# ANALYSIS OF THE HYDRODYNAMIC AND WATER QUALITY CONNECTIVITY OF A MARINE AND A LACUSTRINE ENVIRONMENT: MANILA BAY-PASIG RIVER-LAGUNA LAKE SYSTEM (PHILIPPINES)

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The hydrodynamic and water quality connectivity features and associated material transport characteristics of the Manila Bay-Pasig River-Laguna Lake system were investigated through field surveys, long-term monitoring, and numerical modeling analyses. Field measurements and numerical simulations revealed highly anthropogenic polluted waters mainly originating from the 27-km stretch of Pasig River transported lake-ward during the dry season and discharged bay-ward for the rest of the year. Long term continuous observations demonstrated dry season sea-water intrusion adding to the eutrophic vulnerability of Laguna Lake with the associated entry of high nutrient polluted waters. Manila Bay hydrodynamics established the significant influences of tide, density, and wind in its general circulation. Laguna Lake displayed dominant surface wind-driven current with embayment gyre circulations. Particle tracking analysis demonstrated varying distribution patterns of suspended matter concentration released from Pasig River at different times of the year. Particles released during the southwest monsoon were transported along the north-eastern side of the bay. Particles released during the northeast monsoon however showed concentration distributions at the north-western side. The results corresponded well with the clay and dinoflagellate cyst distribution observed in the bay. Given a cyst dormancy period of 2.5-3.5 months, the numerical simulations are in good agreement with the occurrences of past algal blooms in Manila Bay in terms of timing and location.

***Key Words*** : *Hydrodynamic, water quality, marine, lacustrine, material transport, algal bloom*

## 1. INTRODUCTION

About 50% of humans are aggregated in coastal regions. Marine and lacustrine ecosystems for this matter have been under severe stress from the combined impacts of population growth, economic expansion, and land conversion. Manila Bay and Laguna Lake are among the most important bodies of water in the Philippines in terms of economic and environmental significance. Strategically situated adjacent to the center of urban activity Metro Manila, the Bay/Lake system is the focal point of national development efforts for its vast potential for multi-purpose use.

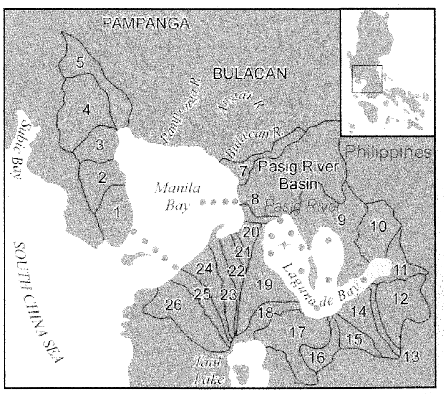


**Fig.1** Study area with field survey and monitoring stations.

Mismanagement and overexploitation however have taken toll on its ecological integrity and economic value. Harmful algal blooms and associated fish kills have become regular occurrences. The fish industry is in jeopardy with alarming rates of decline in production. Effective management of the water system therefore warrants the need for a comprehensive understanding of an integrated bay-river-lake ecosystem functioning. This paper investigates the hydrodynamic and water quality characteristics of the Manila Bay-Pasig River-Laguna Lake system with the use of intensive and extensive field surveys, and high resolution numerical modeling analyses. The study aims to clarify the circulation and transport features of the water system and provide information on the physical factors/dynamics affecting critical ecosystem conditions like harmful algal blooms.

## 2. MATERIALS AND METHODS

### (1) Field observations and monitoring

Observations were conducted extensively and intensively using four measurement approaches since 2001: (1) bottom fixed monitoring of data-logging sensors; (2) vertical profiling of hydrodynamic and water quality variables; (3) water sampling for nutrient analysis; and (4) meteorological observation. Long-term continuous measurements were established to capture seasonal/annual variations of environmental variables. Figure 1 illustrates the relative locations of Manila Bay, Laguna Lake (Laguna de Bay), Pasig River and surrounding watersheds. Field survey (circles) and monitoring (star) stations are also included. Amassed information was used for system analysis, as well as input for model calibration and validation.

### (2) Numerical modeling

The hydrodynamic component of Delft3D (WL|Delft Hydraulics, 2007), FLOW, was utilized to simulate the physics of the Manila Bay-Pasig River-Laguna Lake system. A coupled bay-river-lake model was set up to describe the circulation and mass transport characteristics of the system. The unsteady shallow-water equations were solved in 3D with a vertical sigma-coordinate system laid-out on a horizontal orthogonal curvilinear grid. Flow is forced by tide at the open boundary, wind stress at the free surface, and pressure gradients due to free surface (barotropic) and density (baroclinic) gradients. River discharges were incorporated into the model as positive flux points where a separate watershed hydrologic analysis was performed. The hydrodynamic model was calibrated and validated using hydrographic data from field surveys and long-term monitoring information. Numerical experiments were performed to explicitly investigate the transport and movement of dissolved/particulate substances and/or larval dispersal patterns using particle tracking analysis.

## 3. RESULTS AND DISCUSSION

### (1) Manila Bay and Laguna Lake seasonal hydrodynamics

Manila Bay hydrodynamics have been established to be governed by tide, barotropic and baroclinic pressure gradients, and surface wind stress (Villanoy *et al.*, 1997; Fuji-ie *et al.*, 2005; Pokavanich *et al.*, 2006). With such variability in hydrodynamic forcing, long-term residual circulations are essential for understanding the material transport characteristics of the bay. The strong monsoonal variations render significant differences in wind forcing, as well as the effect of river discharge on bay stratification. Figure 2 shows the residual current for Manila Bay and average flow for Laguna Lake for different prevailing wind periods. There is significant variability in residual current field with respect to wind direction. Residual currents in general flow in the direction of wind, particularly adjacent to the coast. A general counterclockwise gyre movement dominates the bay during the southeasterly (Feb.-May) and northeasterly (Oct.-Jan.) winds of the dry season. The latter demonstrates a broader cyclonic movement probably brought by stronger density differences. A weak anticyclonic circulation on the other hand prevails during the southwesterly winds (Jun.-Sep) of the wet season. The stronger current movement during the dry season implies better vertical mixing compared to the wet season. Flows in general enter the Manila Bay through the south channel and exits through the north. Residual current velocity is strongest at the north channel.

Laguna Lake on the other hand displayed dominant surface wind-driven current in general gyre circulation. Results demonstrate different circulation patterns for the wet (Jun.-Nov) and dry season (Dec.-May) hydrodynamic conditions. Water movement is generally directed for outflow through the Napindan Channel (connecting to Pasig River) in the wet season. The dry season flow pattern on the other hand demonstrated stronger surface wind-driven current enhanced by density difference due to intense solar heating and salt water intrusion. Return flows are also evident due to the reversal of the bay-lake potential energy gradient.

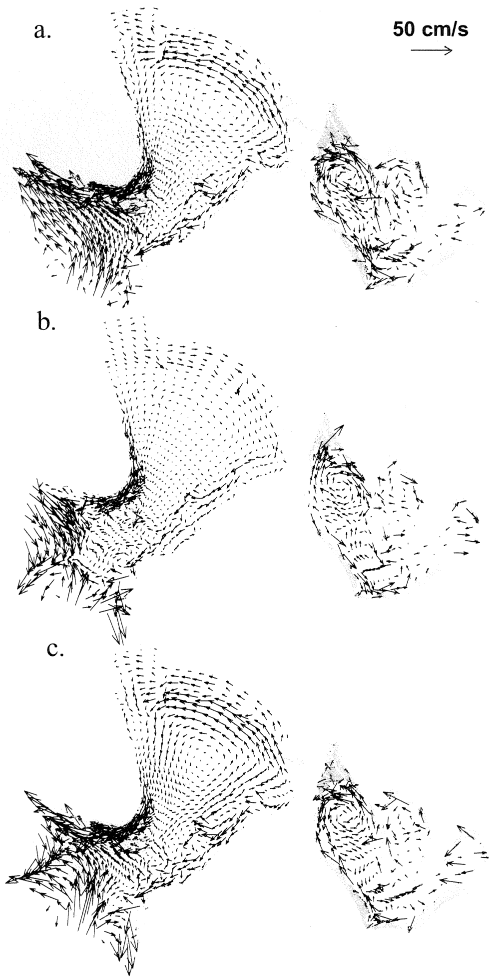


**Fig.2** Residual and average current for Manila Bay and Laguna Lake respectively (a) Feb.-May (b) Jun.-Sep. (c) Oct.-Jan.

## (2) Bay-River-Lake connectivity and eutrophic vulnerability

Pasig River serves as the only outlet of Laguna Lake and effectively, discharges lake watershed runoff and waste load to Manila Bay. In the dry season however, lake water level drops below mean sea level and the change in potential energy gradient impels a reversal in Pasig River flow direction which leads to lake seawater intrusion. Figure 3 demonstrates this phenomenon during the numerical simulation period (2002). Result shows the saline wedge nearly covering the entirety of the lake's west embayment (~1-5 psu), and reaching the central and east lobes of the lake through the south embayment, in weak concentrations however (~1/10 psu). It can be inferred therefore that Pasig River indeed provides the conduit of mass transport between Manila Bay and Laguna Lake. However, it should be realized that the 27 km stretch of the river bisects eight major cities of Metro Manila. It therefore also serves as a sink of urban waste and pollution for this matter. Pasig River receives an estimated domestic sewage of 168 metric tons per day. Thus, aside from being a channel of material transport between two water bodies, it is a significant waste load contributor as well.


**Fig.3** Seawater intrusion plume in 2002 (salinity in psu).

Seawater intrusion has always been perceived to promote fishery in Laguna Lake through increase in primary production. However, this has not always been the case. The phenomenon has always been accompanied by fish kill occurrences. Figure 4 shows water quality data obtained from long-term monitoring at the west lobe of Laguna Lake. The figure demonstrates the entry of saltwater to the lake from late April that lasted until the beginning of July. A decline in chlorophyll-*a* concentration was observed concomitantly, probably due to the saltwater-induced flocculation of suspended matter. During the same period, drops in dissolved oxygen concentrations were recorded near the lake bottom. This might have caused the fish kill incidents in the lake. Apparently, seawater intrusion in Laguna Lake during the dry season carries as well nutrient- and microorganism-rich polluted waters from Metro Manila (through Pasig River) and coastal Manila Bay. Increase in microbial activity results from the higher suspended matter concentration accordingly. Oxygen is consumed faster and is removed more rapidly from the bottom layers as a result. In the advent of sudden wind surges after an extended calm weather therefore, abrupt mixing of the water column may bring large amounts of the anoxic water and reduced substances to the upper layers and significantly cause massive fish mortality. Thus, what is perceived as ideal for fish production is actually detrimental to the fish ecosystem itself.

Manila Bay water quality also demonstrated significant effects from Pasig River discharge, adjacent to the river mouth in particular (Figure 5).

Increases in turbidity are a manifest of the significant material transport originating from the channel. The profile of total nitrogen (N) to total phosphorous (P) ratio indicates low Redfield ratio values (<16) immediately adjacent to Pasig River. This can be attributed to the high phosphorous content of the domestic sewage coming from Metro Manila. A few kilometers from the mouth however, the N:P ratios increase dramatically (>50), particularly near the middle and bottom layers. The optimal growth of phytoplankton was observed to occur within 15 km from the river mouth near the surface. This corresponded well to the measured Redfield ratios for optimal biomass growth (N:P = 16). Low dissolved oxygen levels were found near the bottom adjacent to the river mouth, indicative of the increase microbial activity within the area.

The observed N:P ratio for both Laguna Lake and Pasig River (Figure 6) showed values (<16) below the ideal ratio for optimal growth. Given that anoxic environments are critical for denitrification and sediment phosphorous-release, especially for tropical ecosystems, a nitrogen-limited environment can be inferred for the Manila Bay-Pasig River-Laguna Lake environment.

From the foregoing discussion, it can be inferred that the physical connectivity of Manila Bay and Laguna Lake through Pasig River extends to bio-chemical association. The considerable amount of waste load coming from Pasig River aggravates the already vulnerable eutrophic environments of Manila Bay and Laguna Lake through transport of potentially water quality-degrading materials.

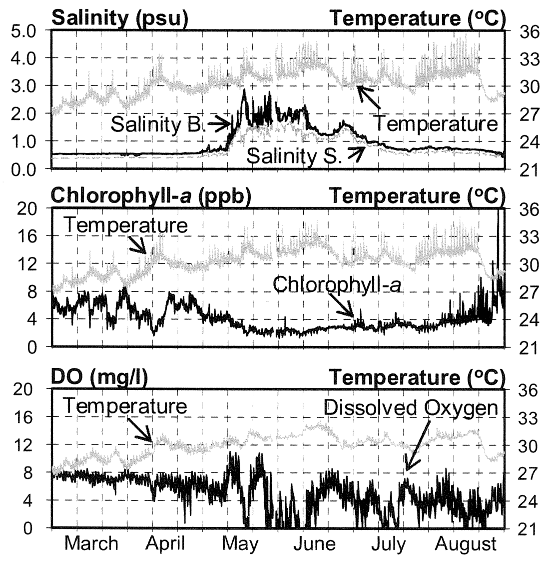


**Fig.4** Temporal comparison of lake water quality parameters.

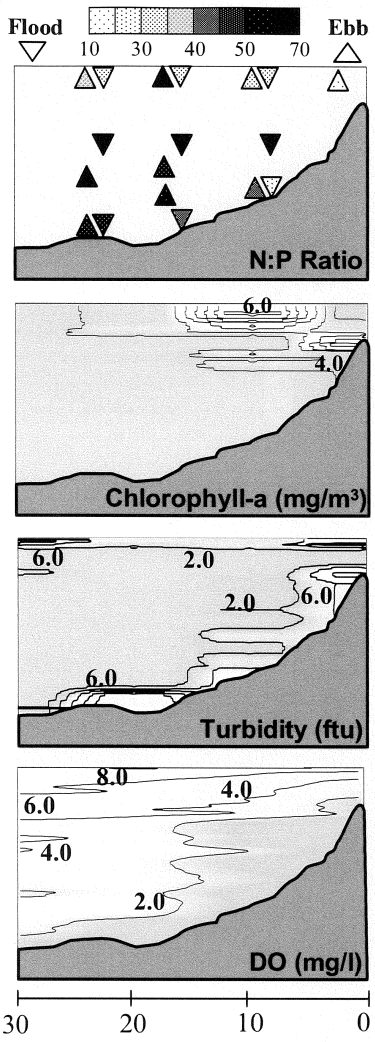


**Fig.5** Profile comparison of bay water quality parameters. Horizontal distance is in km. from Pasig River mouth.

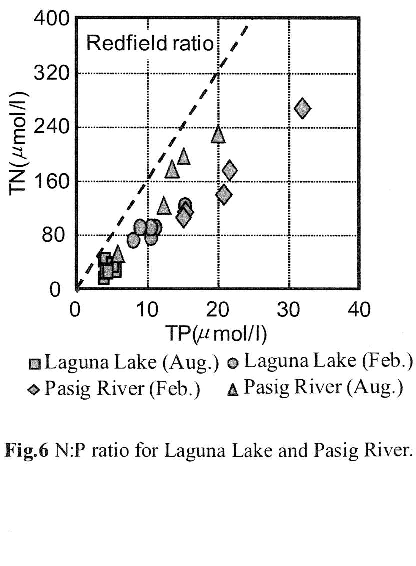


**Fig.6** N:P ratio for Laguna Lake and Pasig River.

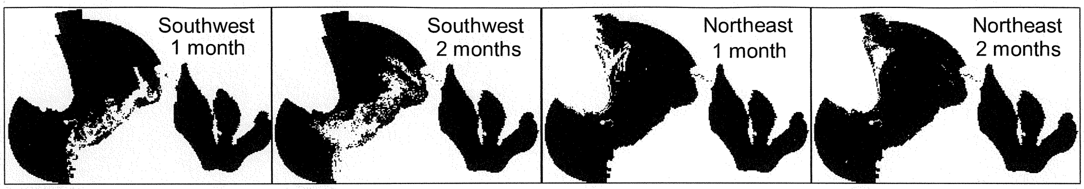


**Fig.7** Horizontal distribution of particles in Manila Bay at different monsoon seasons.

**(4) Material transport, dinoflagellate cyst distribution, and algal blooms**

Manila Bay is one of the areas greatly affected by toxic algal blooms in the Philippines (Azanza *et al.*, 2004). The non-motile resting stage (cysts) of the dinoflagellate in the surface sediments is believed to be the source of initial vegetative population that initiates algal blooms. Based on the study of Azanza *et al.*, (2004), locations of high cysts densities coincide with areas of high clay content. From such association therefore, it is imperative to investigate the material transport characteristics of Manila Bay.

Particle tracking analysis was employed to investigate the transport and movement of suspended matter and/or larval dispersal patterns in Manila Bay at different monsoon seasons. The particles were released at the location of the most polluted tributary of Pasig River (San Juan River). Results revealed varying material transport patterns of particles released from Pasig River at different times of the year (Figure 7). Particle movements corresponded accordingly to the prevailing residual current distribution of the season. During the southwest monsoon (May-Oct.) particles were transported along the north-eastern side of the bay and exit through the south channel along Cavite coast. Particles released during the northeast monsoon (Nov.-Apr.) however showed concentration distributions at the north-western side and exit at the north channel along Bataan coast. The results corresponded well with the clay and dinoflagellate cyst distribution in the bay (Figure 8).

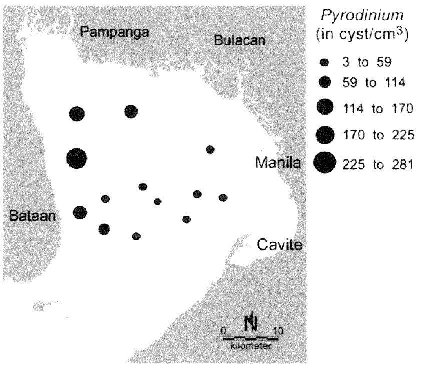


**Fig.8** Spatial distribution of dinoflagellate cysts in Manila Bay (Azanza et al., 2004).

Given a cyst dormancy period of 2.5-3.5 months, suspended matter and nutrient discharged from Pasig River during the northeast monsoon would concurrently coincide with the period of occurrence of algal blooms (Jun.-Aug). The numerical simulation results were therefore in good agreement with the occurrences of past algal blooms in Manila Bay in terms of both timing and location.

## 4. CONCLUDING REMARKS

This study investigated the connectivity of the Manila Bay-Pasig River-Laguna Lake system. Results revealed strong physical-bio-chemical interrelationship of the three systems that accentuated the importance of integrated ecosystem study. Future direction for this research is the improvement of environmental load estimates and the integrated water quality modeling of the system.

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