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How to model algal blooms in any lake on earth

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Algal blooms increasingly threaten lake and reservoir water quality at the global scale, caused by ongoing climate change and nutrient loading. To anticipate these algal blooms, models to project future algal blooms worldwide are required. Here we present the state-of-the-art in algal projection modelling and explore the requirements of an ideal algal projection model. Based on this, we identify current challenges and opportunities for such model development. Since most building blocks are present, we foresee that algal projection models for any lake on earth can be developed in the near future. Finally, we think that algal bloom projection models at a global scale will provide a valuable contribution to global policymaking, in particular with respect to SDG 6 (clean water and sanitation).

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Introduction

Lakes and reservoirs provide essential ecosystem services such as water for drinking and irrigation [1], food supply for many people around the world [2–4] and sites for recreation and tourism [3]. Severe algal blooms threaten these ecosystems for example by producing toxins, odors and by causing oxygen depletion [5]. Worldwide, the occurrence and severity of algal blooms are expected to increase in response to ongoing human-driven nutrient loading and climate change [6–8].

Algal blooms are triggered by excess nutrient loads of particularly phosphorus and nitrogen from the catchment [9] and further promoted by relative high water temperatures [10]. In the natural pristine state, excess nutrients loads from the catchment were rather an exception than a rule, since nutrient availability was limited by slow processes such as weathering of rocks [6]. At present, global anthropogenic nutrient sources double natural sources caused by human activities such as phosphorus mining, industrial nitrogen fixation and fossil fuel combustion [6,11]. Similarly, human activities contribute to global warming which is expected to further aggravate the growth of algal blooms in lakes [7]. To which degree algal blooms respond to excess nutrient loadings and climate change differs among individual lakes. First, this response depends on hydraulic residence time and nutrient loads to the lake which is determined by the location of a lake within a hydrological network. Additionally, lake-specific geomorphological and ecosystem characteristics, such as lake depth, size, light climate and water temperature, determine the sensitivity of a given lake's algal bloom dynamics to nutrient loading and climate change [10,12]. For more details on the effect of different kind of geomorphological and ecosystem characteristics on algal blooms formation please refer to supplementary material 1.

Anticipating how algal blooms will respond to future nutrient loading and climate change can help to prioritize regions for attention and mitigation, evaluate alternative mitigation strategies, and adapt to future ecological changes [13,14•]. Mathematical models can be used to project future global developments based on socio-economic scenarios, as found in, for example, climate research [15] and global nutrient assessments [16]. Such projections have put the potential impacts of global changes at the top of political, societal and economic agendas and helped to formulate the UN Sustainable Development Goals (SDG) [17]. With respect to SDG 6 (clean water and sanitation), projections are especially important to anticipate threats of algal blooms to clean water provision by lakes. The idea to develop models to project future algal blooms is widely supported by initiatives such as ISIMIP (https://www.isimip.org), GLEON (http://gleon.org/) and IPBES (https://www.ipbes.net/).

Here, we provide a roadmap for the development of models to simulate global scale scenarios for algal blooms in freshwater lakes and reservoirs, hereafter referred to as algal projection models. We define algal blooms as locations with a high phytoplankton biomass, including algal scums, reaching a critical level (e.g. chlorophyll-a, dry weight) at which they are expected to threaten ecosystem services (see Poikanen *et al.* [18] for critical chlorophyll-a levels). First, we present the state-of-the-art in algal projection modelling for lakes and reservoirs. Next, we explore the requirements of an ideal algal projection model. Based on these requirements we discuss the challenges and opportunities for future algal projection model development. We conclude that the time is ripe to develop algal projection models for global assessments of lake water quality, which are urgently needed to meet SDG 6.

State-of-the-art in algal projection modelling

Algal projection modelling for freshwater lakes and reservoirs started with the seminal work of Vollenweider, Rast and Lee [19,20]. Using a simple regression model based on hydraulic residence time and nutrient load data, chlorophyll-a concentrations for multiple lakes were estimated. By then, Rast *et al.* [19] noticed: "*Despite tens of millions of dollars spent on water quality management, adequate load and response data are available for less than a dozen water bodies*". Despite Rast's critical note, nowadays, nutrient load data to model lake water quality are still scarce, especially in developing regions [21]. This data scarcity is, to a large extent, caused by the costs and complexity of monitoring nutrient loads. Today, this data scarcity can be addressed by using nutrient load models to estimate nutrient loads to lakes based on different land uses in the lake's catchment [16,22•]. Similarly, data on water temperature at different depths, residence times and local light climate are scarce. This data scarcity can be covered by improved simulations by models such as GLM [23,24] and FLAKE [25]. In contrast, data on key ecological variables for lakes (e.g. lake morphology, phosphorus, nitrogen, and chlorophyll-a concentrations) have become increasingly available at high temporal and spatial scales caused by technological innovations. These innovations constitute, for example, high frequency devices to quantify for example nutrient concentrations, algal biomass and pH [26•], eDNA techniques to identify organisms present in the lake [27], and remote sensing techniques to measure lake morphology [28••] and various water quality parameters (for a full overview see Gholizadeh *et al.* [29]). Increased data availability allowed for modelling, and validation thereof, of an increased number of lakes than has previously been possible (Table 1).

Each model listed in Table 1 has advantages and limitations. The majority of these models are statistical and in most cases based on regression techniques (e.g. GLOBIO-aquatic in combination with Håkanson [30] and the model by Kosten *et al.* [31]). As an advantage, statistical approaches are generally simple and may point to causal relationships [32]. However, statistical techniques do not necessarily reveal an understanding of the true underlying biological processes [33]. For example, a statistical model between fish biomass and dissolved nutrients in the water may show high correlations, however, it fails to acknowledge that fish do not feed directly on dissolved nutrients. A further drawback is that often linear regression is applied in statistical models, which is not capable of capturing sudden threshold shifts or other non-linear relationships. As an example, the growth of an organism may linearly increase with temperature. However, at some point a temperature threshold is reached, leading to a sudden drop in growth rate, which is not covered by the linear regression. Applying a hierarchical 'hurdle' model [34] in which regression analysis is based on a data set that is split into two parts, solves the threshold issue to a certain degree. Another approach is the generalised additive model (GAM) [35] where the relationship between the response and the explanatory variables is allowed to be a smooth function instead of linear. Nonetheless, all statistical approaches are based on data from past conditions which are not necessarily the same in the future [33]. Therefore, care should be taken when statistical models are applied beyond the calibration domain. Consequently, using statistical models for projections of algal blooms is generally not recommended.

Conversely, process-based models like VEMALA v3, PCLake, Delft3D-WAQ/ECO, NiRReLa (Nitrogen Retention in Reservoirs and Lakes) and SiRReLa (Silicate Retention in Reservoirs and Lakes) have the advantage that they include a theoretical understanding of relevant ecological processes. On the other hand, process-based models are more complex than statistical approaches and need calibration using empirical data. NiRReLa and SiRReLa are simple process-based models used for nutrient retention simulations of a large number of lakes worldwide [36–38]. However, neither models have been used to estimate algal blooms, in contrast to VEMALA v3, PCLake and Delft3D-WAQ/ECO [39–41]. VEMALA v3 is used to model phytoplankton concentrations under simulated nutrient loading, however, it is currently only applied to Finnish watersheds [42]. Delft3D-WAQ/ECO is applied to many places around the world using spatial simulations that are highly detailed, which makes the model suitable for simulations