft3D-FLOW (Delft3D Hydraulics, 2007a) was used. The general computation conditions of the hydrodynamic model are shown in Table2. Figure2 shows the horizontal computational grid and bottom topography derived from the bathymetric survey and additional depth points outside the lagoon from base map. Meteorological data (e.g. wind, solar radiation, air temperature, relative humidity) were obtained from weather station. The simulation was performed for two weeks in summer to cover a cycles of neap and spring tide. The heat flux model at water surface took into account the separate effects of solar and atmospheric radiation, and heat loss due to back radiation, evaporation and convection based on Murakami et al. (1985). At open boundaries, the time variations of water temperature were set differently at close-to-the-surface and close-to-the-bottom deriving derived from the field survey. No flux condition was applied to the bottom and closed boundaries. The bed shear stress formulation is related to the current at computational cell just above the bed. The model was calibrated and validated against hydrographic data from the field observations. Figure5 shows the overall agreement between field and simulated data, indicating that the numerical model can accurately reproduce the circulation as well as water temperature feature of the lagoon.

Table2. Computation condition of hydrodynamic model

Item	Condition
Simulation period	21 February – 9 March 2007 (Summer)
Initial condition	Constant water temperature (26Celsius)
Computational mess	Hor. orthogonal curvilinear 74x118 with 11 layer in sigma coordinate
Boundary condition	Observed water level, flow velocity and water temperature
Wind	Uniform time-variation from weather station.
Meteorological data	Air temperature, solar radiation, humidity from weather station
Hor. eddy parameters	Smagorinsky model
Ver.eddy parameters	k-epp model
Bottom stress	Chezy coefficient 150

Water Quality model

The water quality model was developed based on Delft3D-WAQ modeling system environment (Delft3D Hydraulics, 2007b). The model was designed for nitrogen-limited ecosystem corresponding to the observational results and previous literature (McGlone et al., 1995) and composed of 5 compartments, namely, DO, phytoplankton, nitrogen, detritus nitrogen and detritus carbon. Figure6 is the conceptual diagram of the water quality model of PG describing the interacting processes amount compartments. The transport of matter and necessary hydrographic conditions were derived from the well calibrated hydrodynamic model. The initial and boundary condition of the substance in each compartment were obtained based on field observation data. Since there are no available data of nutrient influxes from coastal communities, the amount are derived from model tuning to acquire satisfactory agreement of dissolved oxygen, and phytoplankton concentration between field data and simulation result. Figure7 shows model validation with observational data from Muelle pier. The detailed of the concerned processes are described in the Delft3d-WAQ user manual.

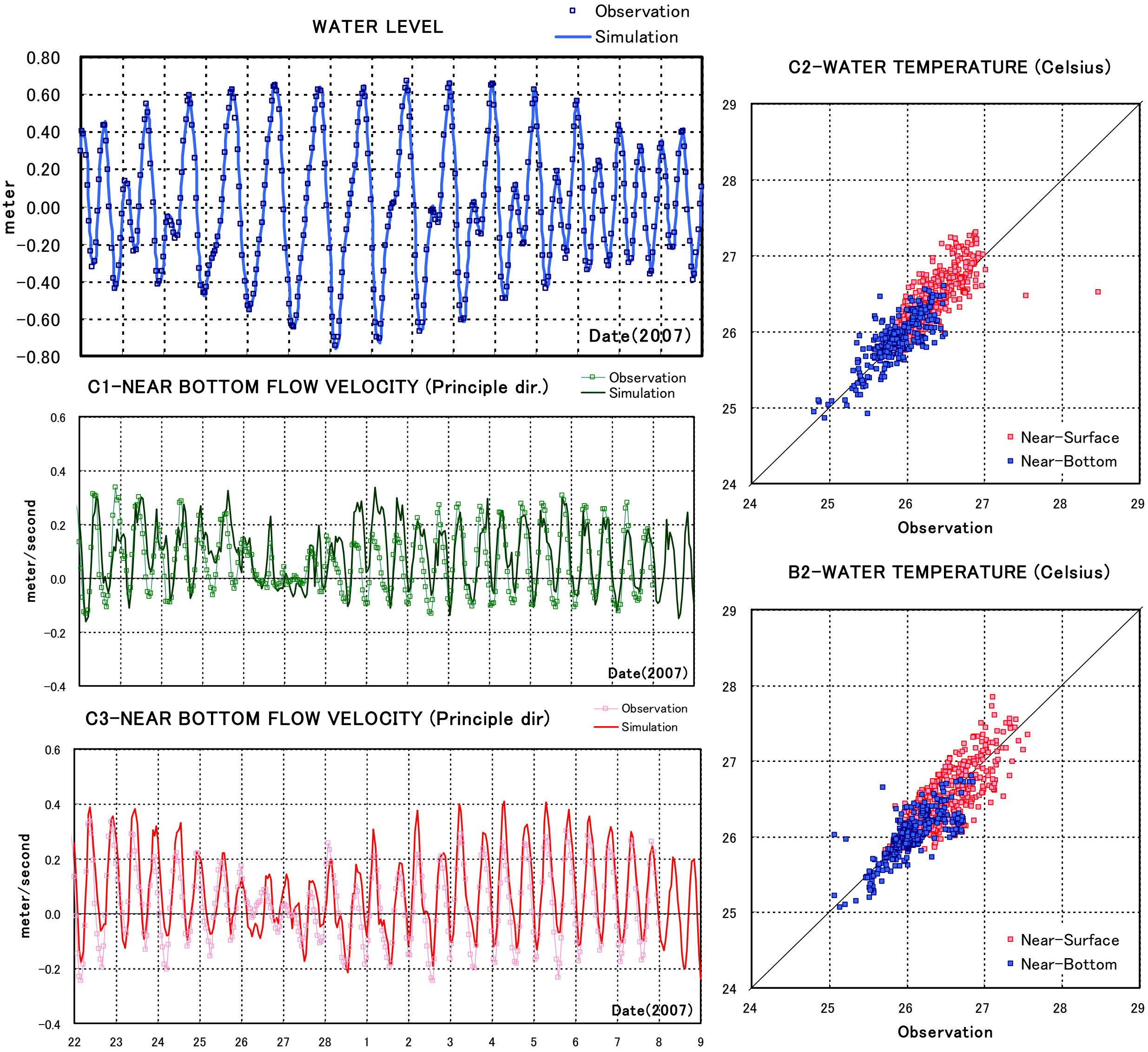

Figure5 Results of model validation showing comparison between observed and simulated water level, flow velocity at channels and water temperature inside the lagoon.

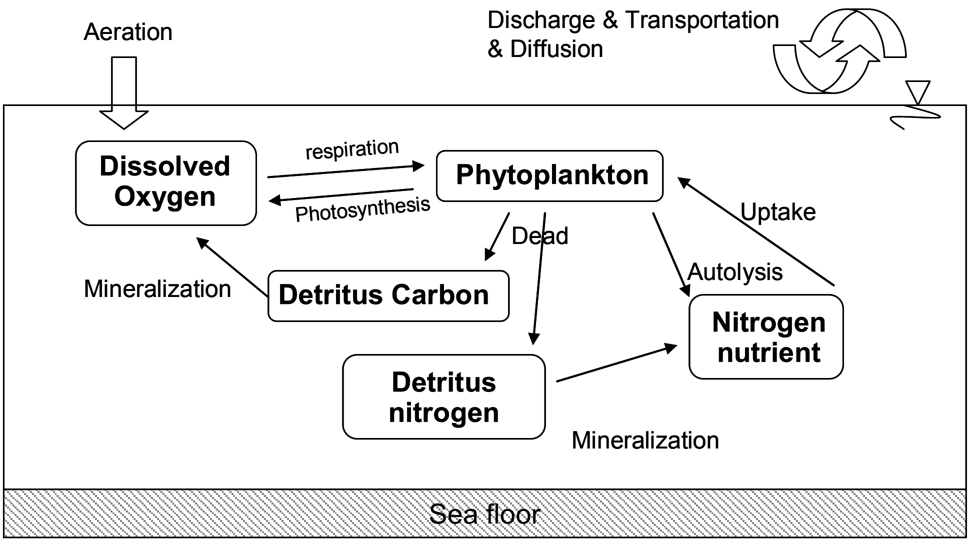

Figure6 Water quality model conceptual diagram for nitrogen-limited environment of PG

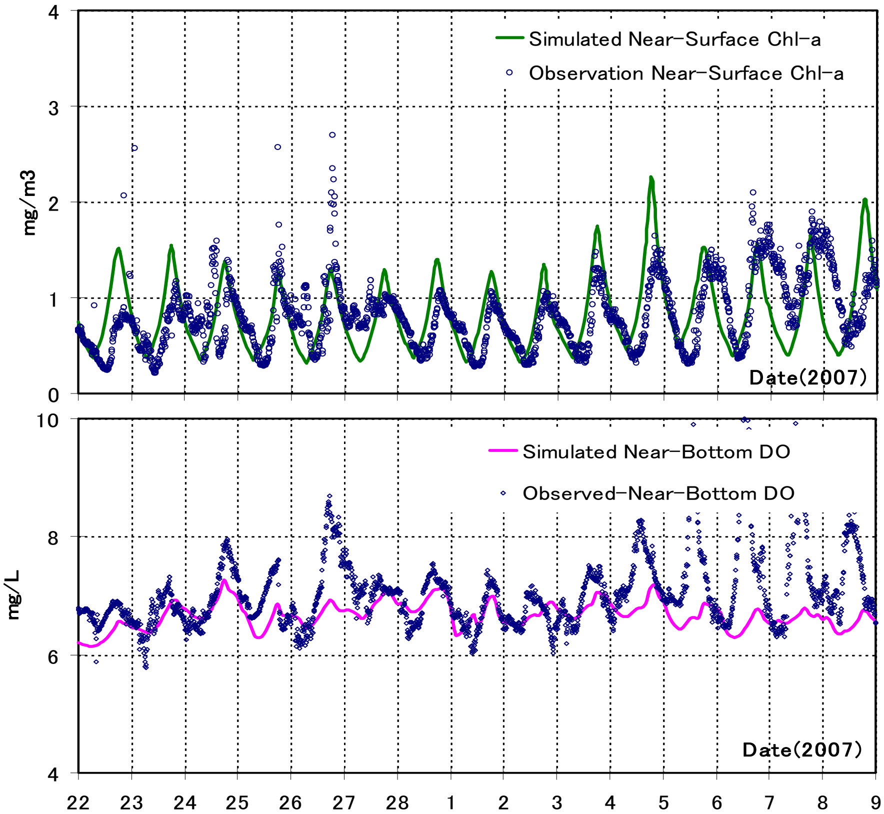

Figure7. Comparisons of chlorophyll-a concentration (upper figure) and dissolved oxygen between observation and numerical simulation at B2 sta.

4. RESULTS AND DISCUSSIONS

General circulation features of Puerto Galera

The present study of numerical simulation and field observation correlated well with results suggested by Villanoy et al. (1994). It is clear that circulation of PG are composed of two current regimes i.e. the swift current at offshore and channels and the sluggish current inside the lagoon as shown in Figure8. Time variation of water level and flow velocity (Figure5) shows unique fluctuation characteristics. The current velocity at channels obtained its maximum value in neap tide, and minimum value during spring tide. Furthermore, velocity fluctuations also exhibited semi-diurnal pattern in diurnal fluctuation of the water level. The tidal average current direction at channels also shown to be eastward. These circulation characteristics are regulated by the water level differences between two ends of the VIP. The water level fluctuations at South China Sea and Sibuyan Sea were not exactly synchoronous, driving currents to slosh back and forth along the passage. Comparison between the water level difference and current velocity at PG gave good correlation (Figure9). The non-zero residual current at channel was produced by eddies motions of speedy current offshore. When the current reverses its direction and flows to the West, the fast-moving current moves through slower-moving water offshore of PG, capturing additional water. The current oscillated and developed waves along its boundary that are known as meanders. The meanders broke off to form eddies, or pockets of water moving with a circular motion, taking with them energy of motion from the main flow and gradually dissipated this energy through friction. These eddies could serve as carriers which transport with them large amount of substances (larvae, nutrient, pollutant, etc.) and deliver to places where they go. Moreover, they could stir the water column right down to the ocean floor and agitate large amounts of sediment causing very well-mixed of the algae-rich warmer upper layer with the nutrient-rich cooler lower layer, thus promoting high productivity over large areas. These processes may be indispensable to maintain high biological productivity in VIP as well as PG lagoon.

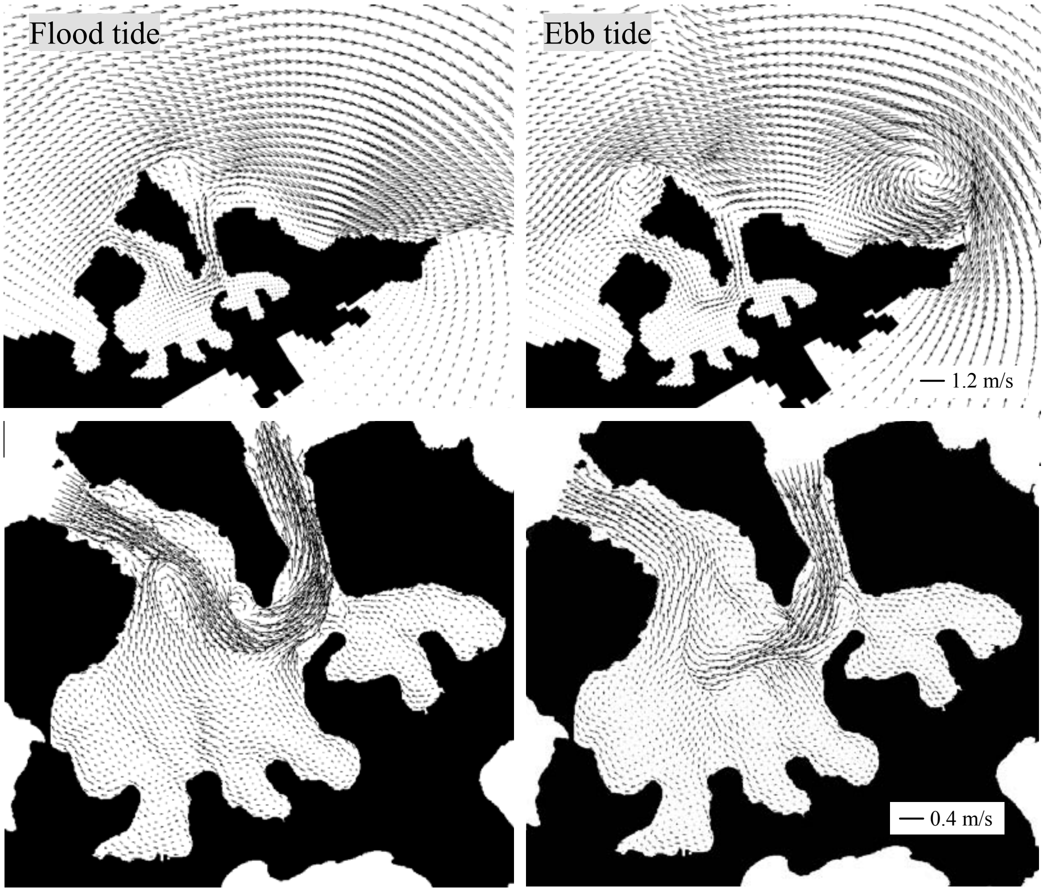

Figure8. Snapshots from hydrodynamic simulation showing swift current offshore accompanied by the large eddying motion of water, the strong current at channels and the sluggish circulation in inner parts of the lagoon.

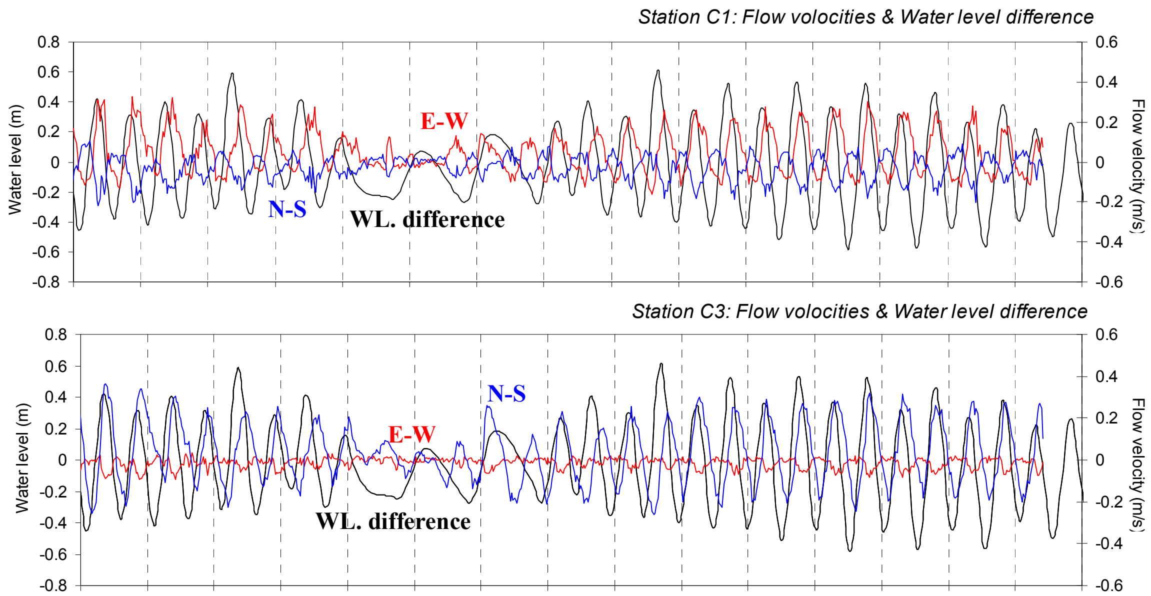

Figure9. Relationship of water level differences between two ends of VIP and North-South (N-S) and East-West (E-W) components of flow velocities.

Biochemical feature of the lagoon

The spatial distributions of 7-day-temporal and depth-averaged concentration of nutrients, phytoplankton and turbidity obtained from analysis of water samples are shown in Figure10. The daily-average distribution of near-sea surface Chlorophyll-a (Chl-a) and dissolved oxygen (DO) concentration from numerical simulation are given in Figure11. The results of Chl-a concentration between simulation and field observation agreed well, showing that the area close to Muelle cove have the highest Chl-a concentration. This area is perceived to receive the largest nutrient influx from community (in the lagoon interior) and pier activities and has longest water residence time (Villanoy et al., 1994). The turbidity and Chl-a concentrations display similar distribution patterns that they tend to be higher along the coastline inside the lagoon and highest at Muelle Cove. This similarity in their spatial distributions suggests they have close relationship, implying that the phytoplankton biomass might be the main contributor to the water turbidity (equilivalent to 1-3 mg/L during field campaign). The data from Fluoroprobe revealed that there were two kinds of algal species dominated in the PG lagoon during the survey, namely, diatom (83%) and green algae (16%). The blue algae, cryptophyta and yellow substances were negligibly small. The nutrients have higher concentrations in the bay interior compared to the channel and outer sea areas. This may indicate that the lagoon is a source of phytoplankton biomass and nutrients to the adjacent coastal waters. The highest daily Chl-a concentration at the water surface was found around 6p.m. and the lowest around 12a.m. Good correlation between time variations of observed DO and Chl-a (not shown here) revealed the significant role of phytoplankton in modifying DO concentration of the surrounding water at this area. Nevertheless, the overall distribution DO concentration indicated that the level of DO inside the lagoon were lower than that at the outer sea. This might be attributed to the higher biological demand of oxygen to decompose wastewater load from the surrounding communities (especially at Muelle cove) inside the lagoon. Nutrient analysis on water samples from the present study agreed well with previous study by McGlone et al. (1995), suggesting that PG lagoon ecosystem is severely limited in nitrogen. The average Si:NO3:PO4 value during the synoptic survey was found to be 7:2:1; much lower than the modified Redfield ratio. The lagoon biochemical properties would be very sensitive to any significant increase in nitrogen compare to changes in phosphate and silicate.

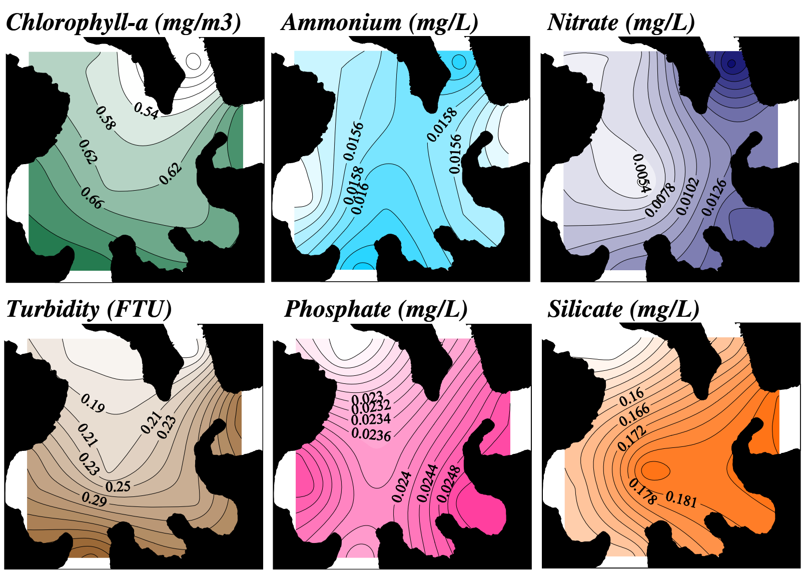

Figure10. 7-days depth-averaged concentrations of water quality parameters from analysis of water sample from field observation.

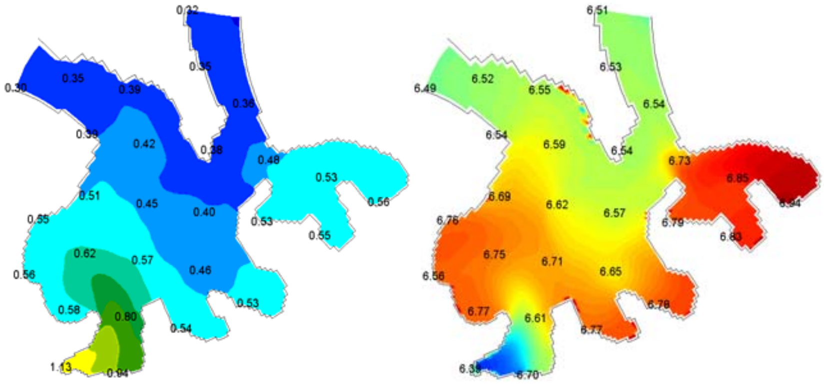

Figure11. Daily-average near suface distribution of chlorophyll-a (left) and dissolved oxygen (right) concentration from the water quality model

Numerical model application for management

Anthropogenic eutrophication is the accumulation of organic production by algae and aquatic plants that results in detrimental changes in water quality and biological populations (Gikas et al., 2006). The problem has recently adversely affected natural coastal ecosystems including PG lagoon. This study employed developed numerical models running in different scenarios to evaluate the resulting water quality condition after 1) reopening the sandbar (Fgiure1) to create the third connection of the lagoon to outer sea to enhance the water exchange, 2) reducing pollutant influx at Muelle pier by half and 3) tripling the pollution influx. The reduction of pollutant influx case infers to the implementation of wastewater treatment facility or better sanitary practice of communities in the future. On the other hand, increasing influx is an analogy to the possible load without any action in future with larger community projecting from present trend of tourism development. Based on simulation results shown in Figure12, the water quality (in terms of DO and Chl-a concentration) for the present condition is quite similar to the case of reopening the sandbar while the other two cases look significantly different. It appeared that halving the wastewater load case translated into a significant improvement of DO concentration, especially at Muelle cove. In contrast, three times increase in effluent discharge will further reduce concentration of DO. In terms of phytoplankton biomass, the more wastewater load, the higher concentration of phytoplankton biomass. Although, the phytoplankton added DO into the water column by photosynthesis, they do respiration and consume DO to decompose their biomass after they die. The zone of high concentration of phytoplankton, therefore, in long-term becomes greatly vulnerable for the development of hypoxia and consequently deterioration of benthic ecosystem. As PG lagoon water turbidity is governed by phytoplankton availability (discussed earlier), high concentration of phytoplankton can block sunlight to reach seafloor harming the health of benthic communities. Furthermore, weak current characteristic of the lagoon inner zone promotes rapid settling velocity of organic detritus of phytoplankton to the bottom. These detritus will be decomposed requiring large amount of DO. It appears that re-opening the sandbar alone can not mitigate the water quality problem. The most effective way to mitigate the water quality problem at Muelle cove is to reduce the amount of input pollution.

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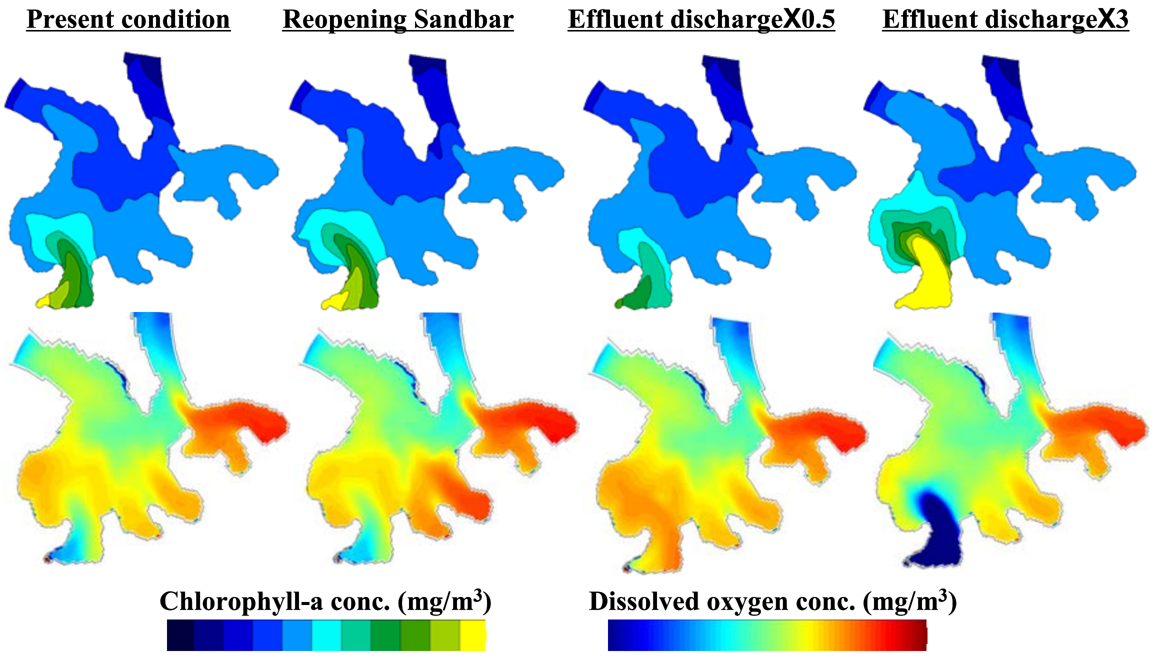

Figure12. Snapshots of water quality simulation model comparing between four different scenarios showing in term of chlorophyll-a (above) and dissolved oxygen concentrations.

REFERENCES

Carpenter K. E., Springer V.G. (2005), The center of the center of marine shore fish biodiversity: the Philippine islands. *Environmental Biology of Fish* Vol.72, No.4, 467–480

Cola, R. and Hapitan, R.M. (2004), Socio-economic study of Puerto Galera coastal communities. A project funded by the USAID Matching Grants Program in support for the conservation program in the Sulu Sulawesi Marine Ecoregion. WWF.

Delft Hydraulics (2007a), Simulation of multi-dimensional hydrodynamic flows and transport phenomena, User Manual Delft3D-FLOW, *WL/ Delft Hydraulics*, 642 pp.

Delft Hydraulics (2007b), Versatile water quality modelling in 1D, 2D or 3D systems including physical,(bio)chemical and biological processes, User Manual Delft3D-WAQ, *WL/ Delft Hydraulics*, 286 pp.

Fortes M.D. (1997), Puerto Galera: A lost biosphere reserve? *South-South Cooperation Programme,* Working Paper NO. 18.

Gikas G.D., Yiannakopoulou T., Tsihrintzis V.A. (2006), Water quality trends in a coastal lagoon impacted by non-point source pollution after implementation of protective measures. *Hydrobiologia*. Vol.563,No.1, 385–406

McGlone S.M.L., Villanoy C.L., Alino P.M. (1995), Nutrient mediated stress on the marine communities of a coastal lagoon (Puerto Galera, Philippines). *Marine Pollution Bulletin*, Vol.31, No. 4-12, 355-366

Murakami M., Y.Oonisishi, H. Kunish (1985), A numerical simulation of the distribution of water temperature and salinity in the Seto Inland Sea, Journal of the oceanographical society of Japan, Vol.41, 221-224

Parsons T., T. MaitaY., Lalli C.M. (1984), *A Manual of Chemical and Biological Methods for Seawater Analysis*. Pergamon Press, Oxford, UK.

Strickland J.D.H., T.R. Parsons (1972), A practical handbook of seawater analysis. *Fisheries Research Board of Canada Bulletin,* 167, 310 pp.

Suzuki R., Ishimaru T. (1990), An improved method for the determination of phytoplankton chlorophyll using N, N-Dimethylformamide. *Jour. of Ocean. Society of Japan.* Vol. 46, 190-194

Villanoy C.L., Udarbe M.J.B., Velasquez I.B., Natividad G.M. (1994), Residence times of passive particles as influenced by modelled circulation in Puerto Galera Bay, Oriental Mindoro. *Paper presented at the 3rd National Symposium in Marine Science*, University of the Philippines in the Visayas, Philippines, 23-24 May 1994.