

Hydrology Research

MODELLING IMPACTS OF SEASONAL WASTEWATER TREATMENT PLANT EFFLUENT PERMITS AND BIOSOLID SUBSTITUTION FOR PHOSPHORUS MANAGEMENT IN CATCHMENTS AND RIVER SYSTEMS

--Manuscript Draft--

Manuscript Number:	HYDROLOGY-D-12-00100R1
Full Title:	MODELLING IMPACTS OF SEASONAL WASTEWATER TREATMENT PLANT EFFLUENT PERMITS AND BIOSOLID SUBSTITUTION FOR PHOSPHORUS MANAGEMENT IN CATCHMENTS AND RIVER SYSTEMS
Article Type:	Research Paper
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Abstract:	<p>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 Test, to simulate water fluxes, sediments, total phosphorus (TP) and soluble reactive phosphorus (SRP) concentrations. The model has been used to assess impacts of both agricultural runoff and point P sources from Waste Water 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 4 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.</p>

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4 1 **MODELLING IMPACTS OF SEASONAL WASTEWATER TREATMENT PLANT**
5 2 **EFFLUENT PERMITS AND BIOSOLID SUBSTITUTION FOR PHOSPHORUS**
6 3 **MANAGEMENT IN CATCHMENTS AND RIVER SYSTEMS**

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18 15
19 16 **ABSTRACT**

20 17 The issues of diffuse and point source phosphorus (P) pollution in river systems are presented
21 18 using a catchment model to assess nutrient behavior, seasonal effluent standards and biosolid
22 19 substitution. A process based, dynamic water quality model (INCA-P) has been applied to four
23 20 UK catchments, namely, the Rivers Tywi, Wensum, Lunan and Test, to simulate water fluxes,
24 21 sediments, total phosphorus (TP) and soluble reactive phosphorus (SRP) concentrations. The
25 22 model has been used to assess impacts of both agricultural runoff and point P sources from
26 23 Waste Water Treatment Plants (WWTPs) on water quality. With increasing costs for P fertilizer
27 24 and P reduction at WWTPs, a strategy of recycling P from WWTPs as biosolids to substitute for
28 25 fertilizers in vulnerable catchments has been investigated. There would be significant reductions
29 26 in P concentrations in these rivers if this substitution were implemented on a large scale, as
30 27 biosolid P can be significantly less soluble than standard superphosphate fertilizers. Reductions
31 28 in SRP concentrations of between 4 and 41% can be achieved using this strategy. The magnitude
32 29 of the reductions is highly dependent on the nature of the river system and land use; upland
33 30 largely unimproved pastures predicting less reductions in water P concentrations than lowland
34 31 heavily fertilised and improved pastures The effects of implementing new effluent discharge
35 32 standards with high levels of P removal have been investigated for the River Wensum and are
36 33 shown to reduce SRP by 30% in the river system. As the cost of P reduction at the WWTPs is
37 34 high, an alternative strategy using seasonal consent standards applied in only summer months has
38 35 been assessed. The modelling suggests that such an approach could reduce SRP by 53%
39 36 compared to the current treatment levels and achieve a substantial reduction in treatment costs
40 37 year round.

41 38
42 39 **INTRODUCTION**

43 40 Sustainable food production and water quality degradation as a result of excessive nutrient inputs
44 41 are two of the biggest problems facing society today. Global food production is ultimately
45 42 dependent on phosphorus (P) supply (Cordell and White, 2011). Increasing concerns are being
46 43 expressed about “peak phosphorus”, or the idea that global P reserves are insufficient to support
47 44 food production in the future. Furthermore, once P enters surface waters via runoff from the
48 45 terrestrial environment or from waste water treatment plants (WWTP) (Comber et al., 2010), it
49 46 can have adverse effects on water quality. Excessive P inputs have been linked to eutrophication

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4 47 in freshwater (Carpenter et al. 1998, White and Hammond 2008) and marine (Nixon, 1995,
5 48 Alexander et al. 2008) environments. Eutrophication effects are more pronounced in summer
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7 49 when flows are low and temperatures are warmer (Jarvie et al. 2006).
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9 51 In Europe, legislation including the Water Framework (WFD; EU 2000), Urban Wastewater
10 52 Treatment (UWWTD; EU1991) and Habitats Directives (EU, 1992) set objectives for
11 53 wastewater or receiving water quality with respect to P. The WFD sets Environmental Quality
12 54 Standards (EQS) for P concentration in rivers and lakes (UKTAG 2013). The current regulatory
13 55 environment poses a major challenge to the water sector in the UK with approximately 700
14 56 WWTP in the UK planning or already implementing measures to reduce P loads to vulnerable
15 57 water bodies. Approximately 1,000 additional WWTP are predicted to be causing downstream
16 58 EQS exceedences owing to their contributions alone (Comber et al., 2010) without considering
17 59 any upstream inputs from agriculture or other WWTP. It has become apparent that a catchment-
18 60 based approach is required to improve water quality and ecological status using a combination of
19 61 measures to reduce agricultural and wastewater derived inputs, including consideration of
20 62 options such as seasonal-based permitting of P discharges from WWTP. Currently water
21 63 companies are obliged to meet annual average targets of typically 1 or 2 mg-P/l all year round,
22 64 depending on the size of WWTP and sensitivity of the receiving water. However, a more
23 65 beneficial ecological outcome may be derived from applying tighter permits during summer
24 66 months when biological activity is at its highest, then allow a more relaxed permit during the
25 67 winter when higher flows and lower productivity ensures that the impacts of P derived from
26 68 WWTP would be significantly reduced.
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32 70 Approximately 90% of the 20 Mt/yr P used in global agricultural fertilizer is currently derived
33 71 from mineral sources (Cordell et al. 2009), predominantly from Morocco, the United States and
34 72 China. There are significant monetary and carbon costs associated with P refining and transport
35 73 to areas where it is applied as fertilizer (Cordell et al. 2009). Recycling P removed during
36 74 wastewater treatment to land as agricultural fertilizer has potential economic, environmental and
37 75 societal benefits. The possible benefits of utilizing biosolids as a fertilizer are explored as
38 76 scenarios in the catchment modeling undertaken here.
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42 78 In the UK approximately one million tonnes of dry solids are produced annually from WWTP
43 79 (UKWIR, 2006). This amount is likely to increase over the next 10 years as a greater proportion
44 80 of sewage is treated, higher treatment standards are applied under the UWWTD and WFD and
45 81 population increases. The main disposal route for sewage sludge is recycling to land as biosolids;
46 82 accounting for approximately 70% of the sludge produced in the UK (CEEP, 2009) and is
47 83 considered by the UK government as the Best Practicable Environmental Option (BPEO).
48 84 Recycling to agricultural land is the most sustainable option as it enables nutrients to be recycled
49 85 to maintain soil fertility and to provide farmers with an alternative to inorganic fertilizers and
50 86 manures which may not have the same environmental benefits and are more expensive.
51 87 Approximately 44% of sludge used on agricultural land is anaerobically digested; the majority of
52 88 this is applied as liquid rather than dewatered sludge cake. Treated liquid sludges (3-6% dry
53 89 solids) are applied to both arable and grassland whilst dewatered sludges (25-38% dry solids) are
54 90 usually restricted to arable land where they can be ploughed or incorporated into the soil
55 91 (UKWIR, 2006).
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4 93 A number of studies have been undertaken assessing the nutrient availability of biosolids. In
5 94 particular, reported data suggests that P present in biosolids derived from sewage sludge, is less
6 95 easily leached from soils after application compared with inorganic fertilizers (Miller and
7 96 O'Connor 2009). Phosphorus leaching has also been reported to be low in Coastal Plain soils
8 97 amended with biosolids whose high concentrations of Al and Fe increased P sorption and reduce
9 98 P solubility (Elliot et al., 2002). Similar results were found by Siddique et al. (2000) in a study
10 99 on soils whose surface horizon texture was loam. Significantly greater amounts of P leached
11 100 from inorganic fertilizer-amended soil than sludge-amended soil. The difference in P mobility
12 101 was explained by the lower P solubility in the sludge compared with the fertilizer. The use of
13 102 biosolids as a fertilizer close to vulnerable water bodies could therefore assist in reducing
14 103 agricultural losses of P.
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19 105 The greatest risk for surface water contamination from P is particulate-P from soil erosion (with
20 106 its associated sorbed-P) by runoff. Biosolids improve soil structure and thus reduce the risk of
21 107 runoff (Evans, 2010). This presents a possible trade-off; organic matter addition promoting stable
22 108 soil structure and reducing phosphate losses as particulate-P, versus the risk of increasing
23 109 bicarbonate-extractable P above the threshold where breakthrough becomes a risk. The risk of
24 110 water pollution by biosolids derived phosphate has been extensively studied by Withers and co-
25 111 workers (e.g. UKWIR, 1997). Animal manure is a greater risk than sludge biosolids because
26 112 they contain more soluble-P. Biosolids have been eluted as a result of the water-borne transfer
27 113 process, which removes soluble-P to the liquid phase and the solid-phase-P has been stabilised
28 114 by biosolids treatment. Smith et al. (2000) added different forms of biosolids to two different
29 115 moist soils (sandy loam at pH 6.2 and calcareous clay at pH 8.1) and measured the change in
30 116 sodium bicarbonate extractable P with time. The majority of the re-equilibration of P between
31 117 the biosolids and the soil occurred within a few hours, followed by a much slower increase in
32 118 extractable-P, which continued for more than 60 days. The pattern of change was related to the
33 119 type of soil and its starting content of bicarbonate extractable P. It was also related to the type of
34 120 treatment to which the biosolids had been subjected. Availability of biosolids-P was in the order
35 121 thermally dried<<cake<liquid. It has been reported that lime-stabilised sludge can leach greater
36 122 proportions of phosphorus than other biosolids (Kostyanovsky et al., 2011). However, recent
37 123 data suggests that this form of sludge treatment is becoming less popular in the UK, with
38 124 anaerobically digested sludge now being favoured (UKWIR, 2006). Injection of sludge into soils
39 125 is also now the preferred option for application, rather than surface spreading, as it both reduces
40 126 runoff likelihood as well as reducing odour issues (UKWIR 1997).
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47 128 Although some leaching has been detected in soils amended with lime stabilized biosolids
48 129 (Kostyanovsky et al., 2011) attributed to the colloiddally facilitated transport of organic P and
49 130 mineralization; the high binding capacity of the biosolids were considered to pose little risk of P
50 131 leaching into groundwater. Most of the anaerobic digested biosolids P was complexed in Al and
51 132 Fe forms with P in the lime stabilized biosolids associated with Ca.
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54 134
55 135 Accurate scenario modeling techniques are needed to explore the potential effectiveness of
56 136 programs of measures considered for application under the WFD. Here we assess possible
57 137 scenarios for catchment-scale P management using INCA-P, a process based, catchment-scale
58 138 model of P dynamics (Wade et al. 2002). In particular, we simulate the impacts of two
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4 139 management practices which may be applied within a catchment to control in-river P
5 140 concentrations. These two management strategies include using different types of fertilizers with
6 141 varying P leaching rates and seasonal end of pipe control of WWTP effluent concentrations via
7 142 seasonal permits, to limit P concentrations in UK rivers under low flow summer conditions,
8 143 when ecological impacts are most significant. The model was used for scenario evaluation in
9 144 four catchments of varying typology and geographic location: the Lunan in Scotland, the
10 145 Wensum in Norfolk, the Test in Southern England and the Tywi in Wales.
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14 147 **METHODOLOGY**

15 148 **INCA model**

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17 150 In order to model P in UK catchments, the dynamic, process based model INCA (Integrated
18 151 Catchment) model has been used. This model is semi- distributed and incorporates the key
19 152 processes operating in both terrestrial and aquatic environments. The philosophy of the INCA
20 153 model is to provide a process-based representation of the factors and processes controlling flow
21 154 and water quality dynamics in both the land and in-stream components of river catchments,
22 155 whilst minimising data requirements and model structural complexity (Whitehead et al., 1998a,
23 156 b). As such, the INCA model produces daily estimates of discharge, and stream water quality
24 157 concentrations and fluxes, at discrete points along the main channel of a river. The model is
25 158 semi-distributed, so that spatial variations in land use and management can be taken into account,
26 159 although the hydrological connectivity of different land use patches is not modelled in a fully-
27 160 distributed manner. Rather, the hydrological and nutrient fluxes from different land use classes
28 161 and sub-catchment boundaries are modelled simultaneously and information fed sequentially into
29 162 a multi-reach river model. The INCA model, in its various forms, has been extensively applied
30 163 across Europe (UK, France, Sweden, Denmark, Norway, Austria, Finland, Romania, and
31 164 Turkey) and around the world in Nepal, Brazil and Canada. The major applications of INCA
32 165 have been published to date in three special volumes of International Journals, namely,
33 166 Hydrology and Earth System Sciences, 2002, 6, (3), Science of the Total Environment, 2006,
34 167 365, (1-3) and Hydrological Research, 2009, 40 (2-3).
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41 169 In this study, we have used the INCA-P version of the model. INCA-P is a physical, process-
42 170 based model, as shown in Figure 1, which simulates flow, sediment, phosphorus (TP, PP and
43 171 SRP) in soils, groundwaters, streams and sediments (Wade et al., 2002b, 2009, Whitehead et al.
44 172 2011, 2013, Crossman et al. 2012, 2013). It has both a land component and a river component,
45 173 allowing it to track P inputs which flow into the river from the land surface throughout the
46 174 catchment. INCA-P is a distributed model and takes account of spatial variations in land use,
47 175 vegetation and hydrology by dividing the catchment into sub-catchments or into a multibranch
48 176 network of tributaries and streams that flow into a main river system (Whitehead et al., 2011).
49 177 The INCA model has partitioning algorithms which calculate the proportions of P adsorbed to
50 178 the soil, something many models do not have, thus making simulations more accurate. It also has
51 179 equilibrium equations controlling the water- sediment exchange based on a Langmuir isotherm
52 180 approach, so that a realistic exchange of P between water phase and solid phases is possible
53 181 (Wade et al, 2009).
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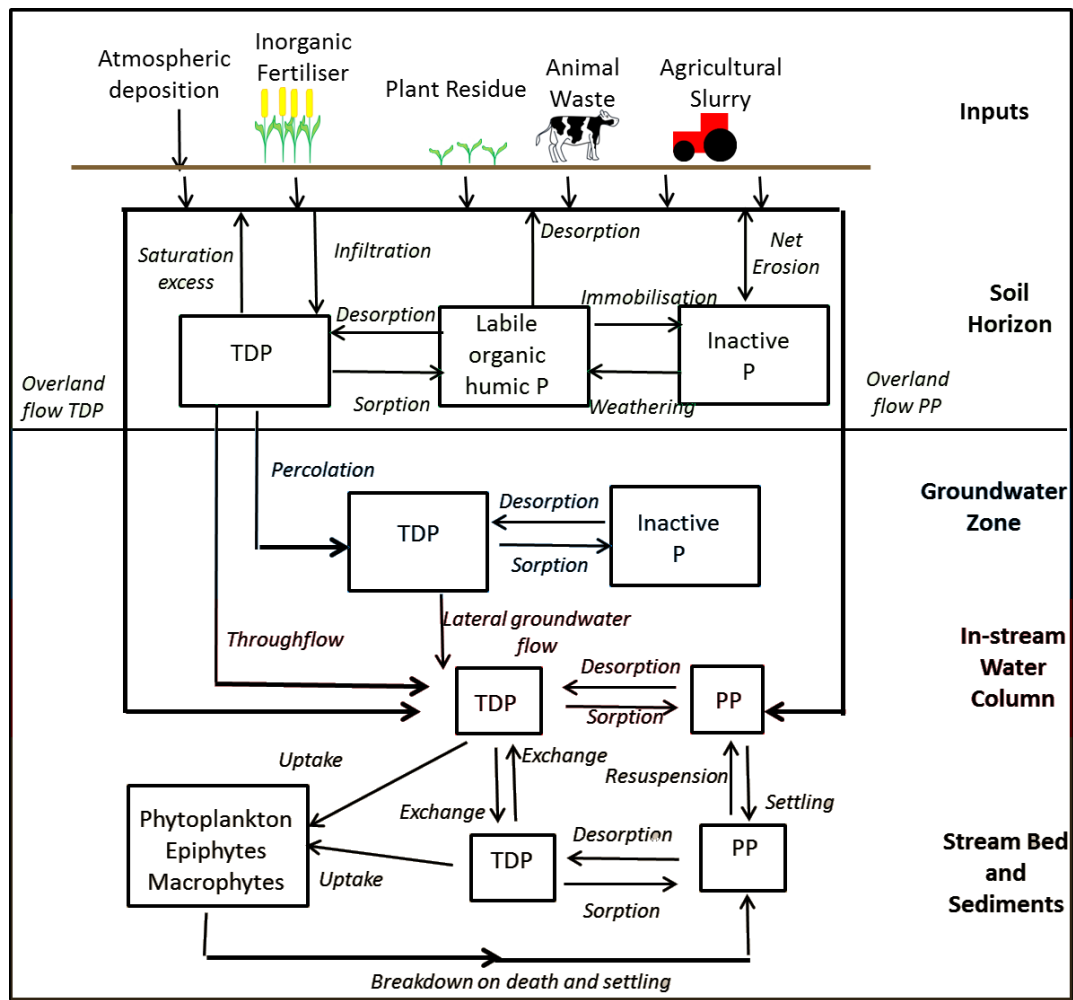


Figure 1 The INCA-P Model nutrient flows and process controls

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 River Test 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 River Test (England) is a high status chalk catchment dominated by grassland with some significant WWTP inputs. The River Wensum (England) is a mixed arable catchment and the Lunan (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 WWTP 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

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205 provide consistency and allow comparison across catchments, fertilizer applications were
 206 assumed to take place in each catchment at the same time of year in the spring.

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 208 **Table 1 Summary of catchment characteristics**
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Catchment	Test	Tywi	Wensum	Lunan
Area (km ²)	1108	1090	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 (Andover/Romsey + 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 84,000 population, across 10 main WWTP, biggest ca. 50,000 (Andover)	Main sewerage for population of 5560 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

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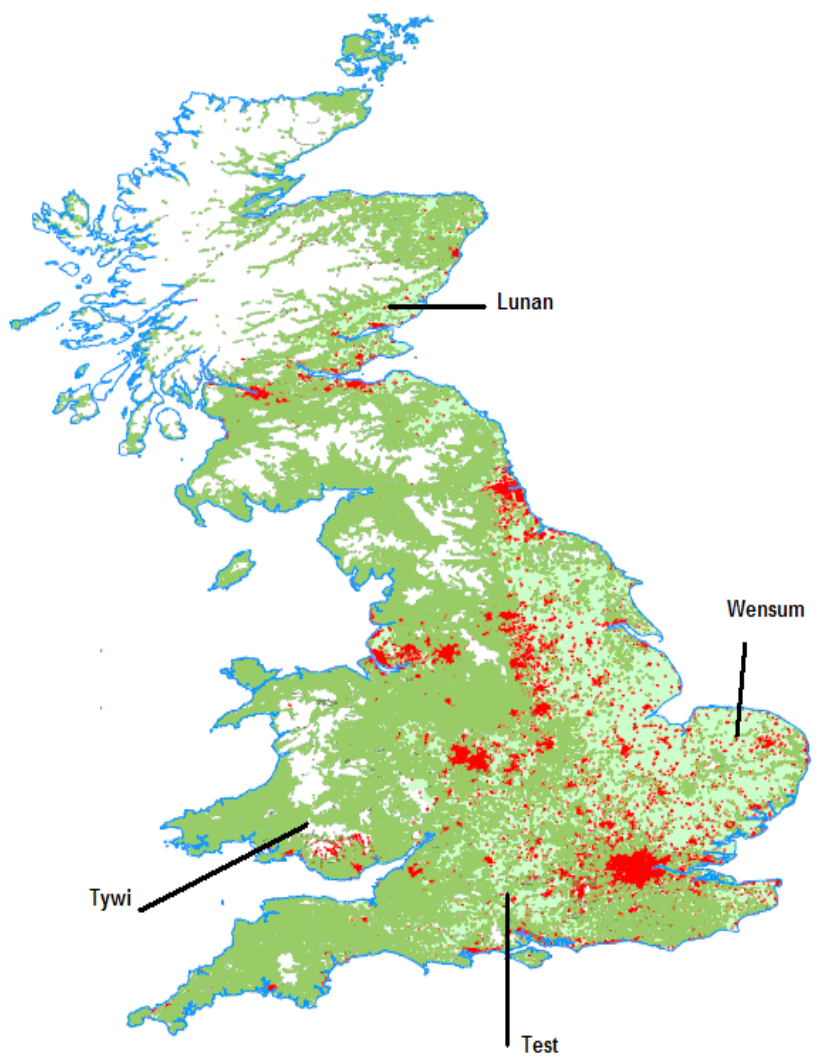


Figure 2 UK map showing locations of the four rivers modeled and also land use (Red areas are urban, light green areas are arable and darker green are pastures)

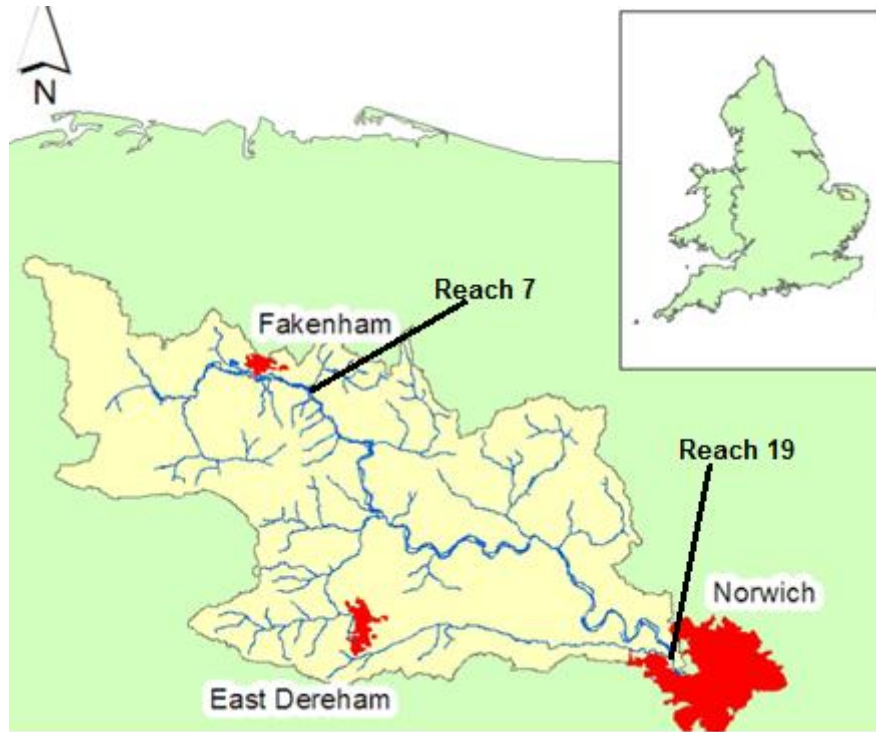


Figure 3 River Wensum Catchment in Eastern England

SCENARIO STRATEGY

Environmental legislation is now driving investment to reduce P discharges to surface waters via the UWWTD which sets numeric annual average TP concentrations of 2 mg/l for works serving populations between 10,000 to 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 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 WWTP across the modelled catchments there is little 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 Test, 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 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 stabilised 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 permits applied from 2010 onwards, reflecting the agreed investment to reduce P loads to the river. In order to determine the contribution from WWTP 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 and 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 fertiliser is used within the catchment.

Table 2 Wensum catchment WWTP data

WWTP within Wensum catchment	Population	Effluent flow ¹ (m ³ /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		2.5	4.53 ³
WWTP2	21,333	3,769	2	1	5.92 ²
WWTP3	601	160	-	2	4.53 ³
WWTP4	16,069	3,300	2	1	4.32 ³
WWTP5	1,144	299	-	1	4.53 ³
WWTP6	620	150	-	-	4.53 ³
WWTP7	3,487	720	-	1	4.53 ³
WWTP8	1,159	262	-	1	4.53 ³
WWTP9	3839	850	-	1	4.53 ³
WWTP10	612	227	-	1	4.53 ³

¹ Permitted dry weather flow. ² Measured data. ³ mean of data reported from Comber et al., (2010)

Table 3 Wensum Catchment Scenarios

Scenario	Permit			Diffuse agricultural inputs
	WWTP2	WWTP4	Remaining WWTPs	

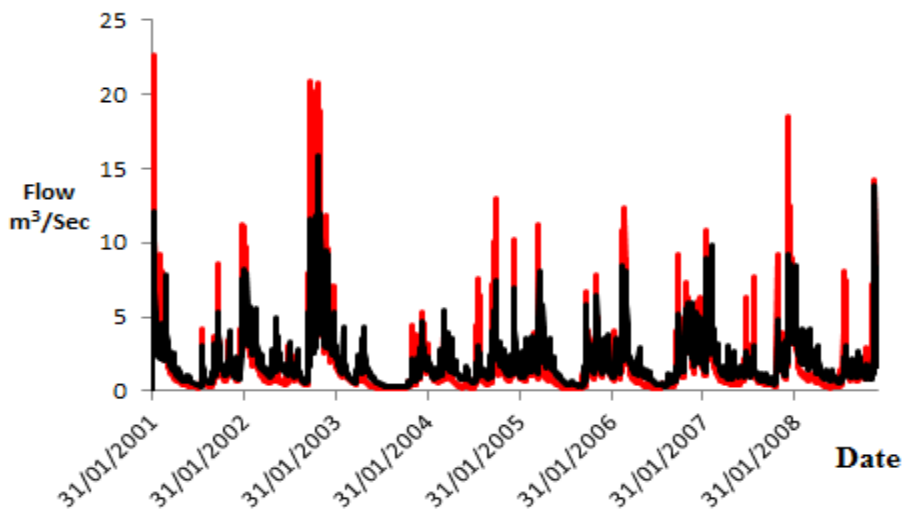
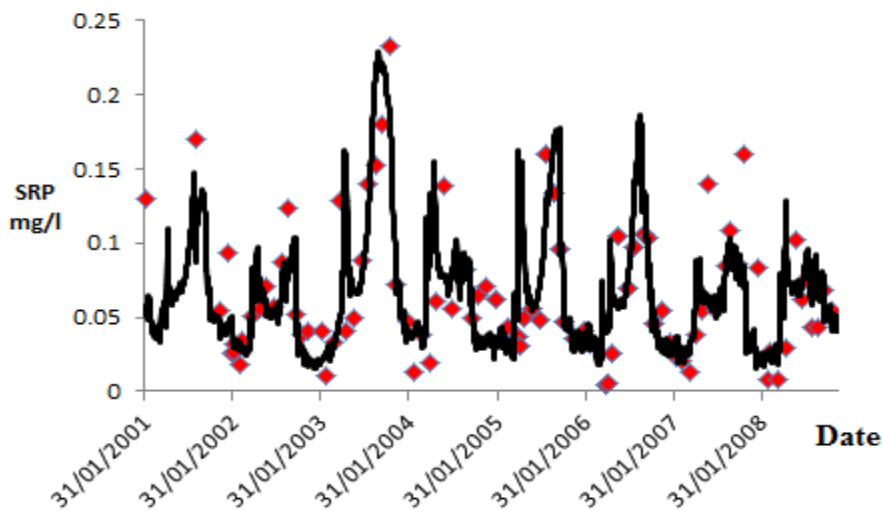
1	2010 onwards permit set at 2 mg/l	2010 onwards permit set at 2 mg/l	2010 onwards permit	Only inorganic fertilizer used on land
2	2010 onwards permit set at 2 mg/l	2010 onwards permit set at 2 mg/l	2010 onwards permit Apr - Sep. No permit in winter (Oct - Mar)	Only inorganic fertilizer used on land
3	April - September permit set at 1 mg/l P	April - September permit set at 1 mg/l P	2010 onwards permit Apr - Sep. No permit in winter (Oct - Mar)	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 Apr - Sep. No permit in winter (Oct - Mar)	Only inorganic fertilizer used on land

SIMULATION AND SCENARIO RESULTS

The INCA-P outputs were compared with measured phosphorus concentrations reported by the Environment Agency (Tywi, Test, Wensum) and Scottish Environmental Protection Agency (SEPA) for the Lunan catchment. An example of the outputs is provided in Figure 4 for the Lunan catchment. For all catchments an acceptable agreement was found based on baseline runs simulating current catchment dynamics. This provided confidence in applying the identified scenarios to the four catchments.

Simulations suggested that biosolid substitution would reduce in-river P concentrations in the four study catchments (Figure 5, Table 3). 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 3). In all cases, the replacement of inorganic fertilizer with biosolids produces a reduction in river P concentrations. Concentration reductions range from around 5% in the River Test to approximately 35% in the Tywi, with the Wensum 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.

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288 **Figure 4 Simulated (Black line) and Observed (Red line) for Flow and SRP in the River**
289 **Lunan**

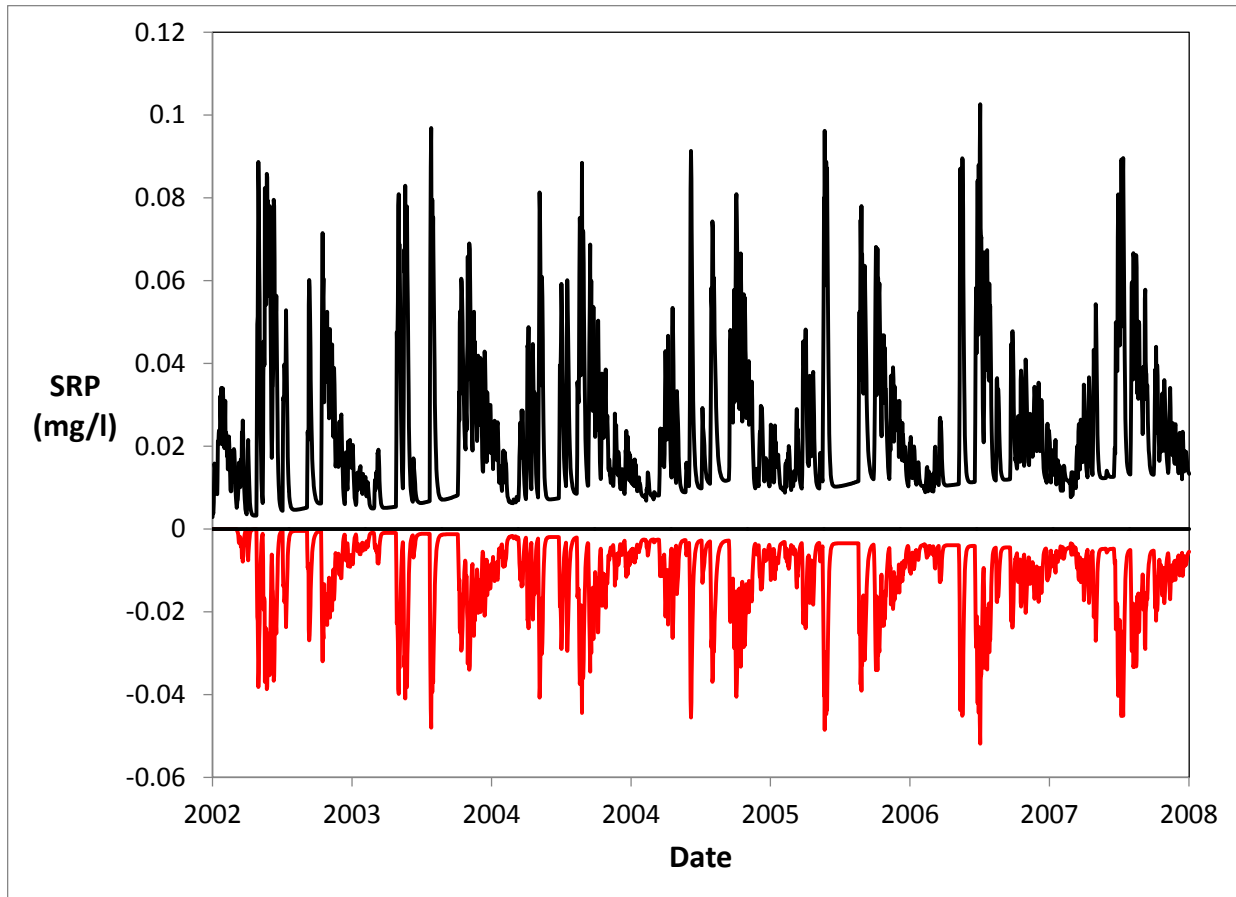


Figure 5 INCA-P output for River Tywi showing baseline Superphosphate (black line) and expected reduction in SRP (red line) that could be achieved with 50% of Inorganic P fertilizer replaced with Biosolids (digested cake)

Table 4 Percentage Reductions in TP and SRP Concentrations from Biosolid Substitution at the Outflow of Four River Catchments

	TP Concentration Percentage Reduction		SRP Concentration Percentage Reduction	
	Lime Stabilised cake	Digested Cake	Lime Stabilised cake	Digested Cake
Tywi	35.1	41.0	36.0	41.2
Lunan	11.3	12.1	11.2	12.1
Wensum	7.9	10.0	4.5	6.1
Test	4.1	4.3	4.1	4.4

Agricultural Impacts, Effluent Treatment and Seasonal Consent Standards

Table 4 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 current operating plan. The second scenario

305 assumes a summer permit of 2 mg-P/l for the all the works during the summer. During winter it
 306 is assumed that there are no permits for the smaller works. In the third scenario it is assumed that
 307 two large works (WWTP 2 and 4) are reduced to 1mg/l with no permits for the smaller works in
 308 winter. The final scenario explored the impact of permits lower than the tightest UWWTD value
 309 for the two largest works (0.25 mg-P/l) for the summer months and no permit for smaller works
 310 in winter.

311
 312 The data in Tables 5 and 6 below show how significant the influence of the WWTP are on two
 313 reaches, one of which is downstream of WWTP4 below Fakenham (Reach 7, Figure 2) and the
 314 other is at the downstream reach of the Wensum at Norwich (Reach 19, Figure 2). Under current
 315 permitting conditions (2010 onwards) winter river P concentrations are close to the high quality
 316 EQS of 0.05 mg/l SRP, whereas summer concentrations are above the EQS. Setting a 1 mg-TP/l
 317 summer permit would reduce in-stream SRP concentrations to close to the EQS. If effluents at
 318 the two largest works were reduced to 0.25 mg/l, the instream concentrations fall well below the
 319 EQS in summer. These reductions are of the order of 30% and 50% during the summer months.
 320 However, the winter concentrations rise because the standards are relaxed at the other WWTPs
 321 and this amounts to an increase of 33% at reach 19, although the instream concentrations are still
 322 within the high quality EQS. The simulations for the Wensum therefore suggest that certain
 323 benefits may be derived from seasonal permits particularly if improved phosphorus removal
 324 (beyond UWWTD requirements) at WWTP can be cost-effectively achieved during summer
 325 months. Also, Figure 5 suggests that reductions in the summer months are approximately
 326 proportional to SRP concentration.

327
 328 Table 5 SRP concentrations simulated under the varying seasonal scenarios compared against
 329 2010 on going permit conditions - Scenario1 (% reduction in brackets)

	WWTP 2 & 4 effluent P concentration (mg/l)	Summer SRP concentration (mg/l)		Winter SRP Concentrations (mg/l)	
		Norwich	Fakenham	Norwich	Fakenham
Scenario 1	2	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)

330 **Note: current permitting conditions apply to other WWTP**

331 Progressive reductions in agricultural P fertiliser inputs in the River Wensum were simulated.
 332 Results showed that reducing diffuse agricultural P fertiliser, whilst leaving WWTP inputs at
 333 current 2010 onwards levels, exhibits a linear response of 2e-4 mg P/l for every % reduction in

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334 agricultural inputs (for any given reach) with a maximum reduction of up to around 35%
335 assuming no point source agricultural discharges.
336

337 **DISCUSSION**

338 The simulations for the rivers illustrate the differing effects of point and diffuse P sources on
339 catchment water quality, and support the needs for multi-option, catchment based plans to
340 effectively reduce overall riverine P concentrations. Applying the INCA-P model to the four test
341 catchments and assessing the impact of substituting 50% of inorganic P fertilizer used within the
342 catchment with biosolids predicted variable decreases in TP and SRP within the catchments. The
343 general reduction in phosphorus loss from agricultural as a result of substituting biosolids for
344 inorganic phosphate fertilizers reflects the lower leaching potential of P from biosolids compared
345 with inorganic phosphates (UKWIR, 1995). This is unsurprising as the biosolids themselves have
346 an adsorption capacity not present in a mineral-based inorganic fertilizer. The amount of P lost
347 via leaching will therefore be controlled by competition for adsorption sites determined by redox
348 potential, pH and Ca concentrations, as well as soil properties such as water content, particle size
349 and organic content. The ability of biosolids to retain P within their own matrix, whilst still
350 making it available for plant growth means that they may be preferentially applied to agricultural
351 land where application of inorganic fertilizer may result in leaching into adjacent watercourses
352 (UKWIR, 2006).

353 The variation in the degree of P reduction within the catchment resulting from using biosolids
354 rather than inorganic phosphate fertilizer may be a result of a number of possibilities:

- 355 • The Test and the Wensum with lower percentage reductions in concentrations being
356 primarily chalk catchments with high base flow indices. This suggests that the biosolids
357 effect will be less significant as nutrient reductions will be delayed by the longer
358 residence times are longer.
- 359 • The Tywi with more surface water flows shows the highest effects reflecting the more
360 rapid response of the catchment.
- 361 • The Lunan with an intermediate base flow index showing a moderate reduction.

362 It should also be noted that some variation in the solubility of biosolid P is to be expected, which
363 will add some degree of uncertainty to the modelled P reductions.

364 Biosolids application cannot be seen as a panacea for the problems of disposing of WWTP P.
365 Like the use of inorganic fertilizers, excessive application of biosolids have been linked to P
366 concentration accumulating in soils in the US (Penn and Sims 2002, Shober and Sims 2003),
367 New Zealand (Wang et al. 2008) and Australia (Pritchard et al. 2007). Different WWTP
368 processes have different effects on P bioavailability and leaching as already discussed earlier
369 (Penn and Sims 2002; Wang et al. 2008). Efforts must be made to balance P leaching rates
370 against phytoavailability so as to ensure optimum plant growth while minimising leaching to
371 receiving waters.

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372 It must be accepted, however, that there are a number of uncertainties impacting on the data
373 generated from the model, including the leaching potential of the different types of biosolids,
374 which (as has been explained in the introduction) will vary depending on its composition, the
375 application process and soil type upon which it is applied. The model serves as a first step
376 towards making informed decisions regarding catchment management.

377 Examining the more detailed outputs generated for the Wensum catchment suggests that further
378 treatment of effluents at the largest WWTPs (2 and 4) would have a significant impact on
379 downstream water quality, albeit at a significant cost without certainty of a change in ecological
380 status. One option for more effective use tertiary treatment would be to undertake seasonally-
381 adjusted phosphorus reduction at WWTP, with enhanced treatment in the summer when
382 biological activity is greatest. The model outputs suggest that reducing phosphorus in the effluent
383 to 0.25 mg/l would typically halve the concentrations in the catchment, to levels well below the
384 current standard (0.12 mg-SRP/l) and below the high EQS status. Owing to higher flows in the
385 winter, leading to greater dilution, then P dosing could be relaxed and still achieve the desired
386 high EQS. An important aspect of any decision to move towards seasonal permitting is if there is
387 a relaxation of permits during the winter, will P be stored in sediment downstream, only to be
388 released sometime in the future? It is possible that P stored in the sediments will be released in
389 the summer. However, it is also possible that less eutrophic conditions caused by lower summer
390 P inputs will preserve well-oxygenated conditions and that the P will remain bound to the
391 sediment.

392 This possible fate of sediment bound P would need to be considered on a case-by-case basis
393 using models such as INCA-P which have a process component for predicting sediment-water
394 interactions. Re-profiling the chemical dosing regime to allow seasonal permitting could lead to
395 better environmental outcomes, in a cost-neutral way for Water Companies, at least in the
396 interim until further source control measures are put in place to reduce phosphorus inputs to
397 WWTP.

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

407 The modelled scenarios also show that reducing agricultural discharges will have a significant
408 impact on river concentrations, which is unsurprising as along with WWTP effluent input these
409 are the dominant sources of phosphorus within the catchment (Comber et al., 2010). Overall, the
410 data suggests that by taking a catchment-based view, it is possible to ensure compliance using
411 seasonal-based permits, taking account of local situations associated with hydrology and
412 ecology. Data such as that presented here, combined with cost-effectiveness of agricultural and
413 effluent-based measures will allow planners to identify the most cost-effective, catchment based
414 programmes of measures to assist in delivering WFD objectives. In all cases, owing to the

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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 there that substitution of inorganic fertilisers 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 there should be investigated further, to provide a more flexible approach (potentially at no overall increase in cost) to meeting WFD objectives.

ACKNOWLEDGEMENTS

The authors would like to thank UK Water Industry Research for funding this work, in particular to the project manager, Manocher Asaadi and the Project Steering Group members for assistance with data collection and interpretation. We would also like to acknowledge the assistance provided by SEPA regarding data supplied for the Lunan catchment in Scotland. We also acknowledge the assistance of the Environment Agency for access to river water quality and flow data.

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