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The interactive responses of water quality and hydrology to changes in multiple stressors, and implications for the long-term effective management of phosphorus

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HIGHLIGHTS

- Eutrophication on the Thames is attributed to soluble reactive phosphorus (SRP).
- We assess effectiveness of SRP management strategies, under scenarios of change.
- Roles of diffuse and point source SRP vary according to future rainfall and runoff.
- In a multi-source catchment individual management strategies are least successful.
- SRP is best managed by combining strategies, and targeting the dominant source.

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ABSTRACT

Soluble reactive phosphorus (SRP) plays a key role in eutrophication, a global problem decreasing habitat quality and in-stream biodiversity. Mitigation strategies are required to prevent SRP fluxes from exceeding critical levels, and must be robust in the face of potential changes in climate, land use and a myriad of other influences. To establish the longevity of these strategies it is therefore crucial to consider the sensitivity of catchments to multiple future stressors. This study evaluates how the water quality and hydrology of a major river system in the UK (the River Thames) respond to alterations in climate, land use and water resource allocations, and investigates how these changes impact the relative performance of management strategies over an 80-year period.

In the River Thames, the relative contributions of SRP from diffuse and point sources vary seasonally. Diffuse sources of SRP from agriculture dominate during periods of high runoff, and point sources during low flow periods. SRP concentrations rose under any future scenario which either increased a) surface runoff or b) the area of cultivated land. Under these conditions, SRP was sourced from agriculture, and the most effective single mitigation measures were those which addressed diffuse SRP sources. Conversely, where future scenarios reduced flow e.g. during winters of reservoir construction, the significance of point source inputs increased, and mitigation measures addressing these issues became more effective. In catchments with multiple point and diffuse sources of SRP, an all-encompassing effective mitigation approach is difficult to achieve with a single strategy. In order to attain maximum efficiency, multiple strategies might therefore be employed at different times and locations, to target the variable nature of dominant SRP sources and pathways.

1. Introduction

Phosphorus is fundamental to the ecological quality of river waters (Jarvie et al., 2002). The soluble reactive portion of phosphorus (SRP) plays a key role in eutrophication (Jarvie et al., 2006) which can decrease habitat quality and in-stream biodiversity (Cooper et al., 2002). SRP is therefore of global, national and European concern. Phosphorus (P) loads to rivers may be derived from both diffuse (e.g. agricultural) and point (e.g. sewage treatment works, STW) sources. Agricultural sources, which are applied to the catchment as fertiliser and delivered to rivers in a dissolved or particulate form through runoff following rainfall events, account for a significant proportion of nutrient loads in UK rivers, supplying over 45% of total P (Cooper et al., 2002). However,

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it is the *concentration* of this SRP during periods of ecological sensitivity that has the greatest influence upon ecological river quality (Jarvie et al., 2006).

Under the EU Water Framework Directive (WFD), a "phosphorus standard" has been developed by which river water quality might be judged to be in "high", "good", "moderate" or "poor" condition. In the River Thames, in the South East of England, eutrophication is a prominent concern. It has been observed along the main channel, and several tributaries (Lack, 1971; Young et al., 1999; Jarvie et al., 2006). The Thames has therefore been identified as having the potential to form the basis for developing national strategies on environmental management of eutrophication (Jarvie et al., 2002). It is a high alkalinity river (Neal et al., 2002), and target concentrations for good status are 0.12 mg P l^{-1} (WFD UKTAG, 2008). SRP concentrations within the Thames are currently only close to the "moderate" boundary (0.25 mg l^{-1} SRP), with an average SRP concentration of 0.26 mg l^{-1}, and peaks of 0.6 mg l^{-1}. However, as the Thames has been highly modified throughout its course, with artificial weirs used both for flood control and navigation, it is feasible that the EU may accept a "moderate" status for this catchment (WFD UKTAG, 2008).

From the 1930s (earliest UK Environment Agency records) to the 1990s, significant increases in nutrient concentrations within surface waters of the River Thames have been observed (Whitehead et al., 2002), attributed to increases in livestock numbers and fertiliser inputs (Ulén et al., 2007). Current projections suggest that over the next 100 years, due to rising population pressures and associated food scarcity, the percentage of land devoted to agriculture will rise (Gregory and Ingram, 2000), with significant implications for in-stream SRP concentrations. However, since the 1990s, under the Urban Waste Water Treatment Directive (UWWTD), a reduction in in-stream SRP concentration has been achieved (Young et al., 1999; Neal et al., 2010). The UWWTD specifies acceptable SRP concentrations for STWs discharging into rivers; 2 mg l^{-1} for STWs serving less than 100,000 people, or 1 mg l^{-1} for STW serving more than 100,000 (European Council Directive, 1991). It is feared however, that a changing climate may increase the sensitivity of the Thames to these inputs, with low rainfall and high evaporation intensifying summer baseflow extremes (Neal et al., 2002). With less dilution of STW effluent, SRP concentrations may begin to rise again, especially if the combined effects of increasing population pressures and drinking water abstraction are also taken into consideration (Neal et al., 2002).

To address the potential for future drought and associated problems of water quality and quantity in the Thames basin, Thames Water Authority recently proposed a "Water Resource Management Plan" to instal a reservoir at Abingdon, 79 km from the catchment headwaters (Thames Water, 2012). This would store water during episodes of higher flow in winter, and release it during low flow summer periods (Jin et al., 2012). Although the initial plan for a larger reservoir (100 million m^3) was rejected by the Secretary of State in May 2011, investigations into alternative water resource strategies, including a smaller 50 million m^3 reservoir continue.

Future climate, land use change, and water resource strategies clearly have significant implications for riverine phosphorus concentrations and water quality management practices. Under changing future conditions, currently successful strategies may fail to maintain EU WFD water quality standards. An understanding of the implications of these changes is therefore integral to the realization of sustainable remediation strategies for water quality issues throughout the UK, or for any catchment where long-term mitigation strategies for P-reduction are being considered (e.g. Lake Simcoe; Whitehead et al., 2011; Crossman et al., 2012). This study evaluates a) the response of water quality and flows in the River Thames to multiple external forcings including changes in climate, increasing agricultural land use, and the installation of a reservoir; b) the impacts of these forcings on the effectiveness of mitigation strategies c) the most effective way forward under an uncertain future. The study uses the following model chain to explore the possible effects of these forcings in the Thames catchment:

1) The LandSFACTS model is used to establish two land use change scenarios, based upon IPCC A2 predictions of population pressure and food scarcity.
2) The KNMI RCM climate model is used to simulate possible climate change in the Thames basin.
3) The HBV and the process-based INCA-P (Integrated Catchments Model of Phosphorus Dynamics; Wade et al., 2002) are combined to evaluate the dynamic behaviour of phosphorus in response to land use, climate change and water resource scenarios.

2. Methodology

2.1. The River Thames system

The River Thames is a major river in southern and south-eastern England, draining approximately 10,000 km^2. It supports around 14 million people (Gardiner et al., 1994), and is heavily farmed, with 35.5% of the catchment used for intensive agriculture. The river is sourced at Cricklade in the Cotswold Hills of Gloucestershire, with a freshwater boundary downstream at Teddington (Fig. 1), below which it discharges into the North Sea. The bedrock varies from high permeability chalk, to low permeability clays (Neale et al., 2006). Mean annual precipitation between 2001 and 2008 was 716.9 mm and mean daily temperature 11.1 °C. Flow in the Thames varies considerably throughout the year, with high flows in winter from October to February of 82.3 $m^3 s^{-1}$ (50th percentile) and lower flows in summer from March to September of 42.2 $m^3 s^{-1}$ (50th percentile). Eight years of flow and water quality data, collected along the Thames by the Environment Agency, are used for model calibration and validation in this study.

2.2. Dynamic modelling of phosphorus using INCA-P

INCA has been applied in over 40 catchments across the UK and EU. It is a dynamic, process-based model, using a semi-distributed approach to simulate the flow of water and nutrients through the terrestrial system (plants, soils) to river reaches, differentiated by land use type. Daily estimates of reach discharge, in-stream total P, total dissolved phosphorus (TDP) soluble reactive phosphorus (SRP), and suspended sediment, are calculated by taking into account the inputs of phosphorus from diffuse inputs, sewage treatment works (STW), sediment interactions and biological processes (Wade et al., 2002, 2007). Information flows through the model from the individual process equations, through the sub-catchment comprised of 6 land use types, up to a network of multiple reaches and tributaries. A mass balance is imposed at all sub-catchment and river reach boundaries, operating on multiple scales: the cell level for each individual land use, the sub-catchment level for multiple land use inputs and transport of nutrient fluxes along reaches, and at the network scale for total loads from all sub-catchments (Whitehead et al., 2011).

INCA-P requires an input time series of precipitation, temperature, hydrologically effective rainfall (HER) and soil moisture deficit (SMD). The latter two are estimated using the HBV (Hydrologiska Byråns Vattenbalansavdelningen) conceptual rainfall–runoff model (Oni et al., 2010). There are four main storage components within the HBV model; snow, soil moisture, and an upper and lower runoff zone. Simplified mathematical expressions representing the underlying physical processes including evaporation rates and snowmelt dynamics route precipitation within and between these four zones (Oni et al., 2010). During the calibration process, parameter values are adjusted within a recommended range (Lawrence et al., 2009) so as to attain a best fit with observed daily stream flow values, using the Nash Sutcliffe Co-efficient, R^2, and Relative Mean Squared