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Development of a chemical source apportionment decision support framework for lake catchment management

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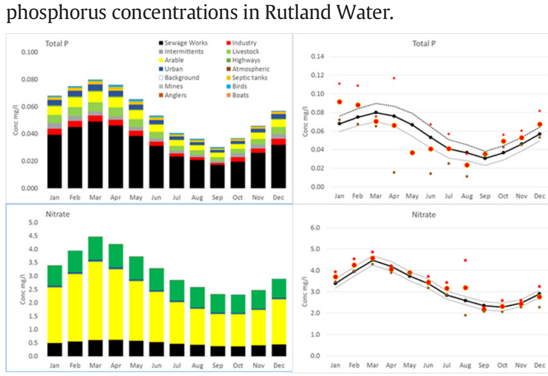
HIGHLIGHTS

- Countrywide source apportionment of chemicals to 763 lakes and reservoir
- Predictions provided for diffuse and point source concentrations and loads
- Validated model for nutrients, metals and organics
- Unique planning tool now used for lake catchment management in the UK

GRAPHICAL ABSTRACT

Modelled (black line) and observed (orange dots) monthly concentrations and source apportionment for total phosphorus concentrations in Rutland Water.



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ABSTRACT

Increasing pressures on natural resources has led to the adoption of water quality standards to protect ecological and human health. Lakes and reservoirs are particularly vulnerable to pressure on water quality owing to long residence times compared with rivers. This has raised the question of how to determine and to quantify the sources of priority chemicals (e.g. nutrients, persistent organic pollutants and metals) so that suitable measures can be taken to address failures to comply with regulatory standards. Contaminants enter lakes waters from a range of diffuse and point sources. Decision support tools and models are essential to assess the relative magnitudes of these sources and to estimate the impacts of any programmes of measures. This paper describes the development and testing of the Source Apportionment Geographical Information System (SAGIS) for future management of 763 lakes in England and Wales. The model uses readily available national data sets to estimate contributions of a number of key chemicals including nutrients (nitrogen and phosphorus), metals (copper, zinc, cadmium, lead, mercury and nickel) and organic chemicals (Polynuclear Aromatic Hydrocarbons) from multiple sector sources. Lake-specific sources are included (groundbait from angling and bird faeces) and hydrology associated with pumped inputs and abstraction. Validation data confirms the efficacy of the model to successfully predicted seasonal patterns of all types of contaminant concentrations under a number of hydrological scenarios. Such a tool has not been available on a national scale previously for such a wide range of chemicals and is currently being used to assist with future river basin planning.

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1. Introduction

Lakes and reservoirs serve as vital sources of drinking water and support valuable ecosystems across the globe. For example, there are more than 500,000 natural lakes larger than 0.01 km^2 (1 ha) in Europe alone. Approximately 80 to 90% of these are small with a surface area of between 0.01 and 0.1 km^2, with only around 16,000 having a surface area exceeding 1 km^2 (EEA, 2015a). There are currently 7000 large dams in Europe (defined as having greater than 1,000,000 m^3 capacity) (EEA, 2015b). Reservoirs and lakes hold approximately 32,000 million m^3 of drinking water across Europe representing around 20% of total supply (Leonard and Crouzet, 1998). In North America the Great Lakes (Erie, Michigan, Huron, Ontario, Superior) contain one fifth of the world's freshwater and 84% of the water supply for the United States of America (USA) and Canada (USEPA, 2017). Other than drinking water, lakes and reservoirs supply power via hydroelectric schemes, augment river flows, provide recreation and are valuable habitats for water fowl and species of fish and invertebrates. There are significant pressures on water quality from numerous sources including urban and highway runoff, industrial discharges, mining and in some cases atmospheric deposition (Comber et al., 2013). Eutrophication is a major source of concern regarding water quality, related mainly to inputs of nitrogen and phosphorus from agriculture and sewage effluents. In Spain, for example 33% of reservoirs were identified as mesotrophic, 27% eutrophic and 10% hypertrophic (Leonard and Crouzet, 1998). Toxic algal blooms occur frequently with the example of suspension of water abstraction from Lake Erie in 2014, affecting half a million people (USEPA, 2017). Loss of potential amenity value has seen extensive steps being taken under European Union (EU) legislation to address these issues.

Lakes and artificial water bodies such as reservoirs are particularly vulnerable ecosystems for a number of reasons:

1) Residence times compared with rivers are often much longer so chemical inputs take longer to be flushed out
2) Accumulation of contaminants is possible in the water column and sediments
3) The lack of flow leads to sediment accumulation within the lentic water body
4) Resident, fish, algae and invertebrates within the lake have few options regarding avoiding the contamination present and therefore may be subject to bioaccumulation and/or toxicity when exposed

To protect lake environments for both in situ ecology and human health via drinking water abstraction, the European Union Water Framework Directive (WFD) (EU, 2000) sets criteria (Environmental Quality standards – EQS) for all water bodies including lakes to meet a defined status categorised as 'Good', for over 30 Priority and Priority Hazardous Substances. In addition, the Drinking Water Directive (98/83/EC) places maximum acceptable concentrations for a wide range of inorganic and organic chemicals which are generally more stringent than environmental standards. Although, compliance can also be controlled through treatment, options for many chemicals are exceedingly expensive and so catchment solutions (source control) are preferable. Regulators therefore need tools to apportion sources of contamination in order to guide future regulation and for known pollution, plan remedial measures in a fair and proportionate way. For the UK this has been achieved through the development of the Source Apportionment Geographical Information System (SAGIS), originally developed for river catchments (Comber et al., 2013) but has now been further developed for lakes. SAGIS combines a number of inputs including modelled, measured and estimated loads from the main point and diffuse sources of metals, organics and nutrients for catchments of England, Wales and Scotland.

Once discharged to a lake catchment, any given chemical will be subject to dilution and undergo various biogeochemical processes, effects that might both be incorporated into a model. However, whereas there have been published reports on load apportionment to lakes and reservoirs and models to determine concentrations within such water bodies by taking account of physico-chemical and biochemical processes (e.g. relationships between biological growth rate and nutrient availability, sunlight and temperature, and phytoplankton and the growth rate of zooplankton; Gough, 1969; Yih and Davidson, 1975), few models have attempted to combine the two. More recent water quality models which simulate lakes specifically include the United States Environmental Protection Agency (USEPA) WASP (Ambrose et al., 1988), and QUAL2E models (Shanahan et al., 1998), the MIKE3 model developed by the Danish Hydraulics Institute (DHI), and the Systeme Hydrologique European (SHE) (Abbott et al., 1986). At a larger spatial scale, catchment models include BASINS (Nasr and Bruen, 2004) and the Environmental Fluid Dynamics Code (EFDC) which is a multifunctional surface water modelling system, which includes hydrodynamic, sediment-contaminant, and eutrophication components. EFDC has been applied to over 100 water bodies including lakes and reservoirs, and is a state-of-the-art hydrodynamic model that can be used to simulate aquatic systems in one, two, and three dimensions (USEPA, 2007).

Source apportionment of nutrient loads within specific catchments is well developed (EEA, 2005) and a number of lakes have been modelled but sources have been aggregated and classified as point, agriculture, and background only (e.g. MESAW model for Lake Peipsi (Vassiljev and Stålnacke, 2003); Lake Mjøsa and Vättern (Nashoug, 1999); Lough Neagh (Dardni, 2007 and Danish lakes (SFT, 2005)). Source apportionment models differ from water quality models in that they have value in risk assessment by determining input loads and to some degree, input locations. For accurate modelling of lentic water bodies a water balance needs to be completed taking into account variability of flow and chemical load as well as any abstractions in the case of reservoirs. Key physico-chemical parameters have to be modelled including sedimentation of suspended solids. There are currently few models which can do this on a local or regional scale and none on a national scale.

Examples of specific models which combine source loads and predicted concentrations include the USEPA CMB8.2 model for has been used to apportion the sources of sediment-bound polynuclear aromatic hydrocarbons (PAHs) in Lake Calumet, Chicago (Li et al., 2003), and mass balance modelling for PAH distributions in Lac Saint Louis, Quebec (MacKay and Hickie, 2000). For nutrients a nitrogen source apportionment model has been developed which converts input loads, based on the surrounding land use, to concentrations using the distributed HBV-N-D and Fyrismodel models for Swedish lake catchments. The models used export coefficients and simple retention equations (Lindgren et al., 2007). For making decisions at a river basin or national level it is necessary to be able to predict loads across many lakes and reservoirs and be able to predict if compliance can be achieved based on predicted concentration data resulting from an identified load reduction mitigation measure being applied.

Lakes and reservoirs are subject to additional and significant chemical sources compared with rivers, particularly nutrients from birds and angling. Birds are recognised as significant sources of nutrients to some lakes (Manny et al., 1994; Marion et al., 1994; Hahn et al., 2008). Fishing is a popular pastime in the UK. Approximately 9% of the population in England and Wales have been freshwater fishing as reported by the Environment Agency in 2010 (EA, 2010). Ground bait, comprising of ingredients such as maize, fish meal, milk protein and semolina, is commonly used, particularly for coarse fishing and nutrient inputs to water bodies from the use of ground bait may present a potential threat to water quality where angling intensity is high (Arlinghaus and Mehner, 2003). These studies have estimated German mean annual gross P-input of 1018 g P $angler^{-1}$ due to ground bait.

This paper describes the significant development of the existing SAGIS model for rivers (Comber et al., 2013) to include 763 lakes and reservoirs within England and Wales. The model utilises national datasets for multiple parameters including hydrology, rainfall, modelled