Eutrophication in a tropical estuary: Is it good or bad?

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Abstract. Coastal eutrophication is defined as the increase of rate of organic supply into an estuary. In the recent global discussion, eutrophication is seen as a negative situation, in fact, it has positive impacts such as increase in primary production which lead to the increase of fisheries production and hence, community income. This paper promotes a simple diagram called eutrophication-benefit curve which correlates between levels of eutrophication and its benefits to both ecological and economical aspects. In the beginning of eutrophication process, environment gets benefit from the increase of the nutritional state of the water which leads to the increase of primary production and fisheries production. This is obvious in the comparison between northern and southern coast waters of Java Island, showing a higher primary production and phytoplankton biomass and hence fisheries production in the northern coast waters of Java compared to those of the southern coast waters of Java. However, the rapid increase of eutrophication level of the northern coast waters of Java Island causes eutrophication negative effects such as oxygen depletion, algae bloom and disturbance of coral reef ecosystems. This paper shows the optimum level of eutrophication level that can give benefit to both ecological and social environment.

Keywords: algae bloom; benefits; coastal eutrophication; hypoxia; phytoplankton; primary production

1. Introduction
Coastal eutrophication is defined as the increase of rate of organic supply into an estuary [1, 2] which can lead to both ecological and societal problems. Other definition about eutrophication is the increase of nutrients in a coastal water which can lead to development of algae biomass or blooms. Despite its varied definition and understanding, eutrophication can be viewed from different angles. Eutrophication can be seen as the increase rate of nutrients, which is mostly coming from the land derived by anthropogenic domestic activities. In the recipient waters, organics will be decomposed by bacteria resulting dissolved inorganic nutrients which is needed by algae for growth. Eutrophication can be viewed as two sides, which are positive (good) and negative (bad). Having positive side means that this process can be beneficial to both ecological and society while that of negative side means that this can lead to various negative consequences to environment.
This paper aims to discuss various consequences of eutrophication for the environment and societal aspects and the case of eutrophication of the tropical embayment of Jakarta Bay is much discussed in this paper. Jakarta Bay is an estuary that has received organic materials transported from about 13 small rivers. Liquid waste in the form of a result of domestic activities in the metropolitan area of Jakarta is the reason for the high organic content and nutrients in this bay. About 11 million people live in this region and almost 80% of liquid waste of domestic residents without being processed is released into the waters of Jakarta Bay, making the Bay of Jakarta as a bay that is experiencing high levels of eutrophication [3]. Coastal eutrophication symptoms were observed in Jakarta Bay, in the form of hypoxic of its near-bottom water [4], algal blooms [4-7], and aquatic biota mass mortality [8].

In tropical coastal seas, e.g. in Indonesia, the severe impacts caused by eutrophication occur especially along the populated coastal area such as at the northern coast of West and East Java [9-11], Lampung Bay [12], and at the Banyuasin River mouth [13]. Degradation of the quality of estuary has led to a significant decreased in fisheries’ production [14, 15].

2. Two sides of eutrophication for both ecological and social aspects
It has been discussed in many papers that eutrophication in some cases is negative, causing loss of ecosystem services, and in its turn, create an economic loss of the society [1, 16, 17]. Various negative losses and impacts of this organic material increase are proven to cause negative consequences for both ecology and social economy [18, 19]. Nevertheless, scientists rarely discuss the benefits of eutrophication for both environmental and social aspects. Some of the benefits of eutrophication include the increase of primary productivity of the waters and will eventually be able to increase fisheries production in its adjacent waters. Marine capture fisheries data showed that the production of fisheries, especially coastal fisheries both demersal and small pelagic are higher compared to those of less eutrophic waters as can be seen in figure 1.

![Figure 1. Conceptual model on the correlation between eutrophication levels and benefits for human. Graph concept and drawn by Ario Damar.](image-url)
eutrophication are: (1) increase of aquatic primary production [1] and (2) increase of fisheries production that will lead to (3) economic benefits through improvement of local fishermen income [1].

We propose a diagram called the correlation between eutrophication level and benefit which correlates between the levels of eutrophication and its ecological and social benefits as presented in Figure 1. In that figure, the level of eutrophication is shown on axis X and the benefits for humans is shown on axis Y. The optimum eutrophication level (A) deliver maximum benefits (B) for the environment and society. In the X axis, the right area of point A is determined as loss zone while that of the left area of point A is identified as the benefits zone. The slope of the curve (α) shows the rate of eutrophication level in increasing the benefit. It is shown that the benefits curve is in the form of a hyperbolic pattern where at the beginning of the eutrophication stage, the increase of the level of eutrophication will provide benefits to human beings, through increased water productivity and fisheries production. The increased levels of eutrophication from oligotrophic to mesotrophic will lead to an increase of primary production and hence fisheries production (the more to the right of the curve) and benefitting human beings.

The production process of organic materials causes the accumulation of organic materials in the waters that will be further decomposed by bacteria. Bacteria decomposition requires a lot of oxygen taken from the environment and can cause oxygen deficiency. The rate of oxygen deficiency will depend on the rate of oxygen renewal that can either supplied by photosynthetic results or air-water diffusion. Problems will arise when the supply rate of oxygen renewal is smaller than the rate of oxygen consumption. At that moment, the system will experience various problems, such as oxygen deficiency (hypoxia), loss of oxygen (anoxia), smelly water, algae blooms, until the mass mortality of aquatic biota. Hence, the balance point of the new oxygen renewal into the system becomes very important and crucial. The ability of an aquatic system in the renewal of oxygen can be pointed out as the carrying capacity of the system, which is in line with the turning point of the benefits curve (figure 1). In the field of eutrophication management, the point where the turning point (A-in figure 1) is achieved is very important and critical to be identified.

In the curve, the slope of the curve (α) and the carrying capacity of coastal aquatic waters depend on the renewal rate of oxygen into the water, the flushing rate of the water, and the presence of grazing organism. However, each estuary is site-specific, cannot be generalized, and resulting strong need to have detail characters of each estuary [1].

Based on the two different views (positive and negative), the important question is when we have to allow an increase in eutrophication and when we have to stop. From the environmental management perspective, however, it is somewhat too risky to seek environmental benefits from eutrophication with the fact that it is too difficult to control the rate of organics into the waters. We cannot give permission to let the organic pollution take place just only to expect some benefits from the increase in primary production. Thus, in many cases, the next question is the greater the benefits or disadvantages caused by this eutrophication. To answer these questions, the study of ecosystem services will be important. With this study, a thorough study of profits and losses would be identified and would be an important ingredient for policymakers to decide the priorities of management in waters of estuaries.

3. Increased rate of primary production
Coastal waters which is highly affected by nutrient enrichment is a productive system, high in primary production, able to support live of various aquatic biota, and good for a system. Java Island in Indonesia is a good example on how eutrophication can be beneficial for social system despite its negative impacts. In the perspective of the anthropo-system, an increase of primary production can be significantly beneficial, as can be further continued by the increase of secondary and hence fisheries productions. Increase in fisheries production is one good example from this perspective. In the coastal sea of Java, especially on the northern coast of this island, the high rates of nutrient supply from the incoming rivers are the main source of organics to fuel primary production.

Table 1 shows the comparison of primary production and phytoplankton biomass values between estuaries of the northern coast of Java and the southern coast of Java. Those two different sites are
different in the nutrient loads due to the typical hydrological character of the island. Topographic feature of Java is creating a series of the hilly area along its southern coast, resulting in typical south to north flow of the hydrological system. The spatial demographic of people is also more concentrated along the northern coast of the island compared to that of the southern coast. With this specific pattern, coastal waters of the northern coast receive higher nutrients compared to that of the southern coast. As result, higher primary production and hence secondary and fisheries production always characterize the estuaries on the northern coast of this island. Conversely, values of primary production of the estuaries of the southern coast of Java Island are characterized by lower primary production values (table 1).

**Table 1.** Comparison of primary production values of some estuaries, comparison between less eutrophic waters of the southern coast of Java (Indian Ocean) with the more eutrophic waters of the northern coast of Java Island (Java Sea).

| Area                                   | Area                  | Annual production (g C m\(^2\) y\(^{-1}\)) | Method | Phytoplankton biomass (ug Chl-a L\(^{-1}\)) | Method | Reference |
|----------------------------------------|-----------------------|------------------------------------------|--------|------------------------------------------|--------|-----------|
| **Southern coast of Java Island**      |                       |                                          |        |                                          |        |           |
| Indian Ocean (Indonesia)               |                       |                                          |        | < 0.80                                   | RS\(^a\) | [22]      |
| - upwelling period                     |                       |                                          |        | 0.80 – 2.00                              | RS\(^a\) | [22]      |
| - before upwelling                     |                       |                                          |        | <0.25                                    | RS\(^a\) | [23]      |
| - upwelling period                     |                       |                                          |        | >1.00                                    | RS\(^a\) | [23]      |
| Lampung Bay, West of Java              |                       |                                          |        |                                          |        |           |
| - inner part (Hurun coast) 1999 \(^a\) |                       | 70                                       | O\(_2\) |                                          |        | [24]      |
| - middle part 2000-2001                 |                       | 40                                       | \(^{14}\)C | 2.22                                    |        | [25]      |
| - outer part 2000-2001                  |                       | 31                                       | \(^{14}\)C | 0.78                                    |        | [25]      |
| Semangka Bay (Indian Ocean-Indonesia)   |                       |                                          |        |                                          |        |           |
| - inner part (river plume) 2000-2001    |                       | 14                                       | \(^{14}\)C | 7.11                                    |        | [25]      |
| - middle part 2000-2001                 |                       | 40                                       | \(^{14}\)C | 1.21                                    |        | [25]      |
| - outer part 2000-2001                  |                       | 22                                       | \(^{14}\)C | 0.44                                    |        | [25]      |
| **Northern coast of Java Island**      |                       |                                          |        |                                          |        |           |
| Porong Estuary, East Java              |                       |                                          |        | 4.75                                    | Spect.\(^b\) | [10]      |
| Wonokromo Estuary, East Java           |                       |                                          |        | 2.51                                    | Spect.\(^b\) | [10]      |
| Jakarta Bay Java Sea                    |                       |                                          |        |                                          |        |           |
| - inner part 1983\(^a\)                |                       | 301                                      | O\(_2\) |                                          |        | [26]      |
| - inner part 1991\(^a\)                |                       | 166 – 214                                | O\(_2\) |                                          |        | [27]      |
| - inner part 2000-2001                  |                       | 503                                      | \(^{14}\)C | 31.4                                    |        | [25]      |
| - middle part 1983\(^a\)               |                       | 49                                       | O\(_2\) |                                          |        | [26]      |
| - middle part 1983\(^a\)               |                       | 55                                       | O\(_2\) |                                          |        | [26]      |
| - middle part 2000-2001                 |                       | 119                                      | \(^{14}\)C | 15.8                                    |        | [25]      |
| - outer part 2000-2001                  |                       | 47                                       | \(^{14}\)C | 2.20                                    |        | [25]      |
| Banten Bay, Java Sea                    |                       | 163                                      | O\(_2\) |                                          |        | [28]      |

\(^a\) Remote sensing method

\(^b\) Spectrophotometric method

4. Increase in fisheries production

As further consequences of the increase of primary production, fisheries production is also increased. This can be seen from the elevated value of fish production in the Java Sea from time to time, despite increase in the number of fishermen (figure 2). Theoretically, biomass formed during the process of primary production is then come into the food web where one of the components is fishes, either carnivore, planktivory, or omnivore. Fisheries statistic of Java Sea shows that these waters are higher compared to that of the Indian Ocean in the southern coast of the island where it is commensurate with the difference in primary production.

The primary productivity in the waters of the northern coast of Java is high [29], which is further converted into secondary production, and hence fisheries production. Figure 2 shows the difference in
fish production comparison between Java Sea (Fisheries Management Area-WPP 712) and the Indian Ocean (Fisheries Management Area-WPP 573 eastern). It can be seen that fish productions of WPP 712 are higher than those of WPP 573. This pattern shows that the high eutrophic waters of Java Sea able to support higher fisheries production which in its turn able to deliver economic benefits for the people.

Figure 2. Fisheries production of the more eutrophic waters of the Java Sea and the less eutrophic waters of the Indian Ocean 2005-2013 [30].

| Location               | Species of algal bloom                          | Abundance (cells m$^{-3}$) | Condition         | Nutrient Impact                      | Reference |
|------------------------|-------------------------------------------------|----------------------------|-------------------|-------------------------------------|-----------|
| Jakarta Bay, Indonesia | Diatom: *Skeletonema* sp., *Chaetoceros* sp., *Thalassiosira* sp. | 2×10$^7$ – 2.1×10$^9$     | Dry seasons       | High N/P ratio                      | Mass mortality of fishes several days after bloom [6] |
| Johor Strait, Singapore| Dinoflagellate: *Takayama xiamenensis*, *Karldinium* | 2×10$^6$ – 1.2×10$^{11}$ | Neap tide         | High N/P ratio                      | Massive fish kills in Johor Straits [33] |
| Rhode Island, United States | Dinoflagellate: *Cochlodinium polykrikoides* | 1×10$^5$ – 3.4×10$^9$ | Summer            | High N/P ratio                      | Red coloration in water affect local sport and commercial fisheries [34] |
| Fujian Water, China    | Dinoflagellate: *Prorocentrum donghaiense*, *Karldinium digitatum* | 4.58×10$^9$ – 1.46×10$^{10}$ | Spring            | n.a                                | Mass mortality of cage-cultured fish [35] |

5. Algae blooms
Algae bloom is one of the chronic effects of eutrophication, through the excessive elevation of nutrients. In tropical waters, with its continuous supply of underwater light for phytoplankton growth, the algae bloom can be more severely occurs since light is always available throughout the year. Rapid development of phytoplankton biomass can be a serious problem both for ecological and societal aspects. Coastal seas of the northern coast of Java Island, such as Jakarta Bay, Banten Bay, Semarang, and other coastal embayment’s are routinely affected by the algae bloom. Once the water is bloomed by
algae, it can be further creating mass mortality of the fishes and disturbing the tourism business of the area.

Until now, blooms of algae have not been fully revealed. In principle, bloom will only occur if two main factors determining phytoplankton growth are available, namely nutrients and light. However, not every time bloom occurs, despite the nutrients and abundant light. The involvement of the third factor is the determinant and alleged as the facilitation of the physical factor of aquatic dynamics [31] such as vertical and horizontal water current.

A famous example of algae bloom has been revealed in a eutrophic Jakarta Bay, were experienced with massive algae bloom [7, 21, 32]. In this tropical estuary, the most frequent species responsible for algae bloom were *Skeletonema costatum*, *Pseudonitzschia*, and *Noctiluca scintillans*. High nutrient concentration and abundant irradiance were the most causative factors for the bloom, but the most decisive triggering factor was the hydrodynamic factor. The bloom was mostly occurred during the period of calm water of the dry period and the transition period between the rainy to dry period. In this less movement of water, phytoplankton was allowed to develop in a accumulation of their biomass and form blooms. Table 2 shows the comparison of some algae blooms phenomena across regions globally in the eutrophic estuaries.

### Table 2. Comparison of some algae blooms phenomena across regions globally

| Location                      | Hypoxia Type | DO (mg l⁻¹) | Potential Cause                                                                 | Response                                   | Reference |
|-------------------------------|--------------|-------------|--------------------------------------------------------------------------------|--------------------------------------------|-----------|
| Jakarta Bay, Indonesia        | Seasonal     | 0 – 6       | Large oxygen demand, weak tidal mixing, high river discharge, and lack of continuous convection | Benthic mass mortalities                   | [20][4]   |
| Pearl River Estuary, China    | Episodic     | < 2.0       | Inflow of nutrients from watersheds and urban areas                           | n.a                                        | [37]      |
| Tokyo Bay, Japan              | Episodic     | < 2.0       | Influx of oceanic water from the outside of the bay                          | Mass mortality on juveniles of mantis shrimp | [38]      |
| Chesapeake Bay, United States | Seasonal     | < 0.2 – 2   | Nitrate loading from the Susquehanna River                                   | Changes on biogeochemistry of the bay, decline in deep-water macrobenthos | [39]      |
| Oregon Coast, United States   | Upwelling    | 0.21-1.57   | Upwelling forcing, anomalously strong flow of sub-arctic water               | Mass die-offs of fish and invertebrates    | [40]      |

6. **Hypoxia**

Hypoxia is one of the consequences of the high rate of organics decomposition in an estuary. A high rate of oxygen consumption by bacteria during the decomposition process, resulting deficit of dissolved oxygen in the water. It is well-known that many eutrophic estuary experiences with hypoxia and even more anoxic. Mississippi river mouth of the Gulf of Mexico is well known for its dead zone [36], especially during summertime when summer vertical stratification develops. The tropical bay of Jakarta Bay is another example of persistent hypoxia in its near-bottom water [20]. In this tropical bay, the hypoxic area of its near-bottom water occupies a large area, mostly located close to the coastline and river mouths. Jakarta Bay experiences with quasi-persistent hypoxic condition due to low transport of surface to bottom water, causing the isolation of low oxygen of the near-bottom water [20].

### Table 3. Comparison of hypoxic areas across regions in the world.

| Location                      | Hypoxia Type | DO (mg l⁻¹) | Potential Cause                                                                 | Response                                   | Reference |
|-------------------------------|--------------|-------------|--------------------------------------------------------------------------------|--------------------------------------------|-----------|
| Jakarta Bay, Indonesia        | Seasonal     | 0 – 6       | Large oxygen demand, weak tidal mixing, high river discharge, and lack of continuous convection | Benthic mass mortalities                   | [20][4]   |
| Pearl River Estuary, China    | Episodic     | < 2.0       | Inflow of nutrients from watersheds and urban areas                           | n.a                                        | [37]      |
| Tokyo Bay, Japan              | Episodic     | < 2.0       | Influx of oceanic water from the outside of the bay                          | Mass mortality on juveniles of mantis shrimp | [38]      |
| Chesapeake Bay, United States | Seasonal     | < 0.2 – 2   | Nitrate loading from the Susquehanna River                                   | Changes on biogeochemistry of the bay, decline in deep-water macrobenthos | [39]      |
| Oregon Coast, United States   | Upwelling    | 0.21-1.57   | Upwelling forcing, anomalously strong flow of sub-arctic water               | Mass die-offs of fish and invertebrates    | [40]      |

Organics accumulation occurs in the sediment in the form of a thick layer of muddy-rich of an organic belt, composing an organic pool that should be decomposed by bacteria. It is of normal situation in the
estuary were characterized by thick organic sediment in its seabed. The water column above it is less in physical movement, causing permanent calm water, and allowing rapid decomposition of bacteria which consume a huge amount of oxygen. Usually, an estuary suffered from hypoxia is a calm estuary, less in physical water movement, and located in physically-protected waters like embayment. This low physical movement allows longer water residence time that will create an accumulation of particles in its sediment. The longer water residence time, the higher accumulation rate of organics in its seabed.

It has been recorded a tremendous increase of hypoxic phenomenon in the global estuary in the last 30 years which is related to the increase of nutrient loads to estuaries [36], which most closely related to anthropogenic domestic waste of major cities. Location of the hypoxic estuaries are always in the adjacent area of big cities such as Tokyo, Jakarta, Bangkok, Manila, San Francisco, and Mumbai.

Comparison between tropical and temperate regions, hypoxic condition of temperate estuaries usually occurs during summer where thermocline develops. This temporal thermocline which creates temporal hypoxia is observed in Chesapeake Bay (Maryland, USA), Pamlico river estuary (North Carolina, USA), Mobile Bay (Alabama, USA), Hillsborough Bay (Florida, USA), Seto Inland Sea (Jepang), German Bight (North Sea, Germany), Port Hacking (Australia), Tolo Harbor (Hong Kong), main harbours in Japan, Tome Cove (Jepang), Trieste Bay (Adriatic, Itali) and Black Sea [36]. Table 3 shows examples of some coastal sea’s eutrophication in some area in the world.

7. Mass mortality of aquatic biota
The mass mortality of aquatic biota is the end of various environmental degradation processes caused by eutrophication. Technically, the mass mortality of aquatic biota can be caused by low oxygen content in the water, toxic algae bloom, or toxic gaseous as a result of the intensified process of organic decomposition [1, 36, 37]. In Jakarta Bay, for example, the mass mortality of aquatic biota is a routine phenomenon caused by lifting up the low-oxygen of near-bottom water to the surface, resulting in asphyxia [41]. A similar process was also found in the Oregon coastal waters [42, 43] in the northern Californian waters.

8. Coral reef disturbances
Besides affecting estuary ecosystems, eutrophication also affects the coral reef ecosystem. An increase of nutrient level in the coral reef ecosystem causes some ecological consequences such as the rapid expansion of algae coverage overlapping the growth of corals [44, 45]. Symbiotic mutualism between dinoflagellate of Symbiodinium sp. with coral animal develops a special relationship mechanism. The algae need nutrients but they need light as well. Chronic effects of eutrophication in the coral reef ecosystem create environmental changes such as higher turbidity and higher nutrient concentration in the water [46]. In the normal situation, living coral coverage dominates the bottom coverage of the landscape, leaving macroalgae as minor spatial coverage. In the eutrophic environments, the elevated nutrient concentration will promote the expansion of macroalgae where they can grow much faster and better, resulting in the dominant occupation of macroalgae in the coral ecosystem [44, 45].

Changes in the nutritional state of the coral environment create some further consequences, and one of the most important is the change in the trophic level proportion [44]. An increase of macroalgae and coralline algae coverage will provide a higher number of foods for associated coral animals, such as fish. In the macroalgae less-dominated coral reef ecosystem, the proportion of coral-eating fish and carnivorous fish are abundant, causing the shift of herbivorous fish to take over the food chain [47].

This can be seen in the study done by Adi [48] in the Thousand Islands coral reef ecosystem of the Jakarta Bay area. Coral reef ecosystem which is located right in front of the eutrophic bay, gradually influenced by its high-nutrient waters. The area consists of around 104 small coral reef-islands, lies in the south to north position, perpendicularly towards Jakarta Bay in the south. Coral reef ecosystem distribution reflects the effects of eutrophication influence brought by Jakarta Bay. Coverage of macroalgae is significantly higher in the southern part of the islands and getting lesser and lesser in the middle and northern part of the islands. Gradual increase of macroalgae coverage and consequently reduce the living coral coverage as it is approaching the mainland is strong evidence emphasizing the
effect of eutrophication in the degradation of coral reef ecosystem, in the form of increase of macro algae coverage and change in the fish composition.

9. Conclusion
It is concluded that although eutrophication is able to deliver positive benefit both for the ecological and social systems, their negative consequences are too much high to be managed. It is too risky to expect benefits from the escalating nutritional status of an estuary. It seems that it is too costly just to expect a productive estuary while its negative consequences are waiting. The best-recommended measures dealing with coastal eutrophication is to reduce riverine nutrient loads into an estuary.

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