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Research paper

Early warning of limit-exceeding concentrations of cyanobacteria and cyanotoxins in drinking water reservoirs by inferential modelling

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ABSTRACT

An early warning scheme is proposed that runs ensembles of inferential models for predicting the cyanobacterial population dynamics and cyanotoxin concentrations in drinking water reservoirs on a diel basis driven by *in situ* sonde water quality data. When the 10- to 30-day-ahead predicted concentrations of cyanobacteria cells or cyanotoxins exceed pre-defined limit values, an early warning automatically activates an action plan considering in-lake control, *e.g.* intermittent mixing and ad hoc water treatment in water works, respectively. Case studies of the sub-tropical Lake Wivenhoe (Australia) and the Mediterranean Vaal Reservoir (South Africa) demonstrate that ensembles of inferential models developed by the hybrid evolutionary algorithm HEA are capable of up to 30 days forecasts of cyanobacteria and cyanotoxins using data collected *in situ*. The resulting models for *Dolicospermum circinale* displayed validity for up to 10 days ahead, whilst concentrations of *Cylindrospermopsis raciborskii* and microcystins were successfully predicted up to 30 days ahead. Implementing the proposed scheme for drinking water reservoirs enhances current water quality monitoring practices by solely utilising *in situ* monitoring data, in addition to cyanobacteria and cyanotoxin measurements. Access to routinely measured cyanotoxin data allows for development of models that predict explicitly cyanotoxin concentrations that avoid to inadvertently model and predict non-toxic cyanobacterial strains.

1. Introduction

Global eutrophication and warming are suggested to cause shifts in plankton communities towards cyanobacteria which are favoured by high concentrations of nutrients, increased atmospheric CO_2 supplies, high temperatures, enhanced thermal stratification, as well as are tolerant to UV radiation (*e.g.* Wagner and Adrian, 2009; Huber et al., 2012; Paerl and Otten, 2013; Michalak et al., 2013). Cyanobacteria species such as *Dolicospermum circinale* Rabenhorst ex Bornet & Flahault (basionym Anabaena circinalis) and *Cylindrospermopsis raciborskii* (Wołoszyńska) Seenayya & Subba Raju may be capable of atmospheric nitrogen fixation, possibly giving them a competitive advantage over other phytoplankton (*e.g.* Paerl, 1990; Burford et al., 2016). Like species from the non-N_2-fixing genus *Microcystis*, *D. circinalie* and *C. raciborskii* may also produce cyanotoxins (saxitoxins and cylindrospermopsins) that have been postulated to have a role in reducing grazing losses by zooplankton (Jang et al., 2007). These cyanotoxins are both neurotoxic and hepatotoxic, and have been shown to cause serious liver, digestive and skin diseases, neurological impairment, and death (Carmichael, 2001). All cyanotoxins pose a risk to human health. High cell concentrations of *D. circinale*, *C. raciborskii* and *Microcystis* sp. in freshwaters, commensurate with cyanotoxin concentrations that exceed guideline or health alert levels, impair water quality and aquatic biodiversity resulting in economic, social and ecological costs worldwide (*e.g.* Smith, 2003).

Increasingly frequent cyanobacteria bloom events in rivers and drinking water supplies – possibly driven by increasing atmospheric and dissolved inorganic carbon concentrations and increased temperatures, challenge water authorities to improve operational and strategic control of cyanobacterial blooms and their toxins. Whilst strategic control is traditionally being supported by scenario analyses using process-based lake models (*e.g.* Recknagel et al., 1995; Chen et al., 2014; Nguyen et al., 2017),

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remote sensing (*e.g.* Lunetta et al., 2015; Matthews and Odermatt, 2015) and inferential models (*e.g.* Recknagel et al., 2014; Ye et al., 2014) have been proven to be suitable for operational forecasting and control. Fig. 1 illustrates the use of process-based and inferential models for different forecasting horizons for cyanobacterial blooms.

This study proposes an early warning scheme (Fig. 2) that runs ensembles of inferential models developed by the hybrid evolutionary algorithm HEA that have been shown to accurately predict the development of cyanobacterial cell and cyanotoxin concentrations in freshwater bodies, on a diel basis driven by present-day *in situ* water quality data from on-line monitoring stations. When the 10- to 30-day-ahead predicted cell concentrations and cell division rates of cyanobacteria, or cyanotoxin concentrations and proliferation rates exceed limit values defined by water authorities in accordance with national drinking water guidelines, operational in-lake control such as intermittent mixing, as well as enhanced monitoring and treatment of cell and toxin concentrations can be implemented.

The scheme proposed in Fig. 2 is applied to Lake Wivenhoe (Australia) and the Vaal Reservoir (South Africa). The two case studies aim to demonstrate that ensembles of inferential models developed by HEA based on high-frequency sensor monitoring data and weekly to biweekly cyanobacteria cell counts or microcystins concentrations can forecast population dynamics of cyanobacteria and total microcystin concentrations up to 30 days ahead. Forecasting horizons of 10 to 30 days would enable water authorities to implement ad hoc operational control measures as suggested in Fig. 1.

2. Materials and methods

2.1. Lake Wivenhoe

Wivenhoe Dam (27° 24′S, 152° 36′E) is located about 45 km to the west of Brisbane in subtropical southeast of Queensland, Australia. Lake Wivenhoe is a warm-monomictic and mesotrophic reservoir about 30 km long with a catchment area of 7020 km^2. It has a maximum depth in excess of 45 m near the dam wall, an average depth of 11 m and a surface area of 108 km^2. It has a drinking water storage capacity of 1.165 GL and additional temporary flood storage capacity 1.4 GL.

Blooms of the filamentous cyanobacteria *C. raciborskii* and *D. circinale* occur regularly in Lake Wivenhoe (Orr et al., 2010). *C. raciborskii* is capable of producing hepatotoxic cylindrospermopsins, and strains in Lake Wivenhoe are toxic. *D. circinale* can produce neurotoxic saxitoxins although to date, strains in Lake Wivenhoe have consistently been shown by HPLC analysis to be non-toxic. Both cyanotoxins present risks to human health (*e.g.* Hawkins et al., 1985) and when present, cyanotoxin concentrations must be reduced to levels below the Health Alert Levels presented in the Australian Drinking Water Guidelines (NHMRC and NRMMC, 2011) during water treatment. Controlling the development of *C. raciborskii* and *D. circinale* within the reservoir is a key goal of Seqwater (www.seqwater.com.au), the water authority responsible for the management of the reservoir. However, these cyanobacteria (especially *C. raciborskii*) are ecologically adaptable (Burford et al., 2016) and can bloom under a range of light, temperature and nutrient regimes. Both species are capable of fixing atmospheric nitrogen (N_2) if necessary (Reynolds, 1984; Bouvy et al., 2000; Moisander et al., 2008).

Daily *in situ* sensor data from Seqwater's routine monitoring program from 2007 until 2015 (see Table 1) were used to develop models for predicting *C. raciborskii* and *D. circinale* cell concentrations and cell division rates for 10, 20 and 30 days ahead through the use of a hybrid evolutionary algorithm HEA. The models were tested against measured cell counts – also from Seqwater's routine monitoring program – to test their accuracy and efficacy in predicting cell concentrations, and to eventually allow them to be incorporated into Seqwater's monitoring program to provide longer range warnings of cell concentrations of *C. raciborskii* and/or *D. circinale* in source water that might exceed operational trigger levels.

2.2. Vaal Reservoir

The Vaal Reservoir (26° 56′S, 28° 7′E) is located approximately 75 km south of Johannesburg and South Africa's largest drinking water reservoir. It is a warm-monomictic and mesotrophic reservoir about 45 km long with a catchment area of 38,500 km^2, a maximum depth of 47 m, a surface of 320 km^2 and a maximum volume of 2.61 GL.

Favourable climate and water quality conditions can lead to blooms of microcystin-producing strains of *Microcystis* sp. in the Vaal Reservoir (Conradie and Barnard, 2012). Therefore, monitoring and control of cyanobacterial blooms is a high priority for Rand

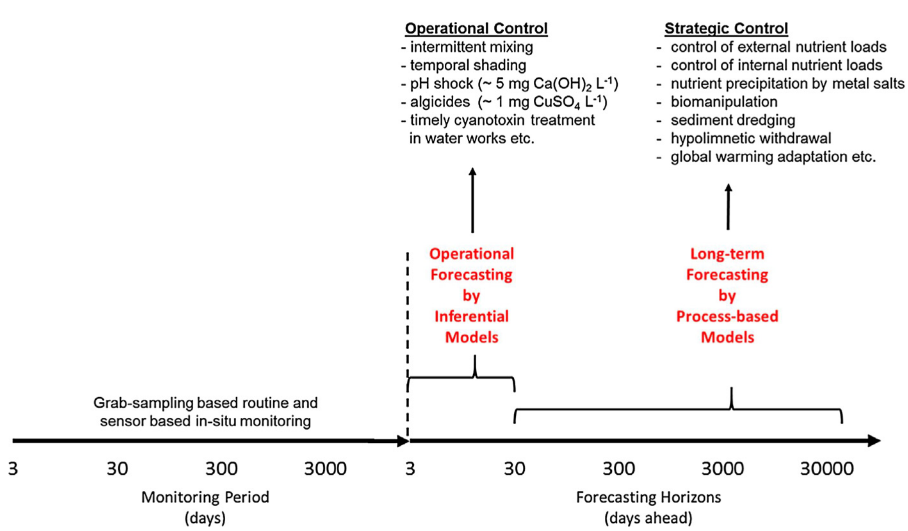

Fig. 1. Suitability of inferential and process-based models for different forecasting horizons of cyanobacteria blooms.