Modelling impacts of seasonal wastewater treatment plant effluent permits and biosolid substitution for phosphorus management in catchments and river systems

P. G. Whitehead, M. N. Futter, S. Comber, D. Butterfield, L. Pope, R. Willows and C. Burgess

ABSTRACT

The issues of diffuse and point source phosphorus (P) pollution in river systems are presented using a catchment model to assess nutrient behaviour, seasonal effluent standards and biosolid substitution. A process-based, dynamic water quality model (INCA-P) has been applied to four UK catchments, namely, the Rivers Tywi, Wensum, Lunan and Hampshire Avon, to simulate water fluxes, sediments, total phosphorus and soluble reactive phosphorus (SRP) concentrations. The model has been used to assess impacts of both agricultural runoff and point P sources from wastewater treatment plants (WWTPs) on water quality. With increasing costs for P fertilizer and P reduction at WWTPs, a strategy of recycling P from WWTPs as biosolids to substitute for fertilizers in vulnerable catchments has been investigated. Significant reductions in P concentrations are achieved if this substitution were implemented on a large scale. Reductions in SRP of between 6% and 41% can be achieved using this strategy. The effects of implementing new WWTP standards are shown to reduce SRP by 30%. Seasonal consent standards applied in only summer months could reduce SRP by 53% and achieve a substantial reduction in treatment costs year round.

Key words | biosolid substitution, catchment model, phosphorus management, WWTP seasonal effluent

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INTRODUCTION

Sustainable food production and water quality degradation as a result of excessive nutrient inputs are two of the biggest problems facing society today. Global food production is dependent on water availability and also nutrient supply, including the key nutrient phosphorus (P) (Cordell & White 2011). Increasing concerns are being expressed about the idea that global P reserves are insufficient to support food production in the future (Cordell & White 2011). Furthermore, once P enters surface waters via runoff from the terrestrial environment or from wastewater treatment plants (WWTPs) (Comber *et al.* 2010), it can have adverse effects on water quality. Excessive P inputs have been linked to eutrophication in freshwater (Carpenter *et al.* 1998; White & Hammond 2009) and marine (Nixon 1995; Alexander *et al.* 2008) environments. Eutrophication effects are more pronounced in summer when flows are low and temperatures are warmer (Jarvie *et al.* 2006).

In Europe, legislation including the Water Framework (WFD; EU 2000), Urban Wastewater Treatment (UWWTD; EU 1991) and Habitats Directives (EU 1992) set objectives for wastewater or receiving water quality with respect to P. The WFD sets Environmental Quality Standards (EQS) for P concentration in rivers and lakes (UKTAG 2013). The current regulatory environment poses a major challenge to the water sector in the UK with approximately 700 WWTPs in the UK planning or already

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implementing measures to reduce P loads to vulnerable water bodies. Approximately 1,000 additional WWTPs are predicted to be causing downstream EQS exceedances owing to their contributions alone (Comber *et al.* 2010) without considering any upstream inputs from agriculture or other WWTPs. 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 discharges from WWTPs. Currently, water companies are obliged to meet annual average targets of typically 1 or 2 mg-P/l, depending on the size of WWTPs 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 ensures that the impacts of P derived from WWTPs would be significantly reduced.

Approximately 90% of the 20 Mt/year P used in global agricultural fertilizer is currently derived from mineral sources (Cordell *et al.* 2009), predominantly from Morocco, the United States and China. There are significant monetary and carbon costs associated with P refining and transport to areas where it is applied as fertilizer (Cordell *et al.* 2009). Recycling P removed during wastewater treatment to land as agricultural fertilizer has potential economic, environmental and societal benefits. The possible benefits of utilizing biosolids as a fertilizer are explored as scenarios in the catchment modelling undertaken here.

In the UK approximately one million tonnes of dry solids are produced annually from WWTPs (UKWIR 2006). This amount is likely to increase over the next 10 years as a greater proportion of sewage is treated, higher treatment standards are applied under the UWWTD and WFD and population increases. The main disposal route for sewage sludge is recycling to land as biosolids; accounting for approximately 70% of the sludge produced in the UK (CEEP 2009) and is considered by the UK government as the Best Practicable Environmental Option. Recycling to agricultural land is the most sustainable option as it enables nutrients to be recycled to maintain soil fertility and to provide farmers with an alternative to inorganic fertilizers which may not have the same environmental benefits and are more expensive. Approximately 44% of sludge used on agricultural land is anaerobically digested; the majority of this is applied as liquid rather than dewatered sludge cake. Treated liquid sludges (3–6% dry solids) are applied to both arable and grassland while dewatered sludges (25–38% dry solids) are usually restricted to arable land where they can be ploughed or incorporated into the soil (UKWIR 2006).

A number of studies have been undertaken assessing the nutrient availability of biosolids. In particular, reported data suggest that P present in biosolids derived from sewage sludge is less easily leached from soils after application compared with inorganic fertilizers (Miller & O'Connor 2009). Phosphorus leaching has also been reported to be low in coastal zone soils treated with biosolids. This is because high concentrations of soil Al and Fe increase P sorption and reduce P solubility (Elliot *et al.* 2002). Similar results were found by Siddique *et al.* (2000) in a study on soils whose surface horizon texture was loam. Significantly greater amounts of P leached from inorganic fertilizer-treated soil than from sludge-treated soil. The difference in P leaching was explained by the lower P solubility in the sludge compared with the fertilizer. The use of biosolids as a fertilizer close to vulnerable water bodies could therefore assist in reducing agricultural losses of P.

The greatest risk for surface water contamination from P is particulate P from soil erosion (with its associated sorbed P) with particulate P being transported by surface runoff. Biosolids improve soil structure and thus reduce the risk of runoff (Evans 2001). This presents a possible trade-off; organic matter addition promoting stable soil structure and reducing phosphate losses as particulate P, versus the risk of increasing bicarbonate-extractable P above the threshold where breakthrough becomes a risk. The risk of water pollution by biosolids derived phosphate has been extensively studied by Withers and co-workers (e.g., UKWIR 1997). Animal manure is a greater risk than sludge biosolids because it contains more soluble P. Biosolids have been eluted as a result of the water-borne transfer process, which removes soluble P to the liquid phase and the solid-phase P has been stabilized by biosolids treatment. Smith *et al.* (2000) added different forms of biosolids to two different moist soils (sandy loam at pH 6.2 and calcareous clay at pH 8.1) and measured the change in sodium bicarbonate extractable P with time. The majority of the re-equilibration of P between the biosolids and the soil occurred within a few hours, followed by a much slower increase in extractable P, which continued for more than 60 days. The pattern of change was related to the type of soil and its starting content of bicarbonate extractable P. It was also related to the type of treatment to which the biosolids had been subjected. Availability of biosolids P was in the order thermally dried $\ll$ cake $<$ liquid. It has been reported that lime-stabilized sludge can leach greater proportions of phosphorus than other biosolids (Kostyanovsky *et al.* 2011). However, recent data suggest that this form of sludge treatment is becoming less popular in the UK, with anaerobically digested sludge now being favoured (UKWIR 2006). Injection of sludge into soils is also now the preferred option for application, rather than surface spreading, as it both reduces runoff likelihood as well as reducing odour issues (UKWIR 1997).

Although some leaching has been detected in soils amended with lime-stabilized biosolids (Kostyanovsky *et al.* 2011) attributed to the colloidally facilitated transport of organic P and mineralization, the high binding capacity of the biosolids were considered to pose little risk of P leaching into groundwater. Most of the anaerobic digested biosolids P was complexed in Al and Fe forms with P in the lime-stabilized biosolids associated with Ca.

New research on modelling techniques are needed to explore the potential effectiveness of programmes of measures considered for application under the WFD. The INCA-P model offers an approach to modelling catchment hydrological and chemical interactions and to assess alternative management strategies to meet the WFD. INCA-P is a process-based catchment-scale research model of P dynamics (Wade *et al.* 2002) and the model has been applied to four catchments of varying typology and geographic location. These are the Lunan River in Scotland, the Wensum in Norfolk, the Hampshire Avon in southern England and the Tywi in South Wales. The simulated catchments provide an interesting contrast and have been investigated to address the issue of phosphorus control in catchments using both biosolids application, as a substitute for traditional P fertilizers, and the control of WWTP effluent discharge concentrations. The effect of new standards for effluent discharges are addressed as well as the potential for using seasonal permits to limit P concentrations in UK rivers under low flow summer conditions, when ecological impacts are most significant.

METHODOLOGY

INCA model

In order to model P in UK catchments, the dynamic INCA (Integrated Catchment) model has been used. This model is semi-distributed and incorporates the key processes operating in both terrestrial and aquatic environments. The philosophy of the INCA model is to provide a process-based representation of the factors and processes controlling flow and water quality dynamics in both the land and in-stream components of river catchments, while minimizing data requirements and model structural complexity (Whitehead *et al.* 1998a, b). As such, the INCA model produces daily estimates of discharge, stream water quality concentrations and fluxes at discrete points along the main channel of a river. The model is semi-distributed, so that spatial variations in land use and management can be taken into account, although the hydrological connectivity of different land use patches is not modelled in a fully distributed manner. Rather, the hydrological and nutrient fluxes from different land use classes and sub-catchment boundaries are modelled simultaneously and information fed sequentially into a multi-reach river model. The INCA model, in its various forms, has been extensively applied across Europe (UK, France, Sweden, Denmark, Norway, Austria, Finland, Romania and Turkey) and around the world in Nepal, Brazil and Canada. The major applications of INCA have been published to date in papers by Whitehead *et al.* (1998a, b, 2011, 2013), Wade *et al.* (2002, 2009) and Crossman *et al.* (2013).

In this study, the INCA-P version of the model has been used. INCA-P is a physical, process-based model, as shown in Figure 1, which simulates flow, sediment, phosphorus (total phosphorus (TP), particulate phosphorus (PP) and soluble reactive phosphorus (SRP)) in soils, groundwaters, streams and sediments (Wade *et al.* 2002, 2009; Whitehead *et al.* 2011, 2013; Crossman *et al.* 2013). It has both a land component and a river component, allowing it to track P inputs

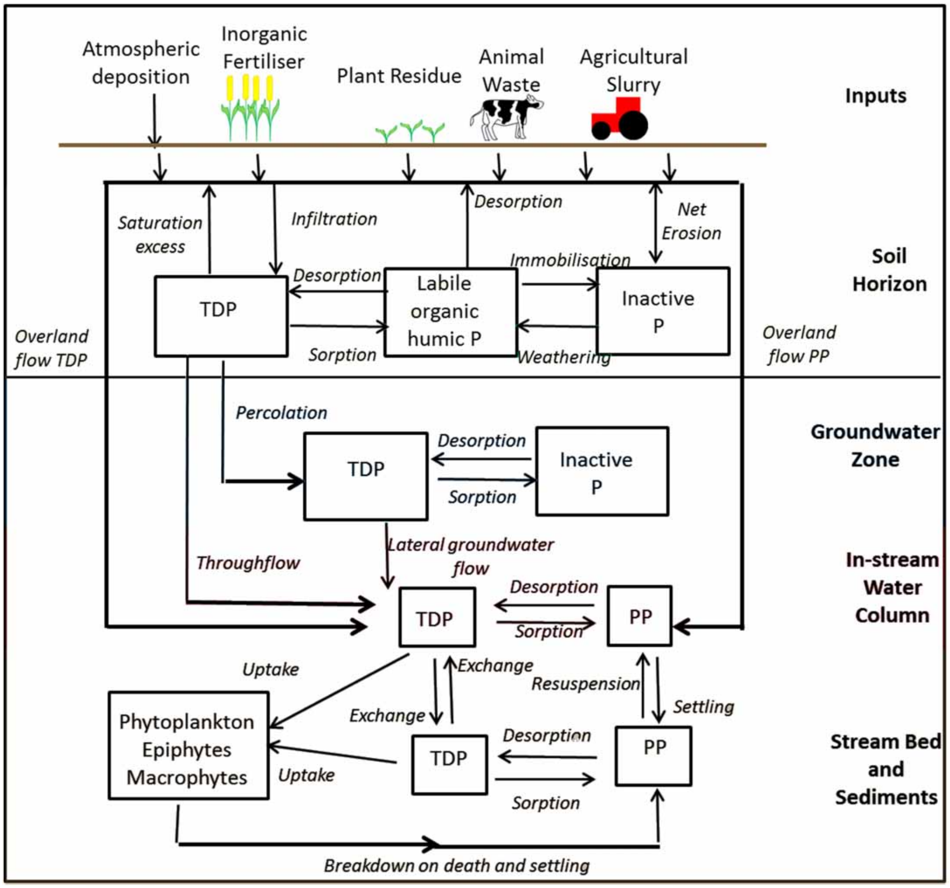

Figure 1 | The INCA-P model nutrient flows and process controls.

which flow into the river from diffuse and point sources. Spatial variations in land use, vegetation and hydrology are simulated by dividing the catchment into sub-catchments or into a multibranch network of tributaries and streams that flow into a main river system (Whitehead *et al.* 2011). The INCA model has partitioning algorithms which calculate the proportions of P adsorbed to the soil, something many models do not have. It also has equilibrium equations controlling the water–sediment exchange based on a Langmuir isotherm approach, so that exchange processes can occur between the water phase and solid phase (Wade *et al.* 2009).

It must be accepted, however, that there are a number of uncertainties inherent in the model as with any complex process-based model, which will affect results generated by the model. As explained in the Introduction, the leaching potential of the different types of biosolids will vary depending on the biosolid composition, the application process and soil type. The model serves as a first step towards making informed decisions regarding catchment management.

Modelled catchments

The model has been set up for four river systems in the UK, as shown in Figure 2, including the River Wensum in East Anglia (INCA-P reaches shown in Figure 3), the Hampshire Avon in southern England, the River Tywi in South Wales and the River Lunan in south-eastern Scotland. The four river systems represent a spectrum of catchment types and cover different P leaching regimes as well as differing soils, geology and land use (Table 1). The River Tywi (Wales) is an upland catchment with more acidic soils and mostly agriculture-derived P inputs, whereas the Hampshire Avon (England) is a chalk catchment dominated by grassland with some significant WWTP inputs. The River Wensum (England) is a mixed arable catchment and the Lunan

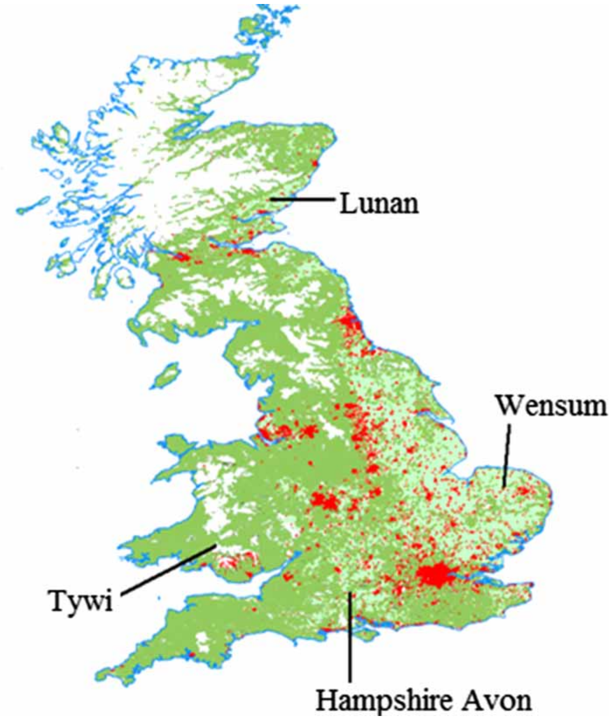

Figure 2 | UK map showing locations of the four rivers modelled.

(Scotland) is a rural arable and peri-urban catchment with significant non-sewered P inputs from septic tanks. All the catchments have direct discharges from WWTPs and these are incorporated into the model reach structure. Observed flow and water quality data at a wide range of monitoring locations, and managed by the UK Environment Agency and the Scottish Environmental Protection Agency (SEPA), have been used to calibrate the model parameters. To provide consistency and allow comparison across catchments, fertilizer applications were assumed to take place in each catchment at the same time of year in the spring.

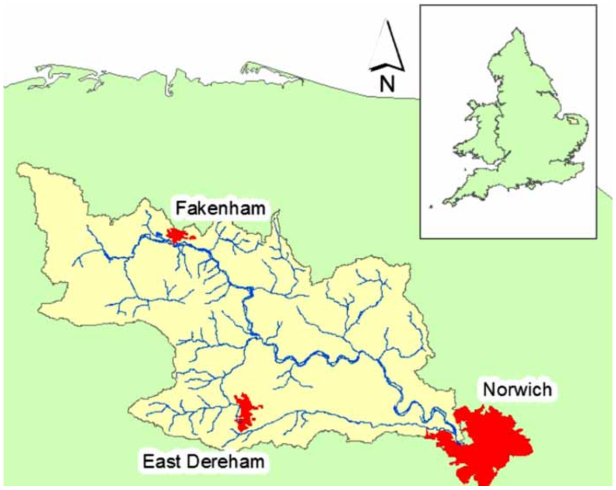

Figure 3 | River Wensum catchment in eastern England.

SCENARIO STRATEGY

Environmental legislation is now driving investment to reduce P discharges to surface waters via the UWWTD which sets annual average TP concentrations of 2 mg/l for works serving populations between 10,000 and 100,000 and 1 mg/l for works serving greater than 100,000 persons. Other permits for 1 mg/l are also set for discharges to sensitive water bodies designated under the Birds and Habitats Directive or WFD. For each catchment modelled, effluent P concentrations were set to reflect those needed to meet the annual average P permit values. The current Best Available Technique for P reduction is considered by the water companies to be dosing with iron or aluminium salts to meet 1 mg/l TP. Where there is no legislative driver (e.g., UWWTD), the concentrations of phosphorus are rarely measured in WWTP effluents. Consequently, for smaller WWTPs across the modelled catchments, there are few reported data as consents for P discharge are typically only applied to works serving populations greater than 10,000. Consequently, a default of 4.53 mg-P/l has been applied to any non-consented discharge. This value was derived from compiling all available effluent quality data and taking a mean concentration (Comber *et al.* 2010). For the Avon, Lunan and Tywi catchment models WWTP effluents were set to their current (as of 2010) permitted/consented concentration using data supplied by the individual water companies.

With INCA-P set up for the four catchments, a number of scenarios were run to determine the impact of different agricultural and WWTP management scenarios on P discharge to receiving waters. For each of the catchments, land use was kept constant as were the fertilizer application times and rates. The only variable changed was the type of fertilizer applied and its solubility. The solubility

Table 1 | Summary of catchment characteristics

Catchment	Avon	Tywi	Wensum	Lunan
Area (km^2)	1,750	1,090	646	66
Predominant land use	Chalk, groundwater dominated. Cereal/ grassland/dairy	Peaty upland soft water, low pH Rough grazing	Chalk/sand/loam. Mostly arable, cereal and root crop production	Scottish lowland catchment
P sources	Diffuse agriculture, cress beds, WWTP (Warminster and Salisbury and several smaller ones)	Mostly diffuse with a few smaller WWTP inputs	Diffuse agriculture + WWTP	Mostly diffuse with smaller WWTP inputs and septic tanks
WWTP data	Mains sewerage for 200,000 population, across 12 WWTP, biggest ca. 45,000 (Salisbury)	Main sewerage for population of 5,560 in 2 main works (Llandovery and Llandeilo)	Mains sewerage for 49,000 population, across 10 main WWTP, biggest ca. 21,000 (Dereham)	Minor discharges plus ~850 septic tanks

of the different forms of biosolid that are available and those of the standard inorganic P are provided in Table 1. Three types of P fertilizer and biosolids substitution were used in the scenarios, namely a base case, assuming use of inorganic phosphorus fertilizer, a scenario with 50% substitution with lime-stabilized biosolids and a scenario with 50% substitution with digested cake biosolids.

Seasonal consent conditions

Previous and current P permits for the Wensum are shown in Table 2 and show the increase in the number of permits applied from 2010 onwards, reflecting the agreed investment to reduce P loads to the river. In order to determine the contribution from WWTPs to total catchment P loads, one scenario was run with effluent P levels set to zero, so effectively removing point sources of P completely. Permitted P values are based on achieving an annual average concentration. However, for the purpose of catchment management seeking to achieve good ecological status, the model simulations were run by setting the mean effluent TP concentrations to 0.25 mg/l during summer when biological activity is at its peak (April to September) and 2 mg/l during winter (October to March) (Table 3). For these scenarios the diffuse agricultural inputs were fixed at the baseline scenario where only inorganic P fertilizer is used within the catchment.

SIMULATION AND SCENARIO RESULTS

The INCA-P outputs were compared with measured phosphorus concentrations reported by the Environment Agency (Tywi, Avon and Wensum) and SEPA for the Lunan catchment. For all catchments, the simulated daily flow matched the observed daily flow with R^2 for the Rivers Tywi, Avon, Wensum and Lunan Rivers at 0.64, 0.75, 0.42 and 0.52, respectively. The water quality system is 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, as shown in Figure 1. However, with water quality we need to ensure that the phosphorus loads are accurately estimated. Figure 4 shows that the simulated and observed monthly loads compare well, with an R^2 value of 0.91 which indicates that the model is capturing the key flux behaviour of the Hampshire Avon catchment. An example of the outputs of the model for flow and water quality compared to observations is shown in Figure 5 for the Lunan catchment.

Simulations suggested that biosolid substitution would reduce in-river P concentrations in the four study catchments (Figure 6, Table 4). The effect is most pronounced during high flow conditions when diffuse P is being flushed into the river system. There are some noteworthy contrasts in the percentage P reduction between rivers (Table 4). In

Table 2 | Wensum catchment WWTP data

WWTP within Wensum catchment	Population	Effluent flow[a] (m³/day)	2005–2010 permit (mg/l P)	2010 onwards permit (mg/l P)	Effluent quality without a permit imposed (mg/l P)
WWTP1	2,445	690	–	2	4.53[c]
WWTP2	21,333	3,769	2	1	5.92[b]
WWTP3	601	160	–	2	4.53[c]
WWTP4	16,069	3,300	2	1	4.32[c]
WWTP5	1,144	299	–	1	4.53[c]
WWTP6	620	150	–	–	4.53[c]
WWTP7	3,487	720	–	1	4.53[c]
WWTP8	1,159	262	–	1	4.53[c]
WWTP9	3,839	850	–	1	4.53[c]
WWTP10	612	227	–	1	4.53[c]

[a] Permitted dry weather flow.
[b] Measured data.
[c] Mean of data reported.
From Comber *et al.* (2010).

all cases, the replacement of inorganic fertilizer with biosolids produces a reduction in river P concentrations. Concentration reductions range from around 6% in the River Wensum to approximately 35% in the Tywi, with the Avon and Lunan both displaying decreases of approximately 10%. An overall decrease in riverine P concentration is to be expected given the reduced solubility of P associated with biosolids. The variation between catchments is likely to be a result of the dominance of agricultural inputs within the Tywi catchment, and, therefore, any reduction in diffuse agricultural inputs will result in significant reductions in in-stream P concentrations.

Agricultural impacts, effluent treatment and seasonal consent standards

Table 5 shows the scenarios modelled for the Wensum, which include the present permitting conditions as well as the impact of seasonal permits (summer permits set between April and September inclusive). The first scenario assumes the 2 mg/l effluent for the large works WWTPs 2 and 4 in Table 2, with all the others remaining at their current high P levels. The second scenario assumes a summer permit of 2 mg/l for all the works during the summer. During winter it is assumed that there are no permits for the smaller works. In the third scenario, it is assumed that two large works (WWTPs 2 and 4) are reduced to 1 mg/l with no permits for the smaller works in winter. The final scenario explored the impact of permits lower than the tightest UWWTD value for the two largest works (0.25 mg/l) for the summer months and no permit for smaller works in winter.

The results in Table 5 show how significant the influence of the WWTPs are on two reaches, one of which is downstream of WWTP 4 below Fakenham (Reach 7, Figure 2) and the other is at the downstream reach of the Wensum at Norwich (Reach 19, Figure 2). Under current permit conditions (2010 onwards) winter river P

Table 3 | Wensum catchment scenarios

	Permit			
Scenario	WWTP2	WWTP4	Remaining WWTPs	Diffuse agricultural inputs
1	2010 onwards permit set at 2 mg/l	2010 onwards permit set at 2 mg/l	2010 onwards permit	Only inorganic fertilizer used on land
2	2010 onwards permit set at 2 mg/l	2010 onwards permit set at 2 mg/l	2010 onwards permit April–September No permit in winter (October–March)	Only inorganic fertilizer used on land
3	April–September permit set at 1 mg/l P	April–September permit set at 1 mg/l P	2010 onwards permit April–September No permit in winter (October–March)	Only inorganic fertilizer used on land
4	April–September permit set at 0.25 mg/l P	April–September permit set at 0.25 mg/l P	2010 onwards permit April–September No permit in winter (October–March)	Only inorganic fertilizer used on land

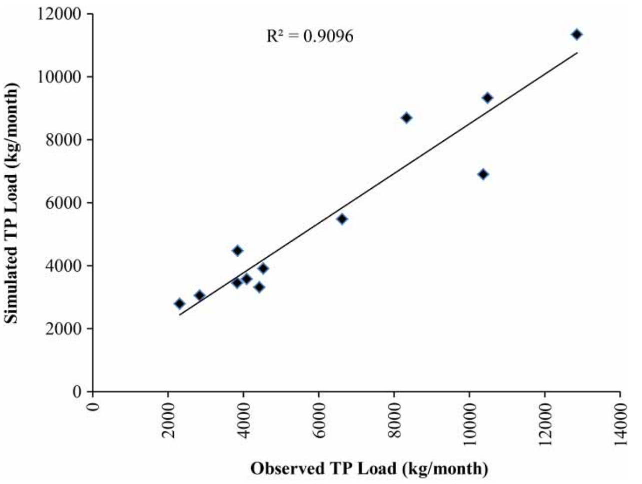

Figure 4 | Simulated and observed monthly phosphorus load in the lowest freshwater reach of the Hampshire Avon.

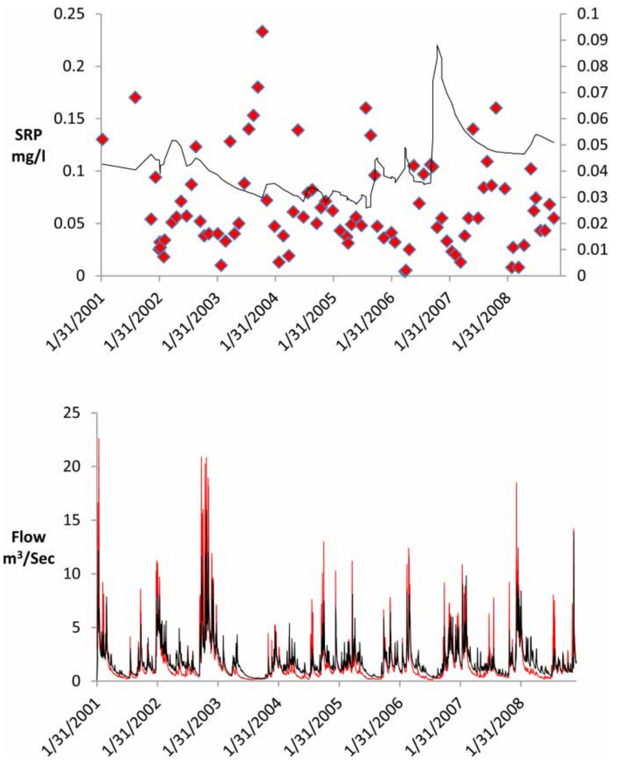

Figure 5 | Simulated (black line) and observed for flow and SRP in the River Lunan.

concentrations are close to the high quality EQS of 0.05 mg/l SRP, whereas summer concentrations are above the EQS. Setting a 1 mg-TP/l summer permit would reduce instream SRP concentrations to close to the EQS. If effluents at the two largest works were reduced to 0.25 mg/l, the instream concentrations fall well below the EQS in summer. These reductions are of the order of 30% and 50% during the summer months. However, the winter concentrations rise because the standards are relaxed at the other WWTPs and this amounts to an increase of 33% at Reach 19, although the instream concentrations are still within the high quality EQS. The simulations for the Wensum therefore suggest that certain benefits may be derived from seasonal permits, particularly if improved phosphorus removal (beyond UWTTD requirements) at WWTPs can be cost-effectively achieved during summer months.

Progressive reductions in agricultural P fertilizer inputs in the River Wensum were simulated. The results showed that reducing diffuse agricultural P fertilizer, while leaving WWTP inputs at current levels, exhibits a linear response of 0.0002 mg-P/l for every per cent reduction in agricultural inputs (for any given reach) with a maximum reduction of up to around 35% assuming no point source agricultural discharges.

DISCUSSION

The simulations for the rivers illustrate the differing effects of point and diffuse P sources on catchment water quality, and support the needs for multi-option, catchment-based plans to effectively reduce overall riverine P concentrations. Applying the INCA-P model to the four test catchments and assessing the impact of substituting 50% of inorganic P fertilizer used within the catchment with biosolids predicted variable decreases in TP and SRP within the catchments. The general reduction in phosphorus loss from agricultural runoff as a result of substituting biosolids for inorganic phosphate fertilizers reflects the lower leaching potential of P from biosolids compared with inorganic phosphates (UKWIR 1995). This is unsurprising as the biosolids themselves have a high adsorption capacity compared to the mineral-based inorganic fertilizer. The amount of P lost via leaching will therefore be controlled by competition for adsorption sites determined by redox potential, pH and Ca concentrations, as well as soil properties such as water content, particle size and organic content. The ability of biosolids to retain P within their own matrix, while still making it available for plant growth means that they may

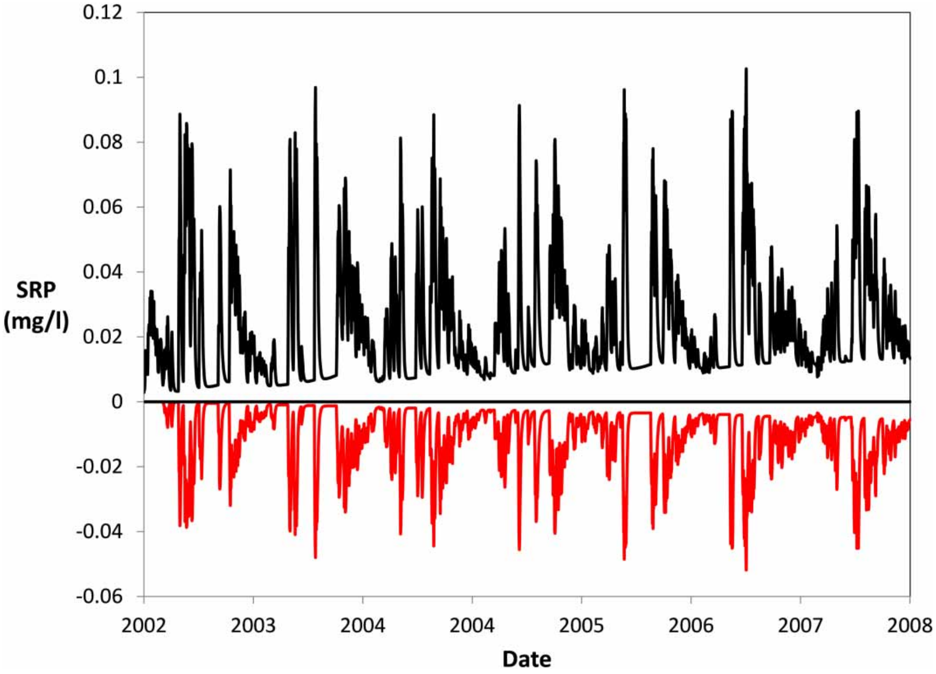

Figure 6 | INCA-P output for River Tywi showing baseline superphosphate (black line) and expected reduction in SRP that could be achieved with 50% of inorganic P fertilizer replaced with biosolids (digested cake).

Table 4 | TP and SRP concentration averages (mg/l) and percentage reductions from biosolid substitution at the outflow of four river catchments

	TP			SRP		
	Fertilizer only	**Lime stabilized**	**Digested sludge**	**Fertilizer only**	**Lime stabilized**	**Digested sludge**
Wensum mg/l	0.13	0.12	0.11	0.042	0.04	0.039
Wensum % reduction		7.7	10		7	6.1
Lunan mg/l	0.063	0.056	0.055	0.047	0.041	0.04
Lunan % reduction		11.3	11.4		12.1	12.2
Tywi mg/l	0.024	0.015	0.014	0.022	0.014	0.013
Tywi % reduction		35	41		36	40.7
Avon mg/l	0.106	0.0951	0.0918	0.096	0.0861	0.0829
Avon % reduction		10.3	13.4		10.3	13.6

be preferentially applied to agricultural land where application of inorganic fertilizer may result in leaching into adjacent watercourses (UKWIR 2006).

The varying P reductions between the catchments, resulting from using biosolids are the result of a number of factors:

- The Lunan, Wensum and Hampshire Avon catchments have lower percentage reductions in concentrations being primarily groundwater driven. This suggests that the biosolids effect will be less significant as nutrient reductions will be delayed by the longer residence times.
- The Tywi with more surface water flows shows the highest effect reflecting the more rapid response of the catchment.

Such model results are always subject to uncertainties, as catchment systems are very complex and a model is

Table 5 | SRP concentrations simulated in the River Wensum under the varying seasonal scenarios compared against 2010 ongoing permit conditions with percentage change in brackets

		Summer SRP concentration (mg/l)		**Winter SRP Concentrations (mg/l)**	
	WWTP 2 and 4 effluent P concentration (mg/l)	**Norwich**	**Fakenham**	**Norwich**	**Fakenham**
Scenario 1	2 on only large works	0.073	0.084	0.040	0.044
Scenario 2	2	0.073 (0)	0.084 (0)	0.053 (33.5)	0.049 (12.5)
Scenario 3	1	0.051 (−30.4)	0.053 (−36.4)	0.053 (33.5)	0.049 (12.5)
Scenario 4	0.25	0.034 (−53.1)	0.031 (−63.7)	0.053 (33.5)	0.049 (12.5)

Note: Current permit conditions apply to other WWTPs.

only a simplification of reality. There are uncertainties in nearly all the flow and water quality measurements and there is also uncertainty in the processes controlled phosphorus behaviour. Nevertheless, the models do give an indication of the behaviour of the catchments to changing hydrology, land use, fertilizer and biosolid application. Biosolid application cannot be seen as a panacea for the problems of disposing of WWTP P. Like the use of inorganic fertilizers, excessive application of biosolids have been linked to P concentration accumulating in soils in the USA (Penn & Sims 2002; Shober & Sims 2003), New Zealand (Wang *et al.* 2008) and Australia (Pritchard *et al.* 2007). Different WWTP processes have different effects on P bioavailability and leaching as already discussed earlier (Penn & Sims 2002; Wang *et al.* 2008). Efforts must be made to balance P leaching rates against phytoavailability so as to ensure optimum plant growth while minimizing leaching to receiving waters.

Examining the more detailed outputs generated for the Wensum catchment suggests that further treatment of effluents at the largest WWTPs (2 and 4) would have a significant impact on downstream water quality, albeit at a significant cost without certainty of a change in ecological status. One option for more effective use tertiary treatment would be to undertake seasonally adjusted phosphorus reduction at WWTPs, with enhanced treatment in the summer when biological activity is greatest. The model outputs suggest that reducing phosphorus in the effluent to 0.25 mg/l would typically halve the concentrations in the stream, to levels well below the current standard (0.12 mg-SRP/l) and below the high EQS status. Owing to higher flows in the winter, leading to greater dilution, then P dosing could be relaxed and still achieve the desired high EQS. An important aspect of any decision to move towards seasonal permitting is if there is a relaxation of permits during the winter, will P be stored in sediment downstream, only to be released sometime in the future? It is possible that P stored in the sediments will be released in the summer. However, it is also possible that less eutrophic conditions caused by lower summer P inputs will preserve well-oxygenated conditions and that the P will remain bound to the sediment. This possible fate of sediment-bound P would need to be considered on a case-by-case basis using models such as INCA-P which have a process component for predicting sediment–water interactions. Altering the chemical dosing regime to allow seasonal permitting could lead to better environmental outcomes, in a cost-neutral way for water companies, at least in the interim until further source control measures are put in place to reduce phosphorus inputs to WWTPs.

The other possible issue associated with seasonal permitting is that the WFD EQS is currently set as an annual average (as are permit conditions). This means that relaxed winter permits could lead to EQS exceedances during the winter which even with enhanced, sub-BAT phosphorus reduction in the summer could lead to annual average phosphorus concentrations in the effluent being greater than the existing permit as well as in-river annual average levels greater than the EQS downstream. Such a situation is not currently allowable in either the UWWTD or WFD. As such, a significant reassessment of the legislation would be required to potentially allow the widespread use of seasonal permitting in the UK, starting with an assessment of the diatom and macrophyte ecology downstream of the WWTPs under varying permitting regimes.

The modelled scenarios also show that reducing agricultural discharges will have a significant impact on river concentrations, which is unsurprising as along with

WWTP effluent input these are the dominant sources of phosphorus within UK lowland catchments (Comber *et al.* 2010; Whitehead *et al.* 2013). Overall, the data suggest that by taking a catchment-based view, it is possible to achieve compliance using seasonal-based permits, taking account of local situations associated with hydrology and ecology. Model results such as those presented here, combined with cost-effectiveness of agricultural and effluent-based measures (Whitehead *et al.* 2013), allow planners to identify the most cost-effective, catchment-based programmes of measures to assist in delivering WFD objectives. In all cases, owing to the variability in catchment hydrology and phosphorus sources, all options need to be considered on a catchment-by-catchment basis.

CONCLUSIONS

This study has shown that concentrations of P within four UK river catchments are dominated by WWTP effluent and agricultural sources. Consequently, control of these sources is essential to maintaining or restoring aquatic ecosystem health. The outputs from the scenarios modelled suggest that substitution of inorganic fertilizers with biosolids may not only be more sustainable (from a resource availability point of view), but offer the potential for reduced loss of P via runoff to adjacent water courses. The INCA-P modelling showed that for all four catchments, modelled substitution of inorganic fertilizer with biosolids results in a decrease in river concentrations, reflecting lower leaching rates. Variations are observed due to differences in land use and the balance between agricultural and diffuse inputs of phosphorus.

Furthermore, the modelling approach has been shown to be able to test scenarios for varying permitting regimes within a catchment in order to reduce phosphorus concentrations in the river during the summer months when eutrophication pressures are at their greatest. Comparing current annual average permit conditions versus innovative options such as seasonal permitting showed that summer river P concentrations can be lowered using tighter discharge limits, which can be relaxed in the winter during periods of higher flows without negatively effecting P concentrations in the receiving waters. Options such as these should be investigated further, to provide a more flexible approach (potentially at no overall increase in cost) to meeting WFD objectives.

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