Spatial distribution and assessment of nutrient pollution in Lake Toba using 2D-multi layers hydrodynamic model and DPSIR framework

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Abstract. Lake Toba is the largest lake in Indonesia utilized as a source of life-support for drinking and clean water, energy sources, aquaculture and tourism. Nowadays the water quality in Lake Toba has decreased due to the presence of excessive nutrient (nitrogen: N and phosphorus: P). This study aims to describe the spatial distribution of nutrient pollution and to develop a decision support tool for the identification and evaluation of nutrient pollution control in Lake Toba. Spatial distribution method was conducted by 2D-multi layers hydrodynamic model, while DPSIR Framework is used as a tool for the assessment. The results showed that the concentration of nutrient was low and tended to increase along the water depth, but nutrient concentration in aquaculture zones was very high and the trophic state index has reached eutrophic state. The principal anthropogenic driving forces were population growth and the development of aquaculture, livestock, agriculture, and tourism. The main environmental pressures showed that aquaculture and livestock waste are the most important nutrient sources (93% of N and 87% of P loads). State analysis showed that high nutrient concentration and increased algal growth lead to oxygen depletion. The impacts of these conditions were massive fish kills, loss of amenities and tourism value, also decreased usability of clean water supply. This study can be a useful information for decision-makers to evaluate nutrient pollution control. Nutrient pollution issue in Lake Toba requires the attention of local government and public society to maintain its sustainability.

1. Introduction
Lake Toba is the largest volcano-tectonic lake located in the province of North Sumatera. The natural beauty of Lake Toba and fascinating Batak culture have been internationally recognized as a tourist destination. Lake Toba is surrounded by seven districts: Karo, Simalungun, Toba Samosir, Tapanuli Utara, Humbang Hasundutan, Samosir, and Dairi. Lake Toba has been utilized as a source of life-support for drinking and clean water, energy sources (hydroelectric plant), transportation, farming, aquaculture and tourism.

The water quality in Lake Toba during the last few years has suffered obvious deterioration due to the presence of excessive nutrient (nitrogen: N and phosphorus: P) derived from point source and non-point sources [1]. Aquaculture as a point source has reached 11.781 units [2] spread throughout seven districts around the lake. While non-point sources consist of human activities in the lake watershed (residential/domestic, tourism, livestock, agriculture and forestry), rainwater and river runoff.

This study aims to describe the spatial distribution of nutrient pollution and to develop a decision support tool for the identification and evaluation of nutrient pollution control in Lake Toba. Spatial
distribution method was conducted by 2D-multi layers hydrodynamic model, while DPSIR (driving force, pressure, state, impact and response) framework was used as a tool for the assessment.

2. Methods

2.1. Data Description

The data used in this study consist of (1) Bathymetry of Lake Toba; (2) Amount, coordinate and loads of fish net cage (FNC) waste; (3) Coordinate of influent, river outflow, water quality, and river loads; (4) Water quality in sampling site; (5) Climatological data; (6) Total population and tourists; (7) Total livestock animals (cattle, horse, goat, swine, rabbit, sheep, chicken and duck); (8) Total area of various land (forest, farms, grassland, rice field); (9) Total fisheries (FNC, fish feeds, and fish production). For number 6-9, the data was obtained from the Environmental Agency of North Sumatera (DLH-SU), Fisheries and Marine Agency of North Sumatera (DKP-SU), and the Central Agency on Statistics of North Sumatera (BPS-SU).

2.2. 2D-multi layers hydrodynamic model

2D-multi layers hydrodynamic model was developed in the previous work [3] (Figure 1). This model was able to describe the spatial distribution of nutrient (N and P) in Lake Toba. Spatial model was obtained from numerical calculation of 2D-multi layers hydrodynamic and water quality model. The numerical calculation was conducted by dividing Lake Toba into 50 × 50 m and 18 layers using Compaq Visual Fortran, and the model output was visualized using ArcGIS 10.2. Model calibration was used to observe the concentration of nutrient compound in several sampling sites in Lake Toba. As a result, this model can be a tool for estimating and monitoring nutrient loads.

Figure 1. 2D-multi layers hydrodynamic model [3].
2.3. DPSIR framework
The DPSIR (Driving force - Pressure - State - Impact - Response) framework, developed by the European Environmental Agency in 1999, is aimed at analysing the cause-effect relationships between interacting components of complex social, economic and environmental systems, and information flow management between its parts [4]. In this study, the main steps of the assessment are described below:

I. A pollution sources assessment, based on assessment methodology, is often referred to as ‘Rapid Assessment’ method [5], which relates driving forces to their pressure on the environment.

II. A nutrient balance assessment, to determine the relation between pressure and state of the environment.

III. Identifying and assessing the response option through which environmental management of these water bodies may be possible.

Pollution sources and nutrient balanced assessment
For estimating pollution from the various sources, this study used the following general formula (Equation 1) and nutrient balanced assessment (Equation 2):

\[
[waste\ load] = [\text{functional variable}] \times [\text{pollution intensity}] \times [\text{penetration factor}] \quad (1)
\]

\[
W_A = C_A \times (Q_{out} + V \frac{v_s^A}{H}) \quad (2)
\]

Whereas the waste load represents the actual input of pollutants into the lake, the pollution intensity represents the amount of waste characteristic produced per unit of a certain functional variable. World Health Organization (1982) and [5] report the functional variable as a pollution factor for quantification of various waste loads based on extensive literature research. The penetration factor enables incorporation of possible pollution reduction effects (e.g. wastewater treatment), which may range from 0, if there is complete reduction, to 1, if there is no reduction. \(W_A\) represents the input of nutrient A [g/y], \(C_A\) is the concentration of nutrient A [g/m^3], \(Q_{out}\) is the lake outflow [m^3/y], \(V\) is the lake volume [m^3], \(v_s^A\) is the sediment velocity for nutrient A [m/y], and \(H\) is the average lake depth [m].

3. Results and Discussion
3.1. Spatial distribution of nutrient pollution in Lake Toba
Figure 2 shows the low concentration of ammonia and nitrite in surface water and it tends to increase along the water depth. The high concentration of ammonia in deep water is caused by ammonia released from sediment. FNC area (Simalungun, Samosir, Humbang Hasundutan, Karo and Dairi) has a high concentration of ammonia in the surface and it decreases along the water depth. This is caused by the ammonification of organic waste from FNC. With the concentration of ammonia more than 0.02 mg/L, FNC could threaten fish. Ammonia exists the water in two forms: NH3 (un-ionized ammonia) and NH4+ (ionized ammonia). NH3 is the toxic form and predominates when pH is high, while ammonium ion is relatively non-toxic and predominates when pH is low. When ammonia accumulates to toxic level, the fish will become lethargic and eventually fall into a coma and die [6].

Otherwise, as shown in Figure 2, the high concentration of nitrate in surface water and it tends to decrease along the water depth. The low concentration of nitrite followed by the high concentration of nitrate in surface water shows that the nitrification process has occurred in this layer. Bacteria oxidize ammonia to nitrite and then, to nitrate. The main factors that affect nitrification rate are ammonia concentration, temperature, and dissolved oxygen concentration. It means DO concentration in surface water is still sufficient to carry out nitrification process.

Figure 3 shows the low concentration of phosphate in surface water and it tends to increase along the water depth, except in FNC area that has high concentration in surface water and low concentration in deep water. This shows that phosphate as a source of nutrient for phytoplankton comes from the FNC,
not from the sediment. If the water level decreases to the maximum elevation of phosphate released from the sediment, eutrophication is feared.

According to the government regulation [7], Lake Toba is classified as Class I water with maximum concentration of ammonia, nitrite, nitrate and phosphate of 0.02 mg/L, 0.06 mg/L, 10 mg/L and 0.2 mg/L respectively [8]. As shown in Figure 2 and Figure 3, the concentration of ammonia, nitrite and phosphate in FNC area has exceed the water quality standard. And the trophic state index for P more than 0.1 mg/L shows that it has reached eutrophic state.

**Figure 2.** Spatial distribution of ammonia (A), nitrite (B) and nitrate (C) in Lake Toba.
3.2. **Nutrient pollution assessment**

This study calculated all possible sources that potentially contributed to nutrient pollution. Average estimated N and P loads are presented in Figure 4. The total annual nutrient load was estimated at 5,577.47 t/y for N and 2,297.57 t/y for P. It may be concluded that aquaculture (FNC) waste and livestock waste are the most important nutrient sources, accounting for approximately 93% of N and 87% of P input. While domestic and other wastes play only a minor role as a nutrient source. For aquaculture waste, Simalungun and Dairi are the largest contributors. While for the livestock waste, it is dominated from Toba Samosir (63% of N and 65% of P) and Samosir (17% of N and 16% of P).

![Figure 3. Spatial distribution of phosphate in Lake Toba.](image)

![Figure 4. Most likely nutrient loads by source and aquaculture loads by district.](image)

The results of the assessment are summarized in Figure 5, which shows the intricate interrelationships between the driving forces, pressures, states and impacts aspects of the DPSIR framework. The main driving force is related to socio-economic, natural resources and benefit of the lakeside zone and also living condition and traditional values of Batakinese which in turn lead to population growth, increased visitors, rapid aquaculture development, livestock, land cultivation and agricultural activities. The pressures resulting from these driving forces concern nutrient loads, largely from aquaculture waste, followed by livestock and domestic waste.

The consequences of the driving forces and pressures are described as point and non-point sources results in increased N and P concentration in the lake that stimulate changes in the nutrient cycle, increased the toxic form of ammonia [6], and intensified algal growth that lead to decreased transparency of water [9], ecosystem health [10], oxygen depletion [11] and increased bacteria and parasite [12].
ultimate impact of these processes to society includes, first of all, massive fish kills [11]. The impact will be the most significant in the bays and shorelines of the lake. These areas are the areas that are mostly affected by pollution and other changes. Furthermore, stench and loss of visual amenity due to dirty water and dead fish reduce the recreational and tourism value of the lake. The water, the shorelines and bays in particular, provide an increasingly suitable habitat for bacterial and parasitic communities that will cause water-borne disease [13]. The overall water quality makes it unsuitable for the provision of water, mainly for consumption.

*Figure 5. Schematic representation of the Lake Toba nutrient pollution cause-effect chain.*

As the response of the assessment above, strategies for the reduction of such loads need to be implemented. For non-point sources, the government should create appropriate means of wastewater collection and treatment for domestic, tourism and livestock waste. Although there is a wastewater treatment in Ajibata (Toba Samosir), it has not been operating effectively. The government should be concerned with the rehabilitation of the existing installation and upgrading communal wastewater facilities. Nutrient runoff and leaching could be decreased more through the replantation of nutrient capturing vegetation on the shorelines of rivers, stream and the lake itself, which creates a natural barrier for nutrient flux to the lake. Point source strategies could be undertaken in terms of planning the FNC zone [3]. Through the designating of more appropriate areas for FNC, nutrient pollution could be better controlled and managed. In addition, the determination of fish production (10,000 t/y) that has already been published by the local government [14] should be implemented immediately.

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