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# Distributed and dynamic modelling of hydrology, phosphorus and ecology in the Hampshire Avon and Blashford Lakes: Evaluating alternative strategies to meet WFD standards

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## HIGHLIGHTS

- Model phosphorus impacts on river phosphorus concentrations in the Hampshire Avon.
- Examine the effectiveness of mitigation policies for P control.
- P sources in the river are sourced equally from agriculture and from STWs.
- P removal from both agricultural sources and STWs are required to meet the WFD.

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## ABSTRACT

The issues of diffuse and point source phosphorus (P) pollution in the Hampshire Avon and Blashford Lakes are explored using a catchment model of the river system. A multibranch, process based, dynamic water quality model (INCA-P) has been applied to the whole river system to simulate water fluxes, total phosphorus (TP) and soluble reactive phosphorus (SRP) concentrations and ecology. The model has been used to assess impacts of both agricultural runoff and point sources from waste water treatment plants (WWTPs) on water quality. The results show that agriculture contributes approximately 40% of the phosphorus load and point sources the other 60% of the load in this catchment. A set of scenarios have been investigated to assess the impacts of alternative phosphorus reduction strategies and it is shown that a combined strategy of agricultural phosphorus reduction through either fertiliser reductions or better phosphorus management together with improved treatment at WWTPs would reduce the SRP concentrations in the river to acceptable levels to meet the EU Water Framework Directive (WFD) requirements. A seasonal strategy for WWTP phosphorus reductions would achieve significant benefits at reduced cost.

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## 1. Introduction

In Europe, legislation including the Water Framework (WFD), Urban Wastewater Treatment (UWWTD) and Habitats Directives set objectives for wastewater treatment and water quality standards with respect to phosphorus (P). The current regulatory environment poses as a major challenge to the water sector in the UK. Approximately 1000 waste water treatment plants (WWTPs) are predicted to be causing downstream exceedences of Environmental Quality Standards (EQSs) as specified under the WFD (Comber et al., 2009). This prediction does not take into account the impacts of upstream inputs, such as from agriculture, or other WWTPs. With approximately 700 WWTPs in the UK planning or already implementing measures to reduce P loads to vulnerable water bodies it is imperative that an accurate assessment of best management practises is made.

It has become apparent that a catchment-based approach is required to improve water quality and ecological status using a combination of measures to reduce agricultural and wastewater derived inputs, including consideration of options such as seasonal-based permitting of P

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discharges from WWTPs. Currently water companies are obliged to meet annual average targets of typically 1 or 2 mg/l of total phosphorus (TP) all year round, depending on the size of a WWTP and sensitivity of the receiving water. However, a more beneficial ecological outcome may be derived from applying tighter permits during summer months when biological activity is at its highest, then allow a more relaxed permit during the winter when higher flows and lower productivity ensure that the impacts of P derived from WWTPs would be significantly reduced.

In this paper we assess the hydrology and water quality of the Hampshire Avon, using the model INCA-P (Wade et al., 2002a; Whitehead et al., 2011). By simulating the phosphorus balances throughout the catchment and applying a series of management strategies, we aim to quantify the effects of alternative control measures such as P removal at WWTPs or P reductions from agricultural sources. Phosphorus budgets and mitigation measures have been investigated from a field data perspective or an export coefficient approach by many lead researchers such as Sharpley et al. (1994), Jarvie et al. (2002, 2006), Johnes and Butterfield (2003), Neal and Jarvie (2005), Neal et al. (2010, 2006) and Zhang et al. (2012), but in this study we utilise a process based dynamic model, which allows a more complete mass balance and an assessment of the dynamic interactions within the catchment.

## 2. The Hampshire Avon

The Hampshire Avon lies within the counties of Dorset, Hampshire and Wiltshire and has a catchment area of approximately 1750 km$^2$ (Fig. 1). It is largely a spring fed, groundwater dominated river giving relatively stable base flow throughout the year. The majority of the river is designated as a Site of Special Scientific Interest (SSSI); it has also been declared as a Special Area of Conservation (SAC) under the European Union (EU) Habitats Directive. Parts of the catchment lie within Areas of Outstanding Natural Beauty (AONB), areas of high scenic quality that have statutory protection in order to conserve and enhance the ecology of the river system. Many of the SSSI units are currently judged to be in an unfavourable condition mainly due to adverse nutrient levels, particularly phosphates, and reduced flows either from abstraction or historic land drainage and channel modifications. Currently only 30% of water bodies in the catchment are considered to be in a good ecological condition (Environment Agency, 2011). Soluble reactive phosphorus concentrations exceeding the Environmental Quality Standard (0.12 mg-P/l) are a major source of water body classification not reaching good status in the Avon. Concentrations exceeding the EQS for ‘good’ status are observed sporadically along the length of the catchment and values generally exceed the value for ‘high’ status (0.05 mg-SRP/l) which a river that is classified as a SAC should be seeking to achieve.

### 2.1. Geology

The Hampshire Avon, although predominantly a Chalk catchment, has a varied geology. Much of the upper catchment is underlain by the Chalk of Salisbury Plain. But elsewhere older formations such as the Upper Greensand, Gault, Lower Greensand, Wealden clay and the Purbeck and Portland limestones are exposed. In other places tertiary deposits such as the London clay, Poole formation, Branksome sand and Barton group all overlie the Chalk. Also, river terrace deposits and alluvium are present in the Avon valley south of Salisbury. Except for some areas in the New Forest, the river is largely spring-fed with the Chalk strata providing a large storage capacity and relatively stable base flow throughout the year. The Chalk and Upper Greensand are classified under the Environment Agency (EA) Policy and Practice for the Protection of Groundwater as highly vulnerable major aquifers,

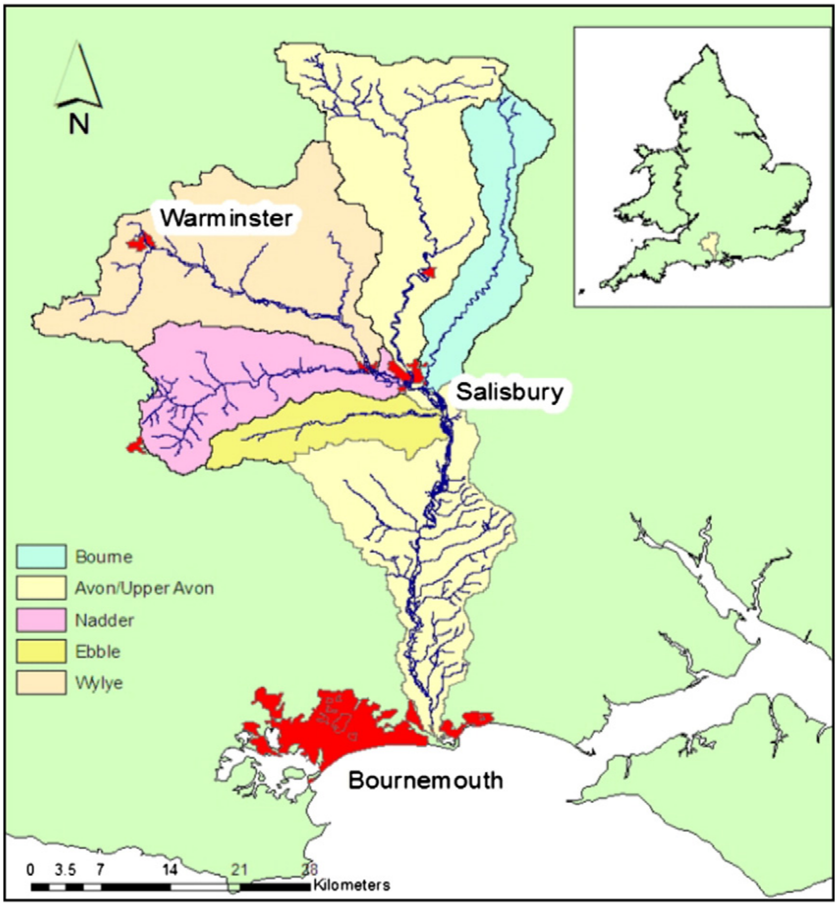

**Fig. 1.** River Avon, Hampshire showing the main tributaries and towns.

providing an important resource for potable, industrial and agricultural supply.

### 2.2. Hydrology

Annual average rainfall in the catchment varies from 700 to 800 mm at the coast to more than 900 mm over the western tributaries of the Nadder and Wylye. The 1961–1990 annual average rainfall for the Avon catchment as a whole was 810 mm, compared to 920 mm for England and Wales. Hydrological differences are observed across the catchment, reflecting the different geologies. The proportion of infiltration which discharges as quick flow is the highest in the Nadder catchment, the headwaters of the Wylye and East Avon catchments, and the streams draining the New Forest. The baseflow indices (BFIs) at gauging stations in the catchment range from 0.70 on the Nadder at Wardour, which drains predominantly Upper Greensand with Chalk and Gault, to 0.92 on the Bourne at Laverstock which drains a permeable Chalk catchment. Thus the underlying and near surface geology does have a significant control on water transfer pathways and hence nutrient processes. There are 12 EA flow gauging stations along the length of the river (Marsh and Hannaford, 2008) and over 30 water quality monitoring stations (Fig. 2) and details of these stations are available from the EA.

### 2.3. Land use

The catchment is predominantly rural in character, with approximately 75% of the land farmed or used for agriculture, as shown in Fig. 3. The area supports a population of over 200,000 people, approximately 60% of which live in the larger towns of Amesbury, Christchurch, Fordingbridge, Pewsey, Ringwood, Salisbury and Warminster. The area is heavily influenced by military activities, with several large military

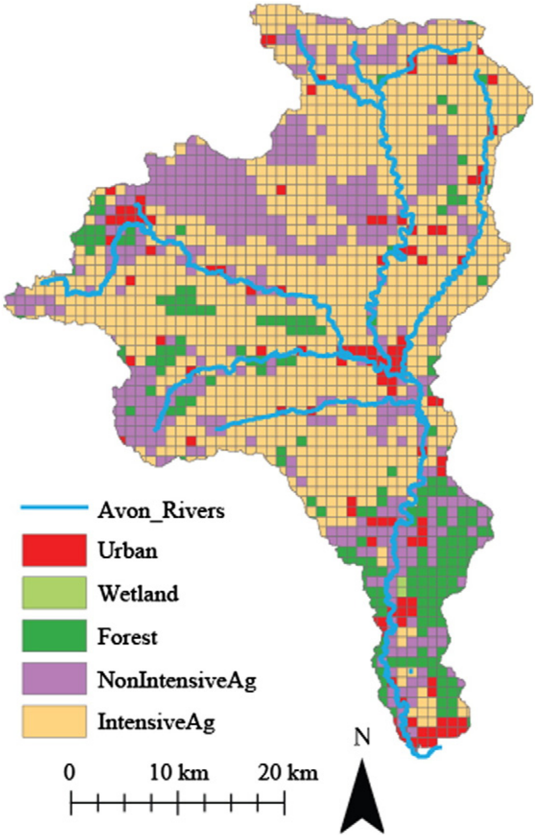

**Fig. 3.** Land use across the Hampshire Avon catchment.

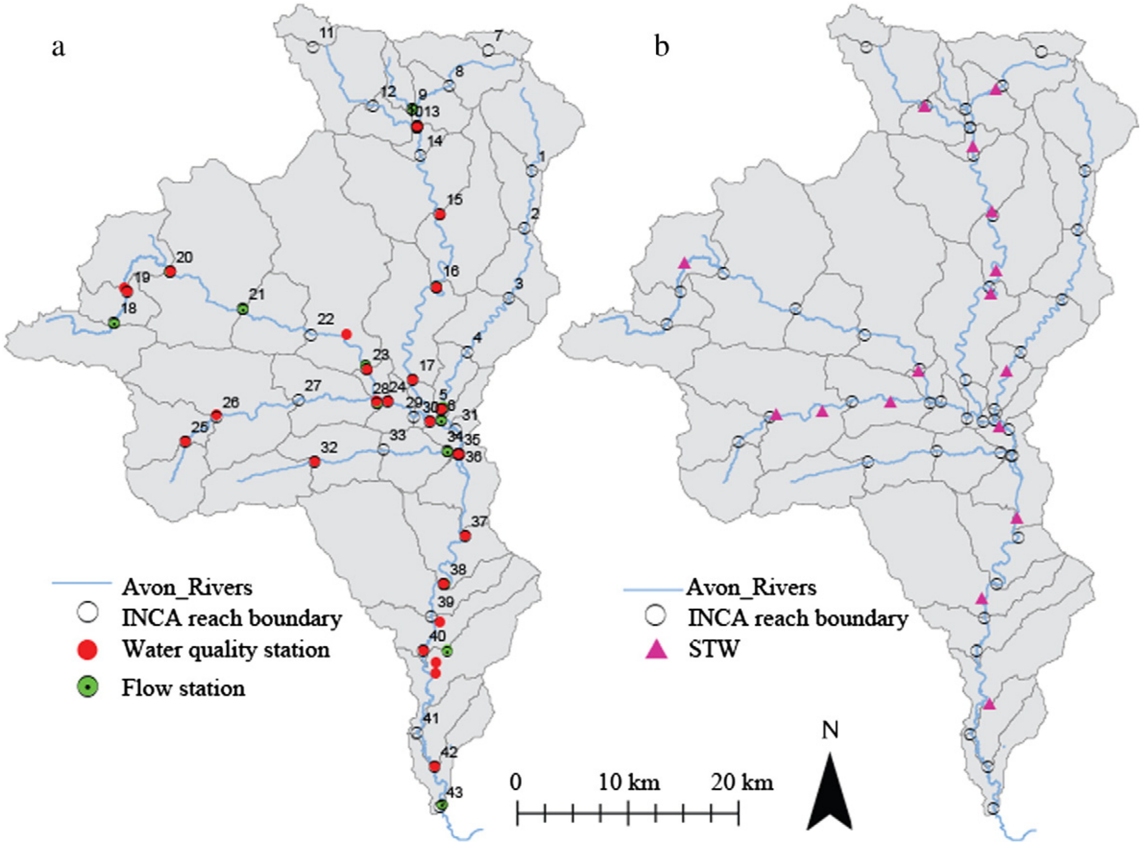

**Fig. 2.** Hampshire Avon flow and water quality monitoring stations, sewage treatment works and INCA-P reach boundaries.

bases mainly concentrated on and around Salisbury Plain. Other industrial activities are mostly light and located within the towns. Agriculture in the catchment is diverse with cereal, cattle and sheep farming identified as the predominant activities. Arable land is predominantly located in the upper catchment and grassland in the valleys and lower catchment. The upper catchment is farmed more intensively than the Lower Avon, large parts of which are still managed on an extensive grazing system (Johnes and Butterfield, 2003). The catchment retains a relatively high proportion of semi-natural habitats in the form of woodland, scrub and marsh.

### *2.4. Current management issues*

There are a number of management pressures on the catchment both in terms of water quality and quantity. Abstractions for public water supplies are from both ground and surface waters in the Hampshire Avon catchment. In some areas, particularly in the upper reaches of the catchment, groundwater abstraction contributes to the risk of unacceptably low flows in rivers during the summer months. Under drought conditions the river bed can dry out with all the loss of ecology that this implies or flows can become very low such that the low dilution results in high P concentrations downstream of sewage treatment works. Agricultural land and farming activities contribute nitrate, phosphorus and sediment to surface and/or ground waters in the river, with P application rates of the order of 23 kg/ha (DEFRA, 2010a,b). Rivers in the catchment receive treated domestic effluent from 12 large municipal sewage works. There are also a significant number of single dwelling or small community discharges via on-site wastewater treatment works or septic tanks within the area, some of which are consented, but many of which comprise septic tank systems which in many cases, are prone to hydraulic failure due to the insertion on impermeable soils and/or poor maintenance. Fish farming and watercress activities also contribute phosphorus loads to the river system.

### *2.5. Current activities in the Hampshire Avon*

A number of activities and research projects are currently being undertaken across the catchment. These include:

1. The whole catchment is a sentinel Department of Environment, Food and Rural Affairs (DEFRA) Demonstration Test Catchment (DTC) setup that assesses the effectiveness of on-farm mitigation measures for reducing diffuse pollution from agriculture to water and its impacts on aquatic ecology, in the context of maintaining a thriving agricultural sector;
2. It also forms part of the 'The Catchment Sensitive Farming Initiative' (CSF) which aims to identify ways to reduce diffuse water pollution from agriculture using targeted on-farm advice and voluntary works, together with some capital funded items such as those targeting farm infrastructure upgrades (DEFRA, 2010a,b);
3. Currently 13 water quality and flow related scientific studies are being conducted in the catchment; these are all documented in Annex 3 of the Avon catchment appraisal study produced by DEFRA (see http://www.avondtc.org.uk/);
4. The Natural Environment Research Council (NERC) funded Macronutrients Cycles Programme has selected the Avon as a core project catchment (see http://macronutrient-cycles.ouce.ox.ac.uk/index.html);
5. In addition to these special studies there is an on-going programme of monitoring undertaken by the EA and Wessex Water. Fig. 2 shows the location of flow gauging stations, water quality monitoring sites and WWTPs. Table 1 lists a set of reaches which utilise these locations as reach boundaries;
6. Tables 2 and 3 show the range of data utilised in the modelling study and the sources of these data.

## 3. The INCA-P model

The INCA model has been developed over many years as part of NERC and EU funded projects (Whitehead et al., 1998a,b). The INCA-P version of the model is process based and simulates the dynamic behaviour of river systems (Wade et al., 2002a,b,c). INCA-P simulates flow pathways and tracks fluxes of solutes/pollutants on a daily time step in both terrestrial and aquatic portions of catchments. The model system allows the user to specify the spatial nature of a river basin or catchment, to alter reach lengths, rate coefficients, land use and velocity–flow relationships and to vary input pollutant deposition loads. INCA-P originally allowed the simulation of a single stem of a river in a semi-distributed manner, with tributaries treated as aggregated inputs. The revised version now simulates phosphorus dynamics in dendritic stream networks as in the case of the Hampshire Avon which has 5 main tributaries (Whitehead et al., 2011).

There are three levels to the model structure, from a cell containing the soil processes, to the land use scale (up to six land uses), then to the sub-catchment level with multiple reaches (Wade et al., 2002a) and finally to the multi-branch setup (Whitehead et al., 2011). As a result, both P retention and transformation are better simulated in the new version. Point sources can be added directly into the main river system or into any of the sub-catchments. The model is based on a series of interconnected differential equations that are solved using a numerical integration method based on the fourth-order Runge–Kutta technique (Wade et al., 2002a). The advantage of this technique is that it allows all equations to be solved simultaneously. Fig. 4 shows the main flow paths and processes in INCA-P. The model performs a mass balance for the catchment, accounting for all inputs and outputs, with a daily time step. It also accounts for reaction kinetics, nutrient recycling, exchange with the sediments plus sediment diagenesis. Details about the process equations are described in Wade et al. (2002a, 2009) and the multi-branch version used in this study is described in Whitehead et al. (2011).

The INCA-P model also has equations for modelling macrophytes and epiphytes (Wade et al., 2002b) and this provides another test of the model. Process equations model the interactions between macrophytes and epiphytes using growth and death rates and during macrophyte growth. This phosphorus is returned to the river in the form of particulate phosphorus (PP), following the death of macrophytes.

### *3.1. INCA-P model application to the Hampshire Avon*

The INCA-P has been set up for the whole of the Hampshire Avon using the reach structure shown in Fig. 2 and Table 1, so that each main tributary is simulated individually. In addition, the model has been set up to incorporate all of the WWTPs in the Hampshire Avon and a list of these is shown in Table 2. Table 3 shows the type and sources of data utilised in the INCA modelling study.

Extensive INCA-P model calibration and validation exercises have been undertaken and satisfactory model fits have been obtained using daily input meteorological data to drive the model and comparing model outputs against observed streamflow and water quality data. There are many aspects to calibration to consider and it is necessary to first ensure that a reasonable representation of the catchment's hydrology is obtained. The model integrates the water flows down the catchment so that a full mass balance is achieved down the catchment. The simulated and observed river discharge for the Avon at the reach below Salisbury (reach 37) for eight years from 01/01/2002 to 31/12/2009 showed good agreement, as indicated in Fig. 5 with an $R^2$ of 0.75 and a Nash–Sutcliffe efficiency coefficient of 0.65. Hydrograph peaks are of similar magnitude and aligned. The recession component of the hydrograph is simulated well and even low flow conditions are well represented. The model fit to 12 other flow gauging stations is given in Table 4.

Given the complexity of the Hampshire Avon with five major tributaries and differing geologies across the catchment, the INCA model validates well with respect to hydrology. The water quality system is

**Table 1**
Hampshire Avon river reaches, and associated areas, lengths and land use. Intensive agriculture is arable land or permanent crops. Non-intensive agriculture is mostly natural grassland.

| Reach | River | Area (km$^2$) | Reach length (m) | Land use (%) | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | Urban | Intensive agriculture | Non-intensive agriculture | Wetlands | Forest |
| 1 | Bourne | 51.2 | 28,535 | 14.3 | 54.1 | 22.6 | 0.2 | 8.8 |
| 2 | Bourne | 26.2 | 26,144 | 12.0 | 42.3 | 34.7 | 0.2 | 10.9 |
| 3 | Bourne | 33.9 | 26,144 | 11.4 | 51.2 | 29.9 | 0.2 | 7.3 |
| 4 | Bourne | 37.9 | 33,984 | 14.1 | 51.8 | 29.8 | 0.2 | 4.1 |
| 5 | Bourne | 16.2 | 11,238 | 27.4 | 43.1 | 26.5 | 0.4 | 2.5 |
| 6 | Bourne | 0.9 | 3357 | 44.4 | 21.7 | 22.4 | 1.0 | 10.5 |
| 7 | Avon | 9.6 | 3772 | 11.1 | 45.0 | 32.1 | 0.3 | 11.5 |
| 8 | Avon | 41.1 | 9937 | 15.4 | 46.7 | 31.9 | 0.5 | 5.4 |
| 9 | Avon | 12.1 | 7038 | 11.6 | 43.8 | 36.6 | 0.8 | 7.2 |
| 10 | Avon | 23.1 | 16,528 | 14.4 | 47.9 | 29.6 | 0.9 | 7.2 |
| 11 | West Avon | 12.9 | 1962 | 16.1 | 54.5 | 27.0 | 0.2 | 2.2 |
| 12 | West Avon | 53.5 | 15,357 | 16.9 | 46.1 | 33.0 | 0.5 | 3.4 |
| 13 | West Avon | 18.2 | 7089 | 14.0 | 57.3 | 24.4 | 0.6 | 3.8 |
| 14 | Avon | 8.2 | 4099 | 12.7 | 58.9 | 24.8 | 0.9 | 2.7 |
| 15 | Avon | 78.0 | 11,696 | 6.5 | 51.1 | 40.1 | 0.3 | 2.0 |
| 16 | Avon | 69.8 | 13,706 | 12.0 | 39.0 | 40.6 | 0.5 | 7.9 |
| 17 | Avon | 68.9 | 16,978 | 14.6 | 48.5 | 32.6 | 0.6 | 3.6 |
| 18 | Wylye | 50.1 | 24,238 | 6.8 | 50.4 | 35.5 | 0.2 | 7.2 |
| 19 | Wylye | 21.9 | 17,484 | 10.0 | 38.8 | 40.0 | 0.2 | 10.8 |
| 20 | Wylye | 41.9 | 24,258 | 16.6 | 24.0 | 37.7 | 0.6 | 21.1 |
| 21 | Wylye | 140.5 | 12,834 | 7.7 | 35.2 | 48.3 | 0.1 | 8.6 |
| 22 | Wylye | 38.8 | 8716 | 11.5 | 50.2 | 32.6 | 0.3 | 5.4 |
| 23 | Wylye | 156.0 | 9413 | 8.7 | 42.2 | 43.0 | 0.2 | 5.9 |
| 24 | Wylye | 8.5 | 4713 | 19.9 | 47.9 | 19.4 | 0.6 | 12.3 |
| 25 | Nadder | 34.1 | 4559 | 9.6 | 25.3 | 50.0 | 0.6 | 14.5 |
| 26 | Nadder | 36.4 | 5646 | 7.3 | 20.3 | 51.8 | 0.8 | 19.8 |
| 27 | Nadder | 101.0 | 11,270 | 9.3 | 46.1 | 27.3 | 0.5 | 16.9 |
| 28 | Nadder | 44.0 | 13,575 | 10.6 | 47.1 | 20.3 | 0.2 | 21.8 |
| 29 | Nadder | 14.1 | 7226 | 23.6 | 42.3 | 22.3 | 0.7 | 11.1 |
| 30 | Avon | 6.9 | 9988 | 53.4 | 21.4 | 18.4 | 1.5 | 5.4 |
| 31 | Avon | 0.0 | 3357 | 68.9 | 4.2 | 9.7 | 2.8 | 14.5 |
| 32 | Ebble | 41.1 | 7789 | 8.7 | 54.5 | 31.6 | 0.1 | 5.1 |
| 33 | Ebble | 39.9 | 8133 | 9.4 | 58.4 | 27.0 | 0.2 | 5.1 |
| 34 | Ebble | 26.8 | 8725 | 14.4 | 42.9 | 37.2 | 0.3 | 5.2 |
| 35 | Ebble | 0.3 | 1686 | 8.9 | 17.2 | 49.4 | 2.6 | 21.8 |
| 36 | Avon | 16.1 | 9846 | 23.9 | 25.5 | 34.7 | 1.1 | 14.8 |
| 37 | Avon | 37.7 | 19,864 | 14.2 | 35.5 | 34.4 | 1.0 | 14.9 |
| 38 | Avon | 42.8 | 12,472 | 12.3 | 24.1 | 40.4 | 1.1 | 22.1 |
| 39 | Avon | 111.0 | 5140 | 10.7 | 37.1 | 34.2 | 0.5 | 17.6 |
| 40 | Avon | 41.0 | 7975 | 7.3 | 6.2 | 43.6 | 1.7 | 41.1 |
| 41 | Avon | 52.8 | 14,573 | 11.1 | 4.1 | 35.4 | 2.4 | 46.9 |
| 42 | Avon | 20.9 | 8301 | 10.5 | 15.2 | 41.9 | 1.4 | 31.0 |
| 43 | Avon | 26.8 | 15,156 | 12.5 | 10.0 | 42.1 | 1.2 | 34.3 |

always more difficult to model due to the complexity of mixing P from different diffuse and point sources, chemical water column chemistry, bed sediment interactions and the effects of plant growth and algal behaviour affecting P balances (Fig. 4). Fig. 5 indicates that over the 8 year period the fit to the observed data is good for both TP and SRP and this is demonstrated in Fig. 6 which shows the simulated and observed monthly loads at the tidal limit (reach 43). The R$^2$ value of 0.91 indicates that the model is capturing the key flux behaviour of the catchments.

**Table 2**
WWTW flow and SRP discharge data between 2000 and 2010.

| WWTW location | River | Average effluent SRP (mg/l) | Average effluent flow (m$^3$/s) |
|---|---|---|---|
| Amesbury | Avon | 1.68 | 0.01 |
| Downton | Avon | 4.19 | 0.03 |
| Fordingbridge | Avon | 3.47 | 0.03 |
| Netheravon | Avon | 1.68 | 0.01 |
| Pewsey | Avon | 0.57 | 0.02 |
| Ratfyn | Avon | 0.73 | 0.03 |
| Ringwood | Bickerley Stream | 2.76 | 0.05 |
| Salisbury | Avon | 1.17 | 0.25 |
| Tisbury | Nadder | 2.25 | 0.01 |
| Upavon | Avon | 3.50 | 0.01 |
| Warminster | Wylye | 3.28 | 0.02 |
| Fovant | Fovant Brook | 2.72 | 0.01 |
| Great Wishford | Wylye | 4.84 | 0.005 |
| Hurdcott | Bourne | 0.65 (TP) | 0.04 |
| Barford | Nadder | 3.25 | 0.001 |
| Marden | Avon | 5.31 | 0.003 |

The modelling of macrophytes was also assessed in the model calibration phase. Macrophyte samples were taken at three sites along the River Avon, Spaniel's Bridge on the West branch of the Avon, Pewsey on the East branch, and the Upper Avon where the East and West branches converge. Samples were taken at 6 monthly intervals, in May and September, from 2005 to 2007. At each site a total of 20 quadrats were taken (a series of five individual transects, each consisting of four 50 cm$^2$ quadrats). Within these quadrats all macrophytes were counted, and subsequently analysed for both wet and dry weights (Flynn et al., 2002). For each sampling date, the average dry matter per m$^2$ was calculated by summing the total dry weight of all macrophytes within each 50 cm$^2$ quadrat, converting to m$^2$, and calculating the mean value between the 20 quadrats. Dry mass per m$^2$ was finally converted to biomass g/C m$^2$ using the conversion factor of 0.268, as determined by Hannu and Karlsson (2006), which was established specifically for primary producing macrophytes. This empirical data was then used for the calibration of modelled data within INCA-P. Due to the limited data available for a relatively short stretch of the river the results are speculative. However they are calibrated to within a reasonable degree of accuracy (within +/−1 standard deviation) as illustrated in Fig. 7.

**Table 3**
Data sources for the Avon modelling study.

| Data | Description | Source |
|---|---|---|
| Observed water chemistry | | |
| TP, SRP, SS | Routine sampling (2–4 times per month) | Environment Agency |
| Hydrological inputs, observed data | | |
| Precipitation and temperature | Daily time series | Met office |
| Discharge | Daily time series | Environment Agency |
| Base flow index | CEH base flow index estimates based on flow gauging data | CEH Hydrometric Register (Marsh and Hannaford, 2008) |
| SMD and HER | daily time series | Met office |
| Land use data, and P inputs | | |
| Land use data | Ecological land classification and land use classifications GIS layer | LCM2000 land coverage map (Centre for Ecology and Hydrology) |
| P inputs to non-intensive agriculture | Grazing inputs | Cattle, pig and sheep populations (DEFRA) combined with associated P input rates (Johnes and Butterfield, 2003) |
| P inputs to intensive agriculture | Fertiliser inputs | DEFRA farm statistics |

## 4. Scenario analysis

The very useful aspect of the INCA model is the ability to undertake scenario analysis in order to evaluate the effects of different management strategies on the catchment water quality. The model can also be used to assess the relative contributions of diffuse sources of P and point sources. This is important so that WWTP effluent control strategies can be placed in context and evaluated against the agricultural diffuse sources of phosphorus. Initially the model has been used to evaluate the effects of changing farming practises on instream P. Fig. 8 illustrates the effects of reducing fertiliser applications by 30% on instream water quality. Such a strategy generates significantly lower concentrations of TP and SRP, with instream reductions of 37% and 40%, respectively, downstream of Salisbury. These reductions are quite large suggesting that an agricultural strategy to reduce P fertiliser use should contribute significantly to the reduction of P concentrations in the river system. Furthermore, these reductions ensure that SRP levels meet the EQS for ‘good’ status under the WFD and in many places achieve ‘high’ status (<0.05 mg-SRP/l) which a catchment of such a high designation should be aiming to achieve.

The results of the INCA-P modelling at catchment scale, which suggest that there is a scope for improving the P water quality of the river using on-farm mitigation are complementary to those recently reported as part of the DTC project by Zhang et al. (2012). This work specifically focussed on farm scale planning and the scope for reducing pollutant emissions using mitigation measures currently available in agri-

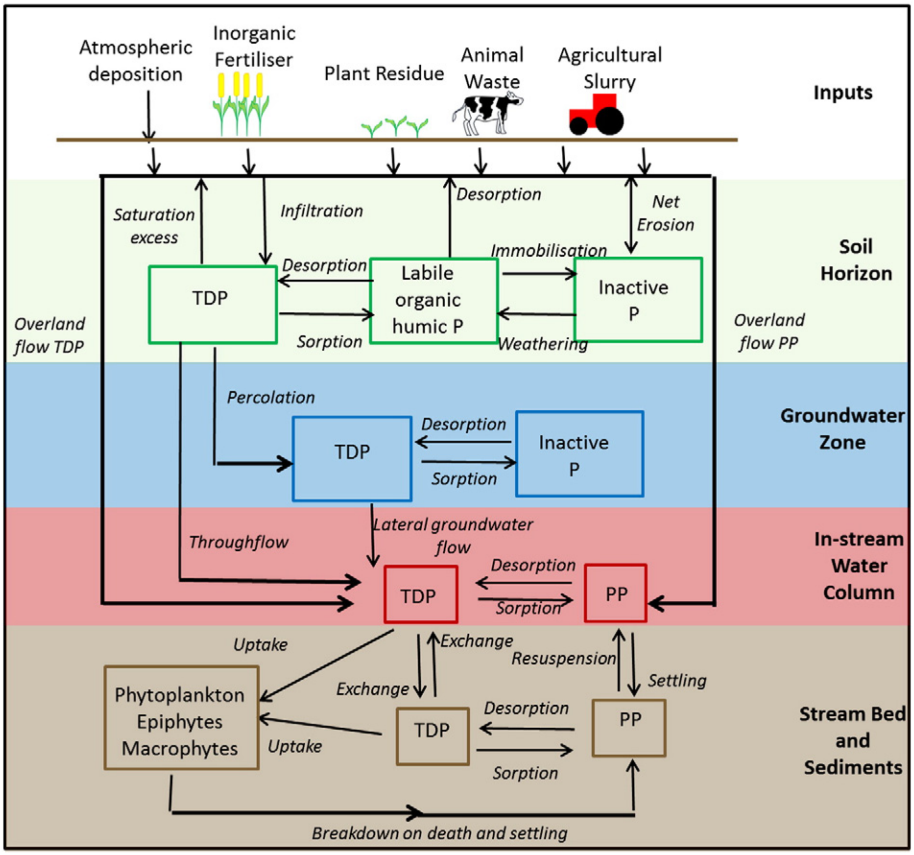

**Fig. 4.** The INCA-P model process pathways.
After Crossman et al. (2012).

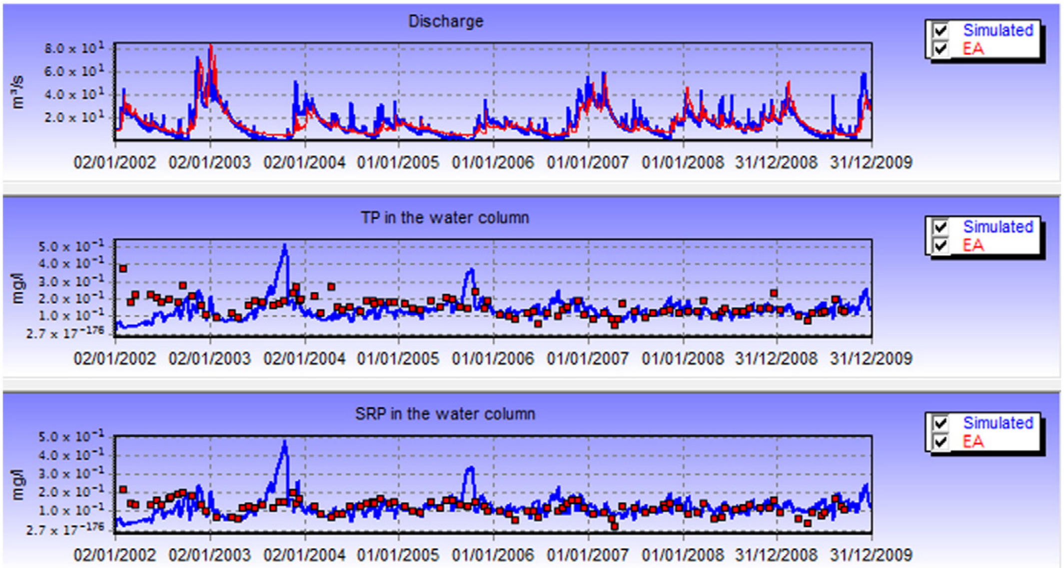

**Fig. 5.** Simulated and observed flow, TP and SRP for the River Avon at Salisbury 2002–2009 (reach 37).

environment schemes or alternative initiatives such as CSF. The farm scale modelling work was undertaken using the new FARMSCOPER (Farm Scale Optimisation of Pollutant Reductions) decision support tool (Zhang et al., 2012). Whilst the FARMSCOPER scenario analysis suggested that the current reduction in diffuse P inputs from agriculture due to the current implementation of best practise is small (~10%), relative to a baseline with no mitigation measures, reductions of up to 47% could be achieved on mixed farms through the application of additional measures with significant costs and up to 44% through the implementation of groups of measures under a cost-neutral umbrella.

### 4.1. WWTP management options

In order to evaluate the effects of a range of management options for point source effluent treatment, a set of scenarios have been evaluated with model results presented at four locations along the river system. The four locations are upstream of Salisbury on the Avon, downstream of Salisbury, the river adjacent to Blashford Lakes (reach 41, Fig. 2) and at the outlet of the catchment at the tidal interface (reach 43, Fig. 2). In addition to the baseline simulation, which uses EA measured TP at the WWTPs, three scenarios were evaluated, as follows:

1) Treating all wastewater effluents in the catchment to a 1 mg/l TP standard (currently considered the best achievable effluent quality using current technology);
2) Treating wastewater to 0.3 mg/l TP, as is currently being undertaken at Warminster (based on optimised treatment);
3) Treatment based on a seasonally changing standard with treatment at 1 mg/l in winter and treatment at the higher 0.3 mg/l level in summer months.

Table 5 shows the effects of the different management options for simulated mean TP and SRP concentrations with the percentage reductions in Table 6. The effect is cumulative downstream as the reductions progressively improve the water quality. The effects of the different levels of treatment can be compared to the current discharges and, as shown in Tables 5 and 6, all treatments improve the water quality. P concentrations can be compared against the WFD targets for streams and, as shown in Table 7, the target for a high calcium stream such as the Hampshire Avon is 0.12 mg/l of SRP for a good ecological status and 0.05 mg/l SRP for a high status. At present the river below Salisbury is of good status and the EA management aim is to get to a higher status, with a target of 0.05 SRP mg/l. Table 5 shows that the 1 mg/l discharge level from the WWTPs would achieve significant improvements in SRP and create a 20% reduction in SRP downstream of Salisbury (Table 6). The higher Warminster standard would increase this reduction to 26% and achieve close to the WFD standard.

**Table 4**
Flow model fit statistics for a range of gauges in the Hampshire Avon catchment.

| River flow gauging station and reach | $R^2$ |
|---|---|
| Avon 14 | 0.725 |
| Avon 16 | 0.723 |
| Avon 38 | 0.745 |
| Avon 43 | 0.746 |
| Ebble 34 | 0.639 |
| Wylye 18 | 0.67 |
| Wylye 20 | 0.78 |
| Wylye 21 | 0.713 |
| Wylye 23 | 0.674 |
| Nadder 28 | 0.799 |
| Bourne 05 | 0.559 |
| Bourne 06 | 0.613 |

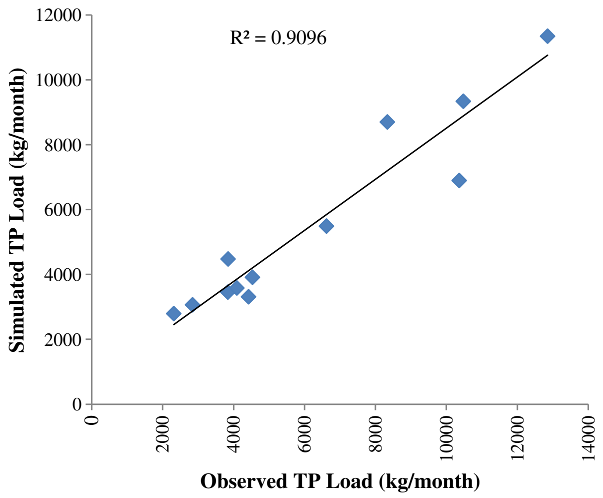

**Fig. 6.** Simulated and observed monthly phosphorus load at tidal limit (reach 43).

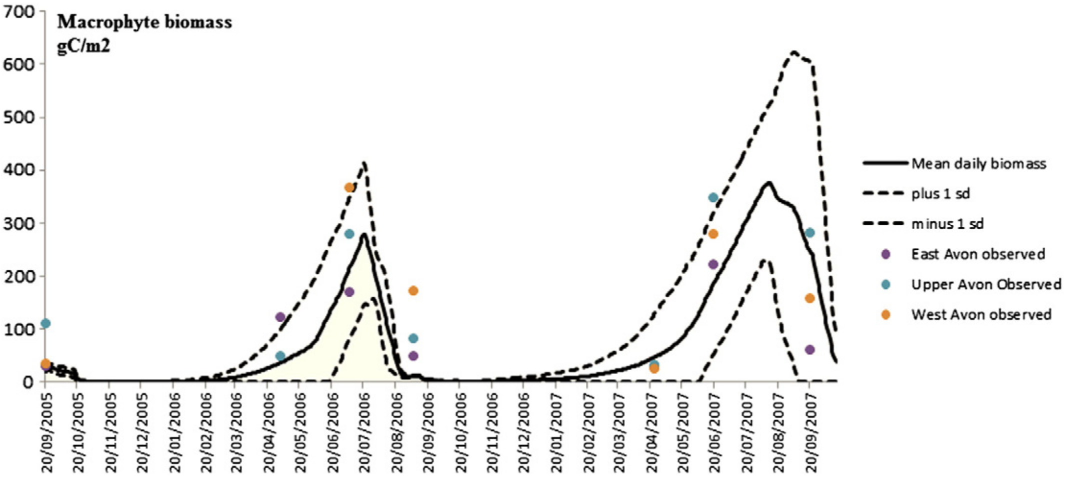

**Fig. 7.** Modelling macrophytes in the Upper Avon.

### 4.2. Seasonal standards

The third approach is to make use of the knowledge that flows and, hence dilution, varies throughout the year and therefore a seasonal standard at the WWTPs might offer a viable and cost saving measure which would improve stream ecology in summer months. This is considered, assuming that in winter months (e.g. October to March) the WWTP standard is set to the 2 mg/l standard and during summer months, the standard is set to the Warminster high quality standard of 0.3 mg/l. The effects on the annual mean concentrations are shown in Tables 5 and 6, demonstrating that it would still be possible to get close to the WFD standard on average. The initial assessment of these results indicates that seasonal effects offer some improvement.

## 5. Modelling Blashford Lakes

Blashford Lakes are located at the lower end of the River Avon, south of Salisbury and at reach 41 in Fig. 2. The lakes are used intermittently by Wessex Water for storage of water abstracted from the River Avon before treatment and are known to suffer from eutrophication problems. Thus the effects of alternative treatment strategies and the impact on Blashford Lakes' water quality are of interest.

Due to the relatively more stable nature of lake environments, the behaviour of the phosphorus in lakes differs to that in rivers. The "trapping" of influent P, by chemical or biological adsorption processes, and the lower potential for P to be flushed out of lake systems can cause accumulation in biota and sediments over a long period of time. This may lead to increased internal loading of P which in turn may have implications on productivity and the trophic status of the lake (Chapra, 2008). The associated increase in productivity from increased P concentrations can be directed towards macrophytes or phytoplankton; P dynamics will vary dependent on what is dominant in the lake system. The relationship between P and lake trophic status is well established and uses empirical relationships between P and chlorophyll-a (Dillon and Rigler, 1974). It is important to note however, that the relationship is not a reliable causal predictor of eutrophication problems or reference state especially where P is not limiting. The nature of the input of P to lake systems is also important; if the received P is dominated by dissolved fractions these will be available for algal uptake, whereas particulate forms are less directly available. Particulate inputs will be subject to recycling processes influenced by the chemical nature of the particulate material.

In order to assess the impacts of management changes on Blashford Lakes the INCA-P model output time series were extracted for the reach 41 at Ellingham, adjacent to the lakes, and fed into a separate lake model (integrated lake and catchment model; Daldorph et al., 2001). The model takes into account lake volume and surface area, quantities of water pumped from the River Avon to the lakes and information on the operation of the lakes. The baseline simulation run and the two scenarios considered for the main river have been fed through the Lake model and the concentrations and percentage change in average SRP and TP for the catchment scenarios are presented in Table 8. Phosphorus removal results in marked reductions in P concentrations in the lake but

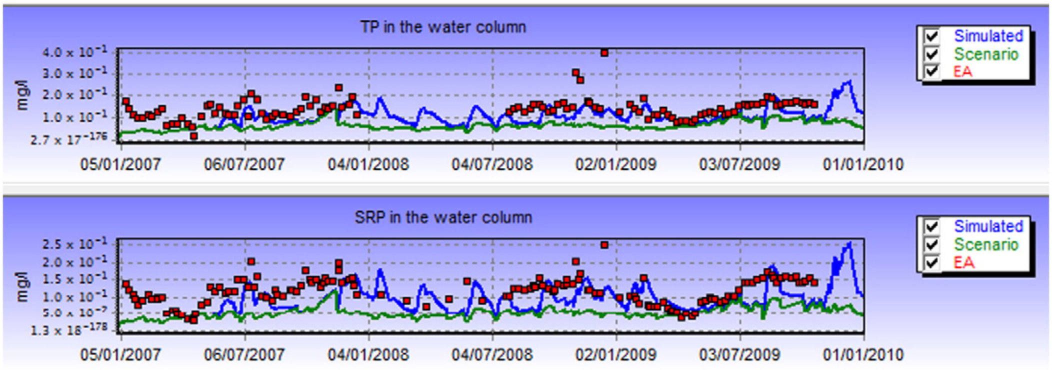

**Fig. 8.** Simulated (blue line) and observed (red dots) TP and SRP below Salisbury (reach 37) together with a scenario assuming a 30% reduction in P fertilisers (green line shows an agricultural P reduction effect). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

**Table 5**
Current and scenario TP and SRP mean concentrations for a range of management options.

| | Existing | | WWTP TP = 1 mg/l | | WWTP TP = 0.3 mg/l | | Seasonal standards | |
|---|---|---|---|---|---|---|---|---|
| | TP mg/l | SRP mg/l | TP mg/l | SRP mg/l | TP mg/l | SRP mg/l | TP mg/l | SRP mg/l |
| Upstream Salisbury | 0.11 | 0.084 | 0.079 | 0.074 | 0.067 | 0.066 | 0.073 | 0.07 |
| Downstream Salisbury | 0.102 | 0.094 | 0.079 | 0.075 | 0.07 | 0.069 | 0.074 | 0.073 |
| River at Blashford Lakes | 0.11 | 0.101 | 0.075 | 0.071 | 0.064 | 0.062 | 0.069 | 0.066 |
| Catchment downstream | 0.106 | 0.097 | 0.073 | 0.069 | 0.062 | 0.06 | 0.072 | 0.069 |

**Table 6**
Percentage change in TP and SRP mean concentrations for a range of management options.

| | WWTP TP = 1 mg/l | | WWTP TP = 0.3 mg/l | | Seasonal standards | |
|---|---|---|---|---|---|---|
| | TP (%) | SRP (%) | TP (%) | SRP (%) | TP (%) | SRP (%) |
| Upstream Salisbury | 28.2 | 11.9 | 39.1 | 21.4 | 33.6 | 16.7 |
| Downstream Salisbury | 25.5 | 20.2 | 34.0 | 26.6 | 30.2 | 22.3 |
| River at Blashford Lakes | 31.8 | 29.7 | 41.8 | 38.6 | 37.3 | 34.7 |
| Catchment downstream | 31.1 | 28.9 | 41.5 | 38.1 | 32.1 | 28.9 |

**Table 7**
Current WDF phosphorus standards for the UK rivers.

| Water type | SRP (mg/l) mean standards for High to Poor WFD chemical status | | | |
|---|---|---|---|---|
| | High | Good | Moderate | Poor |
| Under 80 m altitude and less than 50 mg/l alkalinity | 0.03 | 0.05 | 0.15 | 0.5 |
| Over 80 m altitude and less than 50 mg/l alkalinity | 0.02 | 0.04 | 0.15 | 0.5 |
| Any altitude and more than 50 mg/l alkalinity | 0.05 | 0.12 | 0.25 | 1 |

**Table 8**
Impact of P removals at upstream sewage works on SRP and TP concentrations in Blashford Lake together with percentage reductions.

| Existing concentrations | | WWTP TP = 1 mg/l | | WWTP TP = 0.3 mg/l | |
|---|---|---|---|---|---|
| SRP mg/l | TP mg/l | SRP mg/l | TP mg/l | SRP mg/l | TP mg/l |
| 0.04 | 0.063 | 0.036 (−11.9) | 0.056 (−11.4) | 0.034 (−14.9) | 0.053 (−15.7) |

the impact is moderated by continued internal loading from the sediment so that beneficial impacts on the ecology of the lakes are unlikely to occur in the short term.

## 6. Conclusions

The INCA-P catchment modelling undertaken on the Avon catchment has shown that the contribution of P from agriculture matches the contribution from point sources. Thus management should invoke a joint strategy of reducing P sources from diffuse pollution, either by fertiliser reduction or by appropriate and effective mitigation measures. The selection of these on-farm measures can be guided using the FARMSCOPER decision support tool and work on the Hampshire Avon, including the primary farm types present, has already been published (Zhang et al., 2012). However, a reduction in P from WWTPs in the catchment would also be highly effective in reducing P in the river system. Reduction of WWTP TP concentrations to 1 mg/l produces a significant reduction in instream concentrations and this is further enhanced when a Warminster level treatment of 0.3 mg/l is invoked. Phosphorus removal also results in marked reductions in P concentrations in Blashford Lakes, but the improvements are moderated by continued internal loading from the sediment (Søndergaard et al., 2003).

There is, therefore, a potential rationale to seek limits in P discharges during the summer months, possibly accepting that the current best available technology limit of 1 mg P/l must be improved upon, whilst allowing reduced dosing in the winter. Data from this study suggests that seasonal permitting could be possible; however, it should be approached with caution. Evidence of long term environmental benefits are limited, i.e. PP becoming bioavailable further down the system. A recent UKWIR report on 'Better Regulation' (UKWIR, 2011) assessed options for seasonal consenting and made an important point regarding meeting an annual average P EQS:

> "If the EQS for phosphorus is to be met as an average over the whole year, any increases in concentration in winter must be compensated for by reduced levels in the summer. The effect of switching iron dosing on in summer and off in winter was examined. This approach does not at present seem to be a viable proposition. Whilst treatment is only effective during the summer dosed period, in winter (undosed) the increase in concentration is, for most rivers, not compensated for by increased river flow. Hence the overall annual mean value is higher than that specified in the EQS."

This suggests that the way the Environment Agency assesses compliance would have to be reviewed. The benefits of lower summer P concentrations would need to be balanced against the potential exceedence of EQS in winter, at a time which may have no significant environmental impact. Also, aspects such as storage of "winter P" in sediments with subsequent release in summer would have to be considered. Current evidence suggests that a site-specific assessment needs to be implemented with pilot-studies employed to determine the potential benefits of seasonal permitting to both the receiving water and the water company in terms of practicality and costs.

## Conflict of interest

There are no conflicts of interest in the submitted paper.

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