Short review: Which aquatic ecosystem model should Indonesian lake managers opt for?

A Sunaryani\textsuperscript{1,2}, H A Rustini\textsuperscript{1} and A B Santoso\textsuperscript{1*}

\textsuperscript{1}Research Centre for Limnology, Indonesian Institute of Science (LIPI), Cibinong Science Centre, Bogor, 16911
\textsuperscript{2}Research Unit for Clean Technology, Indonesian Institute of Science (LIPI), Bandung, 40135

*Corresponding author: ari@limnologi.lipi.go.id

Abstract. One of the key requirements of successful water quality management in lakes and reservoirs is a good understanding of the underlying processes within the system. Lake managers, however, need a very simple practical tool to support quality regulation and policy implementation in terms of protecting and restoring these ecosystems. Here, we communicate a starting point from which lake managers, particularly in Indonesia, can gain a better understanding of aquatic ecosystem processes through the integrated application of different models. Until now, numerical aquatic ecosystem models have been used rarely in designing lake and reservoir restoration programs in Indonesia. We highlight the importance of model applications, while noting the difficulties of advancing management plans for Indonesian lakes and reservoirs.

1. Introduction
Lakes, whether natural or artificial, are important for their heritage, ecological, and aesthetic values, as well as water resources. Changes in these inland water ecosystems have been more rapid over the past 50 years than at any other time in human history. Water quality degradation, sedimentation and biodiversity loss are some of the common issues found in lakes across the globe. Pressures on aquatic systems seem to be increasing as the human population and its economic development grow. Preserving the integrity of lakes, however, is essential because they support societal development. This can only be achieved through a better understanding the function and response of aquatic ecosystems to changes.

Over the past five decades, a large number and variety of lake ecosystem models have been developed and published that aim to capture the events and processes that occur in those aquatic systems. Not only do these models provide new insight that enables scientists to understand aquatic environments better, model development also offers managers and policy makers management options that based upon scientific evidence. In the late 1970's, [1] developed a seminal eutrophication model that has been widely used because it is simple and practical, particularly for use by managers. The model is based on the water renewal concept whereby retention of nutrients in the lake is calculated as the balance of concentrations in their inflows and outflows. With the advance of computer technology, more recent models have become much more sophisticated in simulating the details of natural processes [2]. They are able to capture spatial and temporal variabilities within lake ecosystems and...
their response to multiple stressors. Hence, the current choice of models makes it more complicated for users, especially lake managers, to select the appropriate option as the basis of a management plan.

Indonesia has more than 5000 lakes (RC for Limnology LIPI in press.), of various types and sizes, scattered across the country. Fifteen of these have been declared National Priorities for Restoration owing to their unique characteristics, underlying geology, sociocultural interaction, and rapidly growing eutrophication pressures. Over the last decade, efforts have been made to “save” those fifteen lakes but the number of lakes facing rapid eutrophication over that period have actually doubled. Lack of scientific evidence to support the development of an effective restoration programme is hampering efforts by the Indonesian authorities to put an action plan in place. Hence, despite significant investment in infrastructure and other lake restoration activities, the goals and achievements were still far from perfect. Aquatic ecosystem models as tools for quantifying the functions and processes within inland waters were hardly used in guiding the management concept towards a healthy system.

In this paper, we reviewed the use of aquatic ecosystem modelling in supporting lake restoration management plan in Indonesia. We identified three challenges: 1) models are not commonly used to set up restoration targets, 2) there is a need for model integration in practical use, and 3) scientists (i.e. modellers) and lake managers (authorities) should work in a transdisciplinary way. Our aim in this paper is not to provide a comprehensive literature review but to endorse the use of model applications in the restoration and management of lakes.

2. Application of aquatic ecosystem models in Indonesia

The Indonesian government has set up restoration targets for 15 National Priority Lakes (Draft Presidential Decree). To support those targets, in 2009, the Minister of Environment (MoE) released Regulation No. 28 to regulate the allowable loads of pollutant, particularly nutrients, to these lakes based on their estimated carrying capacity. This regulation also provided technical guidance on how to estimate pollution load carrying capacity. The following year, the MoE released Regulation No. 1/2010 on the procedures for water pollution control, which recommended the use of numerical models as a tool to estimate carrying capacity. In addition, Regulation No. 1/2010 explains how model application is a prerequisite to projecting the effects of different management scenarios on inland water restoration.

Due to its simplicity and the underlying assumptions used [3], MoE Regulation No. 28/2009 has been widely applied to the estimation of pollutant load carrying capacity for many lakes and reservoirs in Indonesia (table 1). It is based on a zero dimensional model computation that assumes that a lake is a completely mixed tank. It is used, mostly, for estimating the carrying capacity of lakes or reservoirs in relation to in-lake aquacultural activities. This method can be used to estimate the allowable aquaculture production level (tonnes of fish per year) for any designated water quality. Hence, MoE Regulation No. 28/2009 has been used to estimate the allowable number of floating cage aquaculture operations for many Indonesian lakes and reservoirs, e.g [3; 4].

However, the computation required by MoE Regulation No. 28/2009 does not take into account the complex hydrodynamics and ecological process within the system (for details see [3]). Hence, it is not able to visualise the processes and responses of lakes and reservoirs to inputs that they receive, e.g. of nutrients and contaminants, or to climatic pressures. So, such a computation or model would fail to estimating the carrying capacity of an aquatic ecosystem accurately because it does not take into account the integrity of the system. By adopting a modification of Vollenweider’s eutrophication model, see [5], MoE Regulation No. 28/2009 calculates the concentration of nutrients in the lake or reservoir based on the retention time of the water and the contaminants that it contains. Hence, it would predict that a water body with a long retention time and a high nutrient input would see a worsening of its water quality status, i.e. hypertrophic (figure 1).

In addition to the commonly used MoE model, multi-dimensional models have been applied in some studies in Indonesia (table 1). These models use hydrodynamic forcing to drive the dynamics of ecological component of the model. They simulate physical transport and mixing of the water and, in addition, they are linked to the simulation of ecological and biogeochemical processes. Using a
three-dimensional (3D) model, ELCOM [6], it was revealed that the vertical distribution of dissolved oxygen, iron, methane, and phosphorus in Lake Matano are shaped by vertical variations in transport rates, rather than by sources or sinks [7]. The ELCOM was also used to simulate diurnal stratification in the upper mixed layer of Lake Maninjau and to show that the deep water layer of the lake tends to be stable [8]. Using a different numerical approach, [9] developed a two-dimensional multi-layer model to simulate the transport and distribution of phytoplankton in Jatiluhur Reservoir. This model was leveraged to simulate the eutrophication of Jatiluhur Reservoir in accommodating floating cage fisheries [10], and to assess nutrient pollution from floating cage activities in Lake Toba [11].

Table 1. Lake/reservoir model applications in Indonesia.

| Model name                     | Model dimension | Model application                                                                 | Location                                      | Reference |
|--------------------------------|-----------------|-----------------------------------------------------------------------------------|-----------------------------------------------|-----------|
| MoE Regulation No. 28/2009     | 0D              | pollution load carrying capacity (suspended solids, biological and chemical oxygen demand) | Setu Babakan                                  | [12]      |
| ELCOM/ CAEDYM                  | 3D              | Stratification dynamics                                                           | Lake Matano                                   | [7]       |
| Anon.                          | 2D multi-layer  | Phytoplankton distribution, eutrophication and floating cage localisation          | Jatiluhur Reservoir                           | [9]; [10] |
|                                |                 | Suspended solid distribution                                                       | Lake Tempe                                    | [13]      |
|                                |                 | Nutrient pollution from floating cage activities                                  | Lake Toba                                     | [11]      |

Historically, most aquatic ecosystem models were developed to address simple questions related to the response of water column nutrient, oxygen, and phytoplankton concentrations to human alterations or climatic impacts. However, more recent model development provides a set of analytical tools for setting up restoration targets, i.e. levels of nutrient reduction [e.g. 14], although they often perform poorly in simulating key parameters [15]. To complicate matters further, there is often a lack of sufficient observational data for model validation, particularly in Indonesia [e.g. 10; 13]. Even, the widely used MoE model does not require any validation of its calculations, although its results and
recommendations are very critical for management planning [e.g. 3; 4]. Nevertheless, the MoE Regulation No. 28/2009 does provide a practical tool for estimating the carrying capacity of lakes and reservoirs that receive pollutants. In spite of its inability to represent the natural processes that occur in aquatic ecosystems, it does provide a first look at the status of the environment. Method improvement, particularly in model validation, is definitely required. In addition, Indonesian scientists should be at the forefront of increasing understanding of the unique nature of their inland waters in serving science, as well as society (i.e. lake managers, decision makers and general public).

Figure 1. Relationship between phosphorus load (g m$^{-2}$ y$^{-1}$) and lake water retention time (m y$^{-1}$), see [1], showing the current state of Lake Toba (red dot) from loading estimates of 0.63 g m$^{-2}$ y$^{-1}$ [16]. The restoration target (blue dot) as mandated by North Sumatra Governor’s Decree No.188.44/209/KPTS/2017 is also shown.

3. Model of choice
One of the main problems that lake/reservoir authorities in Indonesia have often found is an excess of nutrients within a system that prevents desired water quality criteria to be met. Taking Toba as an example, the lake has been designated as needing to reach oligotrophic status based on North Sumatra Governor’s Decree No. 188.44/209/KPTS/2017. Using [16]’s estimates of the total phosphorus load to Lake Toba (0.63 g m$^{-2}$ y$^{-1}$), we can plot that the trophic state of the lake showing that it falls into eutrophic status according to Vollenweider’s chart (figure 1). From that figure, the required reduction in phosphorus load to meet its target oligotrophic status can be calculated. However, the questions is, how can that oligotrophic status be reach, what kind of restoration plan should be put in place, and how long it should be implemented for? Better identification and quantification of those target loads are critical for getting to the required trophic state.

MoE Regulation No. 28/2009 does not guide lake/reservoir managers in how to develop restoration actions to tackle such problems. It does, however, help managers know the current water quality state of the system. In contrast, MoE Regulation No. 1/2010 requests various policy options to be applied to lower the pollution load and reduce its impact. While both of these regulations seem to stringently bound to enforcing actions required to lower pollution loads and their impact, it is unclear when the desired condition (e.g. oligotrophic status) will be achieved. The application of a suite of models is, therefore, important for solving environmental issues in lakes and reservoirs as demonstrated by the Lake Toba example, above. This can be initiated from the practical model, i.e. Vollenweider Model [1] or the MoE model, because it provides authorities with a quick insight into whether further action is
required, such as the setting of a management plan to meet the desired condition. Restoration targets should also be set to align with any management plan. However, at this point in time, a better modelling application is required to forecast better the likely outcome of that plan in relation to a range of potential management scenarios. As mandated by MoE Regulation No. 1/2010, evaluation and monitoring programs should also be in place to reviewing progress towards the restoration targets.

A one-dimensional (1D) numerical lake model provides time series simulations of in-lake processes and the visualisation water quality in the water column (figure 2). Although it is more complex than the zero-dimension model (0D), e.g. Vollenweider’s model and the MoE’s model, the 1D model can provide information on projected change designated water quality over time. This model is commonly used to simulate management plan scenarios [e.g. 17]. Various types of 1D model have been, and are being, developed independently in many places around the world [18]. However, the three most commonly used are i.e. DYRESM-CAEDYM, GLM-AED and PCLake [18; 19]. These models integrate hydrodynamic forcing in simulating the ecological system of the lake. Most of these models are now developed under a common framework, known as the Aquatic Ecological MOdelling Network (AEMON) mostly to enable (1) open sharing and exchange of common versions of models and (2) increased use of models for research, policy and ecosystem-based management [19]. In addition, integrating catchment models into these systems could provide better estimates of nutrient loads, due to run off and groundwater seepage, into the system [20]. Coupling these two types of model would advance understanding of the source and fate of nutrients in lakes and reservoirs, thus ensuring that relevant authorities are well informed in terms of restoration targets, time frames, and even infestation costs.

It is very likely that lake authorities need a better understanding of the spatial heterogeneity of pollutant dynamics in lakes and reservoirs, especially in large, deep lakes (e.g. Lake Toba, Lake Matano, Lake Singkarak). Due to their hydrodynamic characteristics, pollutants are not thoroughly mixed throughout these lakes. Massive fish kills in some areas of Lake Toba but not others are a good example of spatial heterogeneity issues in lakes. A three-dimensional (3D) model would improve our understanding of that complexity (Figure 2). The 3D grid design of these models allow users to understand water mass transport due to hydrodynamics forces, such as that demonstrated for Lake Toba in figure 3. Using the ELCOM model, one of the available 3D models, we simulated the transport of passive tracers released in two isolated areas of Lake Toba, continuously, for more than a week. We discovered that the tracer was not spatially distributed; instead it became “trapped” in the areas in which it was released. From this simulation, we can infer that pollutants, if they occur, may not be transported evenly across the lake. In fact, they are spatially distributed according to hydrodynamic forces within the lake. So, source and location of pollution is important in this regard, with isolated areas, e.g. bays, having the potential to conserve the pollutant. This simulation, therefore, provides a potential explanation for why massive fish kills have occurred in some parts of Lake Toba but not others.

The array of model choices given above might provide lake managers, and scientists, with a better understanding of the processes and biogeochemical interactions that occur within the lake ecosystems (figure 2). In terms of practical use in lake restoration programmes, a 0D model is a good tool to start with, especially in terms of identifying the water quality status of the system. This model may also be able to provide the relevant authorities with an overview of the system. However, to follow up, a 1D lake model is needed to provide better forecasting of the likely effects of any potential management scenarios. This can also be improved by coupling the 1D model with a catchment delivery model. A 3D lake model would be very useful in simulating the cause and effect an extreme event that has occurred in the lake, e.g. a massive fish kill.
Figure 2. An array of aquatic ecosystem models commonly used for lake/reservoir simulation.

Figure 3. Simulated distribution of passive tracers introduced into two isolated areas of Lake Toba. This simulation ran under ELCOM.
4. Transdisciplinary work
Aquatic ecosystem models provide tools for lake managers to better quantify the effects of all probable measures implemented during lake restoration programmes. Although models might support lake managers by providing a better understanding of their aquatic ecosystems, model complexity is one of the obstacles that may hinder authorities using models. Although a 0D model is more simple and practical, it still requires a good set of data to run the model and for its validation. As models become more complex, they demand higher parameter complexity. The more complicated and higher parameter complexity in a 1D model is even more marked in a 3D, and advance skills are required to run such applications. Hence, it is likely that only trained scientists (modellers) have the capacity to run these models and provide simulated output. Scientists should be able to provide knowledge transfer so that authorities can be provided with better model outcomes that can convert complex model outputs into a simple and practical package of tools and guidance that is easily understood by authorities. Through this collaborative transdisciplinary work, authorities and scientists can focus on their respective roles in solving emerging issues in relation to lake restoration. A quantitative, scientific evidence based, approach to solving ecosystem problems would, therefore, be evolved through such collaboration.

Better resolution and quality of observational data has facilitated better model simulations into which it is possible to incorporate a greater number of biogeochemical variables and processes. This has benefited lake restoration programmes, because more specific questions can be addressed. High quality observational data can also help model simulation to generate more reliable outputs. Either periodic or high-frequency water quality monitoring, as part of a monitoring programme, are needed to support such model development. Such observations, especially from real-time lake sensors, can reduce errors in model parameterisations. Real-time monitoring programmes are now emerging that provide a promising method for managing the uncertainty of model complexity, given that a complex model requires rich streams of data. This will ultimately support the validation of complex hydrodynamic-ecological models. Thus, a sophisticated integration of lake observations that combine sensor and model infrastructure, in conjunction with human networks, offer benefits to lake restoration programmes in terms of improving how scientists and authorities can, collaboratively, improve the predictive capacity of models the outcomes of decision making.

As aquatic ecosystem models are increasingly used to make predictions in relation to water quality and ecosystem services, integration across scientific disciplines is necessary. Yet, the use of models with high levels of complexity is critical when trying to integrate predictive capacity to meet the needs of management policies. Hence, the boundary between scientific disciplines and functional roles should be eliminated and transformed into a transdisciplinary platform where data, model simulations, predictions and policies are consolidated.

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