Vietnam Journal of Hydrometeorology, ISSN 2525-2208, 2019 (2-1): 48-55
DOI: 10.36335/VNJHM.2019(2-1).48-55

Research Paper

APPLICATION OF ECOSYSTEM MODELING OF PHYTOPLANKTON SIZE STRUCTURE USING STELLA TO ANALYZE ASAN BAY COATAL ESTUARY

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ARTICLE HISTORY

Received: August 06, 2019 Accepted: October 12, 2019
Publish on: October 25, 2019

ABSTRACT

The phytoplankton dynamics considering size structures were investigated in Asan Bay. The contribution of netphytoplankton (>20µm) was high in spring, whereas contributions of nanoplankton (2<20µm) increased from summer to winter. The enrichment of PO_4^{3-} in winter and the increase of radiance in spring often appeared to control phytoplankton community structure in spring. Water runoff might bring $NO_2^-+NO_3^-$ and NH_4^+ into Asan Bay in summer. However, phytoplankton biomass didn't increase in summer season. Based on these results, the variations of phytoplankton size structures might be determined by different light and nutrient availability. Application of dynamical estuarine ecosystem modeling for phytoplankton size structure using STELLA with state variables of the model included major inorganic nutrients ($NO_2^-+NO_3^-$, NH_4^+, PO_4^{3-}, S_i), size classes of phytoplankton (netphytoplankton, nanophytoplankton, two classes of zooplankton (mesozooplankton, microzooplankton), and organic matters (POC, DOC). The results suggest that understanding of phytoplankton size structure is necessary to investigate phytoplankton dynamics and to better manage water quality in Asan Bay. .

Keywords: *Applied ecosystem model, Phytoplankton dynamic, STELLA.*

1. Introduction

The different size phytoplankton can be affected differently by nutrients and light uptakes as well as grazing in water column. Depending on season the growth of each phytoplankton size class is different. In coastal estuaries, phytoplankton dynamics and production are controlled by physical, chemical and biological factors (Sin et al., 2000). Estuarine ecosystems became a key issue in environmental research for coastal waters as well as freshwater environments. Size-structured phytoplankton dynamics were incorporated in estuarine coastal ecosystem model developed by Sin and Wetzel (2002).

In shallow coastal ecosystems, the combination of mixing and nutrient inputs due to wind, tides, river discharges and benthic fluxes is known to influence the phytoplankton community structure and primary production (Dube and Jayaraman, 2008; Kiorboe, 1993; Schwing-

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hamer, 1981; Wen et al., 2008). The coastal ecosystem at transition zone affected from unusual nutrient inputs, together with other environmental conditions (salinity, temperature), bringing continuous nutrient availability for phytoplankton and consequently food supply for marine and estuarine organisms. The systems close to the coastal area have shown to be the main N, P, and Si nutrient source to the water body due to the use of soils for farming and their continental runoff (De Marco et al., 2005). Benthic faunal activity and density play an important role in determining the rates of benthic nutrient fluxes, which enrich the water column and contribute to phytoplankton growth. Even low benthic fluxes can allow diatoms to dominate the phytoplankton community (Claquin et al., 2010).

The spring blooms were observed by many studies in coastal estuaries. Gemmell et al. (2016) applied high-resolution optical techniques, individual-based observations of phytoplankton sinking and a recently developed method of flow visualization around freely sinking cells. Netphytoplankton such as diatoms are an abundant and ecologically important group of silicified eukaryotic phytoplankton. They are estimated to account for 20–40% of the oceanic primary production. Phytoplankton sinking rates are independent of cell size across a range of greater than 106μm3 in rapidly growing cells (Nelson et al., 1995; Waite et al., 1997; Gemmell et al., 2016).

STELLA was also applied for germination and vertical transport of cyst forming dinoflagellate model by Anderson (1998) and reservoir plankton system model by Angelini and Petrere (2000). STELLA was developed as tool for ecological and economic system modeling (Costanza et al., 1998; Costanza and Gottlieb, 1998; Costanza and Voinov, 2001). Bach (2019) applied STELLA to model phytoplankton size structure dynamic in coastal ecosystem (Bach, 2019).

The investigation of phytoplankton structure can examine spatial and temporal variations in chlorophyll a of various phytoplankton size classes and provide more knowledge of phytoplankton dynamic characteristics in coastal estuarine.

2. Methodologies

2.1 Study location

The Sapgyo, Asan, Daeho, Seokmoon and Namyang embankments were constructed in the upper region of the Asan Bay since 1970s (Fig. 1). The large scaled industrial complex was constructed along the coastal of the Asan Bay. The freshwater from embankments interacts with seawater when the gates of embankments are open. Water samples were collected 1m below surface by using Niskin water sampler for more than 5 years at 1 station as Fig.1 in the Asan Bay.

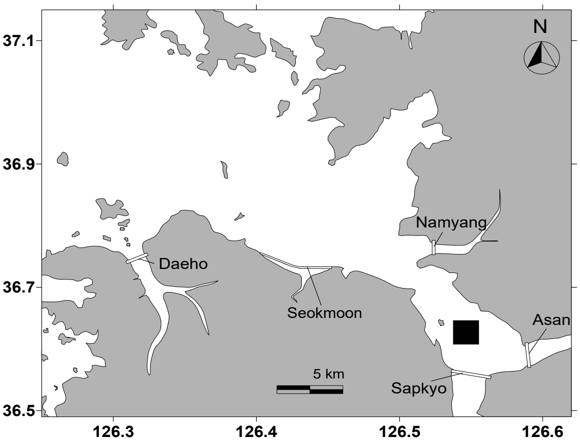

Fig. 1. The study and modeling site in the Asan Bay, South Korea.

2.2 Measurement of environmental properties and chlorophyll a

Water sampling was collected at study site in Fig. 1. For determinations of chlorophyll a, 200 mL of sampled water filtrate was filtered through Whatman® 25mm GF/F glass microfibre filters (0.7 μm) under minimal vacuum (<100 mm Hg). The filters were placed in dark test tubes pre-filled with 8 mL extraction solution (90% acetone and 10% distilled water). After storage for 12 h in chilly condition (4^{o}C), chlorophyll a was measured on a Turner Designs® 10-AU Fluorometer. Nano phytoplankton (< 20μm) and netphytoplankton (> 20μm) were sized by mesh and analyzed in Microbial Ecology Laboratory, Mokpo National Maritime University.

Ambient nutrients (NO_2^-, NO_3^-, NH_4^+, PO_4^{3-}, dissolved Si) were analyzed by using Bran Luebbe autoanalyzer (Parsons et al., 1984). DOC, POC, microzooplankton (> 200 μm and < 330 μm) and mesozooplankton (> 330 μm) were analyzed and identified in Laboratory of Department of Environmental Engineering, Kwangju University. Nutrient loadings from freshwater were estimated by multiply of monthly nutrient concentrations at the stations near dikes of Asan and Sapgyo lakes with monthly water discharge amount of each lake through dike.

2.3 Model description

Dynamical estuarine ecosystem modeling of phytoplankton size structure using STELLA has developed in Bach (2019). The model was applied for site in Fig. 1. The ecosystem model includes 10 state variables (Bach, 2019): nano- (< 20 μm), net- (> 20 μm) phytoplankton; microzooplankton (> 200 μm and < 330 μm), mesozooplankton (> 330 μm); nutrients NO_2^-+ NO_3^-, NH_4^+, PO_4^{3-}, dissolved S_i, and non-living organic materials, DOC and POC. Large and small phytoplankton are differentiated in their ability for nutrients, light limitations, temperature dependent metabolism and assimilation rate. Germination of netphytoplankton was considered together with wind forcing effect.

Grazer variables were differentiated by the size structure of potential prey, as well as their half-saturation foods and assimilation rates (at 10^{o}C) and affected by temperature response factor. POC, DOC were released from phytoplankton accumulation and zooplankton excretion and mortality. Nutrients were enriched by bacterial degradation of organic matter and grazer excretion. The ecosystem model was integrated with STELLA 7.0 using the function (a numerical variable time step differential equation solver using a 4th order Runge-Kutta method).

3. Results and discussions

Temperature was not significant controlling factor for phytoplankton, however, increase of temperature in spring contributed for the growth of phytoplankton. Salinity could be affected by annual precipitation. Especially, water runoff from land have decreased salinity significantly in summer. Radiance increased in spring. It could create increasing of light attenuation coefficients in water. However, depending on stations with different factors such as turbidity light attenuation coefficients were nonlinear on radiance. Generally, the contribution of large cells (netphytoplankton, >20μm) to total concentrations of chlorophyll a was high from February to April and then it decreased until early May. However, the contribution increased again during late May to early June with small peak. In contrast, abundance of nanophytoplankton and were dominant from May to November. In summary, the contribution of micro-sized class was evident in spring whereas nano-sized classes were more significant from summer to winter in Asan Bay. Annually, total chlorophyll a peaked in spring and decreased from spring to winter. The total chlorophyll a have trended high concentration at studied station in spring. The difference among different season suggest that temperature, light and water runoff can affect to spatial variations of chlorophyll a. Water runoff from farms as well as industrial zones flowed into Asan Bay that peaked NO_2^-+NO_3^- and NH_4^+ in summer. Besides, NH_4^+ and PO_4^{3-} had small peaks in winter, therefore, they contributed for growths of phytoplankton in spring. Silicate appeared no significant evidence for phytoplankton controlling factor. These results indicate that phytoplankton size structures in Asan Bay depend on not only nutrients but also light as well as temperature. The investigation of spatial and temporal variations in chlorophyll a of various phytoplankton size classes may evaluate precisely phytoplankton dynamics.

The calibration of ecosystem model was applied by adjusting values of parameters which were not observed by the field study or the literature for the Asan Bay. These parameters included optimal light intensity for net-, nanophytoplankton, respiration rate of phytoplankton, mortality rate of phytoplankton, mortality rate of zooplankton, respiration rate of zooplankton, excretion rate of zooplankton, hydrolysis rate of POC, degradation rate of DOC, fraction of DOC in sinking

The field measurement and model state variables of phytoplankton classes, zooplankton classes, organic matters and nutrients were shown in Figs. 2 and 3. The model output data were compared to field measurements of state variables. Simulated netphytoplankton approached very closely field observations (Fig. 2A). Simulation output of nanophytoplankton was similar to field concentrations although seasonal peaks were not simulated accurately (Fig. 2B). Especially, large cells contributed about 80% to the total chlorophyll a during spring. However, the contribution increased again during late May to early June with small peak. In contrast, abundance of small cells (nanophytoplankton, 2~20μm) were dominant from May to November. In summary, the contribution of netphytonplankton was evident in spring whereas nanophytoplankton was more significant from summer to fall in Asan Bay. Under low nutrient concentration conditions such as in May or September, phytoplankton can reduce cell size to nanophytoplankton to adapt to these conditions. Mesozooplankton and microzooplankton were expressed in Figs. 2C-2D.

Variation of measured POC was similar to simulated variation, however DOC was difficult to validate since few data were observed (Figs. 2A-3B). Ammonium showed good agreement with field data except for the peak observed in July 2004 (Fig. 3C). The great simulation was observed for nitrite+nitrate outputs (Fig. 3D). For orthophosphate and dissolved silicate, the simulations were similar to field data except the peak of orthophosphate (Figs. 3E-3F).

The prediction of the long-term planktonic evolution studied the global stability for the coexistent equilibrium of phytoplankton-zooplankton system by Zhao et al. (2018). The numerical simulations were investigated that increasing the cell size, the system goes into oscillation. Cell size was qualitatively similar to the result of the experimental analysis. Cell size affected the growth and reproduction of phytoplankton, evolutionary interactions between phytoplankton and zooplankton were closely related to the cell size of phytoplankton (Zhao et al., 2018). Physical features of the area strongly influenced phytoplankton biomass distributions, composition and size structure after high volumes of river discharge occurred during February. The dynamic circulation of February resulted in high photosynthetic capacity of the abundant phytoplankton population (Mangoni et al., 2008). Macedo and Duarte (2006) developed three one-dimensional vertically resolved models to investigate differences between static and dynamic phytoplankton productivity in three marine ecosystems: a turbid estuary, a coastal area and an open ocean ecosystem. The quantitative importance of these differences varied with the type of ecosystem and it was more important in coastal areas and estuaries (from 21 to 72%) than in oceanic waters (10%).

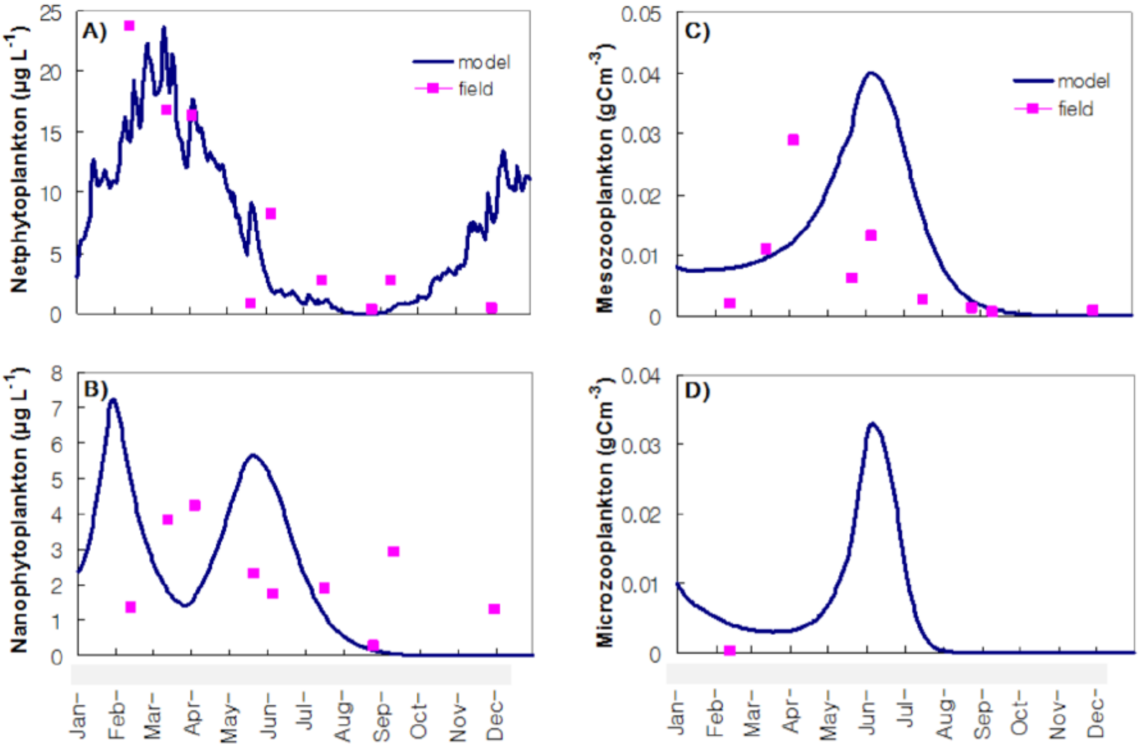

Fig. 2. Results for size classes chlorophyll a (net- and nano-), meso- and microzooplankton in the polyhaline zone of the Asan bay system. Field data for chlorophyll a size classes.

The timing, location, and monsoon mixing or intensity of storms and associated rainfall amounts also affect nutrient makeup and discharge to coastal waters. Freshwater discharge can deliver nutrients to the coastal zone and determines the hydrologic properties of the water column, including vertical stratification, water residence time, salinity, turbidity, and clarity. Therefore, the composition, concentration, and delivery of nutrients depend on how the watershed has been modified by agricultural, urban, and industrial activities.

Coastal and estuarine ecosystems are also influenced by seasonal and multi-annual hydrologic variability. Large estuarine ecosystems are affected by multiple stressors, including nutrients and other pollutants, changes in light regime (turbidity), temperature, mixing, and circulation, they exhibit a range of biogeochemical and trophic responses to short and long term hydrologic changes, which are changing in place and time. These stressors may alter the ecological characteristics of these large systems. The delivery of anthropogenic nutrients and other pollutants to coastal waters is in a highly dynamic state, as development and accelerated loading.

Phytoplankton biomass and primary production related size-fractionated, together with net community metabolism, were measured in a coastal ecosystem (Ría de Vigo, NW-Spain) during a full annual cycle (Cermeño et al., 2006). In seasonally, this ecosystem was characterized by two distinct oceanographic conditions, upwelling and downwelling favourable seasons. The seasonal with upwelling provides a feasible explanation for the continuous dominance of large-sized phytoplankton such as netphytoplankton. Large phytoplankton during favourable conditions for growth affected to an enhancement of the ecosystem's ability to export organic matter to the sediment and to adjacent areas, as well as to sustain upper trophic levels (Cermeño et al., 2006; Garcia et al., 2008; Moloney and Field, 1991).

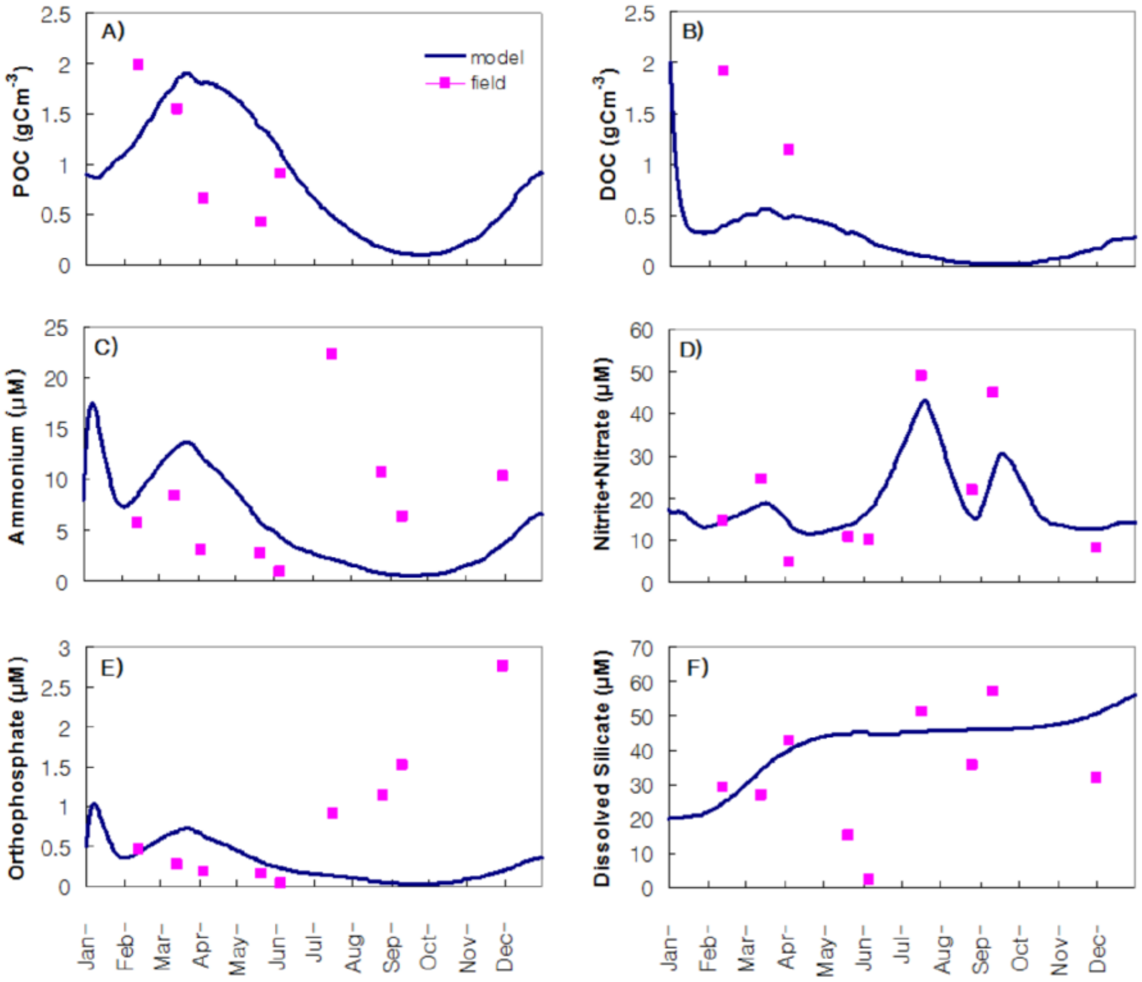

Fig. 3. Results for particulate organic matter (POC), Dissolved organic matter (DOC) and nutrients (ammonium, nitrite+nitrate, orthophosphate and dissolved silicate) in the polyhaline zone of the Asan bay system. Field data for POC, DOC and nutrients were collected.

4. Conclusion

Applied model could figure out phytoplankton growth in field study station where estuarine and coastal ecosystem suffered nutrient enrichments and change of hydrology from embankments in Asan Bay. In spring, netphytoplankton were highly abundance at the study station. Inversely, nanophytoplankton were abundant in both spring and fall. Netphytoplankton had high relationships with total chlorophyll a, as well as primary productivity at study site that demonstrated the important role of netphytoplankton in contribution for Asan Bay phytoplankton during spring. NH_4^+ and PO_4^{3-} had small peaks in winter, therefore, they contributed for growths of phytoplankton in spring. Input of freshwater into Asan Bay peaked NO_2^-+NO_3^- and NH_4^+ in summer, nevertheless, this season appeared no significant evidence for chlorophyll a increase of phytoplankton. Therefore, the size structures of phytoplankton were controlled by not only nutrients but also light exposure and temperature. The applied model also demonstrated that physical processes including wind mixing, water transparency, temperature as well as nutrients affected phytoplankton dynamics and response of phytoplankton could be related to the environmental changes in the coastal estuarine area.

Acknowledgements

We thank Microbial Ecology Laboratory, Mokpo National Maritime University for this *study. Thanks are also given to Department of Environmental Engineering, Kwangju University to share zooplankton and POC, DOC data.*

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