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Simulating water quality and ecological status of Lake Vansjø, Norway, under land-use and climate change by linking process-oriented models with a Bayesian network

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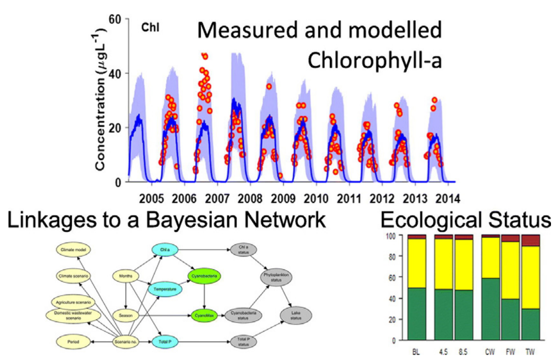
HIGHLIGHTS

- A Bayesian Network chained to a lake model allows predicting cyanobacteria biomass.
- Choice of both climate model and climate scenario influence P loads to lake.
- Land-use scenarios largely determine lake response and ecological status.
- Modelling highlights the need for more data on legacy P and impact of browning.

GRAPHICAL ABSTRACT



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ABSTRACT

Excess nutrient inputs and climate change are two of multiple stressors affecting many lakes worldwide. Lake Vansjø in southern Norway is one such eutrophic lake impacted by blooms of toxic blue-green algae (cyanobacteria), and classified as moderate ecological status under the EU Water Framework Directive. Future climate change may exacerbate the situation. Here we use a set of chained models (global climate model, hydrological model, catchment phosphorus (P) model, lake model, Bayesian Network) to assess the possible future ecological status of the lake, given the set of climate scenarios and storylines common to the EU project MARS (Managing Aquatic Ecosystems and Water Resources under Multiple Stress). The model simulations indicate that climate change alone will increase precipitation and runoff, and give higher P fluxes to the lake, but cause little increase in phytoplankton biomass or changes in ecological status. For the storylines of future management and land-use, however, the model results indicate that both the phytoplankton biomass and the lake ecological status can be positively or negatively affected. Our results also show the value in predicting a biological indicator of lake ecological status, in this case, cyanobacteria biomass with a BN model. For all scenarios, cyanobacteria contribute to worsening the status assessed by phytoplankton, compared to using chlorophyll-a alone.
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1. Introduction

Eutrophication of lakes due to nutrient inputs from agriculture and wastewater is a widespread environmental problem (Schindler et al.,

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2016). 55% of European waterbodies failed to meet the objective of good ecological status mandated by the Water Framework Directive (WFD) (EU, 2000), with nutrient pollution being one of the most significant causes. Eutrophic lakes may have blooms of toxic blue-green algae (cyanobacteria), fish kills, unpalatable drinking water, and unaesthetic bathing water (Carvalho et al., 2013).

Climate change may exacerbate these problems (Chapra et al., 2017), for example, by increasing water temperatures or by increasing precipitation, impacting nutrient loads from the catchment. Mitigation measures undertaken to fulfil the WFD may be offset by the effects of climate change. Conversely, climate change may ameliorate eutrophication by diluting nutrient concentrations through increased precipitation and discharge. Eutrophic lakes thus face multiple stressors, and the combined effects can be synergistic or antagonistic (Hering et al., 2015).

Quantitative assessment of the future combined effects of these multiple stressors on lake eutrophication benefits from the use of models. Future climate conditions are typically estimated by means of downscaled global climate models (GCM), allowing to simulate future discharge from the lake catchment using a hydrological model. A biogeochemical model simulates nutrient losses in runoff, and a lake model simulates the lake temperature, nutrient concentrations and algal abundances. A Bayesian network approach may be used to estimate the combined effects of these environmental changes on the abundance of cyanobacteria and on the ecological status of the lake, as stipulated by the WFD (Moe et al., 2016).

Here, we use a linked chain of models (Couture et al., 2014) and feed the outputs from these into a Bayesian network (Moe et al., 2016) to evaluate alternative scenarios (storylines) that combine future mitigation measures and climate change. We project the phosphorus (P) transport from the catchment to Lake Vansjø, estimate the probability of cyanobacteria blooms, and estimate the probability that the lake will acquire "good ecological status" in the future.

Lake Vansjø in south-eastern Norway is a meso-eutrophic lowland lake in a catchment dominated by forestry and agriculture. It has occasional blooms of cyanobacteria (Haande et al., 2011). The lake and the major inflowing river have been monitored since the 1970s and 1980s, respectively. Management measures taken to limit the inputs of nutrients have included restrictions on agricultural activities, limitations on fertilizer applications, buffer strips, artificial wetlands, and installation and upgrading of sewage systems (Barton et al., 2016). The site is one of several case studies in the EU project MARS (Managing Aquatic ecosystems and water Resources under multiple Stress) (Hering et al., 2015). The MARS project has set up a framework for studying multiple stressors on lakes across the climatic and geographic gradients in Europe. Several common climate scenarios and economic storylines are used to assess possible alternative future ecological conditions at 16 case studies across Europe.

2. Materials and methods

2.1. Study site

The Vansjø-Hobøl catchment (area = 675 km^2), also known as the Morsa catchment, is located in south-eastern Norway (59°24′N 10°42′E) (Fig. 1). The Hobøl River, with a mean discharge of 4.5 m^3 s^{-1}, drains a sub-catchment of 336 km^2 (301 km^2 before the monitoring gauge and 35 km^2 after) into Lake Vansjø, the catchment's main lake. Lake Vansjø has a surface area of 36 km^2 and consists of several sub-basins, the two largest being Storefjorden (eastern basin, draining a catchment of 244 km^2) and Vanemfjorden (western basin, draining a catchment of 58 km^2). The water-column of both basins remains oxygenated throughout the year. The deeper Storefjorden basin (max depth 41 m) drains to the shallower Vanemfjorden basin (max depth 19 m) through a shallow channel, with an overall water residence time of about 13 months. The outlet of Vanemfjorden discharges into the Oslo Fjord (Fig. 1). The Storefjorden basin is used as the drinking water source for 60,000 inhabitants in the city of Moss and surroundings, and both basins are extensively used for bathing, fishing and other recreational activities.

Land cover of the Vansjø-Hobøl catchment is dominated by forest (78%) and agriculture (15%), of which the agricultural land-use is mainly for cereal production (89%). The local catchment for Vanemfjorden has the highest proportion of vegetable crops (<1%). Agricultural activities contribute about 48% of the total P input to the river basin, followed by natural runoff (39%), wastewater treatment plants (WWTP) (5%) and wastewater from scattered dwellings (8%) (Skarbøvik and Bechmann, 2010b).

The lake has a long history of eutrophication from at least the 1970s when systematic monitoring of the lake began. Total P concentrations in Vanemfjorden lie between 20 and 40 μg P L^{-1} (Skarbøvik et al., 2016), which is above the threshold for the good ecological status as required by the Water Framework Directive (Fig. 2). Lake Vansjø, and in particular the western basin, Lake Vanemfjorden, experienced blooms of toxin-producing cyanobacteria causing beach closures due to high toxin levels, although blooms have largely collapsed after 2007 (Fig. 2).

2.2. Data

2.2.1. Hydrology

Catchment hydrology was constrained using daily flow over a 30-yr period (01/01/1983–31/12/2013) measured at the gauging station at Høgfoss (near Kure) (Station #3.22.0.1000.1; Norwegian Water Resources and Energy Directorate, NVE).

2.2.2. Meteorological data

Observed precipitation, temperature and wind records at Lake Vansjø were obtained from daily weather data at the Norwegian Meteorological Institute stations (1715 Rygge; 1750 Fløter; 378 Igsi) located between the two lake basins (59°38′N, 10°79′E).

2.2.3. Water quality

Water chemistry and temperature data were provided by the Vansjø-Hobøl monitoring programme, conducted by the Norwegian Institute for Bioeconomy Research (NIBIO) and by the Norwegian Institute for Water Research (NIVA) (Haande et al., 2016). Suspended sediment (SS) and total phosphorus (TP) in the Hobøl River have been sampled weekly or bi-weekly since 1985 as part of a monitoring programme (Skarbøvik and Haande, 2012; Skarbøvik et al., 2017). Water-column sampling of epilimnion P, nitrogen (N), chlorophyll-α (Chl) and phytoplankton, as well as other parameters have been sampled weekly or bi-weekly since 1976, at the deepest site of both basins using a depth-integrating tube sampler from 0 to 4 m depth (Skarbøvik and Haande, 2012). For both basins values of TP, particulate phosphorus (PP), and dissolved inorganic P (termed ortho-phosphate PO_4 in the database) are accessible for both basins through NIVA's online database (http://www.aquamonitor.no).

2.2.4. Land cover data and sources of P load

The land cover for the Vansjø-Hobøl catchment was constructed from GIS digital terrain elevation maps provided by NIBIO and complemented by a recent report on the fertilization regimes of agricultural fields (Skarbøvik and Bechmann, 2010a). Historical nutrient inputs from wastewater treatment plants (WWTPs) were obtained from the online database KOSTRA, maintained by Statistics Norway (http://www.ssb.no/offentlig-sektor/kostra). TP and SS data were analysed downstream of Høgfoss, at Kure (Skarbøvik et al., 2016). P loadings from scattered dwellings came from NIBIO's online GIS information system, GISavløp.

2.2.5. Phytoplankton data

Bi-weekly Chl and cyanobacteria data from 2005 to 2014 were downloaded from NIVA's monitoring database (http://www.

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