Effectiveness of eutrophication control by phosphorus reduction: development of the INCA-P model

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Executive summary

The Environment Agency (the Agency) needs to be able to model the runoff of nutrients from land to waterbodies (river and lakes) to assess the hydrochemical and ecological response to eutrophication control measures, such as nutrient removal at Sewage Treatment Works (STWs) and land management changes. The Habitats Directive and Water Framework Directive require the Agency to undertake such assessments at a catchment level.

This report is concerned with the development of the Integrated Catchments model of Phosphorus dynamics (INCA-P) and the provision of a model-based assessment of the phosphorus dynamics within three major UK river systems: the Ant (Norfolk), the Lugg (Powys, Herefordshire) and the Kennet (Wiltshire and Berkshire). These three systems are of interest because they represent regionally significant water resources, and provide contrasting upland and lowland systems impacted by both diffuse and point sources.

To set up and calibrate the model, this study utilised data from both past and contemporary studies to describe the catchment hydrology, the phosphorus concentrations and ecology of the stream water, the land use distribution and land management practices within each river system. In all three river systems, the spatial and temporal variations in the observed stream water phosphorus and suspended sediment concentrations exhibit complex patterns and a highly heterogeneous response. These patterns represent the complex interaction between the factors and processes controlling the transport and retention of phosphorus within the land and in-stream phases, and the influence of point source inputs.

Daily data have proved invaluable in assessing INCA-P's ability to simulate catchment phosphorus dynamics, and it is highly recommended that fine-scale water quality measurements are made in other hydrochemical research programmes to help understand system dynamics and to constrain and develop environmental models. The lack of detailed point source data is particularly problematic not only in the application of INCA-P, but also in the general assessment of the relative contribution from point and diffuse sources. It is recommended that consideration be given within the Environment Agency to the collection of such data. Despite this, analysis of the land use and management data coupled with a detailed assessment of the point source inputs and the Agency's archived water quality data provided a powerful technique for assessing the spatial and temporal variations in the phosphorus inputs to the three systems, especially when the analysis was integrated within INCA-P to evaluate the land and in-stream mass-balances.

INCA-P is based on the mixing of waters from different land use types and flow pathways, with the concentrations of the direct runoff, soil water and groundwater end-members modified by the driving input data and the simulated processes. Given the model was able to simulate the first-order spatial and temporal variations in the flow, suspended sediment, phosphorus (as total phosphorus, total phosphate and orthophosphate) concentrations in the Ant, Lugg and Kennet river systems, then this representation appears reasonable. Moreover, the results of a sensitivity analysis supported this model structure.

In each application, the equations describing the macrophyte and epiphyte growth reproduced a sine-wave response, with a peak in macrophyte growth in the spring/summer period. Such a response has been observed in other UK rivers for which data are available. The model was also able to simulate the response observed in the stream water boron and phosphorus concentrations, and the macrophyte biomass resultant from phosphorus stripping at Marlborough Sewage Treatment Works on the Kennet.

In addition, the model was used as a tool to determine the relative proportion of point and diffuse inputs in the Ant and Lugg systems. This suggested that only approximately 1 per cent of the phosphorus input to the land reaches the stream. In the upper and lower regions of the Lugg, which represents a transition from livestock-based farming in the headwaters to more arable production and a greater number of point sources in the lower reaches, the estimated relative contribution of point and diffuse sources, based in INCA-P outputs, is 1:9 and 1:1 in the headwaters and lower reaches, respectively. Furthermore, within the Lugg, INCA-P coupled with a Geographical Information System based data-analysis, has been used to assess the location of phosphorus-rich areas, the contrast between upland and lowland reaches, the contribution of the Lugg to the phosphorus load in the Wye, and to assess the potential affects of phosphorus stripping on in-stream phosphorus concentrations.

INCA-P is an intermediate-complexity modelling tool and requires training to learn how to set up and apply it. There are some data costs associated with applying the model to a river system, though typically these will be less than £1,000. It is not envisaged that the model could be applied to assess the phosphorus budget at a national scale. Instead, the model would form part of a hierarchy of models in which steady-state models such as the Export Coefficient Method or the Phosphorus Indicators Tool would provide a national summary of phosphorus loss, and INCA-P would provide a detailed assessment of an individual catchment where a particular research or management question exists.

Further work is required to improve the model’s simulations of soluble reactive phosphorus concentrations in the stream. As a first step, it is proposed that two new stores are required to explicitly track soluble reactive phosphorus. Despite this need for modification, this application of INCA-P has clearly demonstrated its utility as model of phosphorus dynamics within large river systems, being able to link hypothesis regarding the factors and processes controlling phosphorus transport and retention. The model has been shown to be useful as a learning tool regarding the hydrochemical functioning of river catchments and for estimating the likely response to environmental perturbations such as the introduction of tertiary phosphorus treatment at sewage treatment works. Thus, INCA-P is a useful tool for assessing the effectiveness of eutrophication control by phosphorus reduction.

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1. Introduction

1.1 The phosphorus water quality issue

It is now widely accepted that phosphorus (P) is the major limiting nutrient in UK freshwater systems for the majority of the year, although nitrogen (N) can be limiting in lakes and may control ecosystem diversity to a greater extent than phosphorus. As such, there are concerns regarding the effects of increased phosphorus loads to lakes and river systems as these can over-enhance the nutrient status of a water body. This over-enhancement can affect the composition and diversity of aquatic plant species, attached algae and phytoplankton by changing the competitive balance (Mainstone, 2000). For example, studies of the major rivers draining into the Broads Special Area of Conservation (SAC) / Broadlands Special Protection Area (SPA) have shown a link between nutrient over-enrichment and adverse impacts on the submergent plant communities, increased phytoplankton abundance and increased frequency of algal blooms (Moss *et al.*, 1985; Moss *et al.*, 1988).

Phosphorus in river and lake systems is derived from external and internal loads. External loads come from diffuse and point sources on the land surface. Within the UK, the major diffuse sources result from the application of fertiliser to crops and manure from farm animals, while the major point sources are derived from Sewage Treatment Works (STWs) and industrial discharges. Internal loads are generated from phosphorus sources within the water body, such as the sediment and decaying organic matter. Phosphorus is a highly reactive element and the dynamics of its transport both in the plant-soil system and within the aquatic environment are complex. Moreover, the relative contributions of phosphorus from the external and internal sources are highly variable in both space and time (Jarvie *et al.*, 2002).

Nutrient over-enrichment lies at the centre of European Union (EU) and UK environmental policy, which is designed to mitigate and prevent water quality problems such as eutrophication, and to reduce the water treatment costs for producing water suitable for industrial and public consumption. As part of EU legislation that includes the Water Framework, Habitats and Urban Waste Water Treatment Directives, it is necessary to regulate the phosphorus loads entering lake and river systems considered sensitive to nutrient inputs (Council of the European Union, 2000). However, control measures introduced in response to Directives and environmental policies, such as those incorporated in Asset Management Plans (AMPs), must balance the need between protecting the water resource, the maintenance of a viable local and national economy, and the provision of drinking water and effluent disposal.

Mathematical models can aid the understanding of phosphorus dynamics within river systems, since such models begin to link ideas of phosphorus transport and storage thereby aiding the understanding of the hydrochemical and ecological functioning. Moreover, models are required to quantify the potential impacts of changing phosphorus loads on the water quality and ecology of aquatic environments. Such quantification is especially important when assessing the consequences of introducing potential control measures derived from current legislation.

Models of phosphorus in lake systems have evolved from mass balance, steady-state models (Vollenweider, 1975; Vollenweider, 1976) to dynamic representations that account for sediment-water interactions, stratification and macrophyte dynamics (Asaeda and Van Bon, 1997; Chapra, 1997). More recently, the Agricultural NonPoint Source Pollution model (AGNPS) and the Water Quality Analysis Simulation Program (WASP) have been integrated to assess the temporal and spatial changes in external and internal loads to a reservoir (Kao *et al.*, 1998). Models of phosphorus loadings to rivers such as the Export Coefficient Method (ECM) (Johnes, 1996) are also available. However, while ECM provides a relatively simple method for estimating the spatial variation in phosphorus loading at the national and international scale, it does not include process representation and therefore can not generate daily time-series of phosphorus concentrations. As such, it may under-estimate phosphorus export under high flow conditions. To some extent, this problem is addressed by the model of Gubrek and Sharpley (1998), which models phosphorus export from source areas within a catchment and routes the export to the stream. However, the data intensity of this model limits its application to small research catchments.

1.2 The Integrated Catchments Model of Phosphorus dynamics (INCA-P)

The Integrated Catchments Model of Phosphorus dynamics (INCA-P) provides a process-based representation of the factors and processes controlling phosphorus dynamics in both the land and in-stream components of river catchments while minimising data requirements and model structural complexity (Wade *et al.*, 2002b). INCA-P aims to extend current research and is designed to investigate:

- the transport and retention of phosphorus in the terrestrial and aquatic environment, and
- the impacts of the phosphorus load on the in-stream macrophyte biomass.

This new model builds on the established Integrated Nitrogen in Catchments Model (INCA) which is a dynamic, process-based hydrochemical model that simulates nitrogen in river systems and plot studies, and the ‘Kennet’ model which simulates in-stream phosphorus and macrophyte/epiphyte dynamics (Wade *et al.*, 2001; Wade *et al.*, 2002a). As such, INCA-P represents an advance towards a generalised framework for simulating water quality determinands in heterogeneous river systems which started with the INCA model.

The input fluxes that the INCA-P model takes into account are:

- inorganic-P fertiliser and farmyard manure (FYM)
- slurry applications
- livestock wastes.

Various output fluxes (plant uptake, movement to firmly bound P forms) are subtracted from these inputs before the amount available for stream output is calculated (Figure 1). These inputs and outputs are differentiated by land use type and varied according to environmental conditions (e.g. soil moisture and temperature). The model accounts for stocks of inorganic and organic phosphorus in the soil (in readily available and firmly bound forms), in groundwater and in the stream reaches (Figure 2).

The model simulates the flow of water through the plant/soil system from different land use types to deliver the phosphorus load to the river system. This is then routed downstream after accounting for direct effluent discharges and in-stream biological and sediment interactions (Figure 3). As such, the INCA-P model produces daily estimates of discharge, and stream water total phosphorus (TP) and soluble reactive phosphorus (SRP) concentrations and fluxes at discrete points along a river's main channel (Figure 2). Because the model is semi-distributed, 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 the same manner as a fully distributed approach such as SHETRAN (Birkenshaw and Ewen, 2000). Instead, the hydrological and nutrient fluxes from different land use classes and sub-catchment boundaries are modelled simultaneously, and information is fed sequentially into a multi-reach river model.

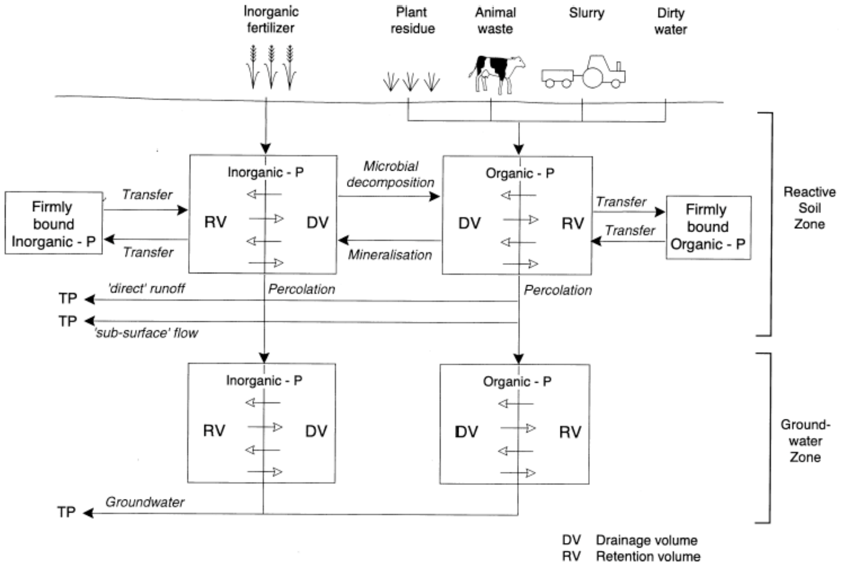

Figure 1 Structure of the cell model used to simulate phosphorus processes and transport mechanisms within the land component of INCA

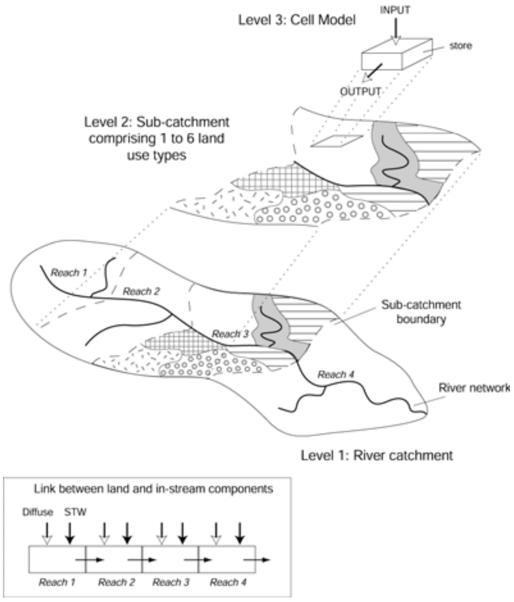

Figure 2 Integration of the landscape delivery and in-stream components of INCA-P.

At level 1, the catchment is decomposed into sub-catchments. At level 2, the sub-catchments are sub-divided into six different land use types. At level 3, the soil nitrogen transformations and stores are simulated using the cell model. The inset diagram shows the link between the land-phase delivery and in-stream components at level 1: the diffuse inputs from the land-phase are added to the effluent point source inputs and routed downstream.

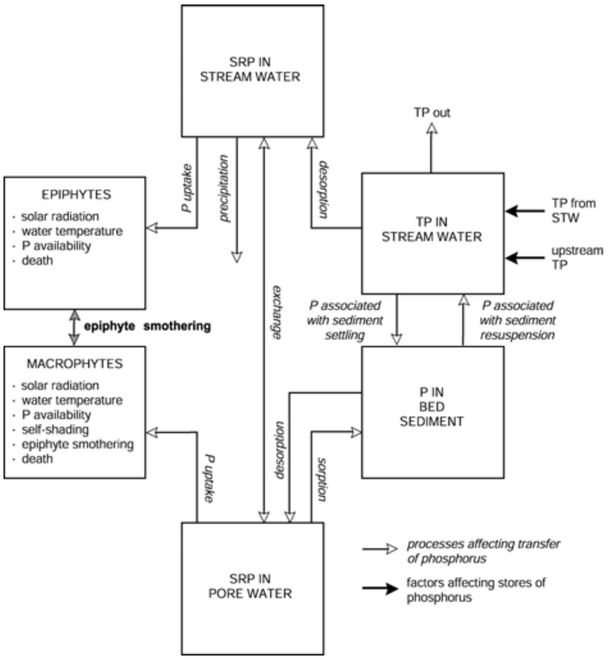

Figure 3 Phosphorus inputs, processes and outputs in the in-stream component

1.3 The scale issue and water quality modelling

Currently, there are three major issues in hydrological and hydrochemical modelling resultant from the fact that the hydrological, hydrochemical and ecological factors and processes are highly heterogeneous in space and time (Beven and Freer, 2001). First, the scale of field or laboratory measurements is often different to the scale at which the model is developed and intended for application: measurements (e.g. phosphorus leaching rates) are often made at a single point in space, whereas in a catchment-scale model, such rates may be applied to a field or land use type (Durand *et al.*, 2002). Given this issue, most models require calibration: the unknown model parameters are adjusted until the model output matches, or at least closely matches, some observed data – typically an observed time-series of flows and in-stream concentrations (Freeze and Harlan, 1969). This process causes the second difficulty since, given the uncertainty in the calibration process, it is difficult to know the model structure, or the parameter set which provides the best system representation. Moreover, this difficulty hinders the physical interpretation of the model parameters. Finally, the third difficulty is that the calibration of the model parameters necessarily fixes the relationship between model input and output. This introduces further uncertainty into the ability of such models to predict the environmental response to climatic variability or land use change, since such change is likely to shift the relationship between different hydrochemical and ecological processes.

A number of mathematical methods can be applied to help understand the implications of these difficulties for specific model applications, including the application of the Monte Carlo based General Sensitivity Analysis and Generalised Likelihood methodologies. These involve obtaining a number of parameter sets that produce acceptable model behaviour and re-running them through the model to produce an envelope of response, which therefore includes some estimate of the uncertainty in the model parameters and structure. In addition, sensitivity analysis can be used to help identify the model structure by indicating which aspects predominately control the model output, and which parameters are correlated and therefore cause possible over-parameterisation. Such approaches include the well-established method of Spear and Hornberger (1980) and the newly developed Shuffled Complex Evolution Metropolis algorithm (Vrught *et al.*, 2003a; Vrught *et al.*, 2003b). To apply such techniques, it is recommended that the models are applied to systems that are data-rich. The data can be used to define and constrain the model, or provide a rigorous test of its ability to simulate the dynamics of a system (Beven, 2000).

1.4 Study's aims and objectives

This report has two aims. The first is to present the developments of the INCA-P model and the second is to describe the model's ability to simulate the phosphorus dynamics of contrasting river systems.

The study's objectives were to:

- develop INCA-P through its application to simulate the phosphorus dynamics and fractionations within the water column and pore waters along the main channel of three major river systems –

contrasting in physical character, but all impacted by nutrient over-enrichment and with a significant data resource;

- use uncertainty analysis to help identify the model structure and parameters;
- test the operational potential of INCA-P by its application to address scientific questions required to implement current environmental legislation and the associated environmental management.

The three river systems chosen for this study are:

- the River Ant in Norfolk
- the River Lugg in Powys and Herefordshire
- the River Kennet in Wiltshire and Berkshire.

These provide contrasting areas, constituent geology, soils and land use, and phosphorus issues (Table 1).

By pursuing these aims and objectives, it is hoped to improve the capability to assess phosphorus dynamics in river systems and to predict the consequences of changes in diffuse and point source phosphorus inputs.

The report has the following structure:

- sections 2 to 4 describe the model's application to the three river systems
- section 5 contains a report of the sensitivity analysis
- section 6 discusses the implications of the applications and sensitivity analysis
- section 7 provides concluding remarks
- section 8 contains a list of references
- section 9 contains a list of acronyms used in the report

Appendices A–F contain tables of model parameter values relating to each of the three river systems. Appendices G and H present the ranges of values obtained for the model parameters, while Appendix I presents data from the River Ant Application.

Table 1 Catchment characteristics of the three study areas*

	River Ant	River Lugg	River Kennet
Area (km^2)	49	886	1033
Rainfall (mm)	656	850	782
Runoff (mm)	198	394	295
Loss (mm)	458	456	487
Base Flow Index	0.86	0.54	0.87
Q10 (m^3/s)	0.4	26.1	16.9
Q95 (m^3/s)	0.16	1.48	3.76
TP (mg/litre)	0.05 – 0.3	0.05 – 1.0	0.05 – 0.7
Geology	Tertiary: sands and clays	Uplands: Silurian Lowlands: Old Red Sandstone, extensive valley gravels	Cretaceous: 80 per cent chalk
Soils	50 per cent sand and gravel and 50 per cent loam		Mixture of alluvial soil including silts over clays or flints and fine silty loams
Land use	Arable	Upland: forestry, grazing, arable Lowland: arable, urban	Arable
Interest	Slow flowing and can have phytoplankton blooms. P stripping at two STWs.	Distinct upland and lowland areas. Many point source inputs.	Faster flowing than Ant and has stands of macrophytes. Epiphyte blooms in upper reaches. P stripping at Marlborough STW.

*Hydrological data are taken from CEH (2003). Catchment areas quoted are those of the lowest downstream discharge gauge.

2. Application to the River Ant

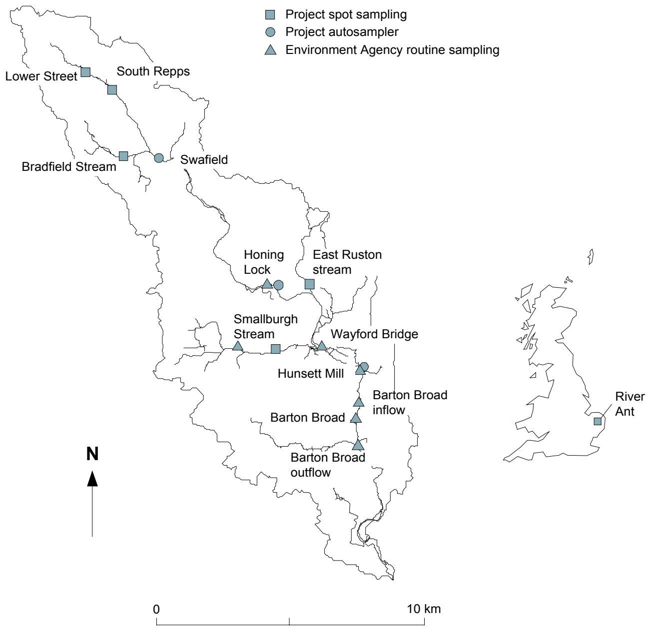

Figure 4 River Ant catchment showing hydrochemical sample sites

2.1 Study area and data resource

2.1.1 Study area

The River Ant in East Anglia was chosen as the study area because:

- it is a significant regional resource
- it is known to be in an area sensitive to changes in phosphorus inputs
- it has a wealth of background data with which to apply INCA-P (Figure 4).

The River Ant flows southwards from north Norfolk to join the River Bure, before draining into the North Sea. The contributing areas at Honing Lock (the only gauging station on the Ant) and Hunsett Mill (the lowest sampling point used in this study) are 47 and 86.7 km^2, respectively. Downstream of Hunsett Mill, the River Ant flows into Barton Broad, a component of the Broads Special Area of Conservation (SAC) and Broadland Special Protection Area (SPA). The river below Hunsett Mill is tidal.

The land use within the catchment is dominated by arable and livestock production. The latter is typically limited to the few remaining areas of undrained grazed marshes and is not intensive (Johnes, 1996). The human population of the catchment is 15,700, of which 5,400 live in the small town of North Walsham (within the catchment boundary). The catchment is approximately 25 km in length with a number of side streams joining the main channel. The soils are typically brown silty-loam overlying shallow sandy subsoil (Wick 3 series, Soil Survey 1984) and the geology is predominantly comprised of tertiary sands and clays.

The long-term mean annual rainfall is 656 mm. Together with the flatness of the land and the relatively free-draining soil, this means that the generation of surface and shallow subsurface storm runoff is limited. The low rainfall, frequent summer storms and high evapotranspiration rates dominate the hydrology. The mean rainfall of 656 mm over the catchment generates approximately 200 mm of runoff equivalent to a mean flow of 0.31 m^3/s at Honing Lock. The Base Flow Index[1] is 0.86, which suggests that most of the water drains down through the soils to a groundwater compartment and, on average, only 14per cent of the water flows from the soils directly into the river system (Gustard *et al.*, 1992). However, significant storms generate mean flow rates of 1.1 m^3/s, and these generate rapid movement of water, sediments and attached phosphorus into and down the river system. The flat, relatively free-draining land and the low rainfall limit the potential for the transport of nutrients from diffuse sources. In addition, the low river gradients allow rapid sedimentation of particulate nutrients once delivered to the river (Johnes, 1996).

The Norfolk Broads provide a case study of the restoration of eutrophic lakes where extensive collaborative research has been carried out into methods of restoration by the Environment Agency and the Broads Authority, with the co-operation of Anglian Water. Although the focus of the research has shifted, over time there has been an emphasis on monitoring of selected sites to gain an understanding of long-term responses. A regional project has produced an assessment of the effectiveness of the initial phosphorus control measures introduced on the River Ant from 1981 and the River Bure from 1986 onwards. Between 1993 and 1996, a joint project between the Agency, the Broads Authority and English Nature using an EU LIFE grant, developed novel techniques of lake restoration, including biomanipulation and sediment iron dosing. The work has enabled the development of a restoration strategy based on the need to minimise phosphorus inputs. As a result, significant investment has been made by Anglian Water and the Broads Authority to further enhance phosphorus control (Barton Broad Restoration Project).

Historically, there were large phosphorus inputs to the River Ant from sewage works and, in the early 1980s, there was a major campaign to reduce point source phosphorus loading on the River Ant. This strategy had considerable success, e.g. phosphorus levels fell from 0.6 mg/litre at Honing Lock to 0.1 mg/litre following diversion of the North Walsham effluent to the North Sea. Further reductions were obtained when phosphorus stripping units were installed at Stalham sewage treatment works. In addition, the Broads Authority is removing phosphorus-rich sediment from Barton Broad.

2.1.2 Data resource

The significant research effort regarding the water quality of the Broads means there has been extensive monitoring of water quantity and quality in the River Ant. The Agency (and its predecessors) has accumulated a substantial database describing the water quantity and quality from 1966 to the present day. In the most recent study (a joint initiative between the Agency and the University of Reading), the focus was on monitoring the dynamic behaviour of hydrochemistry and sediments, and to quantify the diffuse sources of phosphorus in the catchment (Johnes *et al.*, 2003). To supplement

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[1] BFI can be thought of as a measure of the proportion of the river runoff that derives from stored sources.

these detailed water quality data, a farm survey was performed to determine the land use area and distribution within the system, and to characterise fertiliser practice. In addition, data describing the hydrology, elevations and effluent inputs was collated. Table 2 gives details of the hydrochemical sampling programme carried out during this collaborative study, while Table 3 summaries the INCA-P input data.

Table 2 **Hydrochemical sampling programme undertaken in the Ant system from April 1999 to November 2000**

Site	Determinand	Sampling frequency
Lower Street	Water temperature, pH, suspended sediment, TP, SRP, TDP	Weekly
South Repps	Water temperature, pH, suspended sediment, TP, SRP, TDP	Weekly
	Pore water SRP and iron, sediment TP and iron	Once
Swafield	Water temperature, pH, suspended sediment, TP, SRP, TDP	Twice-weekly
	Autosampler TP, suspended sediment, iron and calcium	24-hourly (TP 12-hourly)
	Storm sample TP , suspended sediment and SRP	4-hourly and 2-hourly
	Bedload	Weekly
	Pore water SRP and iron, sediment TP and iron	Once
	Epiphytic algae	Once
	Discharge	March – September 2000
Honing Lock	Water temperature, pH, suspended sediment, TP, SRP, TDP	Twice-weekly
	Autosampler TP, suspended sediment, iron and calcium	24-hourly (TP 12-hourly)
	Storm sample TP, suspended sediment and SRP	4-hourly and 2-hourly
	Bedload	Weekly
	Pore-water SRP and iron, sediment TP and iron.	Once
	Epiphytic algae	Once
	Phytoplankton	June to September 2000
Hunsett Mill	Water temperature, pH, suspended sediment, TP, SRP, TDP	Twice-weekly
	Autosampler TP, suspended sediment, iron and calcium	24-hourly (TP 12-hourly)
	Storm sample TP , suspended sediment and SRP	4-hourly
	Pore water SRP and iron, sediment TP and iron	Once
	Epiphytic algae	Once
	Phytoplankton	June to September 2000

Source: Johnes *et al*., 2003
TDP = Total Dissolved Phosphorus

Table 3 **Summary of INCA-P input data**

	Resolution	Period of data collection	Storage/ retrieval method	Source	Reference
Spatial data					
Land cover	1 km^2	1990	ESRI ArcInfo GIS	CEH	Barr *et al*., 1993
Farm survey	Field		Microsoft Excel	Agency/ AERC	Johnes *et al*., 2003
*River networks	1:50 000		ESRI ArcInfo GIS	CEH	Moore *et al*., 1994
*Reach boundaries	50 m		ESRI ArcInfo GIS	CEH	
Temporal data					
TP, SRP, SS stream water concentrations	Daily (3 sites) and weekly (4 sites)	Apr 1999 to Nov 2000	Microsoft Excel	Agency/ AERC	Johnes *et al*., 2003
Pore water SRP and kg P/kg sediment	Spot in 3 reaches		Microsoft Excel	Agency/ AERC	Johnes *et al*., 2003
*MORECS rainfall, temperature and soil moisture	Daily		Microsoft Excel	ADAS	Hough *et al.*, 1987
Fertiliser survey	Monthly		Microsoft Excel	Agency/ AERC	Johnes *et al*., 2003
Growing season	Lumped mean per MORECS square		Report	Met Office	Hough *et al.*, 1987
Discharge	Daily		Microsoft Excel	CEH/ Agency	
Flow velocity	Spot (Bure)		Report	Agency	
Base Flow Index	Each flow gauge			CEH	Gustard *et al*., 1992

*Data purchased from third parties

ADAS = Agricultural Development and Advisory Service; AERC = Applied Environmental Research Centre; CEH = Centre for Ecology and Hydrology; MORECS = Meteorological Office Rainfall and Evapotranspiration Calculation System; SS = suspended sediment

Stream water hydrochemical data

In the joint preceding study by the Agency and the University of Reading, samples were collected for an 18-month period from April 1999 to November 2000 from eight sites, five on the main channel of the Ant and three on major tributaries – Bradfield Stream, Smallborough Stream and East Ruston Stream (Figure 4). INCA-P simulates the water quality of the main river channel only, and therefore only the sites along the main channel are considered in this study.

At three of the five sites (Swafield, Honing Lock and Hunsett Mill), detailed hydrochemical data are available describing stream water Total Phosphorus (TP) and suspended sediment concentrations at a daily time-step. At these three sites, stream water Soluble Reactive Phosphorus (SRP) concentration data are also available at a twice-weekly resolution. At the other two sites, Lower Street and South Repps Common, weekly measurements of TP, SRP and suspended sediment concentrations were made (Table 2). Determinations of TP, SRP and suspended sediment concentrations were made at 2 and 4 hourly intervals at Swafield, Honing Lock and Hunsett Mill during storm flow conditions. These data have not been used to date in this study as INCA-P simulates a daily time-step. In addition, single pore water TP and SRP concentration measurements were made at three sites, providing an indication of the downstream spatial variation. The methodologies for the hydrochemical determinations are described by Johnes *et al. 2003*).

The results of the hydrochemical monitoring illustrated the importance of frequent sampling in slow flowing rivers where the majority of sediment transport in the water column takes place in high flow events. Based on the data collected the following conclusions were deduced from the data analysis by Johnes *et al. 2003*):

1. It has been estimated that one-third of the total phosphorus load delivered to Barton Broad was transported in storm flow events over the period studied. Loads calculated for the Ant indicate the dominance of particulate phosphorus as a component of the total phosphorus load delivered to Barton Broad from the Upper Ant catchment. This pattern is evident both upstream and downstream from major STWs.
2. The data also suggest that the particulate phosphorus (PP) load may be generated in-stream through sorption of SRP to clay minerals in the presence of Fe(III) or as phosphorus sorbed to soil particles eroded from agricultural land (particularly in the headwater reaches where land is cultivated close to the stream margin).
3. The data collected from the bed load sampling programme confirmed that significant quantities of sediment were being transported as bed load under base flow conditions, and that previous work in these systems had failed to include this source of phosphorus and sediment transport in the construction of phosphorus budgets for Barton Broad.
4. Insufficient data were collected in this programme to allow generation of an accurate estimate of the total mass of material transported as bed load annually, but there is sufficient evidence to warrant further investigation of this pathway. It may be that due to the lack of impediment to flow presented by Honing Lock, a far greater proportion of the sediment and particulate phosphorus delivered to Honing Lock would be delivered downstream to Barton Broad.
5. The sediment chemistry data revealed a pattern indicating a legacy of phosphorus storage in channel bed sediments many years after phosphorus control measures had been put in place at the major STWs. The most notable effect was evident in the sediments at Honing Lock; this probably dates back to phosphorus loads delivered to this reach prior to the diversion of the effluent from North Walsham STW.

6. Despite the introduction of phosphorus control measures at South Repps and Stalham STWs, the phosphorus reserves accumulated in the channel bed sediments continue to provide a source for internal phosphorus loading on the water column downstream from these STWs.

7. It is not currently clear how long it would take for these accumulated deposits to flush downstream to Barton Broad. Given the ongoing phosphorus release from bed sediment to the Honing reach two decades after diversion of the effluent at North Walsham, however, low gradient and slow flowing systems such as the Broadland rivers may take decades to respond fully to phosphorus control measures put in place in the river catchments. INCA-P has been designed to allow an estimate of these time lags in system response by simulating the sorption of phosphorus to suspended sediment and the deposition and re-suspension of sediment to and from the river bed, and the transfer of suspended sediment down the main channel. At present, INCA-P does not model bed sediment entrainment, but this mechanism is simulated in the new model, INCA-sed, currently being developed at the University of Reading.

8. Remobilisation of bed load under moderate to high flow events appears to be a significant mechanism for PP transfer downstream. This may be the primary mechanism by which the sedimentary load is flushed from the system.

9. The field monitoring programme has focused on investigating in-stream phosphorus hydrochemistry dynamics. It has been successful in this respect, but it has provided insufficient data on sedimentary phosphorus sources within the channel and the wider catchment to determine conclusively the origins of this load. This should be the focus of further investigation.

Hydrological data

Daily mean flows for the gauging station at Honing Lock were obtained from the Surface Water Archive at CEH in Wallingford. These data were originally collected by the Agency and cover the period from 1966 to 2002. The gauging station is a crump-type weir utilising the fall of an old navigation lock. Immediately upstream of the gauge is a large marshy area with dense weed growth, from which some flow bypasses the station. Groundwater abstractions moderately reduce the natural runoff.

The data describing the daily Hydrologically Effective Rainfall (HER), Soil Moisture Deficit (SMD) and air temperature were derived from the single-station Meteorological Office Rainfall and Evaporation Calculation System (MORECS version 2; (Hough *et al.*, 1997), and were purchased through ADAS.[2] As part of MORECS, suggested dates are provided, which vary spatially by MORECS grid square, for the onset of growth and harvest/die-back for different crops, grassland growth, and tree bud burst and leaf fall.

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[2] The current cost of daily MORECS data covering a 2-year period is £460 + VAT. This price includes data for up to four land use types for a single soil wetness class.

A relationship between flow and velocity was derived in a previous study for the River Bure using a tracer experiment in terms of $v = aQ^b$, where v is the velocity, Q is the discharge, and ‘a’ and ‘b’ are parameters (Universities of Huddersfield and Nottingham Trent). The River Bure catchment is adjacent to the Ant, and the two are similar in hydrological character. For the Bure, the ‘a’ and ‘b’ parameters were determined as 0.09 and 0.9, respectively.

Farm survey

The farm survey was conducted from April 1999 to April 2000 (Figure 5). Farmers were asked to provide field-scale details of land use area and distribution by crop type, livestock numbers and distribution across each farm, and the rates and timing of fertiliser and manures applications by crop type (Johnes *et al.*, 2003). The survey has provided a record of land use and management in the Upper Ant catchment alongside the observations of phosphorus transport within the River Ant and its tributaries. The survey covered 69 per cent of the total catchment area measured to Hunsett Mill.

In areas where landowners could not be located, crops and grass were mapped by field observation, and application rates and stocking densities were assumed to be the same as those on adjacent farms. The data were mapped within ESRI’s ArcInfo GIS. For non-agricultural land, data from the Institute of Terrestrial Ecology (ITE) Land Cover database were imported into ArcInfo GIS to determine the area of woodland, urban land and ungrazed marsh in each sub-catchment. The distribution of land uses within the Ant catchment is illustrated in Figure 5 and detailed in Table 4.

Table 4 Land use classes used in the application of INCA-P to the Ant system*

Land class	Area (ha)	ECM land class	INCA-P land class	INCA-P livestock distribution
Permanent grass	557	Permanent grass	Grassland	Cows (82 per cent), horses (97 per cent), sheep and goats (98 per cent) on grassland
Temporary grass	0	Temporary grass		
Marshland	36.5	Rough grazing		
Spring barley	742	Cereal	Cereal	
Winter barley	832			
Winter wheat	952			
Maize	57.3			
Linseed	15.8			
Oil seed rape	11.5			
Potatoes	572	Other arable	Other arable	Pigs (100 per cent) on other arable
Sugar beet	771			
Artichoke	0.01			
Bean	39.1			
Pea	23.6			
Turnip	4.5			
Blackcurrants	40.3			
Fruit	1.6			
Gooseberries	2.9			
Strawberries	6.5			
Set-aside	322	Set-aside	Set-aside	
Woodland	163	Woodland	Woodland	
Urban	807	Urban	Urban	

* The figures in brackets relate to the proportion of the number of each livestock found on each land use type.

The cultivation of cereal and root crops dominates the land use throughout the Upper Ant catchment. Potato and sugar beet production were dominant in the headwater region above Swafield Bridge, while winter cereal cultivation was dominant in the lower region of the catchment between Honing Lock and Hunsett Mill. Set-aside land was fairly evenly distributed within the catchment and accounted for between 5 and 8 per cent of the total area. Permanent grassland was a minor land use, being largely concentrated in the riparian zone. Woodland and rough grazing accounted for only a small proportion of the surveyed area (4 per cent).

Cattle, horses, pigs and sheep were distributed on areas of permanent grassland throughout the catchment, with a greater proportion of pig production in the headwater region above Swafield Bridge. Sheep production was concentrated in the lower region between Honing Lock and Hunsett Mill. Cattle were distributed throughout the catchment, with the highest density between Wayford Bridge and

Honing Lock. Cattle and pigs were also distributed on potato and sugar beet fields, with direct grazing of fodder crops a common practice.

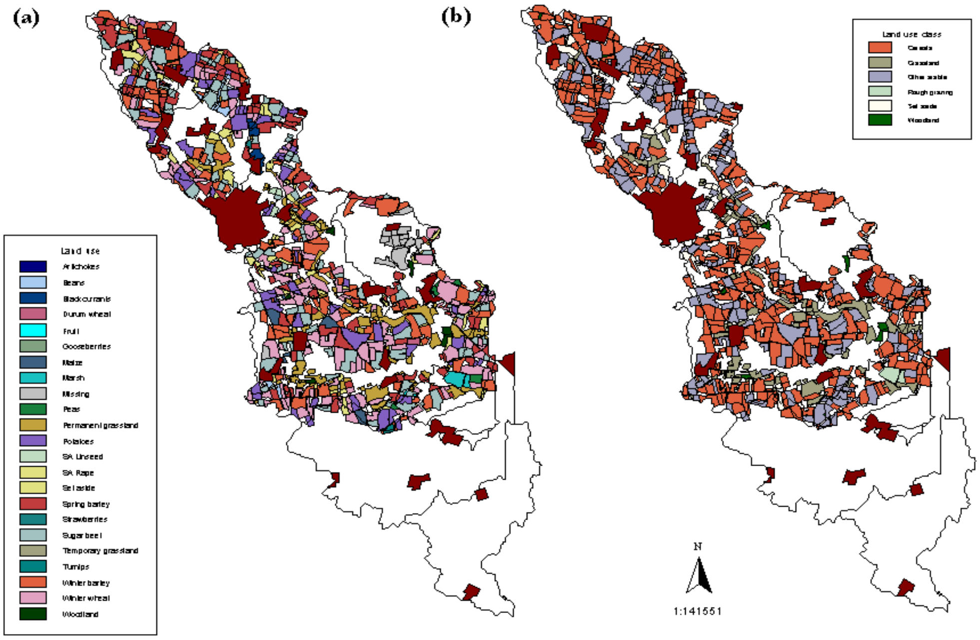

Figure 5 **Land use areas defined from the 1999-2000 farm survey in the Ant system**

Effluent inputs

A database was provided by the Agency detailing the nature of sewage treatment facilities within the Upper Ant catchment on a parish basis. This database was derived from parish-scale population census data for the region, together with Anglian Water and Agency records of the proportion of the population in each parish connected to each major Sewage Treatment Works (STW) in the catchment. Estimates were also provided of the population equivalent (PE) in each parish estimated to be connected to small packet treatment works and septic tank systems. Further information was provided on:

- populations living within the Upper Ant catchment but discharging their wastes outside the catchment or downstream from Hunsett Mill;
- populations living outside the Upper Ant catchment, but discharging their wastes to sewage treatment facilities within the catchment above Hunsett Mill;
- the proportion of the phosphorus load removed through phosphorus stripping at the South Repps and Stalham STWs.

In addition, daily flow and monthly TP concentration data were obtained for the two major STWs in the system (Stalham and South Repps). For the minor works, little information was available to describe the actual flows and TP concentrations delivered to the receiving water. For these works, the only indication of possible outflow loads was from the Export Coefficient Method.

2.1.3 Summary

The newly collected and historic data provided an excellent resource with which to develop and test the INCA-P model, although the collation of these data represented a significant task with costs associated with obtaining the sub-catchment boundaries (see Section 2.2.1) and input hydrological data. However, analysis of the data alone has yielded significant new insights regarding phosphorus dynamics within the system (Johnes *et al.*, 2003).

Specifically, the data generated by the field programme highlight the importance of bed load transport and storm events as the key pathways for phosphorus transport from the headwaters of the River Ant to the point of inflow into Barton Broad. The data collected also allowed an accurate estimate to be generated of the daily rates of phosphorus flux within the system and confirmed an earlier conclusion from a study of the Bure catchment that routine weekly and monthly sampling in these rivers was leading to a substantial under-estimate of the total phosphorus load exported annually.

The data also highlight the erroneous conclusions that might be reached regarding the rate of phosphorus export from land to stream if this were based on monitoring of soluble reactive phosphorus (SRP) fractions alone. In the year of study, 80 per cent of the total phosphorus load delivered to the River Ant at Hunsett Mill was transported as particulate phosphorus.

The data from the field programme tentatively confirms the existence of internal phosphorus stores within the Ant channel bed, probably generated prior to the 1980s, which are likely to take some time to flush out of this low gradient, slow-flowing river system.

2.2 INCA-P set-up and calibration

The model was set-up and calibrated for the period 15 April 1999 to 14 April 2000. These dates were chosen because they cover the simultaneous period of the farm survey and the intensive water quality monitoring of the Ant system.

2.2.1 Sub-catchment boundaries

Within INCA-P, the number of reaches and the locations of the downstream ends of each reach are chosen by the user. Typically, the downstream location is chosen to coincide with that of a gauging station, hydrochemical or ecological monitoring point, or upstream of a major tributary or effluent input. In addition, some downstream reach boundaries are chosen to sub-divide an otherwise ‘long’ reach into two smaller reaches.

There is no fixed definition of ‘long’ in this case; though typically a reach length of 10,000 m was not exceeded. This figure has been used in previous applications, and found to provide a reasonable compromise between useful model output and minimising the cost associated with purchasing the boundaries of the areas contributing to each reach. Further work is required to test what length of reach provides a reasonable compromise between (i) the assumption that each reach behaves as a fully mixed, stirred tank reactor and (ii) the cost of data purchase.

The boundaries of the reaches' contributing areas, termed in this report the 'sub-catchment boundaries' and shown in Figure 6, were derived by CEH from a 50 m resolution Digital Terrain Model (DTM) under license from Ordinance Survey (Morris and Flavin, 1990; Moore *et al.*, 1994). National Grid references, which define the downstream end of each reach, are given by Ordinance Survey to CEH for input into its calculation system. There was a charge to obtain the reach boundaries.[3]

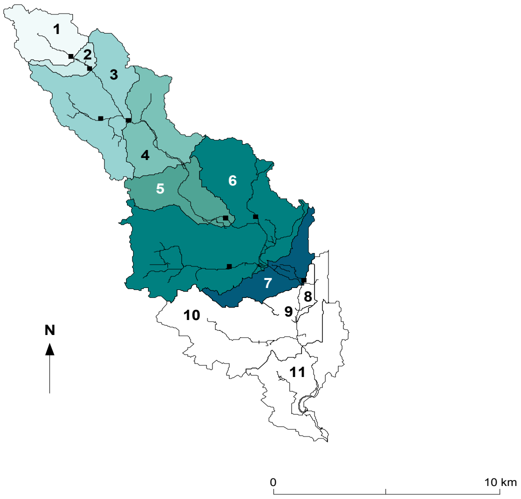

Figure 6 **Reaches and sub-catchments defined in the Ant system for the application of INCA-P**

Table 5 **Hydrological and hydrochemical monitoring of the reaches***

Sub-catchment	Name	Cumulative area (ha)	Grid reference
1*	Lower Street	715	TG263351
2*	South Repps Common	910	TG270345
3*	Swafield Bridge	2559	TG277335
4	North Walsham	3618	TG311298
5*	Honing Lock	4449	TG332271
6	Wayford Bridge	8000	TG347248
7*	Hunsett Mill	8679	TG274320

*Hydrochemical monitoring points in the 1999–2000 water quality survey.

Seven reaches were defined for the application of INCA-P to the Ant system (Figure 6 and Table 5). Five reach boundaries where chosen to coincide with the locations of the hydrochemical sampling sites and the flow gauging station at Honing Lock. Two additional reaches were defined at North Walsham and Wayford Bridge to prevent over-long reaches. Both these sites are also points of interest within the system; the waste from the STW at North Walsham was diverted from the Ant to the

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[3] At academic rates, this is currently £140 (+ VAT) for an administration charge, plus £9 (+ VAT) per sub-catchment boundary.

North Sea, and Wayford Bridge represents the upstream extent of the navigable section of the River Ant. The Ant system was not modelled downstream of Hunsett Mill as this was the lowest monitoring point in the 1999–2000 study and, below this site, the flow is tidal.[4]

2.2.2 Derivation of land use classes

Six land use classes were used in the application. These six land use classes were chosen to match those used in an application of the Export Coefficient Model (Johnes, 1996) to the Ant system, and are generalisations of the land use types identified in the farm and field surveys (Table 4). Within ArcInfo GIS, the land use data were allocated to each of the sub-catchments.

Reducing the number of land use types simplified the INCA-P model structure. It is currently uncertain whether using more land use types would benefit the model's ability to represent the system: additional land use types introduce more model parameters and therefore more degrees of freedom to be determined through calibration.

The areas of the six INCA-P land use types, derived from the farm survey, were multiplied by a correction factor to account for the unmapped areas in each sub-catchment. It was assumed that the land use observed in each sub-catchment was typical of the unmapped area, and therefore the correction factor, *cf* for each sub-catchment was defined as follows:

$$cf_{j,i} = \frac{Area_i}{\sum_{j=1}^{6} x_{j,i}} \qquad [1]$$

where:

$Area_i$ = area (ha) of sub-catchment

i, and $x_{j,i}$ = j^{th} area of the six INCA-P land use classes measured in the farm survey of sub-catchment, i.

2.2.3 Phosphorus inputs from fertiliser

The fertiliser application rates for the six INCA-P land use classes were derived from the measured monthly rates (kg phosphorus/ha) for crops in specific fields. This was achieved by multiplying the observed application rates by the crop area in each field to provide a monthly application load. These loads where then grouped by sub-catchment and INCA-P land use class to provide an estimate of the monthly load by land use type per sub-catchment.

These monthly loads were converted to a daily application rate (kg P/ha/day) by dividing the monthly load by the number of days per month and the land class area within each sub-catchment. Dividing by the number of days per month assumes a uniform application rate through the month. While this is a simplification of observed fertiliser practice,[5] the assumption allows for the behaviour of all farmers

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[4] INCA-P does not simulate bi-directional flows.

[5] A farmer will generally apply a fertiliser dressing to a field in less than one day.

within the system who may apply fertiliser dressings on different days of the month. It was assumed that the fertiliser was entirely comprised of inorganic-P.

2.2.4 Phosphorus inputs from grazing livestock waste

The farm survey identified the land use on which the majority of different livestock types grazed. As expected, cattle, sheep and horses predominately grazed grassland, while pigs were found on sugar beet and potatoes. Phosphorus inputs from cattle, sheep and horses were therefore added to the 'Grassland' land class and phosphorus inputs from pigs to 'Other Arable'.

The livestock numbers observed in each sub-catchment were corrected for the unmapped area in each sub-catchment using a correction factor based on equation [1], where the land area was replaced by the head of livestock. The corrected estimates of the head of livestock in each sub-catchment were then multiplied by the phosphorus produced per head of stock per year to produce annual load estimates per INCA-P land use per sub-catchment (Johnes, 1996). It was assumed that 70 per cent of the livestock waste was in the inorganic-P form and the remainder organic-P, and thus 70 per cent of the phosphorus load was apportioned to an inorganic-P and the remainder as an organic-P input.

The daily rate of the inorganic and organic phosphorus inputs was determined by dividing the loads by the number of days in the simulation period (366 days). Given the lack of information on when and how many head of livestock where housed during winter, it was assumed that all livestock grazed outside for the entire year.

2.2.5 Phosphorus inputs from farmyard manure and slurry applications

From the farm survey some applications of farm yard manure, slurry and sewage effluent cake to sugar beet and potatoes were recorded. When calculating the daily application rates, it was assumed that the ratio of inorganic to organic phosphorus content of the FYM and slurry was 70:30, and that the application was spread evenly over the year.

2.2.6 Growing seasons

Table 6 Growing seasons used in the INCA-P application to the Ant system*

Land use	Planting or bud burst	Harvest or leaf fall	Assumptions
Spring barley	18 Mar	21 Aug	
Winter wheat	20 Mar	23 Aug	
Winter barley	10 Mar	2 Aug	
Cereal	**10 Mar**	**23 Aug**	
Early potatoes	8 Mar	18 Jun	
Main crop potatoes	5 Apr	30 Sep*	*Haulm (stems & stalks) destruction
Sugar beet	26 Mar	25 Oct	
Other arable	**8 Mar**	**25 Oct**	
Grassland	**1 Jan**	**31 Dec**	Roots active all year
Set-aside	**1 Jan**	**31 Dec**	Non-rotational, same as grass
Deciduous	18 Apr	17 Oct	
Orchards	3 May	27 Sep	
Coniferous	-	-	
Woodland	**1 Jan**	**31 Dec**	Coniferous roots may be active all year. SMD and soil temperature control phosphorus uptake.
Urban (parks and gardens)	**1 Jan**	**31 Dec**	All impermeable

*Dates are derived from input data used in the MORECS model for MORECS square 196. The dates in bold represent the range used for each INCA-P land class.

MORECS provides an estimate of the duration of the growing season for different land use types. Within MORECS, these estimates are used to calculate evapotranspiration. However, these estimates also provide dates for crop planting and harvest, and tree bud burst and leaf fall across the UK, which can be used to constrain INCA-P. These data are available for each MORECS grid square (Hough *et al*., 1997). Thus, the estimates for square 196, which includes most of the Ant system, were used (Table 6).

Where estimates were available for a number of different crops types forming part of a single INCA-P land class, the range of dates that incorporated all growing seasons was used. Grass roots are noted as being active all year, and therefore the growing season was assumed to be year round, with phosphorus uptake rate a function of SMD and soil temperature (Wade *et al*., 2002b). It was also assumed that set-aside, and parks and gardens within urban areas, behave in this manner. Within INCA-P, it is possible to specify the plant phosphorus uptake rate for each land use; thus, the uptake from grassland, set-aside and urban areas (and all land use types) can be differentiated.

2.2.7 Calibration of the system hydrology

By calibrating the Identification of Unit Hydrographs and Component Flows from Rainfall, Evaporation and Stream-flow Data (IHACRES) model using the observed daily flows at Honing Lock and actual precipitation data purchased from ADAS, it was possible to derive an HER time-series for 15 April 1999 to 14 April 2000. This HER time-series was subsequently used as input to INCA-P.

IHACRES was initially used to derive a time-series of HER for the simulation period of 1 January 1995 to 31 December 2000. The new HER input was derived because, in a preceding application of INCA-P, the simulation of the observed daily mean flows at Honing Lock for the period 1 January 1995 to 31 December 2000 using the HER derived from the MORECS model as input to INCA-P was poor. Peaks in the observed discharge were not reproduced in the simulated daily flow time-series, even after manual calibration of the INCA-P residence time parameters and those relating velocity and discharge. On inspection, peaks in the observed mean daily flow time-series related to periods of zero HER derived from the MORECS model (Figure 7).

IHACRES is a catchment-scale rainfall–stream-flow model developed by the Institute of Hydrology (IH) (now subsumed into CEH) and the Centre for Resource and Environmental Studies (CRES), Australia National University (Jakeman *et al.*, 1990). The model is based on the derivation of a unit hydrograph for total stream flow, although the model can be set up in parallel boxes to simulate a ‘quick’ and ‘slow’ flow response. The model has low data requirements, i.e. time-series of precipitation, stream flow, and a third variable by which evapotranspiration effects can be approximated. In this application, this third variable was air temperature (pan-evaporation or potential evaporation derived from hydrometeorological measurements could be used). The model has only five parameters that describe the catchment wetness and rate at which it decays in the absence of rainfall.

IHACRES was applied using a two-box in-parallel configuration to capture the different response of the soil water and groundwater. While it is known that the contribution from different hydrological pathways and stores within the soil water and groundwater is highly heterogeneous in both space and time, the application of IHACRES represents a pragmatic approach to the derivation of the HER (Durand *et al*., 2002). IHACRES may be useful to derive the HER time-series in other river systems to which INCA-P is applied; the model is freely available from CEH and can be downloaded from the Internet (www.nwl.ac.uk/ih/www/products/mswihacres.html).

The application of the HER time-series derived from IHACRES for the period 1995 to 2000 (Table 7) proved more successful at simulating the observed daily mean flow time-series observed at Honing

Lock (Figure 7). The coefficient of determination relating the fit of the simulated daily mean flow time-series to that observed improved from <0 to 0.2 (see Section 2.2.12). Consequently, IHACRES was used to derived the HER time-series for the period 15 April 1999 to 14 April 2000. The parameters derived from this second application of IHACRES are listed in Table 7.

Table 7 IHACRES parameters derived from the simulation of flows at Honing Lock for the period 15 April 1999 to 14 April 2000

Parameter	Units	Value
Reference temperature, R	^{o}C	20
Delay	days	1
Temperature modulation factor, f	^{o}C^{-1}	2
Catchment drying time constant, τ_w	Ø	16
*Volume forcing constant, C	mm^{-1}	0.0038

*Calculated following model calibration. All other parameters are set by the user.

The following equations, which form part of the IHACRES model, were used to derive the HER time-series using the input air temperature and rainfall time-series, and the parameters derived from the calibration of IHACRES (Littlewood *et al.*, 1997).

The value of the catchment drying time constant, $\tau_w(t_K)$ at a reference temperature, *R*, is given by the following equation:

$$\tau_w(t_k) = \tau_w e^{0.062 f (R - t_k)} \qquad [2]$$

where t_k is the air temperature on day, *k*, and *f* is the temperature modulation factor which controls the sensitivity of $\tau_w(t_K)$ to changes in the temperature. For time intervals with rain, the decay of the catchment wetness index (s_k) still occurs, but it also incremented by a proportion, *C*, of the rainfall, r_k. A value of *C* is calculated automatically during the model calibration such that the volumes of effective rainfall and observed stream flow over the model calibration period are equal.

$$s_k = Cr_k + \left(1 - \frac{1}{\tau_w(t_k)}\right) s_{k-1} \qquad [3]$$

The HER, u_k, (the proportion of the rainfall which leaves as stream flow) is the product of the rainfall, r_k, and the catchment wetness index:

$$u_k = r_k s_k \qquad [4]$$

The values of u_k,, which formed a daily time-series, were those used as input to INCA-P.

To further improve the fit between the simulated and observed flows within INCA-P, the initial flows in the direct runoff, soil-water and groundwater boxes for each land use type where adjusted until the base-flow response closely matched that observed. The Base Flow Index (BFI), which represents the partition between the soil water and groundwater and which was obtained from the hydrometric register for the gauge at Honing Lock, was applied to each reach in the system (CEH, 2003) (BFI = 0.86). To simplify INCA-P, the parameter Δ, which is the threshold flow (m^3/s) in the soil-box above which direct runoff is invoked, was set to zero so that the direct runoff was generated for all flows. Recent work carried out to apply INCA-sed, a new model of sediment dynamics, to the River Kennet has shown that this is a reasonable assumption, and this parameter will be removed from INCA-P.

Table 8 Reach parameters and estimated width, length and derived depth

Reach	a*	b	Final volume (m^3)	Width (m)	Length (m)	Depth (m)
Lower Street	1.0	0.7	2065	1.5	2000	0.7
South Repps Common	1.0	0.7	740	1.5	1250	0.24
Swafield Bridge	1.0	0.7	5286	3.0	2000	0.88
North Walsham	1.0	0.7	3886	3.0	4000	0.32
Honing Lock	0.4	0.7	7708	4.0	4250	0.45
Wayford Bridge	0.4	0.7	10640	4.0	4500	0.59
Hunsett Mill	0.1	0.7	16234	8.0	1750	1.16

*The parameter a is used to relate the velocity to the discharge using the relationship $v = aQ^b$.

The residence times in each of the land use classes were then adjusted such that:

- the residence times of the direct runoff and soil boxes controlled the time to peak of the simulated hydrograph;
- the residence time in the groundwater box controlled the decay of the falling limb.

As such, the residence times relate more to lag times between a precipitation event and the peak in the hydrograph and the decay time, rather than a true measure of soil water or a groundwater turnover time.

The initial values of the volumes in the direct runoff, soil water and groundwater boxes were set based on preconceived notions of equivalent water depths per km^2. The drainage volume in the soil-box relates to the amount of water in the macropores or drains which is readily able to move and, by a piston effect, most strongly influences the rising hydrograph limb. The soil retention volume represents the water volume stored in the soil that responds more slowly, and may make up the majority of the water storage in the soil (similar to the field capacity concept). This water may be thought of as stored in the micropores. The groundwater volume represents the sum of the mobile and immobile water stored in the aquifer, while the time constant used to describe the rate of water transfer to the stream applies to the mobile phase only.

The relationship between the velocity and the discharge in each reach is specified in Section 1.1.1.

The value of 'b' affects the time of the response of the flow to a rainfall input, while the parameter 'a' affects the initial storage in the reach. Thus, the parameters 'a' and 'b' were calibrated to ensure the in-stream reach volumes and the associated depths were reasonable, and to improve the hydrological fit (Table 8). Setting the ‘a’ parameter to 0.1 for all reaches slows down the flow to around 6 km/day and has no discernable effect on the flow dynamics.

However, the water depths in the reaches, calculated from the volume of water stored in the reach at the end of the simulation period and the estimated reach length and width, are too deep compared to observation. This suggests a possible error in the estimates of the reach lengths and widths as well as uncertainty in the optimum value of the ‘a’ parameter. Further work is necessary to determine the most appropriate value of the ‘a’ parameter and errors in the estimates of the reach length and width in order to characterise both the flow velocity and reach depth.

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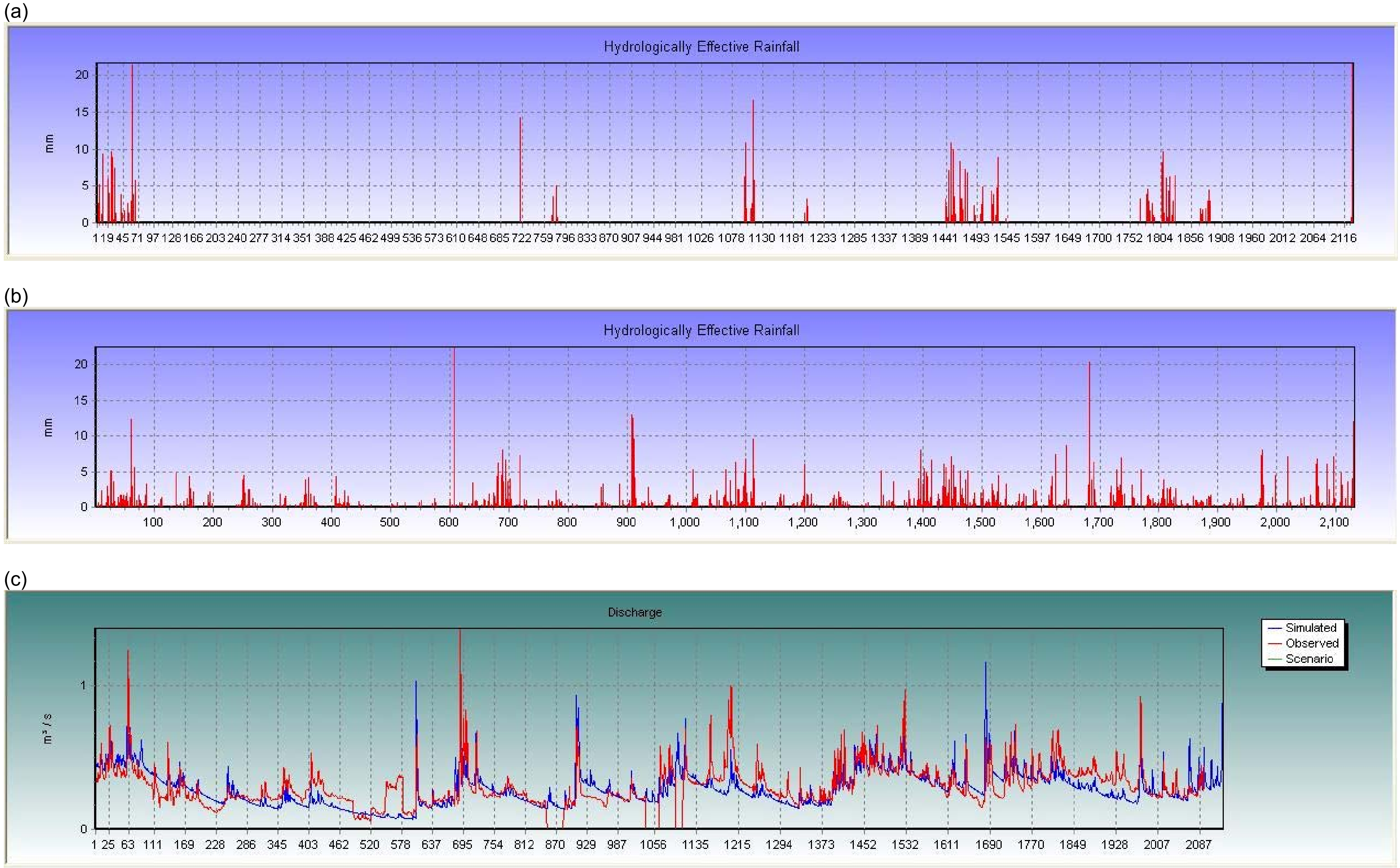


Figure 7 **HER derived from (a) MORECS model and (b) IHACRES, and (c) the observed and simulated daily mean flows at Honing Lock, Reach 5***

*In all three graphs, the x-axis is the number of days since the 1 January 1995.

2.2.8 *Initial TP and suspended sediment concentrations in the land phase*

No measurements of Total Phosphorus or suspended sediment concentrations in the overland, macropore, matrix or ground water flows within the Ant system were available. Because of this and the issues regarding the usefulness of such point-scale measurements in catchment applications, initial TP concentrations in the land phase of the model were set by calibration. Comparisons of the calibrated TP concentrations with TP concentrations measured in field experiments from other systems were done to check that the resultant calibrated concentrations were, at least, consistent with observation (Table 9) (Heathwaite and Dils, 2000). The initial groundwater TP concentrations of 30 µg P/litre appear sensible as measurements of orthophosphate concentration in a borehole in the Ant have a mean and modal concentration of 120 and 20 µg P/litre, respectively.

The initial suspended sediment concentrations for all six land uses are given in Table 10. The initial groundwater and soil-water concentrations were set to the observed concentrations at low and high flows, respectively. The initial concentration of the direct runoff was set so that the simulated peak suspended sediment concentrations closely matched those observed.

Table 9 **Initial TP concentrations (µg P/litre) in the land phase of INCA-P**

Land use/pathway	Direct runoff	Soil water	Groundwater
Grassland	330	330	30
Cereal	1030	1030	30
Other arable	1100	1100	30
Set-aside	60	60	30
Woodland	60	60	30
Urban	60	60	30

Table 10 **Initial suspended sediment concentrations for all INCA-P land-use types applied to the Ant system**

Pathway	Initial concentration (mg/litre)
Direct runoff	150
Soil water	10
Groundwater	3

2.2.9 *Effluent inputs*

Only the effluent inputs from the sewage works at South Repps, Stalham, East Ruston and Honing were considered in the model. These all discharge directly to the Ant. Septic tanks were not included in the model.

Observed effluent daily flows and monthly TP concentrations at South Repps and Stalham STWs were used to describe the daily effluent inputs from these works. To generate a daily time-series of TP concentrations, the observed values were used to infill the missing values from day after sampling until the day preceding the next observation. No daily flow or monthly concentration data were available for East Ruston and Honing STWs. As such, the daily flow at each works was estimated from the Population Equivalent (PE) served by the works (data from Johnes *et al.*, 2003) multiplied by 180 litres/day/PE (a value widely used by the Agency to determine daily flow). A value of 7 mg P/litre was provided by the Agency as an estimate of the effluent phosphorus concentration. The input effluent data used in the model application to the Ant are summarised in Table 11.

Table 11 Effluent inputs used in the Ant application (April 1999 to April 2000)

Reach	Mean daily flow (m^3/s)	Mean daily TP concentration (mg P/litre)	STW
1	–	–	–
2	0.0009*	0.19*	South Repps
3	–	–	–
4	–	–	–
5	0.0007	7	Honing
6	0.0001	7	East Ruston
7	0.0188*	0.33*	Stalham

*Measured time-series were used as input.

Other potential data sources were explored to describe the input of phosphorus from sewage effluent to the Ant river system. As part of an application of the Export Coefficient Model to the Ant catchment, estimates of the phosphorus inputs from all major, minor and private works and septic tanks within the catchment were made to estimate the total effluent input rather than just the phosphorus discharged directly to the main channel of the Ant from two STWs. These estimates were calculated from the population contributing to each works and coefficients that accounted for the degree of phosphorus removal.

An equivalent flow and concentration for each reach was derived for input to the in-stream component of INCA-P in two steps. First, an estimate of the mean flow per population was derived from the flow data and population served by the South Repps and Stalham STWs. The estimate was 230 litres/day, which was 27 per cent higher than the typical estimate of 180 litres/day used by the Agency. Secondly, the load was divided by the estimated flow rate to provide an estimate of the TP concentration (Table 12).

Calibration of the model with (a) the observed effluent inputs from South Repps and Stalham STWs and the estimates for Honing and East Ruston STWs, and (b) the loads derived from the ECM provided contrasting results. The calibration based on (a) providing a better fit to the observed stream water TP concentrations and that based on (b) tended to over-estimate the observed stream water TP concentrations in all reaches. This result suggested that only the direct discharges to the main channel should be used when applying the model rather than all the point source inputs within the catchment.

Within INCA-, therefore, phosphorus point sources discharging to tributaries are represented in the general 'diffuse' input to the main channel from each sub-catchment. Consequently, although Ross Foods is an important local source of phosphorus, its discharges are not included in the model since the site does not discharge directly into the main stem of the River Ant. When the point source discharges to Smallburgh tributary (including those from Ross Foods) were added in to the calibrated model, there was only a marginal increase in resulting in-stream Total Phosphorus and Soluble Reactive Phosphorus concentrations. A fully distributed version of INCA-P would address the issues of modelling tributaries and the point sources discharging to those tributaries. The creation of a fully-distributed version is intended as part of the future development of the INCA modelling approach.

Table 12 Input loads from STWs, private STWs and septic tanks in the Ant catchment*

Reach	Population	Flow (m^3/day)	Flow (m^3/s)	TP load(kg P/year)	TP concentration (mg P/litre)
1	350	83	0.001	153	5.06
2	747	177	0.002	19	0.29
3	816	193	0.002	357	5.06
4	329	78	0.001	143	5.03
5	1,193	282	0.003	531	5.15
6	1,385	328	0.004	628	5.25
7	6,039	1429	0.017	924	1.77

*TP loads were derived from the ECM Export Coefficient Model applied to the Ant system (Johnes *et al.*, 2003).

2.2.10 Other land phase parameters

To achieve a model fit by manual calibration, the parameters relating to the land phase processes of plant uptake and transformation into firmly bound phosphorus forms were adjusted (as well as initial TP and suspended sediment concentrations and in-stream parameters). The terms relating to mineralisation and immobilisation were not adjusted, as it was assumed that equilibrium existed between mineralisation and immobilisation. This was done to simplify the model structure and to reduce the number of parameters for calibration.

The plant uptake parameters were adjusted until the simulated annual output load was within the range specified in the literature (see Section 2.3.3). The parameters controlling the transfer of phosphorus into firmly bound stores and vice-versa where adjusted to produce the best fit to the stream water TP concentrations. The land phase parameters are listed in Appendix A.

2.2.11 Macrophyte and epiphyte dynamics and other in-stream parameters

No data were available to describe the macrophyte and epiphyte biomass in terms of carbon mass per plant surface area (gC/m^2) within the Ant system. Using Mean Trophic Rank (MTR) and Trophic Diatom Index (TDI) to predict the biomass or using chlorophyll *a* concentrations requires further investigation. Such investigation will be part of the current NERC Lowland Catchment Research

(LOCAR) project, in which macrophyte and epiphyte biomass and coverage are being intensively monitored for two years on the River Lambourn at Boxford.

Given the lack of carbon biomass data, the model parameters relating to the ecological component of the model were calibrated to the growth dynamics observed in other UK rivers. These parameters were:

- macrophyte growth and death rates
- epiphyte growth and death rates
- half-saturation concentrations for macrophytes and epiphytes
- macrophyte self-shading term.

While the observed biomass could not be used, the onset of growth and die-back were assumed to be similar to those observed in the studies of southern England where biomass peaks are observed between July and September for *Callitriche*, which is one of the macrophytes found at Honing Lock and is abundant in the chalk streams of southern England. Moreover, measurements of the partial pressures of carbon dioxide, chlorophyll *a* and dissolved phosphorus concentrations along the main stem of the Ant suggest that biological production is only significant at the Swafield Bridge sample site (Johnes *et al.*, 2003). The reaches below Wayford Bridge are dredged, thus removing any submergent macrophytes. Therefore, the model was set-up so that there was no simulated growth of macrophytes in these lower reaches. It is intended to collaborate with Benoir Demars, an aquatic ecologist based at the Macaulay Institute, who has monitored the macrophyte response to nutrient removal in the River Wensum, a river system adjacent to the Ant. It is hoped that these macrophyte data will be made available and these data, together with stream water chlorophyll *a* concentrations measured in the Ant, can be used to test the model in future applications.

The in-stream parameters controlling the simulation of the settling and resuspension of sediment, and the sorption of phosphorus to and from the suspended and bed sediments were also set by calibration. However, the problems of parameter equifinality and a lack of detailed data describing the bed sediment transport and phosphorus content meant it was difficult to identify an optimum set of parameters. As such, the relative contribution of phosphorus to the water column from external and internal sources remains uncertain. The in-stream parameters are listed in Appendix B. The parameter controlling the sorption and desorption of phosphorus to, and from, sediment is the K_d value. The initial pore water TP concentration can also be set to define the historic pore water TP concentration.

2.2.12 Goodness of fit assessment

Three measures were used to supplement the visual assessment of the goodness of fit between the observed and simulated concentrations of TP, SRP and suspended sediment.

The first was the Determination Coefficient (DC), which was defined as:

$$DC = 1 - \frac{\sum_{i=1}^{n}(S_i - O_i)^2}{\sum_{i=1}^{n}(O_i - \mu)^2} \qquad [5]$$

where μ is the mean of the observed data, and S_i and O_i are the simulated and observed values, respectively, for the i^{th} of n observations. The coefficient compares the ability of the model to simulate the observed data compared with calculating the observed mean and using the value as a predictor of the observed time-series. If the value of the coefficient is 1.0, then the model simulation is an identical match to the observations. If the coefficient has a negative value, the mean value of the observations is a better predictor than the model. As the coefficient is a dependent on squared values, then the result is biased by the higher values of flow or concentration.

The Correlation Coefficient (CC), the second measure, was given by the square root of the Determination Coefficient:

$$CC = \sqrt{DC} \qquad [6]$$

The third measure of the goodness of fit was the Explained Variance (EV), which was defined as

$$EV = 1 - \frac{\sum_{i=1}^{n}(S_i - O_i - \mu_\varepsilon)^2}{\sum_{i=1}^{n}(O_i - \mu)^2} \qquad [7]$$

where μ_ε is the mean of the error, S_i-O_i, and all the other symbols are as defined in equation [5].

2.2.13 Summary

The available data were used to constrain the model by specifying detailed spatial and temporal phosphorus inputs from fertiliser, livestock, manures and effluent inputs. The model was then calibrated by adjusting the model parameters until the output stream water flows, total phosphorus, soluble reactive phosphorus and suspended sediment concentrations matched those observed as closely as possible. In addition, the annual process loads simulated by the model were checked with literature values.

2.3 Results

2.3.1 Hydrological simulation

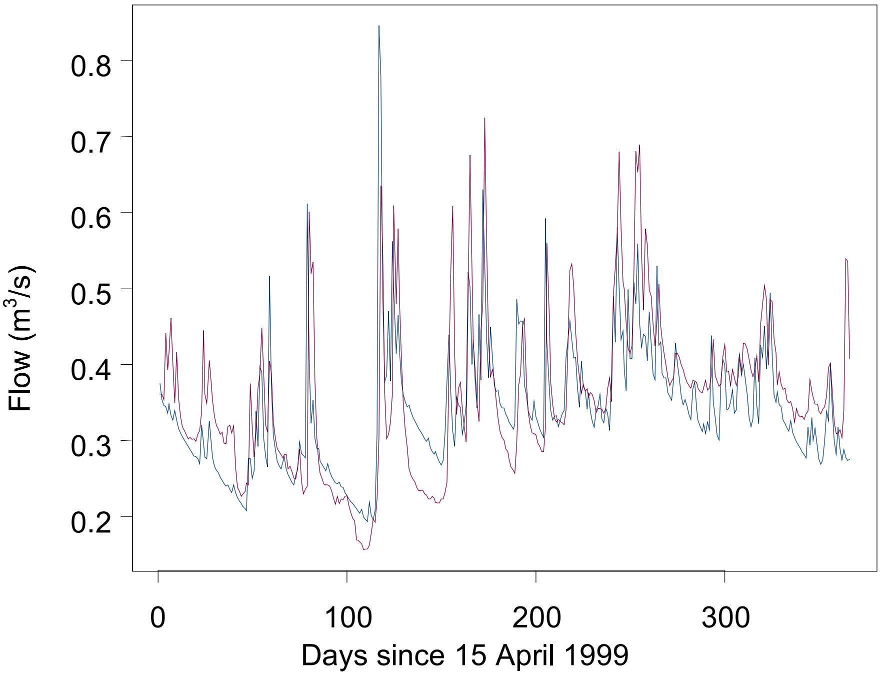


Figure 8 Simulated and observed flows at Honing Lock (reach 5)

To a first approximation, the simulated flows match those observed (Figure 8 and Appendix I). The three goodness of fit measures are all positive, indicating the flow characteristics of the system have been reasonably represented by the model structure and that the HER time-series derived from the IHACRES model is useful (* Table 13 and Table 14). In addition, the estimated water depth for each reach is sensible and the 'a' and 'b' parameters set for the Hunsett Mill reach of 0.1 and 0.7, respectively, are similar to those measured in tracer studies of the River Bure – an adjacent river system at a point draining a similar catchment area, for which the parameters were determined as 0.09 and 0.9, respectively (Universities of Huddersfield and Trent).

INCA-P both under and over-estimates different peak flow events, and the model both under and over-estimates the recession following a storm event. This result is an indication of the complexity of the flow–pathway activation, which is highly heterogeneous within the system as it is a function of localised factors such as precipitation inputs, the wetting and drying character of the soils, and surface compaction.

2.3.2 In-stream phosphorus and suspended sediment concentrations

The observed flows, and both the phosphorus and suspended sediment concentrations exhibit highly heterogeneous patterns in both space and time. The fractionation of the TP into SRP, soluble unreactive phosphorus (SUP) and PP forms is also highly spatially and temporal variable. This indicates the complex interaction between factors such as phosphorus input from point and diffuse sources, soil moisture, soil and water temperature, and processes such as mineralisation and plant uptake.

In addition to environmental factors, land management within the system can alter the flow and phosphorus dynamics. For example, there are areas of the catchment where arable crop production practices lead to capping of the soils, and other areas where direct grazing of vegetable crops by farm livestock causes extensive soil compaction. Under such conditions, the Base Flow Index may be much reduced, with a lower rate of infiltration and a higher rate of surface and near-surface quick flow generated during storm events (Johnes *et al.*, 2003). Where these farming practices are extensive within a sub-catchment or close to a watercourse, they will lead to a steeper rising limb on the storm hydrograph and an increase in the rate of sediment erosion and sediment-associated nutrient transport from land to stream. This capping may be reflected in the highest mean suspended sediment concentration being observed in reach 3, which has the greatest number of livestock, although the sample site at Honing Lock is surrounded by wetlands and woodland which may act to reduce sediment delivery (Figure 12).

The simulation of the observed daily TP concentrations in all reaches was reasonable. The model was able to characterise the concentrations at low flows and to simulate the increase in concentration during high flow events (Figures 9–11, and Appendix I). Twice daily TP samples were collected at the three sites and all the observed stream water TP concentrations are plotted in Figures 9–11.

The values of the goodness of fit measures reflect the difficulty of building a model able to represent the spatial and temporal heterogeneity of the factors and processes determining the daily TP concentrations. The simulated mean flow and mean SRP and TP concentrations in reaches 2, 5 and 7 also characterise the spatial variations in the mean observed flow and stream water SRP and TP concentrations (Figures 12 and 13).

This result indicates that the basic ‘mixing-model’ representation of the catchment provides a basis on which to develop INCA-P. Namely, the first order phosphorus dynamics can be explained as a mixture of ‘end-member’ waters from three diffuse sources (direct runoff, soil and groundwater) where the end-members vary between land use types. Moreover, during calibration, it became apparent that the model was very sensitive to the initial values of TP concentrations set for the three stores for each land use type, and that these initial conditions control the dilution and concentration of TP within the stream. Therefore, the philosophy of simulating the phosphorus dynamics in the land and in-stream components of the system using mixing concepts appears appropriate.

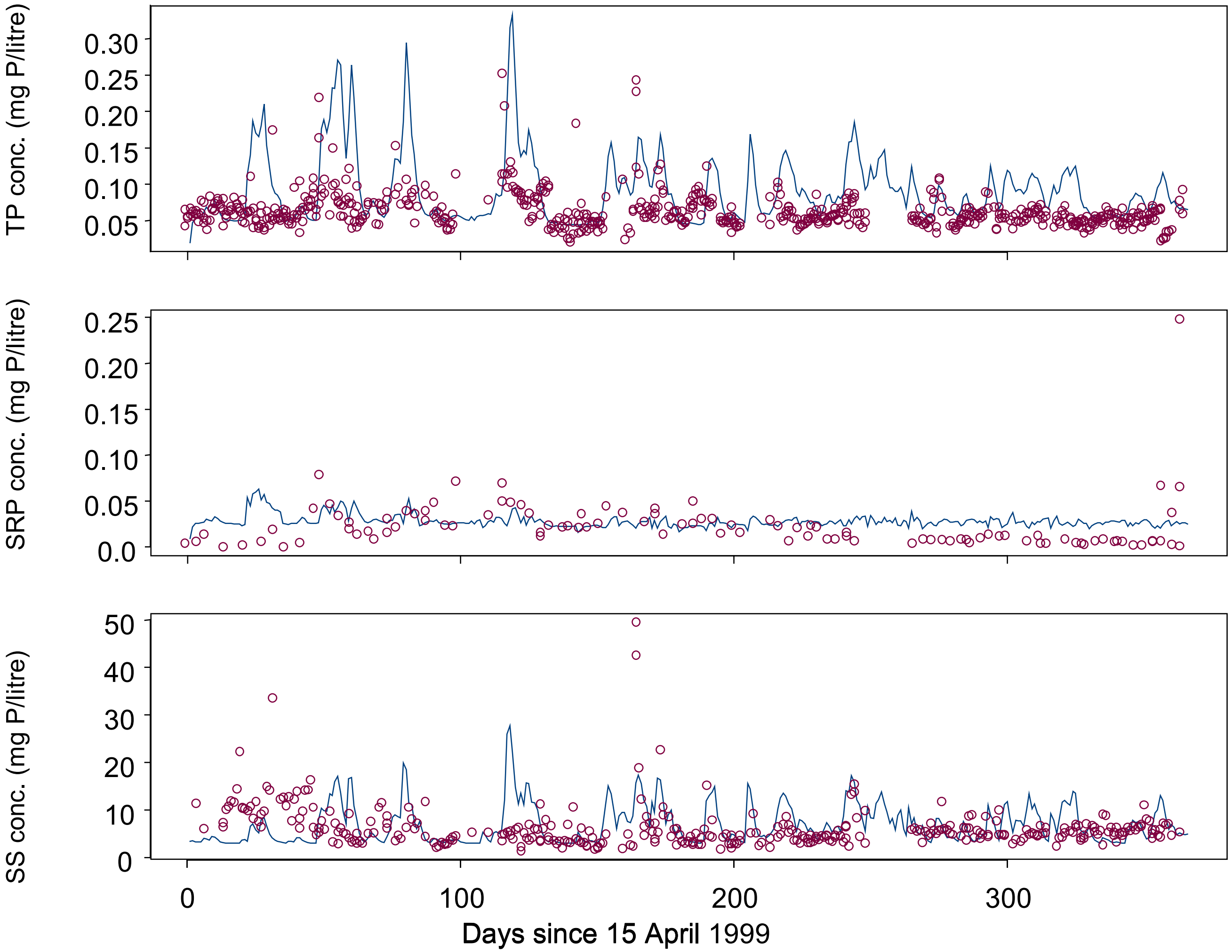


Figure 9 **Simulated and observed (a) TP, (b) SRP and (c) suspended sediment concentrations at Honing Lock (reach 5)**

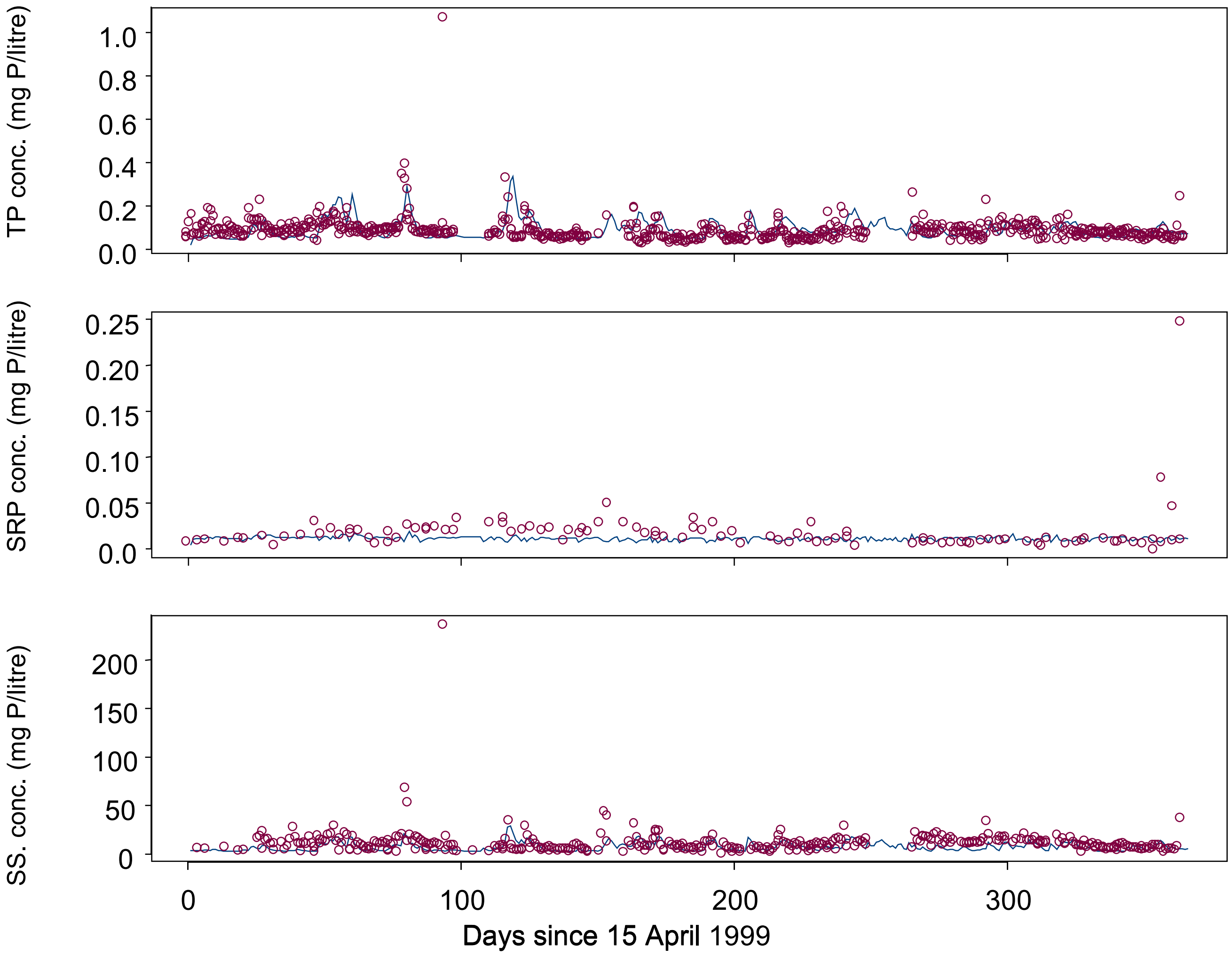


Figure 10 Simulated and observed (a) TP, (b) SRP and (c) suspended sediment concentrations at Hunsett Mill (reach 7)

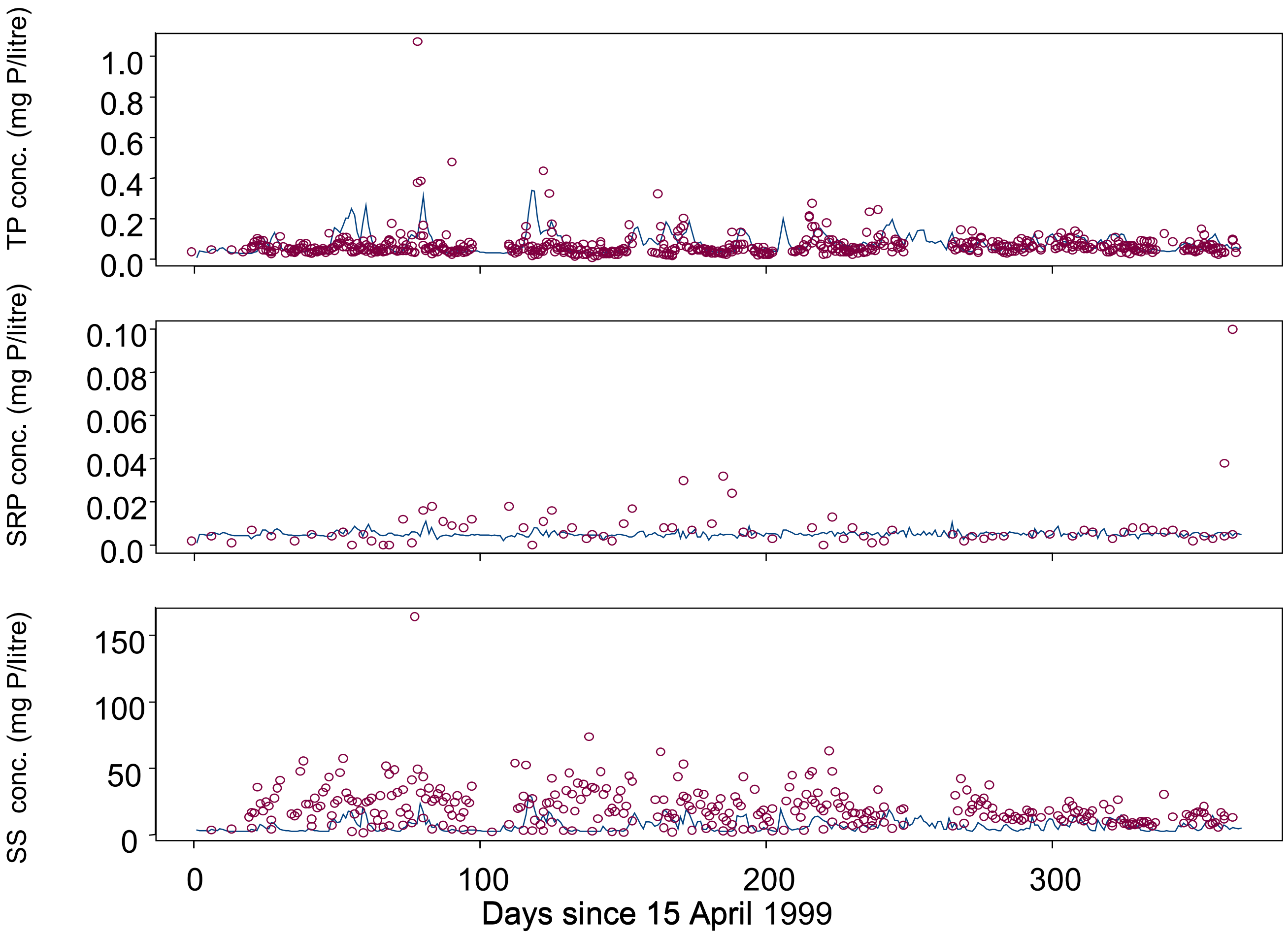


Figure 11 **Simulated and observed (a) TP, (b) SRP and (c) suspended sediment concentrations at Swafield (reach 3)**

Table 13 **Determination coefficient for flow, TP and SRP and suspended sediment in reaches along the Ant system***

Reach	Flow(m^3/s)	TP(mg P/litre)	SRP(mg P/litre)	SS (mg l/litre)
Lower Street	–	< 0	< 0	< 0
South Repps Common	–	< 0	< 0	0.16 (0.40)
Swafield Bridge	–	< 0	< 0	< 0
Honing Lock	0.41 (0.64)	< 0	< 0	< 0
Hunsett Mill	–	< 0	< 0	< 0

*Correlation coefficient is given in brackets.

Table 14 **Explained variance for flow, TP, SRP and suspended sediment in reaches along the Ant system**

Reach	Flow (m^3 s)	TP (mg P/litre)	SRP (mg P/litre)	SS (mg/ litre)
Lower Street	–	< 0	< 0	< 0
South Repps Common	–	< 0	< 0	< 0
Swafield Bridge	–	< 0	< 0	< 0
Honing Lock	0.42	< 0	< 0	< 0
Hunsett Mill	–	< 0	< 0	< 0

There is uncertainty in the estimates of the point source phosphorus contribution from STWs and septic tanks. Estimates of the phosphorus load from South Repps and Stalham from daily flow and monthly phosphorus data for the year from April 1999 to 2000 are 19 and 839 kg P/year, respectively: the load estimates derived from the application of the Export Coefficient Model are 5 and 200 kg P/year for South Repps and Stalham, respectively. Thus, while the approximation used in this application for South Repps is reasonable, the load delivered from Stalham may be an over-estimate and therefore questions the reliability of these estimates. It is difficult to determine the point source contribution accurately without more frequent measurements of TP and flow at other STWs.

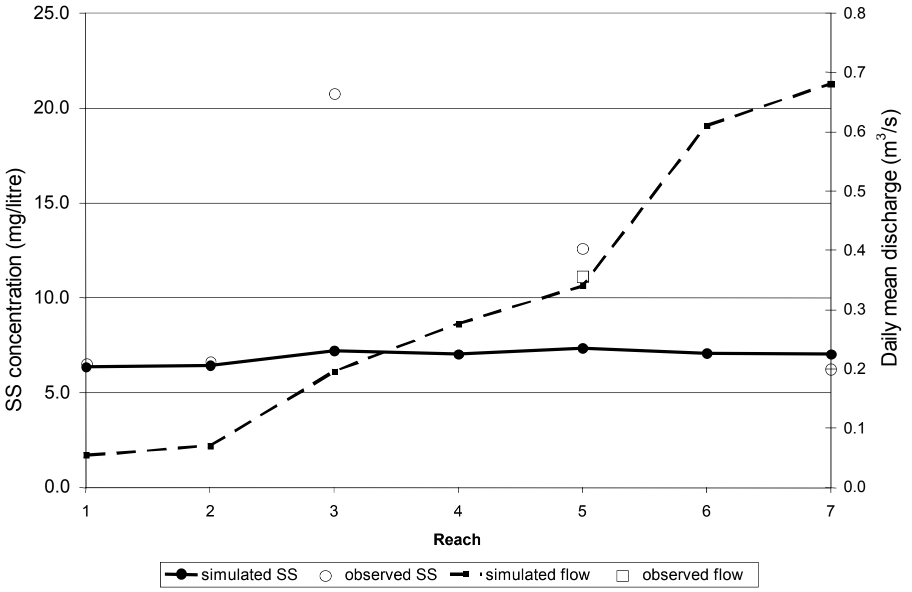


Figure 12 **Simulated and observed flows and suspended sediment concentrations along the River Ant**

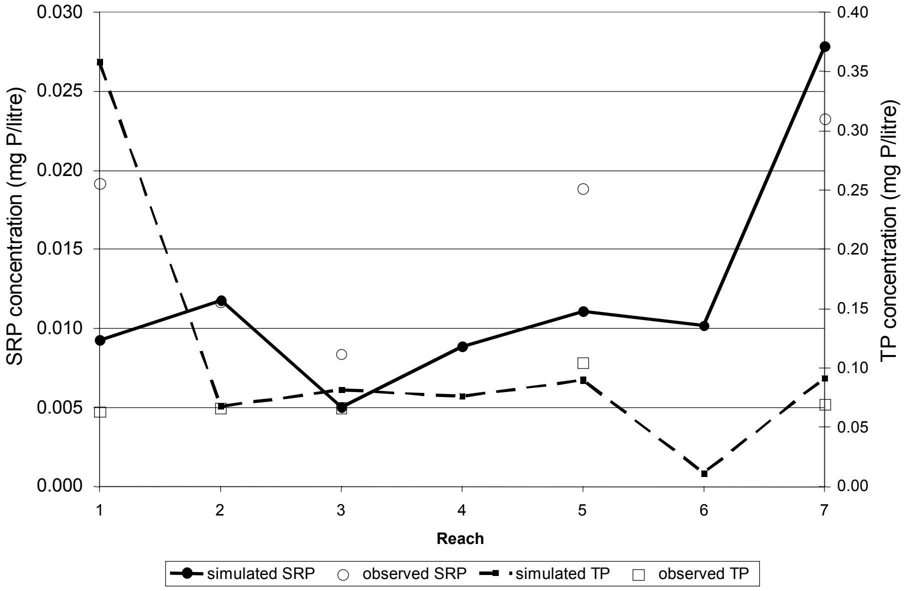


Figure 13 **Simulated and observed SRP and TP concentrations along the River Ant**

INCA-P is able to simulate the mean in-stream SRP concentrations in reaches 2, 3 and 7, but the characterisation of the daily dynamics is poor. Improvement in the representation of the SRP dynamics will be sought in future developments.

Despite the uncertainty in the SRP dynamics, the model is able to produce macrophyte and epiphyte growth curves typical of lowland chalk rivers (Figure 14). This indicates that the equations within the model describing macrophyte and epiphyte growth are useful for describing the biological response of the system.

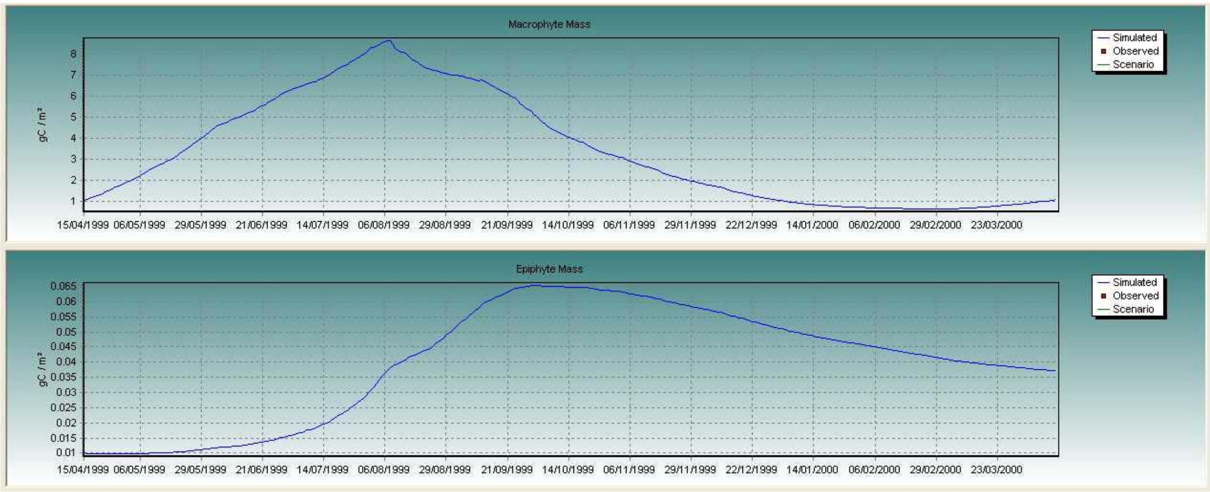


Figure 14 Simulated macrophyte and epiphyte biomass at Honing Lock (reach 5)

The in-stream suspended sediment concentrations are reasonably simulated in reaches 1, 2 and 7. This suggests the first order changes in the suspended sediment can also be explained as a simple mixing of sediment ‘end-member’ concentrations. As in the case of TP, INCA-P does not explain the detailed daily dynamics because it does capture the complex, highly heterogeneous variations in the different source area contributions. A new model of river system suspended sediment dynamics has recently been developed at the University of Reading, INCA-Sed, and it is envisaged that this new model will be used to replace the simple mixing model within the current version of INCA-P.

Given that work is required to improve the simulations of SRP concentration, then the current simulations of the SRP in the pore-water also require further investigation. Currently, the simulated pore-water SRP concentrations under-estimate those observed (Table 15). Given the uncertainty in the stream water and pore water simulated SRP concentrations, it is unclear how much phosphorus in the water column is derived from internal, rather than external, loads. The model simulations suggest that SRP concentrations are much greater in the overlying water column than in the pore waters, and that phosphorus is therefore likely to move from the water column to the stream bed. This result contradicts the findings of Johnes *et al*. (2003) and therefore questions the INCA-P representation of phosphorus sorption to and from the bed sediment. On inspection, the relationship between phosphorus in the pore water and the bed sediment within INCA-P may need to be changed to explicitly track the SRP fraction (Figure 46).

Table 15 **Comparison of observed and simulated pore water SRP concentrations (mg P/litre) along the Ant system**

Reach	Observed range at depths of 0 to 4 cm	Simulated
South Repps	0.07 to 0.52	0.010
Swafield Bridge	0.03 to 0.08	0.002
Honing Lock	0.06 to 0.80	0.004
Hunsett Mill	0.04 to 1.17	0.019

2.3.3 Land phase and in-stream TP loads

Table 16 **Comparison of the simulated and observed (kg P/ha/year) process loads from UK and US studies**

Process	Sub-catchment 3	Sub-catchment 5	Observed range
Crop uptake			
Cereal	25	24	19–27[1]
Other arable	18	17	14–21[1]
Grassland	33	28	12–40[2,3]
TP export			
Cereal	0.2	0.2	0.07–7.5
Other arable	0.4	0.4	0.07–7.5
Grassland	0.2	0.2	0.2–9.7
Woodland/forest	-	0.1	0.007–0.9
Urban	0.1	0.1	0.9–3.4

[1] Sharpley, 1995

[2] Foy *et al.*, 1997

[3] Brookes *et al.*, 1984

The annual loads (kg P/ha/year) of TP exported from different land uses are generally within the range reported within the literature for UK and USA river systems and plot experiments (Table 16).

For phosphorus uptake into cereal, the calibrated load is at the higher end of the observed range.

For arable, the phosphorus uptake is much higher than the reported range; this may be a result of the over-estimation of the phosphorus input from pigs to forage crops. In addition, the phosphorus exported from the land phase within INCA-P is the sum of the mass contributions from the three flow paths (direct runoff, soil water and groundwater). In the literature, however, the TP export is often the mass of phosphorus leached from the lower layers of the soil profile. Thus, the TP export from the INCA-P model is likely to be greater than the observed leaching rates.

The simulated phosphorus uptake from grassland is below the range observed. Given the uncertainty in the model calibration due to parameter equifinality, it is difficult to compare the simulated and observed loads. Despite this, comparison of the simulated and observed process loads is useful as it allows INCA-P to be constrained to a greater extent than if hydrological and hydrochemical data were used alone.

Comparisons between the simulated and observed TP loads within the stream are presented in Table 17. The observed loads were determined using Methods 2 and 5 proposed by Webb *et al.* (2000), which are currently suggested as the most reliable methods for load interpolation. As flows were only measured at Honing Lock, the observed loads at Swafield and Hunsett Mill are based on flow estimates.

Table 17 Comparison of observed loads (kg P/year)* based on observed flows and flow estimates, and the loads simulated by INCA-P and the ECM

Method	Swafield	Honing Lock	Hunsett Mill
Measured flows			
2	–	1,040	–
5	–	1,053	–
Scaled specific flows			
2	488	–	1,408
5	495	–	1,407
Stage measured flows			
2	381	–	–
5	384	–	–
INCA-P	537	1,031	2,098
ECM	1,367	2,260	4,388

*Calculated using Methods 2 and 5 of Webb *et al.* (2000)

A stage board was installed at Swafield and the stage–discharge relationship was established as:

$$Q_s = 0.0515 H_s + 0.0106 \qquad R^2 = 0.66 \qquad [8]$$

where Q_s is the mean daily flow and H_s is the stage at Swafield, S. The flows estimated at Swafield were related to those measured at Honing Lock as follows:

$$Q_s = 0.3578 Q_H + 0.0346 \qquad R^2 = 0.61 \qquad [9]$$

where Q_H is the mean daily flow at Honing Lock. This relationship was used to infill flow data missing from the record at Swafield and to extrapolate the Swafield record to cover the period 15 April 1999 to 10 June 1999, when the stage board was not in place.

In addition, the mean daily flows at Swafield and Hunsett Mill were estimated as a factor of the specific flow. Namely, the flows at Honing Lock were divided by the contributing area to provide a flow per unit area. The flow per unit area was then multiplied by the contributing area to Swafield and Hunsett Mill, respectively, to provide a time-series of flows at each location.

The simulated annual loads at Swafield and Honing Lock are both within 8 per cent of those observed. At Hunsett Mill, the annual load is a 49 per cent over-estimate (Table 17). Diffuse inputs are the predominant source of TP in the River Ant from Lower Street to North Walsham, with inputs from 'cereal' and 'other arable' contributing the most (Figure 15). This result reflects the predominance these two land use types within the Ant catchment and the effect of phosphorus stripping at South Repps STW in reach 3.

Downstream of Honing Lock (reach 5), the contributions from Honing , East Ruston and Stalham STWs are apparent, with a 1:3 ratio between point and diffuse source contribution to the in-stream phosphorus load in reach 7 (Hunsett Mill). However, the uncertainty regarding the point and diffuse source contributions affects any estimates of the partition between point and different diffuse sources, and therefore conclusions regarding the relative contribution remain tentative. Comparison of the phosphorus inputs from fertiliser and manures calculated in this study with those estimated in Layer 1 of the Phosphorus Indicators Tool (Heathwaite *et al.*, 2003) would provide a useful cross-check of the estimates generated in this study.

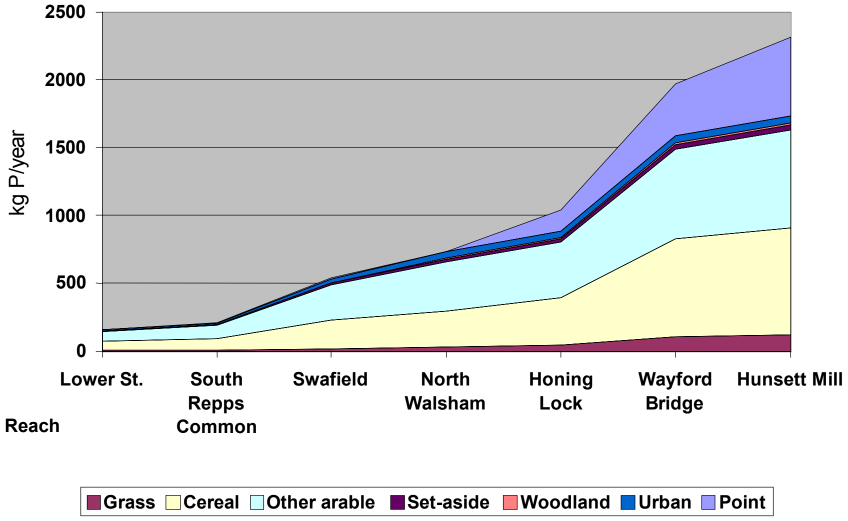


Figure 15 **Partition of phosphorus inputs to the Ant system between point and diffuse sources**

3. Application of INCA-P to the River Lugg

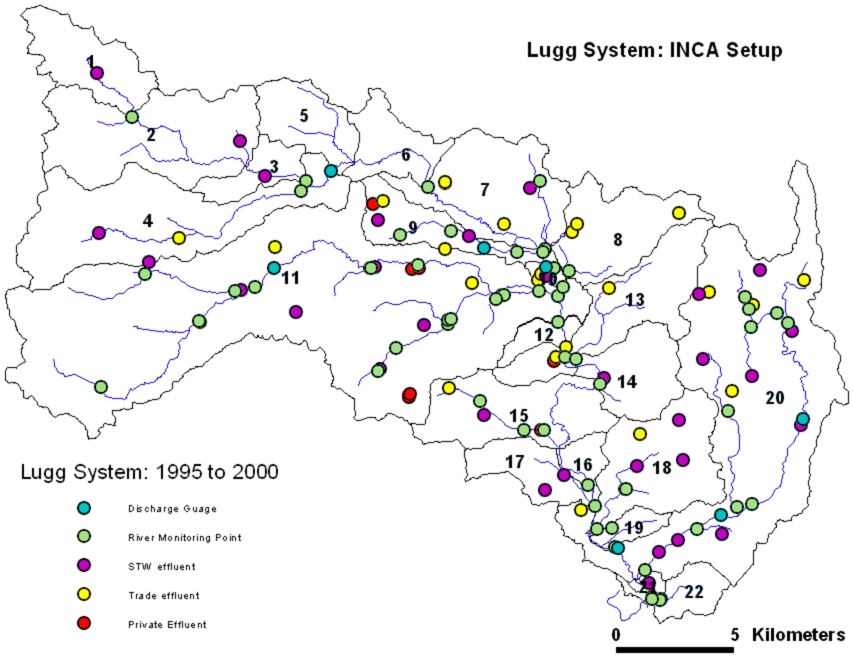


Figure 16 **The River Lugg and its tributaries: the location of the discharge gauges, river monitoring points and effluent inputs**

3.1 Study area and data resource

3.1.1 Study area

The River Lugg flows in a south-easterly direction from Powys to join the River Wye in Herefordshire before draining into the Bristol Channel. The contributing area at Lugwardine Bridge, the lowest of the three gauging stations on the Lugg, is 885 km^2, and the total catchment area is 1,077 km^2.

The River Lugg was chosen as a study area because it is known to have very high (approximately 1 mg P/litre) stream water phosphorus concentrations (measured as total phosphate) in its lower reaches. Such is the concern about its water quality that, in 1994, the Lugg was designated a ‘eutrophic sensitive’ area under the Urban Wastewater Treatment Directive. Moreover, the lower Wye, into which the Lugg drains, is an Area of Outstanding Natural Beauty and considered to be of high ecological value – being a historically important Atlantic salmon (*Salmo Salar*) fishery.

For catchment management, it is important to determine the impact of the high phosphorus concentrations on the river ecology and the relative contributions from point and diffuse sources. The latter is important so that measures taken to reduce phosphorus in the stream can be targeted appropriately at point or diffuse sources, or both. In addition, the Lugg has contrasting upland and lowland areas, and like the Ant, a wealth of background data with which to apply INCA-P (Figure 16).

3.1.2 Data resource

Data describing the water quantity and quality from 1993 to the present day were available from Agency archives. The other data were collated to describe the hydrology, land use and land management for the application of INCA-P. Apart from the land use and management data, the data sources were the same as those used to set up the River Ant application (Table 18). For the Lugg application, land use and livestock numbers were derived from the ADAS MAGPIE database. This dataset is based on the Defra agricultural census for 1995, and has been remapped by land use to account for undisclosed data (Lord, 2000).

Table 18 Summary of INCA-P input data for the Lugg application

	Resolution	Period of data collection	Storage/retrieval method	Source	Reference
Spatial data					
Land use and livestock numbers	1 km^2	1995	ESRI ArcInfo GIS	ADAS	
Fertiliser practice	Geoclimatic region		Microsoft Excel	AERC	Johnes *et al.*, 2003
*River networks	1:50,000		ESRI ArcInfo GIS	CEH	Moore *et al.*, 1994
*Reach boundaries	50 m		ESRI ArcInfo GIS	CEH	
Temporal data					
TPh, OP, SS stream water concentrations	Variable, typically monthly	1992 to present day	Microsoft Access	Agency/ AERC	
*MORECS rainfall, temperature and soil moisture	Daily		Microsoft Excel	ADAS	Met Office, 1981
Growing season	Lumped mean per MORECS square		Report	Met Office	Met Office, 1981
Discharge	Daily		Microsoft Excel	CEH/ Agency	
Base Flow Index	Each flow gauge		Report	CEH	Gustard *et al.*, 1987

*Data purchased from third parties.

OP = orthophosphate; TPh = total phosphate

Land use and management

The land use comprises mixed arable and cattle production. Grassland and woodland dominate in the upper regions, with woodland also scattered along the headwater and middle reaches of the main channel of the Lugg. Arable cultivation becomes the dominant land use in the lower part of the Lugg. Livestock production is dominated by sheep in the headwaters and by cattle in the middle and lower part of the catchment. There are notable clusters of pig production in the River Arrow sub-catchment and to the south of Leominster, and a notable cluster of poultry in the Hindwell Brook tributary (Figure 17).

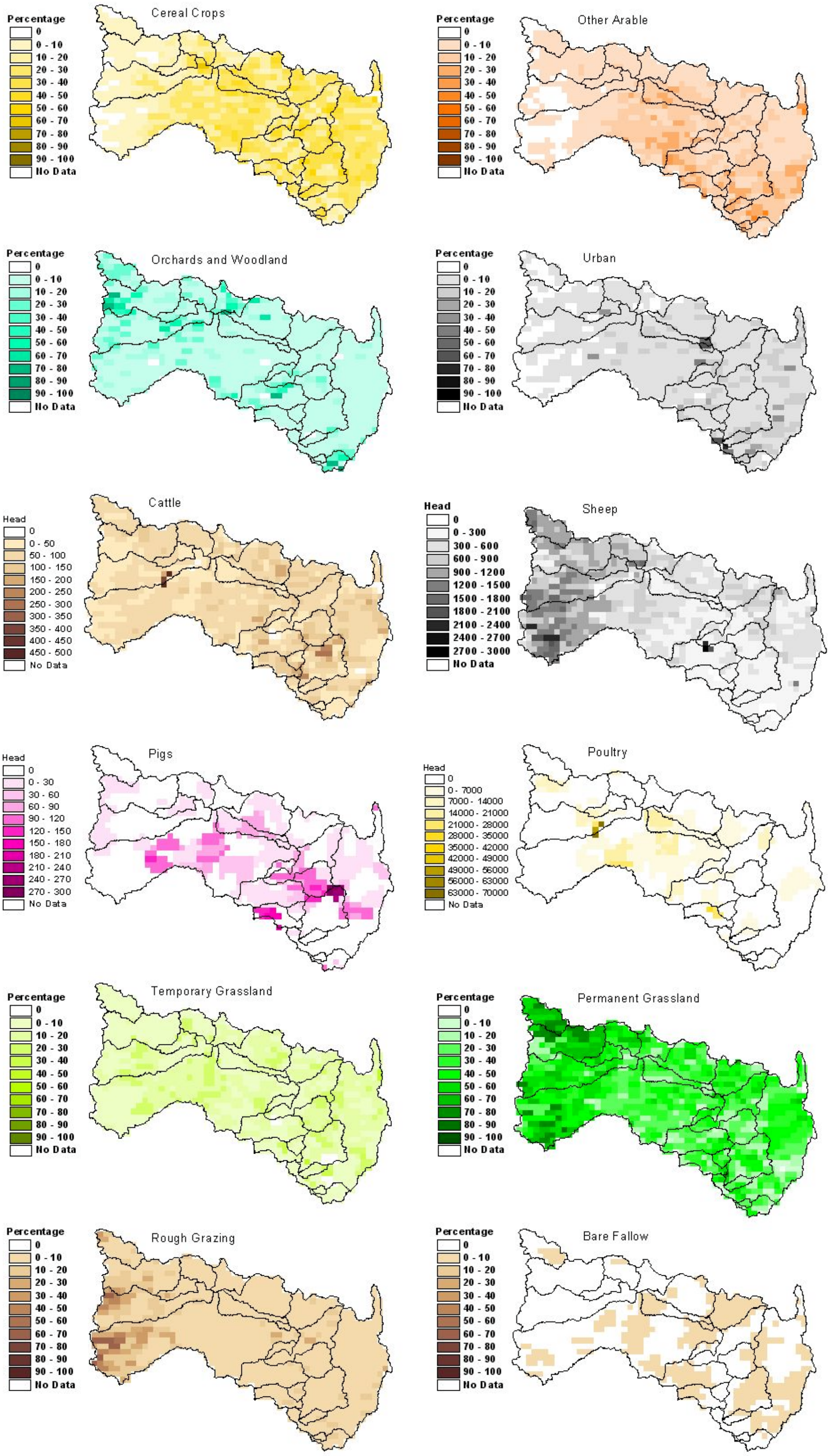


Figure 17 Land use and livestock numbers in the Lugg Catchment*

*Derived from the ADAS MAGPIE database 1995.

Hydrological data

Rainfall within the catchment is spatially variable: at Butts Bridge and Lugwardine Bridge, in the upper and lower reaches, the long-term annual mean rainfall is 1,048 and 850 mm, respectively. A mean rainfall of 1,048 mm over the catchment generates approximately 394 mm of runoff, equivalent to a mean flow of 11.1 m^3/s at Lugwardine Bridge.

The Lugg is predominately underlain by Old Red Sandstone, although the headwaters drain Silurian rocks of the Radnor Forest. The Base Flow Index is 0.66: this value reflects this mixture of impervious rocks in the headwaters, and the sandstone aquifer and extensive deposits of gravel in the valleys, which provide significant base flow and moderate flood peaks (CEH, 2003). The 10 percentile flow of 26 m^3/s indicates the Lugg is likely to have a high capacity to transport phosphorus attached to sediment during storm events.

To represent the spatial variability in the hydrological inputs of the Lugg system, two time-series were used: single-site MORECS data were bought from the Meteorological Office via ADAS. These two time-series were for weather stations at Llandrindod Wells (in the Ithon catchment, outside the Lugg) and Madley, representing the upper and lower reaches, respectively.

Stream water and effluent hydrochemical data

The nutrient water quality of the River Wye and River Lugg has been assessed in detail by Jarvie *et al.* (2003) using the Agency data archive. The Agency measures total phosphate (TPh) and orthophosphate (OP) in the Lugg catchment, although there is some uncertainty regarding the exact methodologies used. For the purpose of this study, the following standard methods have been assumed.

Both total phosphate and ortho-phosphate are measured using unfiltered samples. The difference is that the ortho-phosphate determination uses cold acidification, whereas the total phosphate measurement uses a hot extraction methodology. The hot acid extracts more inorganically-bound phosphorus (i.e. phosphorus bound to amorphous/poorly crystalline Al and Fe oxides and hydroxide phases). However, the hot extract alone will not extract:

- refractory inorganically bound (crystalline Al-Fe oxides and hydroxides and allumino-silicate minerals)
- organic phosphorus and organically bound phosphorus components.

Because the total phosphate determination does not use acid-persulphate digestion (which breaks down organic phosphorus), the value obtained is not the same as total phosphorus (as measured by CEH and the Agency.

There are 57 routine monitoring points within the Lugg catchment, of which eight are on the main stem (Figure 18). In addition, there are approximately 50 recognised inputs of STW effluent to the River Lugg and its tributaries, and a further 37 and 33 private and trade effluents, respectively.

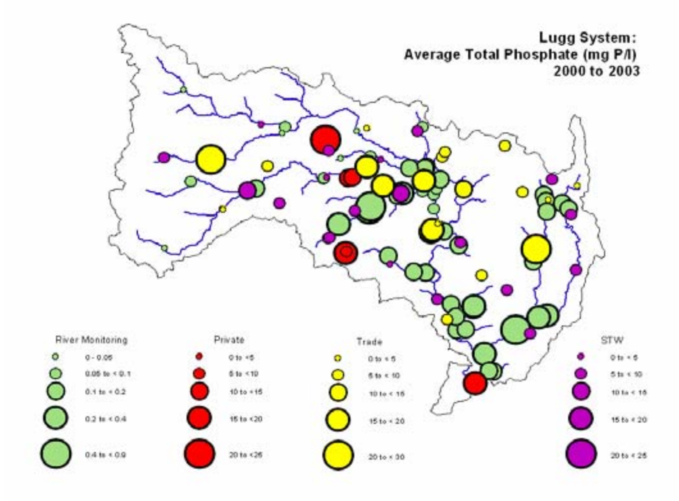


Figure 18 **Stream water and effluent TPh concentrations (mg P/litre) in the Lugg catchment**

The headwaters and reaches of the Lugg downstream of the confluence with the River Arrow had contrasting observed mean stream water TPh concentrations (Figure 18). In the headwaters of the Lugg and Arrow, the mean concentrations are typically around 0.05 mg P/litre: the highest mean concentrations, of approximately 0.4–0.9 mg P/litre are found in the lower reaches of the Lugg, and the River Frome and Stretford Brook tributaries.

Comparison with land use maps and the location and density of point source inputs indicates that the higher stream water TPh concentrations correspond to the more intensive agricultural practices and the higher loadings from point sources found in the lower reaches and tributaries. Many of the smaller, often private, STWs can have very high phosphorus concentrations in the effluent – reaching up to 30 mg P/litre in the most extreme case – although low flows from these works means the overall contribution in terms of load is small (Figure 19). The largest STWs within the catchment are Leominster, Weobley, Kington, Moreton and Bromyard, which were designed to serve population equivalents of the 10,854, 2,935, 2,681, 2,721 and 4,500, respectively. The main trade effluents are from food processing at Cadburys and Symonds Cider. Phosphorus stripping was introduced at Leominster STW and Cadburys in 1998.

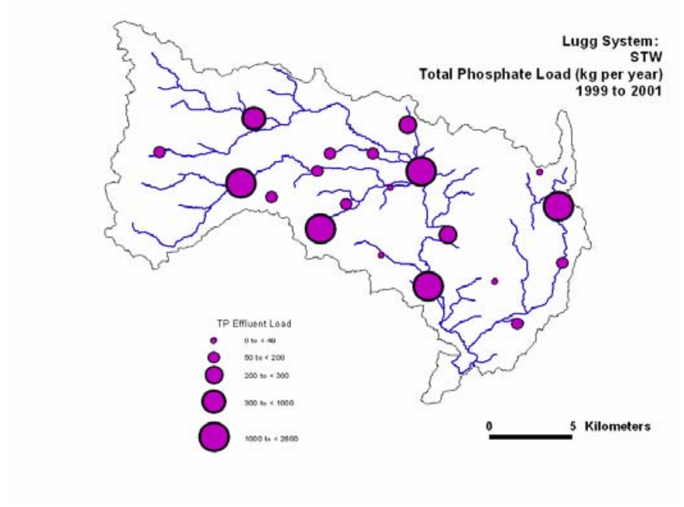


Figure 19 **Mean TPh load (kg/year) delivered from STWs to the River Lugg (1999–2001)**

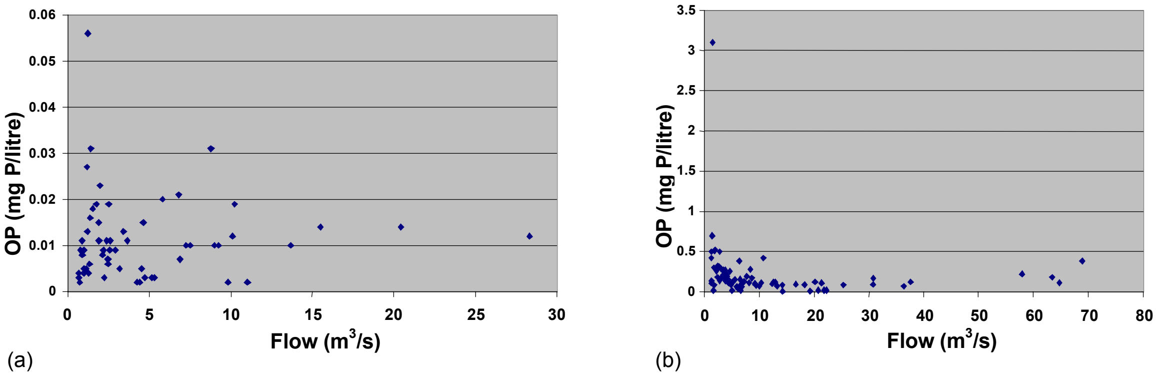


Figure 20 **Relationship between stream water OP concentration and flow at (a) Monaughty and (b) Lugwardine Bridge.**

The contrast between the headwaters and the lower area of the Lugg catchment is also apparent in the in-stream phosphorus dynamics (Figure 20). At Monaughty in the upper reaches, the stream water ortho-phosphate concentrations show a complex relationship with flow, and it is possible to discern two clusters of points. One cluster is associated with increasing OP concentrations as flow increases from 0 to 30 m^3/s, and another is associated with the dilution of a point source, Llangunllo STW, at flows between 0 and 10 m^3/s. The increase in OP concentration with flow is typical of a diffuse source contribution, though the response is complicated by the complex interaction between source area and flow-pathway within the contributing catchment area.

At Lugwardine Bridge, the stream water OP concentrations are an order of magnitude higher than those observed at Monaughty. The concentration–flow relationship again suggests the influence of both point and diffuse sources; although an increase in concentration with flow is evident, the pattern is dominated by the dilution of OP at lower flows (0–20 m^3/s).

3.1.3 Summary

In summary, the data show a simple spatial pattern in the stream water TPh concentrations, with concentrations increasing with higher inputs from diffuse and point sources. However, since the intensification of agriculture corresponds to greater urbanisation and therefore more point source discharges, it is difficult to separate their influence on in-stream phosphorus concentrations and loads.

3.2 INCA-P set-up and calibration

The model was set-up and calibrated for the period 1 January 1995 to 31 December 2000. These dates were chosen since they cover the period of available data. Many of the assumptions made to set-up INCA-P for the River Lugg were identical to those used to in the Ant application (see Section 2). As such, only significant deviations from these assumptions are described here.

3.2.1 Sub-catchment boundaries

Twenty-two reaches were defined for the application of INCA-P to the Lugg system; the sub-catchments are shown in Figure 16 and described in Table 19.

Eight reach boundaries were chosen to coincide with the locations of the hydrochemical sampling sites, and three to coincide with the flow gauging stations. The remaining reaches coincide with reaches defined as part of a SIMCAT modelling exercise.

Table 19 **Reaches and sub-catchments defined in the Lugg system for the application of INCA-P**

Sub-catchment	Name	Cumulative area (ha)	Grid reference	Water quality monitoring	Flow gauge
1	Monaughty	30	SO237682	☐	
2	ds Norton Brook	101	SO310650		
3	Rossers Bridge	114	SO348641	☐	
4	Byton	200	SO364647		☐
5	ds Lime Brook	228	SO379652		
6	Mortimers Cross Bridge	249	SO426637	☐	
7	ds Main Ditch	303	SO501596		
8	Butts Bridge	340	SO502588		☐
9	Eaton Bridge	364	SO507585	☐	
10	us R. Arrow	367	SO513573	☐	
11	Ford Bridge	659	SO509551	☐	
12	Hampton Court Bridge	667	SO514528	☐	
13	ds Humber Brook	715	SO522522		
14	ds Bodenham Brook	742	SO536511		
15	ds Wellington Brook	790	SO511470		
16	Wergins Bridge	798	SO528446		
17	ds Moreton Brook	820	SO533433		
18	ds Little Lugg	868	SO531415		
19	Lugwardine Bridge	876	SO546406		☐
20	ds Frome	1060	SO560386		
21	Mordiford Bridge	1062	SO570374	☐	
22	Wye confluence	1077	SO565371		

ds = downstream

3.2.2 Derivation of land use classes

Six land use classes were used in this application: cereal, other arable, grassland, woodland, set-aside and urban. These six land use classes were chosen to match those used in the application of INCA-P to the Ant system and are generalisations of the land use types identified in the MAGPIE database (Table 20).

Table 20 Land use classes used in the application of INCA-P to the Lugg system

ADAS MAGPIE land use class	INCA-P land use class
Winter wheat	Cereal
Winter barley	Cereal
Spring barley	Cereal
Oilseed rape	Cereal
Oats	Cereal
Mixed corn	Cereal
Rye	Cereal
Triticale	Cereal
Maize	Cereal
Linseed	Cereal
Potatoes	Other arable
Beans	Other arable
Peas	Other arable
Horticultural crops	Other arable
Hops	Other arable
Kale/cabbage/savoy/kohl rabi/rape for stock feed	Other arable
Turnips/swedes/fodder beet/mangolds for stock feed	Other arable
Sugar beet	Other arable
Set-aside	Set-aside
Permanent grassland	Grassland
Temporary grassland	Grassland
Rough grazing	Grassland
Woodland	Woodland
Urban	Urban

3.2.3 Phosphorus inputs from fertiliser

Fertiliser application rates for the six INCA-P land use classes were taken from Johnes and Butterfield (2003), who applied the Export Coefficient Method to sub-catchments of the Wye and Hampshire Avon as part of the Phosphorus and Sediment Yield Characterisation (PSYCHIC) project.

The application rates were differentiated by geoclimatic region and, for the purpose of the calculation, the phosphorus load to permanent and temporary grassland was calculated separately (because they have different fertiliser input rates in the ECM scheme) and then summed to provide a total input to 'grassland'. These application rates were multiplied by the land use area in each sub-catchment to provide annual application loads (kg P/year) for each land use type. An estimate of the monthly load was made by distributing the fertiliser load based on the timings observed in the Ant farm survey (see Section 2.1.2).

These monthly loads were converted to a daily application rate (kg P/ha/day) by dividing the monthly load by the number of days per month and the land class area within each sub-catchment. Unlike the application of INCA-P to the River Ant, which was based on a survey of fertiliser practice, the partition between inorganic-P fertiliser, FYM and slurry was unknown. As such, it was assumed that the fertiliser application rates account for the total application of phosphorus – be it from manufactured fertiliser or FYM or slurry – and therefore the ratio of inorganic to organic P content of the total phosphorus applied was 70:30.

The calculated annual phosphorus inputs from fertiliser are shown in Figure 21.The largest inputs are to the ‘other arable’ land use, and this reflects the higher fertiliser input rates in the ECM scheme. The input rates from grassland and cereal are approximately constant through the catchment at 9 and 22 kg P/ha/year, respectively, whereas the input rate to ‘other arable’ varies between 70 and 90 kg P/ha/year.

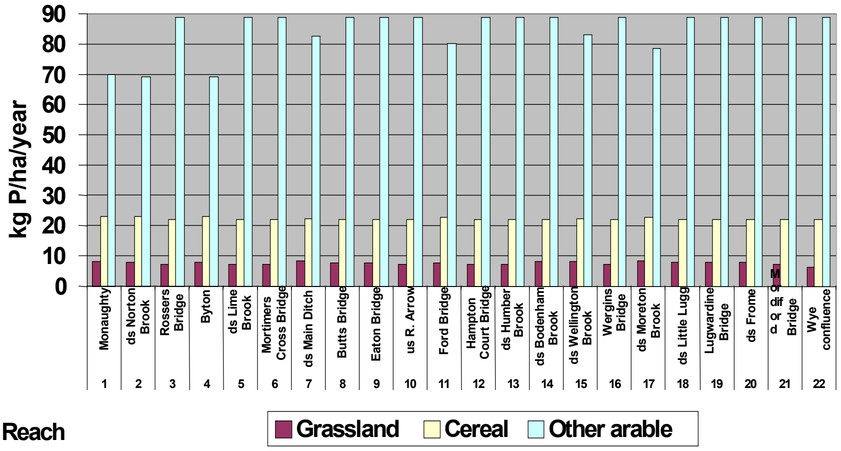


Figure 21 Annual input phosphorus rates (kg P/ha/year) of fertiliser to the land uses in the Lugg catchment

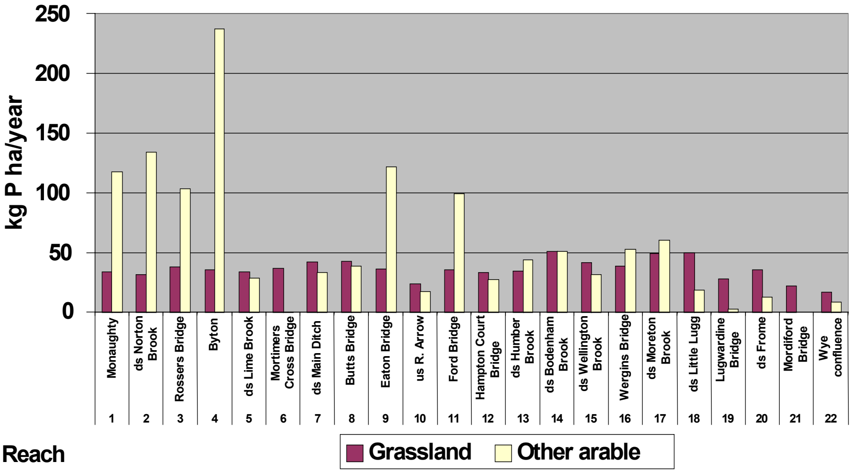


Figure 22 Annual input phosphorus rates (kg P/ha/year) from livestock to the land uses in the Lugg catchment

3.2.4 Phosphorus inputs from grazing livestock

The annual phosphorus inputs per hectare from grazing livestock are shown in Figure 22. The Ant farm survey identified that cattle and sheep predominately grazed grassland, while pigs were found on sugar beet and potatoes. Thus, the phosphorus inputs in the Lugg catchment from cattle and sheep were added to the 'grassland' land class and the phosphorus inputs from pigs to 'other arable'. The input from poultry was also added to 'other arable'. A 70:30 split between inorganic-P and organic-P was also assumed.

The daily rate of the inorganic-P and organic-P inputs was determined by dividing the loads by the number of days in the year, adjusted for leap years. Given an absence of information regarding when and how many head of livestock where housed during winter, it was assumed that all livestock grazed outside for the entire year. The higher inputs from livestock to 'other arable' in the upper reaches of the Lugg are caused by high concentrations of poultry in reaches 1 to 4, and 9 and 11. Reach 11 (the River Arrow sub-catchment) also has relatively high numbers of cattle, sheep and pigs. The inputs to grassland vary between approximately 20 and 50 kg P/ha/year, and the inputs to 'other arable' between 5 and 240 kg P/ha/year. This input rates and those for fertiliser input rates agree with estimates compiled for the ECM (Johnes and Butterfield, 2003).

3.2.5 Growing seasons

The estimates for MORECS square 235, which includes most of the Lugg system, were used (Table 21). The same assumptions used to define the growing systems for the Ant system were used in the application of INCA-P to the Lugg system.

Table 21 Growing seasons used within the INCA-P application to the Lugg system*

Land use	Planting or bud burst	Harvest or leaf fall	Assumptions
Spring barley	23 Mar	26 Aug	
Winter wheat	21 Mar	24 Aug	
Winter barley	11 Mar	3 Aug	
Cereal	**11 Mar**	**26 Aug**	
Early potatoes	20 Mar	20 Jun	
Main crop potatoes	15 Apr	15 Sep*	Haulm (stems & stalks) destruction
Sugar beet	1 Apr	25 Oct	
Other arable	**20 Mar**	**25 Oct**	
Grassland	**1 Jan**	**31 Dec**	Roots active all year
Set-aside	**1 Jan**	**31 Dec**	Non-rotational, same as grass
Deciduous	22 Apr	17 Oct	
Orchards	7 May	27 Sep	
Coniferous	-	-	
Woodland	**1 Jan**	**31 Dec**	Coniferous roots may be active all year. SMD and soil temperature control phosphorus uptake.
Urban (parks and gardens)	**1 Jan**	**31 Dec**	All impermeable

*Dates are derived from input data used in the MORECS model for MORECS square 235. The dates in bold represent the range used for each INCA-P land class.

3.2.6 Calibration of the system hydrology, hydrochemistry and ecology

The daily MORECS time-series describing the HER, SMD and air temperature from Llandrindod Wells and Madley were used to represent upper reaches 1 to 9, and the lower reaches 10 to 22, respectively (Figure 23). IHACRES was not used to modify the HER time-series.

At Llandrindod Wells, the HER and SMD show that the calibration period from 1 January 1998 to 31 December 2000 was wetter than the period 1 January 1995 to 31 December 1997. The model was calibrated as described for the Ant calibration; the ‘a’ and ‘b’ parameters were 0.04 and 0.67, respectively. The other parameters are listed in Appendix D. No flow was routed through the direct runoff box, so the application was effectively based on two stores –soil water and groundwater.

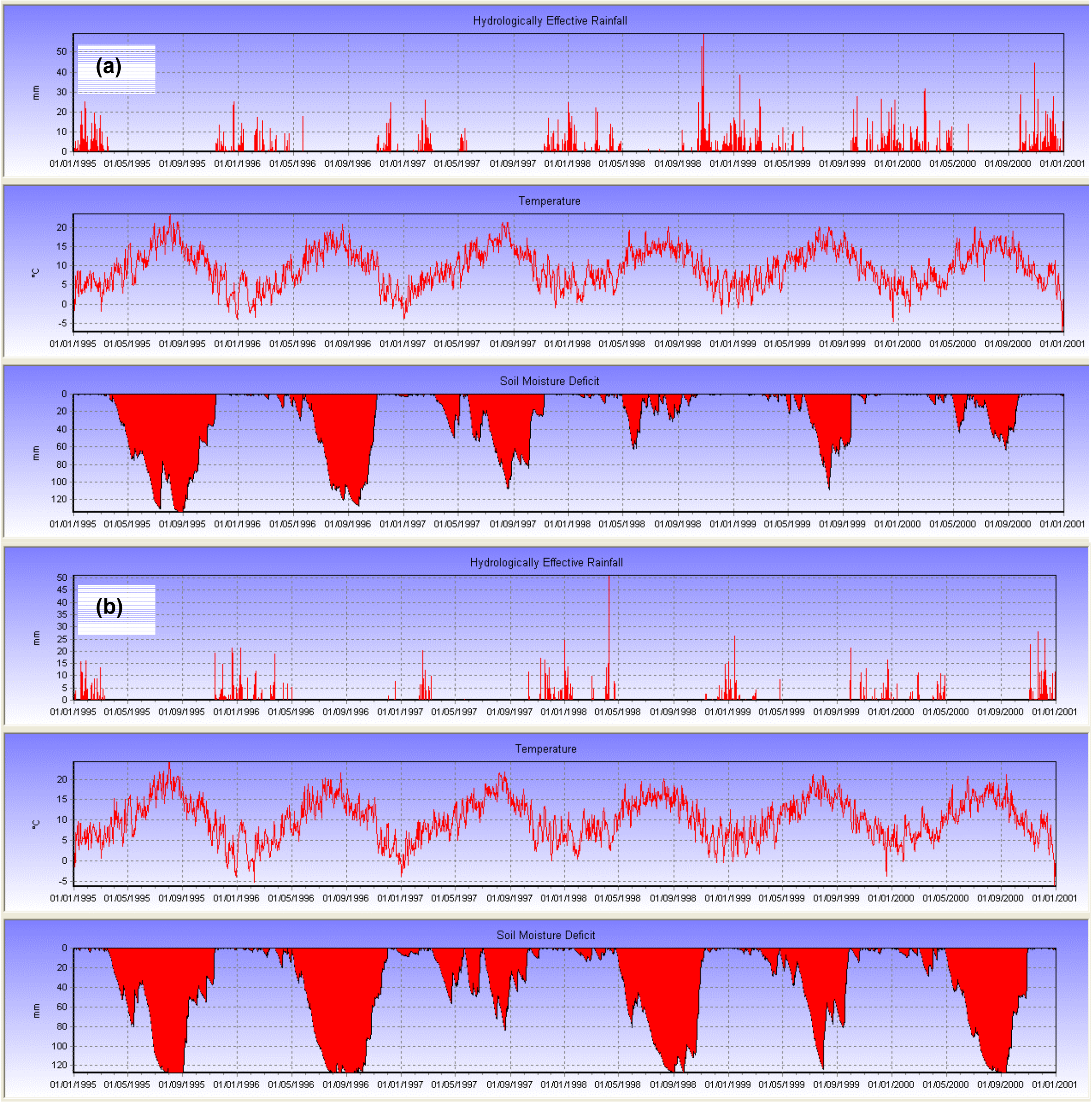


Figure 23 HER, air temperature and SMD time-series from (a) Llandrindod Wells and (b) Madley for the period 01 January 1995 to 31 December 2000

The initial TPh and suspended sediment concentrations in the land phase of the model were set by calibration. The calibrated TPh concentrations and TPh concentrations measured in field experiments from other systems were compared to check consistency with observations (Table 22) (Heathwaite and Dils, 2000). The initial groundwater TPh concentration of 2 µg P/litre appears sensible as measurements of orthophosphate concentration in boreholes in the Wye range from 2 to 200 µg P/litre.

The initial suspended sediment concentrations for all six land uses are given in Table 23 .

Table 22 **Initial TPh concentrations (µg P/litre) in the land-phase of INCA-P applied to the Lugg system**

Land use/pathway	Soil water	Groundwater
Grassland	200	2
Cereal	200	2
Other arable	200	2
Set-aside	20	2
Woodland	20	2
Urban	20	2

Table 23 **Initial suspended sediment concentrations for all INCA-P land use types applied to the Lugg system**

Pathway	Initial concentration (mg/litre)
Soil water	80
Groundwater	10

Only those effluents discharging directly into the main stem of the River Lugg where included in this application (Table 24). This was because the effluent inputs from other works were accounted for in the diffuse input from the sub-catchments and moreover the influence of STWs on in-stream phosphorus concentrations and loads is thought to be localised.

Tertiary stripping was applied at Cadburys and Leominster in 1998, and monthly time-series describing the effluent TPh concentrations are available for these two effluent inputs. The other effluent inputs were modelled as constant inputs through the simulation period. The effluent flows were estimated from Agency records of the mean effluent flow, the population equivalent (multiplied by 180 litres/day, or the maximum permissible flow. The mean effluent TPh concentration was calculated from time-series data of monthly frequency. The flows and concentrations used in the application are given in Table 2.

Table 24 Input loads from STWs and trade effluents directly into the main stem of the River Lugg*

Reach	Effluent name	Population equivalent	Flow	TPh concentration	TPh load
1	Llangunllo	120	0.0003	4.69	37
3	Presteigne	1,851	0.0059	4.52	841
7	Lucton	550	0.0019	3.63	212
10	Leominster*	10,854	0.0332	4.92	5,145
12	Cadburys*	–	0.0637	5.42	10,881
14	Bodenham	600	0.0014	7.71	338
16	Moreton	2,721	0.0072	9.45	2,139
21	Mordiford (Sufton)	134	0.0003	15.60	137

*Time-series of monthly effluent TPh concentrations were used instead of mean values.

As in the Ant application, the parameters relating to the land phase processes of plant uptake and transformation into firmly bound phosphorus forms were adjusted in addition to the initial phosphorus and suspended sediment concentrations, and in-stream parameters. The terms relating to mineralisation and immobilisation were not adjusted, as it was assumed that they were in equilibrium. The land phase parameters are listed in Appendix C.

The plant uptake parameters were adjusted until the simulated annual output load was within the range specified in the literature (see Section 2.3.3). The parameters controlling the transfer of phosphorus into firmly bound stores and vice-versa were adjusted to produce the best fit to the stream water TPh concentrations.

No data were available to describe the macrophyte and epiphyte biomass in terms of carbon mass per plant surface area (gC/m^2) within the Lugg system. The model's ability to simulate macrophyte and epiphyte growth was tested; it was found to simulate sine-wave growth and death of macrophytes and epiphytes. The in-stream parameters are listed in Appendix D.

3.3 Results

3.3.1 Hydrological simulation

The observed flows show an increasing trend from 1995 to 2001 comparable with the input HER and SMD time series. To a first approximation, the simulated flows match those observed at all three gauging stations (Figure 24). The 'a' and 'b' parameters (0.04 and 0.67, respectively, for all reaches) are the same as those used in the application of INCA-N to the River Twyi – a similar system to the Lugg (Whitehead, 1998). INCA-P both under and over-estimates different peak flow events, although the simulation of the base flow recession is good.

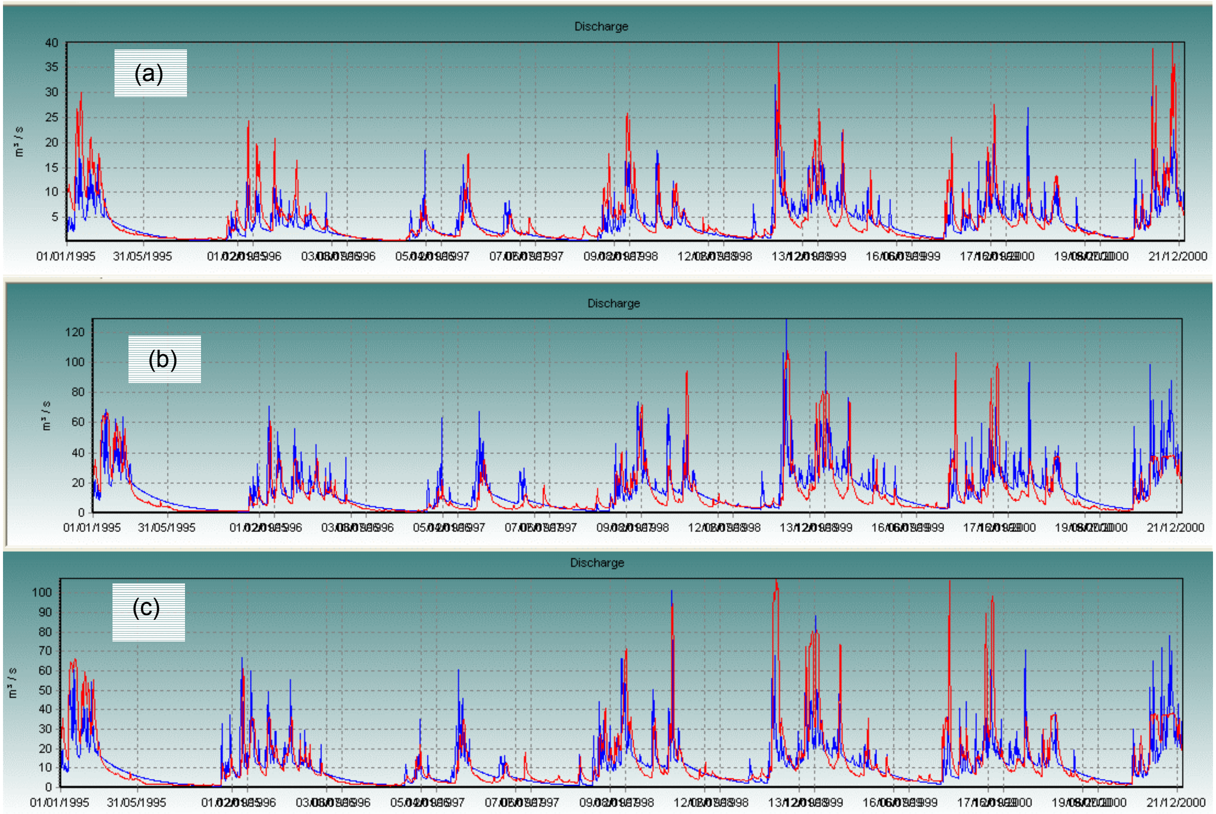


Figure 24 **Simulated and observed flows at (a) Byton (reach 4), (b) Butts Bridge (reach 8) and (c) Lugwardine Bridge (reach 19)**

3.3.2 In-stream phosphorus and suspended sediment concentrations

As in the Ant application (see Section 2), the simple mixing model approach that forms the basis of INCA-P was able to reproduce the spatial and temporal variations of the in-stream TPh, OP and suspended sediment dynamics to a first approximation (Figures 25–28).

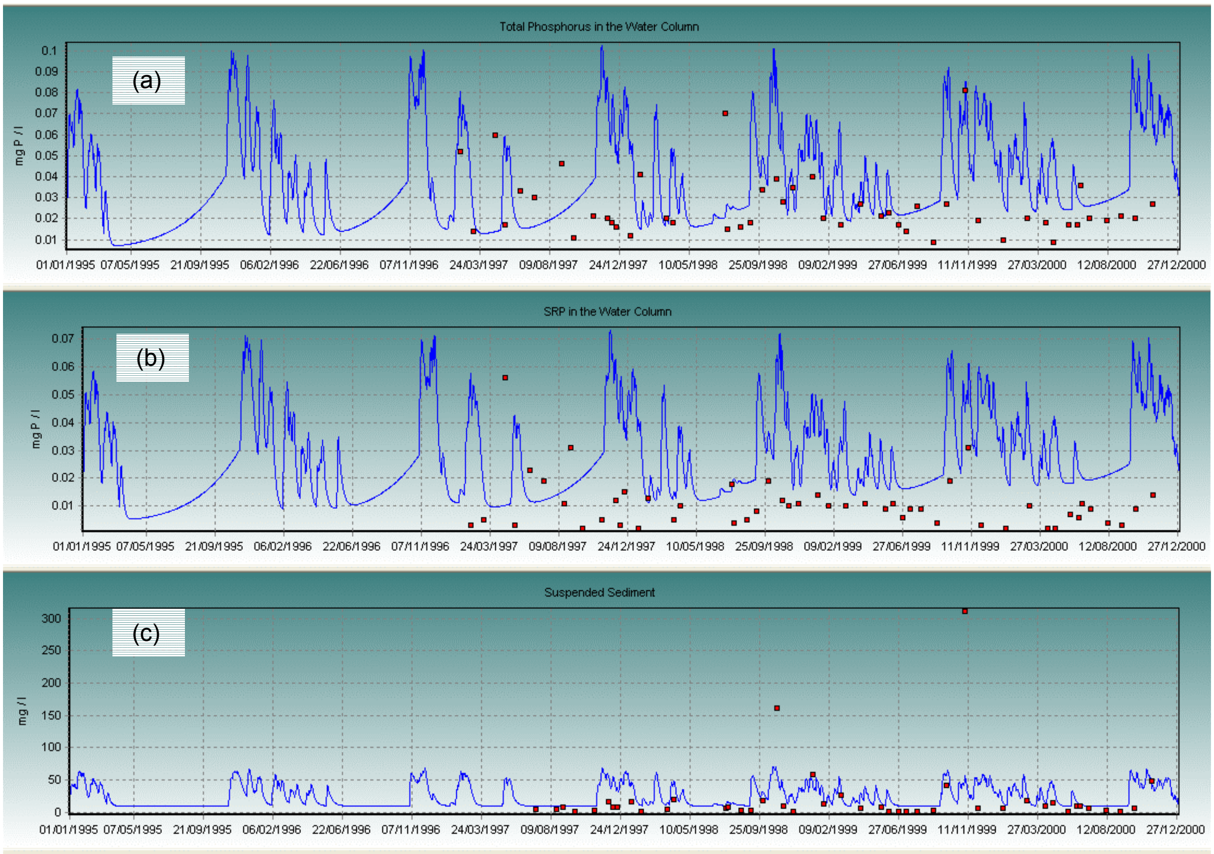


Figure 25 **Observed and simulated (a) TPh, (b) OP and (c) suspended sediment concentrations at Monaughty (reach 1)**

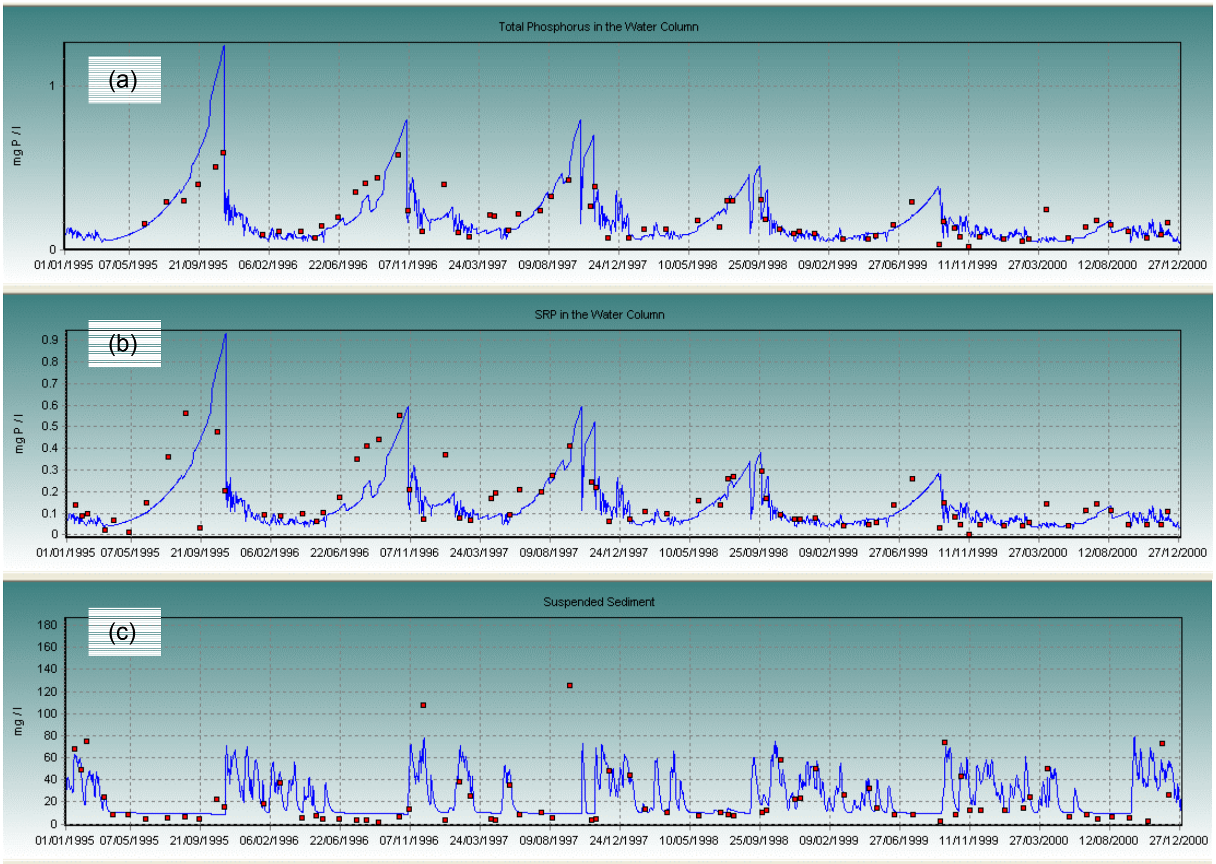


Figure 26 Observed and simulated (a) TPh, (b) OP and (c) suspended sediment concentrations at Hampton Court Bridge (reach 12)

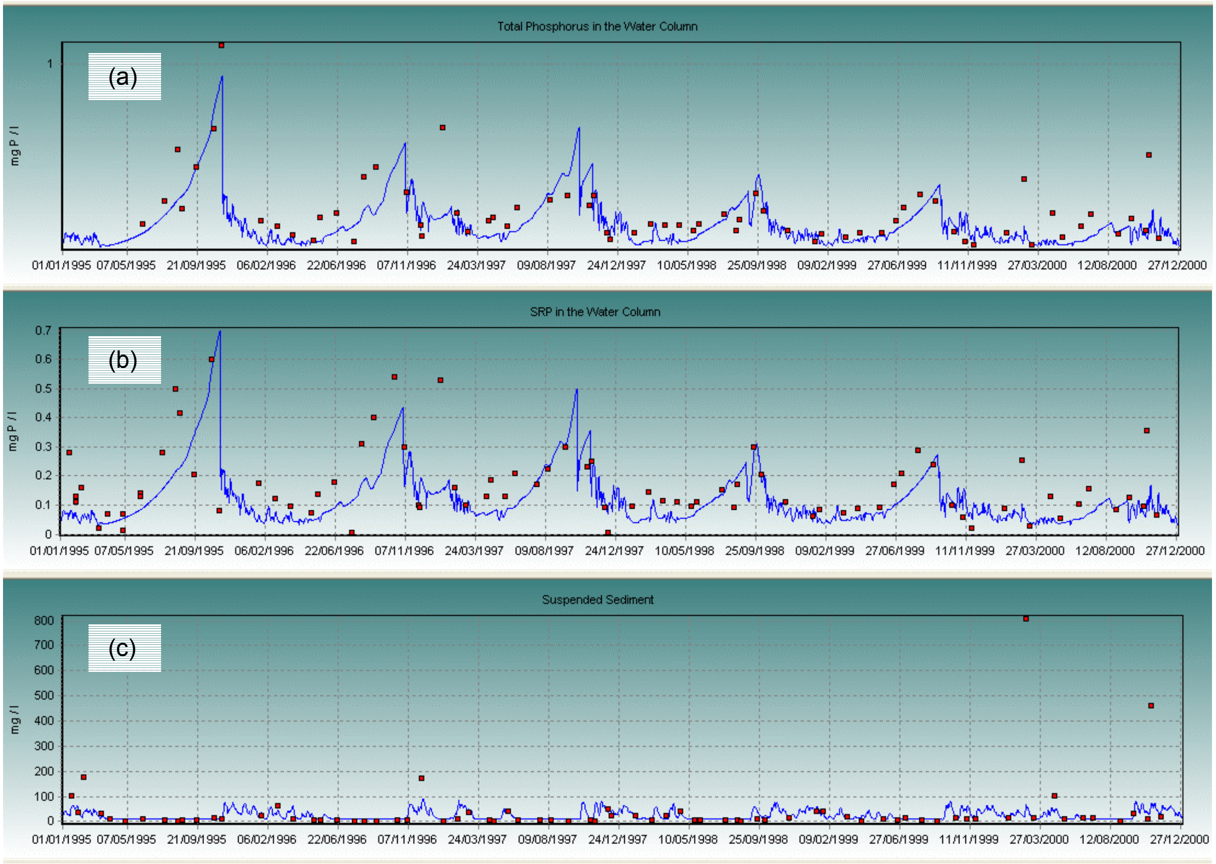


Figure 27 Observed and simulated (a) TPh, (b) OP and (c) suspended sediment concentrations at Mordiford Bridge (reach 21)

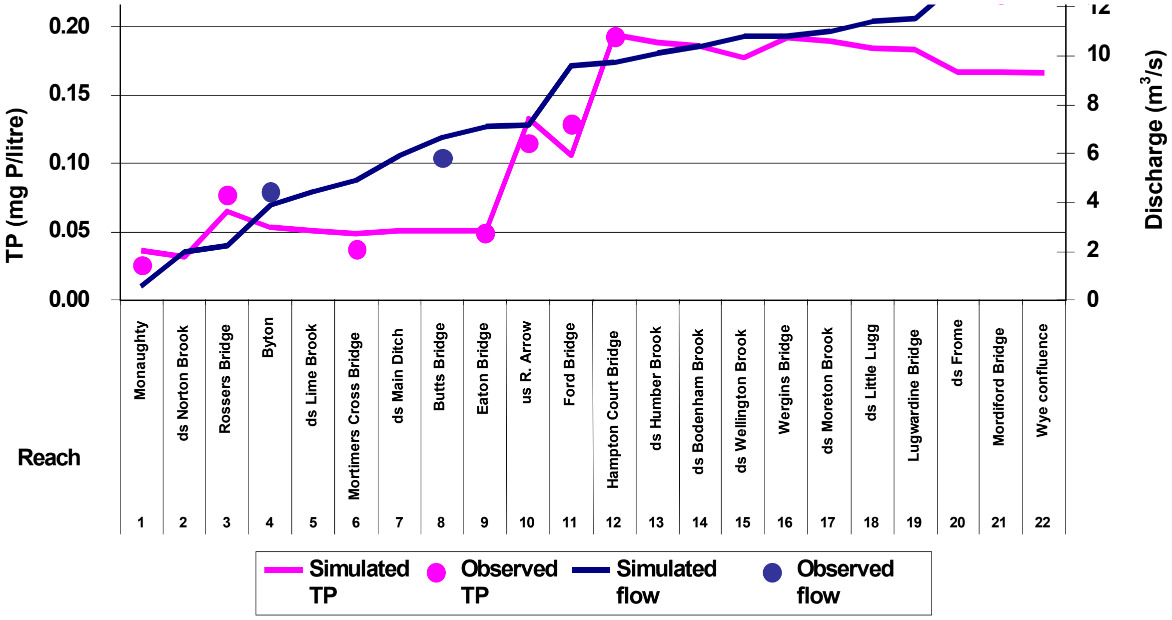


Figure 28 Simulated and observed flows and TPh concentrations along the River Lugg

In reach 1 in the headwaters at Monaughty, the influence of diffuse sources is most apparent on the observed stream water TPh and OP concentrations (see Section 3.1). In this reach, the simulated stream water phosphorus concentrations are the poorest fit to those observed due to the complexity of capturing the response of the highly heterogeneous source areas and flow path activation. In particular, the observed base flow concentrations tend to be over-estimated indicating that the retention of phosphorus in the soil, groundwater or stream system is under-estimated.

Further down the main channel of the Lugg at Hampton Court Bridge and Mordiford Bridge, the simulated in-stream phosphorus concentrations match well those observed. In these reaches, the system is simpler to model; the phosphorus dynamics are dominated by the dilution of point source inputs. At both Hampton Court Bridge and Mordiford, the model is able to reproduce the general downward trend in the observed time-series of stream water TPh and OP concentrations. At Hampton Court Bridge, the reach receives effluent from Leominster STW from which phosphorus was stripped in 1998. The decrease in TPh and OP is therefore partly due to the removal of phosphorus from the final effluent. However, the higher flows in 1999 and 2000 increased the dilution capacity at a time when the effluent concentration from Leominster (and Cadburys) was lower. The over-estimation of the in-stream phosphorus concentrations in 1995 is most probably due to the under-estimation of the flow in the reach during the summer.

Since both ortho-phosphate and total phosphate are measured on an unfiltered sample, then the two are highly correlated (Jarvie *et al.*, 2003). Consequently, since the model is able to simulate the total phosphate concentration, the simulation of the ortho-phosphate concentrations is also good as these are effectively modelled as a fixed fraction of the total phosphate (Equation [12]). The most sensitive parameter controlling the simulated stream water OP concentrations is the fraction of SUP in equation [12] (see Section 6.6.1), which controls the OP:TPh ratio.

The observed mean stream water concentrations also highlight the effect of point source contributions along the longitudinal profile of the Lugg. In the headwaters, the low background phosphorus concentrations from diffuse sources are modified by point source contributions in reaches 1 and 3 (Figure 28 and Table 24).

Downstream of Eaton Bridge, both the mean observed and simulated total phosphate concentrations increase; the observed values from 0.05 to 0.11 mg P/litre. The observed and simulated mean concentrations then increase further due to the cluster of point source in reaches 10 to 12, which include Leominster and Cadburys, to a concentration of approximately 0.17 mg P/litre.

Due to the lack of observations between Hampton Court Bridge and Mordiford Bridge, it is difficult to determine whether the simulated variations in the mean concentrations are reasonable. The observed data suggest an increase in concentration in the lower reaches. However, the simulated data between these two sample sites, suggests possible dilution. The simulated summer flows tend to be over-estimated at Lugwardine Bridge when compared with observations possibly resulting in an over-dilution of the point source contributions. There are three alternative reasons for this:

- a point source discharging directly into the lower reaches may have been omitted or under-estimated;

- the influence of the point sources on the Frome should be included or the downstream influence of the effluent inputs at Leominster, Bodenham and Moreton STWs, and Cadburys extends down the reach;
- the diffuse source input has been under-estimated in the lower reaches.

Both the observed and simulated stream water TPh concentrations indicate a threshold between two sections of the Lugg. Upstream of the confluence with the River Arrow, the Lugg can be characterised by low TPh concentrations (around 0.05 mg P/litre), whereas downstream in the area of greater urbanisation and agricultural intensification, the stream water concentrations are higher (approximately 0.16 mg P/litre). The mean simulated OP concentrations are almost identical in the water column and stream bed, suggesting an equilibrium over the period studied (Figure 29).

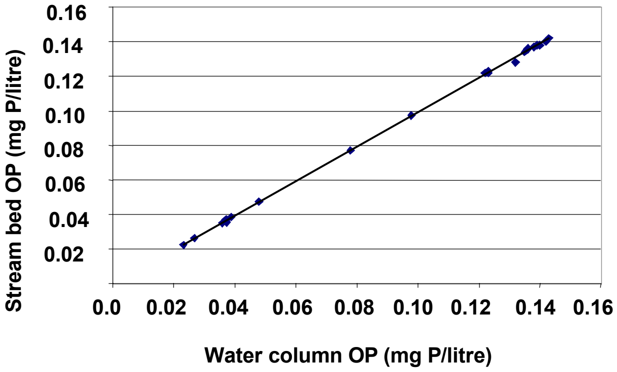


Figure 29 **Relationship between simulated mean stream water OP concentrations in the water column and pore water**

Table 25 and Table 26 present the results of the same three goodness of fit tests that were used for the River Ant application (see Section 2.2.12). These results demonstrate a good hydrological fit at all three gauging stations and satisfactory results for total phosphate, ortho-phosphate and suspended sediment.

Table 25 **Determination coefficient for flow, TPh and OP and suspended sediment in reaches along the Lugg system***

Reach	Flow(m^3/s)	TPh (mg P/litre)	OP(mg P/litre)	SS (mg l/litre)
Byton	0.58 (0.76)	-	-	-
Butts Bridge	0.36 (0.60)	-	-	-
Hampton Court Bridge	–	< 0	0.06 (0.23)	0.28 (0.52)
Lugwardine Bridge	0.47 (0.69)	-	-	-
Mordiford Bridge	–	0.47 (0.68)	<0	0.10 (0.41)

*Correlation coefficient is given in brackets.

Table 26 **Explained variance for flow, TPh, OP and suspended sediment in reaches along the Lugg system**

Reach	Flow (m^3 s)	TPh (mg P/litre)	OP (mg P/litre)	SS (mg/ litre)
Byton	0.59	-	-	-
Butts Bridge	0.38	-	-	-
Hampton Court Bridge	–	< 0	0.23	0.29
Lugwardine Bridge	0.48	-	-	-
Mordiford Bridge	-	0.47	0.28	0.11

3.3.3 Land phase and in-stream TPh loads

The annual loads (kg P/ha/year) of TPh exported from different land uses are generally within the range reported within the literature for UK and USA river systems and plot experiments (Table 27). Apart from plant uptake from grassland in the upper reaches, both the simulated phosphorus plant uptake and export rates are at the lower end or below the range of the observed data. A mass-balance on the phosphorus input to the land phase suggested that only 1 per cent of the phosphorus input to the land reaches the water column; the remaining 99 per cent is stored either in the soil, the groundwater or the stream bed sediments. To calibrate the model to the observed stream water phosphorus data, much of the phosphorus input to the system was simulated to be retained in the soil.

Table 27 **Comparison of simulated and observed process loads (kg P/ha/year) from UK and US studies**

Process	Sub-catchment 1	Sub-catchment 12	Sub-catchment 21	Observed range
Crop uptake				
Cereal	15	15	15	19–27[1]
Other arable	20	11	8	14–21[1]
Grassland	12	10	7	12–40[2,3]
TP export				
Cereal	0.84	0.34	0.34	0.07–7.5
Other arable	0.72	0.18	0.14	0.07–7.5
Grassland	0.32	0.12	0.09	0.2–9.7
Woodland/forest	0.03	0.02	-	0.007–0.9
Urban	-	0.02	0.02	0.9–3.4

[1] Sharpley (1995)

[2] Foy *et al*. (1997)

[3] Brookes *et al*. (1984)

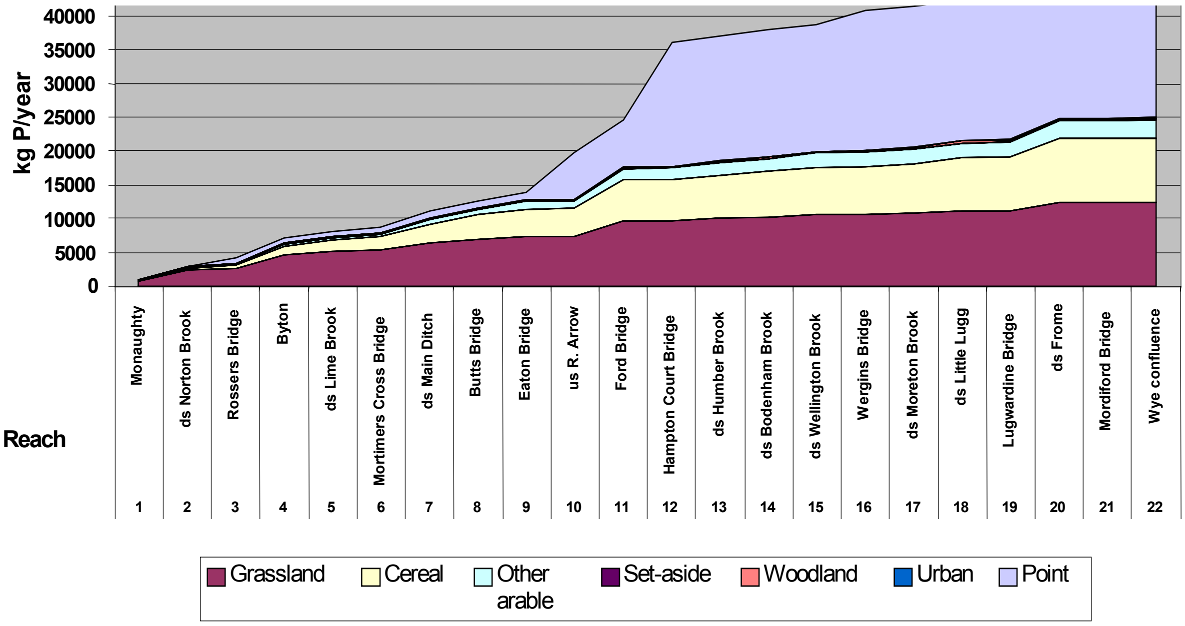


Figure 30 **Cumulative export load (kg P/year) from the land to the river in the Lugg catchment compared with the point source load**

A comparison of the point source loads with those exported from the different land use types included in INCA-P is shown in Figure 30. These data exhibit the same threshold as the mean observed stream water TPh concentrations: the profile can be divided into two sections above and below Eaton Bridge. In the upper reaches, the ratio of load contribution from point and all diffuse sources is 1:9 and, in the lower reaches, the ratio is 1:1.

The influence of the River Lugg on the River Wye was determined by comparing the load delivered from the Lugg to the Wye with the observed load at Redbrook on the Wye, which is the lowest gauging station (Jarvie *et al.*, 2003). Between 1995 and 2000, the Lugg contributed 13–35 per cent of the load measured in the Wye (Table 28). The greatest influence occurred in 1996, the driest year considered and before phosphorus stripping at Cadburys and Leominster. Thus, in drier years, the point sources in the Lugg had more of an impact on the Wye. Following phosphorus stripping and during wetter years, the influence was less.

Table 28 Comparison of calculated OP loads (kg P/year) calculated from INCA-P simulations in the Lugg and from observed data in the Wye

Year	**Precipitation (mm/year)**		**Load (tonnes P/year)**		**Impact of Lugg (per cent)**
	Llandridod Wells	**Madley**	**Lugg at confluence with Wye**	**Wye at Redbrook**	
1995	993	774	33	171	19
1996	876	648	27	77	35
1997	921	785	33	230	14
1998	1,409	806	39	306	13
1999	1,352	797	36	220	16
2000	1,380	799	33	247	13

Source: Jarvie *et al.* (2003)

The uptake and release from sediments and plants in each reach was assessed by mass balance (Table 29). Specifically, the change in phosphorus stored in each reach was calculated over the study period using the following equation:

$$\Delta S = I_U + I_D + I_P - O \qquad [10]$$

where:

ΔS is the change in phosphorus stored in the period (kg P)
I_U, I_D, I_P are the input phosphorus loads (kg P) from upstream, diffuse and point sources, respectively
O is the output load (kg P).

The change in storage within each reach is a very small percentage, approximately 0.01 per cent of the TPh output from each reach over a year. This result suggests that, on the reach scale of the INCA-P model (500–10,000 metres), phosphorus is neither stored nor released. The simulated stream bed TPh concentrations are approximately four times greater than the concentrations in the overlying water column and the two concentration time-series display the same dynamic patterns indicating equilibrium between the two. This result needs further verification using the measurements made as part of the PSYCHIC project (see Section 3.2.3). It is also important to identify any local variations that may not be simulated by INCA where the reach length in this application ranges from 500 to 11,000 metres.

Table 29 Uptake and release of phosphorus in the reaches of the River Lugg

Reach	Output (kg P)	Upstream (kg P)	Diffuse (kg P)	Point (kg P)	ΔS (kg P)	Uptake or release
1	896	0	850	37	–10	Release
2	2,877	896	1,977	0	–4	Release
3	4,215	2,877	500	841	3	Uptake
4	7,205	4,215	2,990	0	0	Equilibrium
5	8,111	7,205	910	0	5	Uptake
6	8,698	8,111	581	0	–6	Release
7	11,056	8,698	2,142	212	–5	Release
8	12,623	11,056	1,583	0	17	Uptake
9	13,786	12,623	1,164	0	1	Uptake
10	19,673	13,786	39	5,844	–4	Release
11	24,582	19,673	4,916	0	7	Uptake
12	36,200	24,582	131	11,487	0	Equilibrium
13	37,032	36,200	830	0	–3	Release
14	37,912	37,032	549	338	6	Uptake
15	38,678	37,912	803	0	37	Uptake
16	41,013	38,678	161	2,139	–35	Release
17	41,475	41,013	461	0	–1	Release
18	42,480	41,475	986	0	–18	Release
19	42,610	42,480	134	0	4	Uptake
20	45,712	42,610	3,114	0	12	Uptake
21	45,908	45,712	37	137	–21	Release
22	46,049	45,908	136	0	–4	Release

Given importance of point source inputs within the Lugg catchment, two scenarios were examined to explore the potential effects of adding phosphorus stripping to all the effluents listed in Table 24.

- The first scenario is the removal of all point sources by the reduction of the effluent concentration to 0 mg P/litre for each discharge. This is an extreme case and unlikely ever to be implemented, yet it allows the affects of the diffuse sources alone to be examined.
- The second scenario is the reduction of the effluent concentration to 1 mg P/litre. This concentration is typical of what has been achieved at Cadburys and Leominster following phosphorus stripping.

For each scenario, the model was run for the period 1 January 1995 to 31 December 2000 to simulate a range of hydrological conditions.

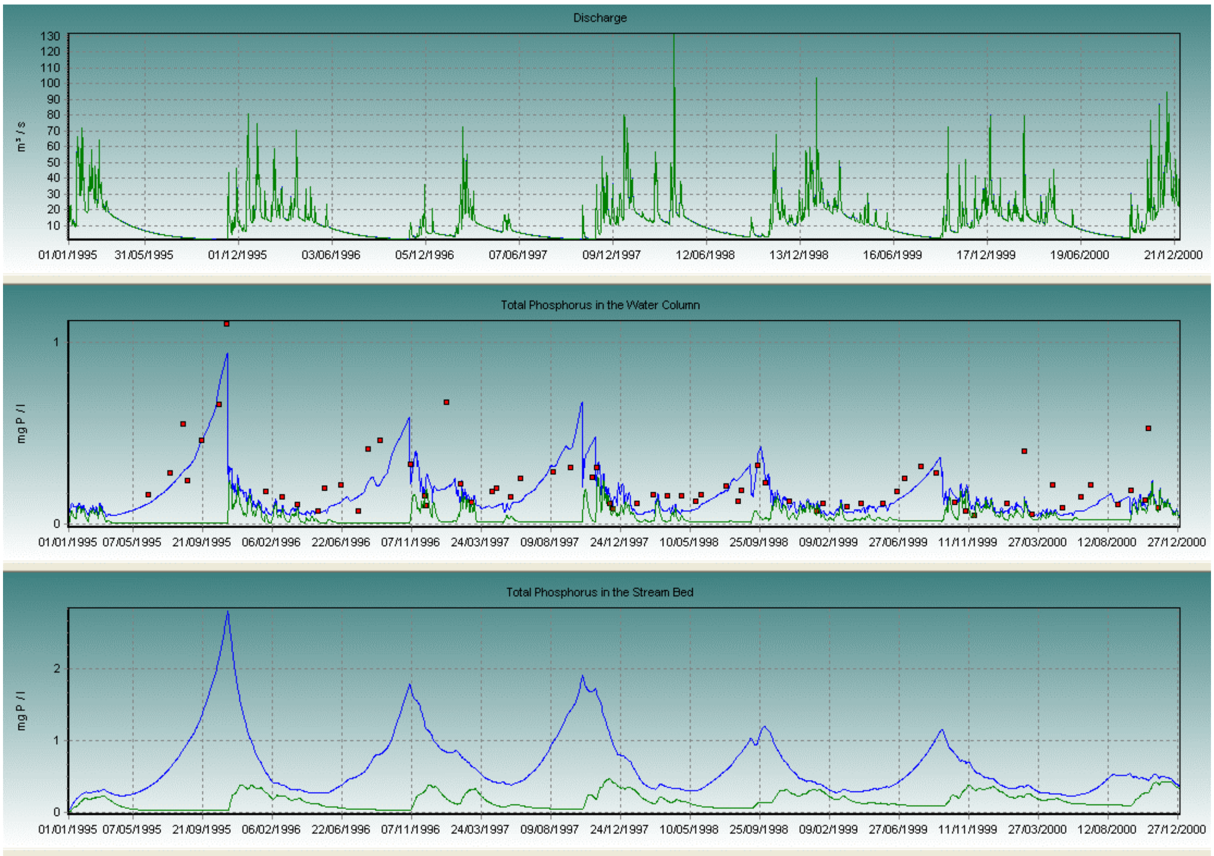


Figure 31 Simulated effect on the stream water and stream bed TPh concentrations at Mordiford Bridge of removing all phosphorus from the effluents discharging into the River Lugg

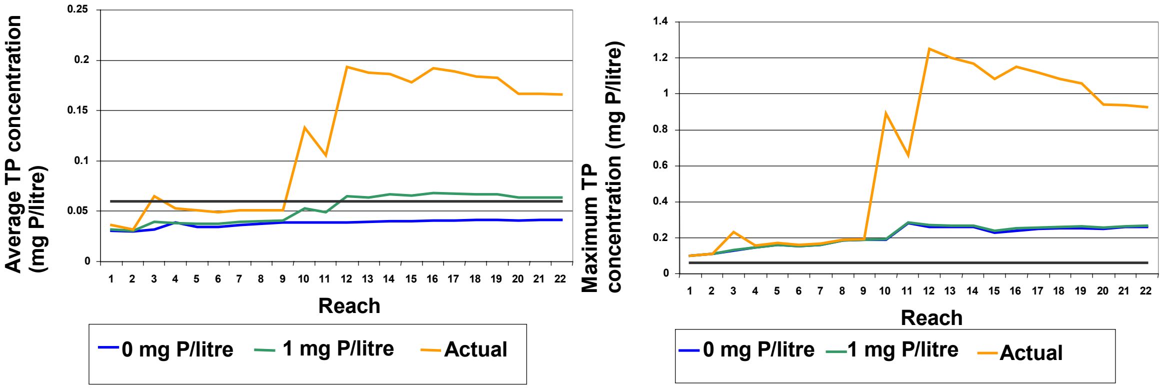


Figure 32 Simulated effect on the mean and maximum stream water TPh concentrations of reducing the effluent concentration to 0 and 1 mg P L-1 in point discharges to the River Lugg

Removing the point source contribution alters the relationship between flow and in-stream concentration (Figure 31). As to be expected, the pattern of effluent concentration during the summer and dilution during the spring to autumn is replaced by a pattern typical of diffuse source domination, i.e. higher phosphorus concentrations during storm events, with the highest concentrations occurring during the first autumnal storms. During the summer, the simulated stream water concentrations falls to zero as no phosphorus is transported from the land to the river due to simulated phosphorus sorption on soils, plant uptake and in-stream uptake.

Both scenarios result in simulated mean and maximum stream water TPh concentrations at, or below, the values calculated when the observed effluent discharges were used for model calibration (Figure 32). The reduction in the mean and maximum concentrations is greatest in lower reaches, which receive more effluent than the upper reaches. Removing all the phosphorus from effluent results in simulated mean concentrations below 60 µg P/litre – a threshold used to define eutrophic status (in lakes). Following the simulated reduction in effluent concentration to 1 mg P/litre, the simulated mean concentration ranges from 63 to 68 µg P/litre in the lower reaches. The simulated maximum concentrations also fall, although these are all still well above the 60 µg P/litre threshold; they range from 100 to 290 µg P/litre in the upper and lower reaches, respectively.

3.4 Conclusions

The application of INCA-P to the Lugg river system has provided important information on:

- the location of 'phosphorus-rich' areas within the catchment
- the upland/lowland contrast within the system
- the relative contribution of point and diffuse sources
- the influence of the Lugg on the Wye.

The results indicate the importance of the point source contribution to the in-stream phosphorus load in the lower reaches of the Lugg. Preliminary scenarios suggest that further phosphorus stripping may further reduce the mean stream water phosphorus concentration close to 60 µg P/litre. However, further work is needed to verify this result and to understand the potential ecological implications and likely costs.

4. Application of INCA-P to the upper River Kennet

4.1 Study area and data resource

4.1.1 Study area

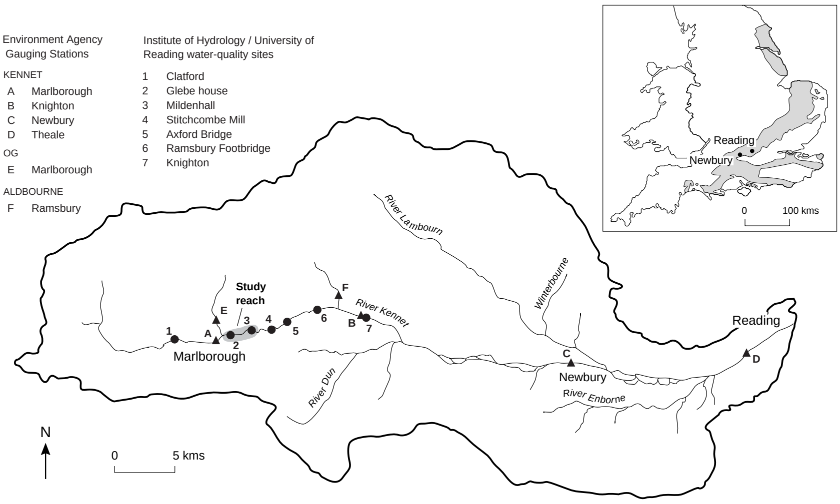


Figure 33 **The River Kennet and its tributaries: location of Agency river gauging stations and the CEH/University of Reading intensive water quality monitoring sites**

The River Kennet drains an area of approximately 1,200 km^2 in southern England and is a major tributary of the River Thames (Figure 33). Rising from a source 190 metres above sea level, the river flows broadly eastwards for around 40 km before entering the Thames at Reading at 32 metres above sea level. Cretaceous Chalk covers approximately 80 per cent of the total catchment area. As such, the river system is of particular interest because Cretaceous Chalk is representative of large areas of lowland UK. The relief is dominated by gently sloping valleys, with the highest point on the Marlborough Downs at 294 metres.

The long-term annual precipitation over the catchment is 774 mm, though approximately only 38 per cent becomes river flow due to high evapotranspiration (CEH, 2003). The river flow is dominated by groundwater inputs since the chalk strata form an important aquifer. Consequently, the flow response is highly damped except for the Enbourne tributary, which is underlain by Tertiary Clay. The long-term annual mean flow at Theale, the lowest gauging station on the Kennet, is 9.64 m^3/s (294 mm of runoff). The mean annual flood is estimated as 37.3 m^3/s and the flow exceeded 95 per cent of the time is 3.84 m^3/s.

The catchment is mainly rural, with arable agriculture being the predominant land use. There are several large towns along the main stem and, as such, treated sewage and industrial effluent are discharged directly into the Kennet (Figure 34). The catchment provides water for public and industrial supply by means of direct surface and groundwater abstractions. A substantial yield of 70–90 Ml/d is abstracted from the chalk aquifer by 33 boreholes arranged in the seven well fields that make up the West Berkshire Groundwater Scheme. As part of the scheme, the Agency owns an abstraction licence which, in extreme drought periods only, can be used to augment flows in the River Lambourn. In turn, this augments the Kennet and Thames allowing Thames Water Utilities Ltd to abstract more potable water with which to supply London. This licence has been used two or three times in the last 20 years.

There are concerns that algal growth may be having an adverse impact on the macrophytes within the upper reaches of the River Kennet. Anecdotal evidence suggests that algal growth in 1997, which had a particularly dry summer, was greater than in other recent years with both the macrophytes and the river bed covered by epiphytic and epiplithic algae.

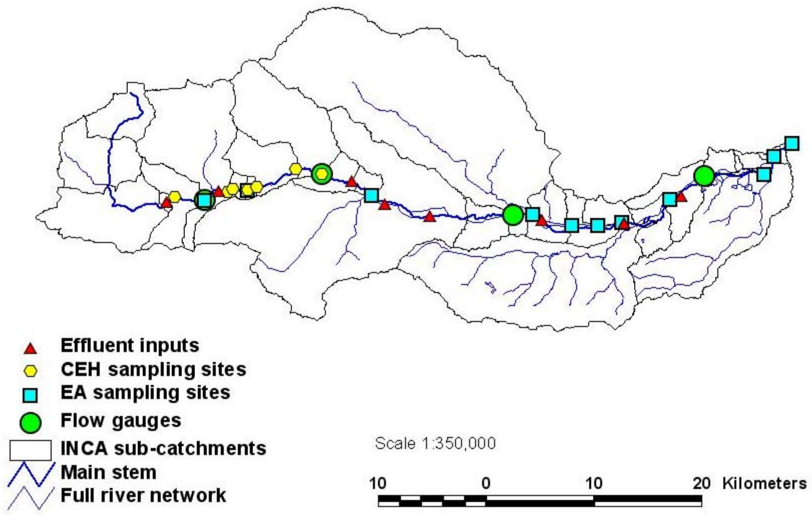


Figure 34 **The River Kennet and its tributaries: location of effluent discharges, CEH and Agency routine monitoring points, and flow gauges**

4.1.2 Data resource

The original intention was to apply INCA-P to the whole catchment and the land use data were prepared for the whole catchment. However, the model was applied only to the river upstream of Knighton. There were two reasons for this. Firstly, CEH and the University of Reading undertook a detailed hydrochemical and ecological monitoring campaign at seven sites in 1997 and 1998 (see Figure 33) to monitor the response to phosphorus stripping at Marlborough STW. Secondly, prior applications of INCA-N to the upper Kennet revealed problems in simulating the flows in the upper reaches, and these need to be addressed to model the correct dilution of point source inputs. Thus, the study area comprised 11 reaches in the Upper Kennet from Clatford to Knighton (Figure 35 and Table 31).

Table 30 summarises the INCA-P input data for models' application to the upper reaches of the River Kennet.

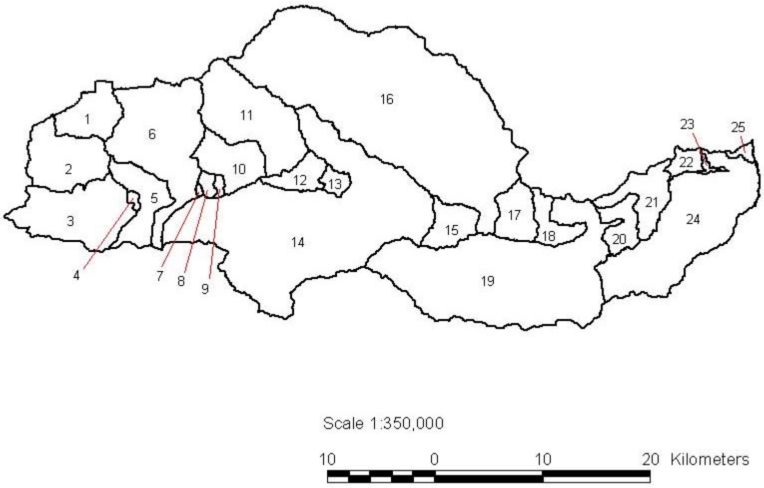


Figure 35 Reaches and sub-catchments of the River Kennet (reaches 1–11 used for application of INCA- P)

Table 30 Summary of INCA-P input data for the Kennet application

	Resolution	Period of data collection	Storage/ retrieval method	Source	Reference
Spatial data					
Land use and livestock numbers	Farm returns	2000	ESRI ArcInfo GIS	Defra	
Fertiliser practice	Geoclimatic region		Microsoft Excel	AERC	Johnes *et al.*, 2003
*River networks	1:50,000		ESRI ArcInfo GIS	CEH	Moore *et al.*, 1994
*Reach boundaries	50 m		ESRI ArcInfo GIS	CEH	
Temporal data					
TP, SRP, SS and boron stream water concentrations	Weekly	1997 to 1998	Microsoft Excel	Agency/ AERC	
*MORECS rainfall, temperature and soil moisture	Daily		Microsoft Excel	ADAS	Met Office, 1981
Growing season	Lumped mean per MORECS square		Report	Met Office	Met Office, 1981
Discharge	Daily		Microsoft Excel	CEH/ Agency	
Base Flow Index	Each flow gauge		Report	CEH	Gustard *et al.*, 1987

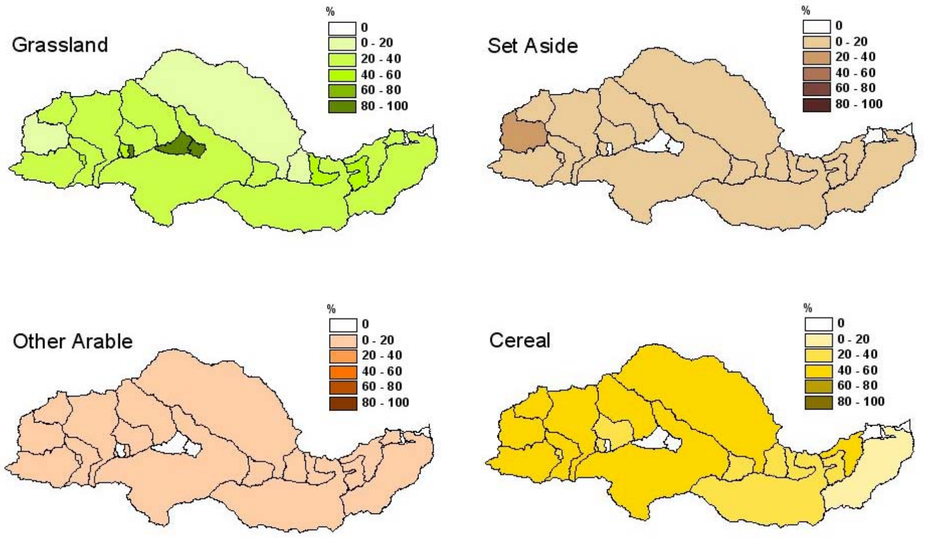
*Data purchased from third parties.

Land use and management

The Kennet catchment is predominantly rural, and the main land uses are cattle and sheep grazing, and cereal cultivation (Figure 36). The main towns in the catchment are Hungerford, Newbury and Reading. As such, the Kennet is impacted by both point and diffuse sources of pollution.

Marlborough is the main settlement in the upper Kennet and is located just upstream of the major point source discharge in the upper reaches, Marlborough STW. On 25 August 1997, Thames Water plc began a phosphorus reduction trial at Marlborough STW using chemical treatment (iron dosing) to reduce phosphorus concentrations in the final effluent. There is one minor sewage input at Clatford (upstream of Marlborough STW), which serves the small village of Fyfield.

The Defra Annual Agricultural Census 2000 was used to describe the land use and livestock numbers, based on farm-scale returns. Due to the Non-disclosure Act whereby the identity of single farms are protected, the data are treated before release to third parties. As such, these data were treated with caution as they contain undisclosed values and assumptions must be made to redistribute the data. Furthermore, since the returns are based on farms, it can be difficult to translate the data to sub-catchments as, although the farm might be inside the catchment, the farm land might not. The ADAS MAGPIE database describes a redistribution of these Defra statistics into 1 km^2 grid cells. Through the provision of funds to ADAS, there is a collaborative effort to compare INCA-P and the PSYCHIC model in the Lugg system, and consequently the MAGPIE data for the Lugg were released to AERC free of charge. To obtain the MAGPIE data for the Kennet, there would have been a charge of £250 (+VAT). Given the budget constraints and an interest in seeing how useful the treated statistics were, it was decided to use the Defra data in this instance.



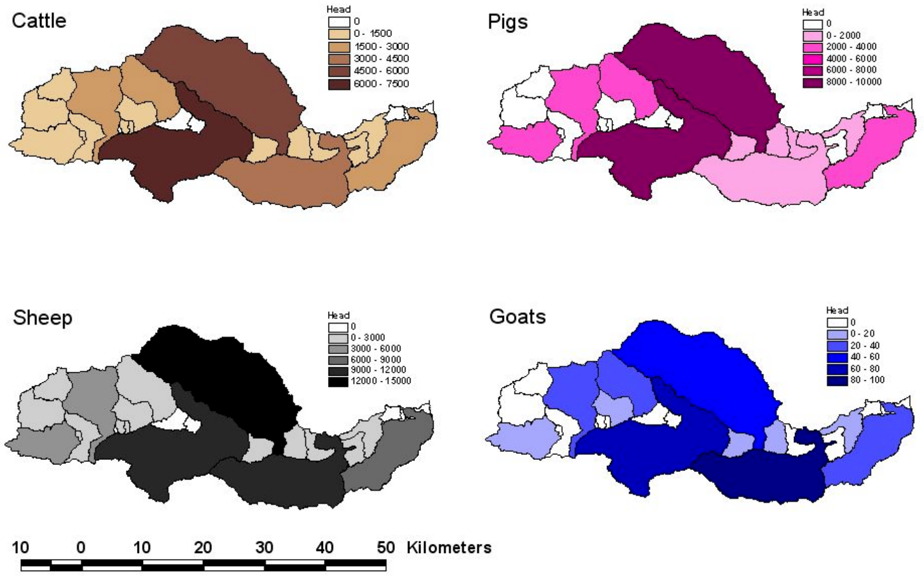


Figure 36 **Land use and livestock numbers in the Kennet catchment derived from the Defra Annual Agricultural Census 2000**

The Defra data includes totals of different crop areas and livestock numbers for the whole catchment as well as for each of the INCA sub-catchments. To account for the missing data in a particular sub-catchment, the reported areas or livestock numbers were summed and subtracted from the whole catchment number. This gave a figure for the 'undisclosed' crop area or head of livestock, which was distributed evenly over the remaining catchment area. Some assumptions were made, based on the Ant farm survey, about where livestock graze, i.e. sheep, cattle and goats on grass, pigs on other arable.

Hydrological data

The Base Flow Index is 0.95, indicating that the Kennet is predominantly groundwater fed. In the north and west of the catchment where the chalk aquifer is unconfined, it is recharged directly by rainfall. One HER, SMD and air temperature MORECS dataset was used, which was derived from a station at Marlborough. Again this dataset was bought via ADAS from the Met Office.

Stream water and effluent hydrochemical data

Weekly water chemistry samples were taken upstream at each of the seven sample points and analysed for Total Phosphorus (TP), Soluble Reactive Phosphorus (SRP), Boron (B) and suspended sediment concentrations (Neal *et al.*, 2000a). Thames Water provided mean daily flows and TP concentrations relating to the effluent discharged from Marlborough STW. The Agency data archive provided a population equivalent and a mean TP concentration for Fyfield STW; the daily flow was derived from the population equivalent multiplied by 180 litres/day. A detailed analysis of the water chemistry data is presented elsewhere (Neal *et al.*, 2000a; Jarvie *et al.*, 2002).

Ecological data

The macrophyte and epiphyte biomass within the reach was also measured when practical between April 1998 and December 1998 at Mildenhall (Flynn *et al.*, 2002). The predominant macrophyte in the reach is water crowfoot, otherwise known as *Ranunculus penicilatus var. calcareous* (R. W. Butcher) C. D. K. Cook. This plant is particularly valued because of its attractive flower and the cover it offers to fish, particularly Brown Trout (*Salmo trutta*). Other macrophytes present included *Callitriche obtusangula* (Le Gall) and *Rorippa nasturtium-aquaticum* (L.) Hayek. The epiphyte biomass measured provides an estimate of that on the macrophytes; it does not include any phytoplankton growth in the water column or any epiplithic algae.

4.2 INCA-P set-up and calibration

The model was set-up and calibrated for the period 1 January 1997 to 31 December 1998. These dates were chosen because they cover the period of available data that span the phosphorus reduction at Marlborough STW. Many of the assumptions made to set-up INCA-P for the upper River Kennet were identical to those used in the Ant application (see Section 2). As such, only the significant deviations from these assumptions are described.

4.2.1 Sub-catchment boundaries

Eleven reaches were defined for the application of INCA-P to the upper Kennet system; the sub-catchments are shown in Figure 35 and described in Table 31. Seven reach boundaries where chosen to coincide with the locations of the hydrochemical sampling sites, and two to coincide with the flow gauging stations. The remaining reaches are chosen to prevent over-long reaches.

Table 31 Reaches and sub-catchments defined in the Kennet system for the application of INCA-P

Sub-catchment	Name	Cumulative area (ha)	Grid reference	Water quality monitoring	Flow gauge
1	Source	2,400	SU118786		
2	Avebury	5,800	SU097699		
3	Fyfield	10,900	SU147681		
4	Clatford	11,000	SU159688	☐	
5	Marlborough	13,400	SU187686		☐
6	Glebe House	21,100	SU208693	☐	
7	Mildenhall	21,200	SU213696	☐	
8	Stitchcombe	21,400	SU227695	☐	
9	Axford	21,600	SU235698	☐	
10	Ramsbury	24,000	SU271714	☐	
11	Knighton	29,700	SU295710	☐	☐

4.2.2 Derivation of land use classes

Six land use classes were used in this application: cereal, other arable, grassland, woodland, set-aside and urban. These six land use classes were chosen to match those used in the application of

INCA-P to the Ant system, and are generalisations of the land use types identified in the Defra Annual Agricultural Census database (Table 32).

Table 32 Land use classes used in the application of INCA-P to the Kennet system

Defra land use class	INCA-P land use class
Winter wheat	Cereal
Winter barley	Cereal
Spring barley	Cereal
Oats	Cereal
Mixed corn	Cereal
Rye	Cereal
Triticale	Cereal
Potatoes	Other arable
Beans	Other arable
Peas	Other arable
Horticultural crops	Other arable
Hops	Other arable
Kale/cabbage/savoy/kohl rabi/rape for stock feed	Other arable
Turnips/swedes/fodder beet/mangolds for stock feed	Other arable
Sugar beet	Other arable
Maize	Other arable
Set-aside	Set-aside
Linseed	Set-aside
Oilseed rape	Set-aside
Permanent grassland	Grassland
Temporary grassland	Grassland
Rough grazing	Grassland
Woodland	Woodland
Urban	Urban

4.2.3 Phosphorus inputs from fertiliser and livestock

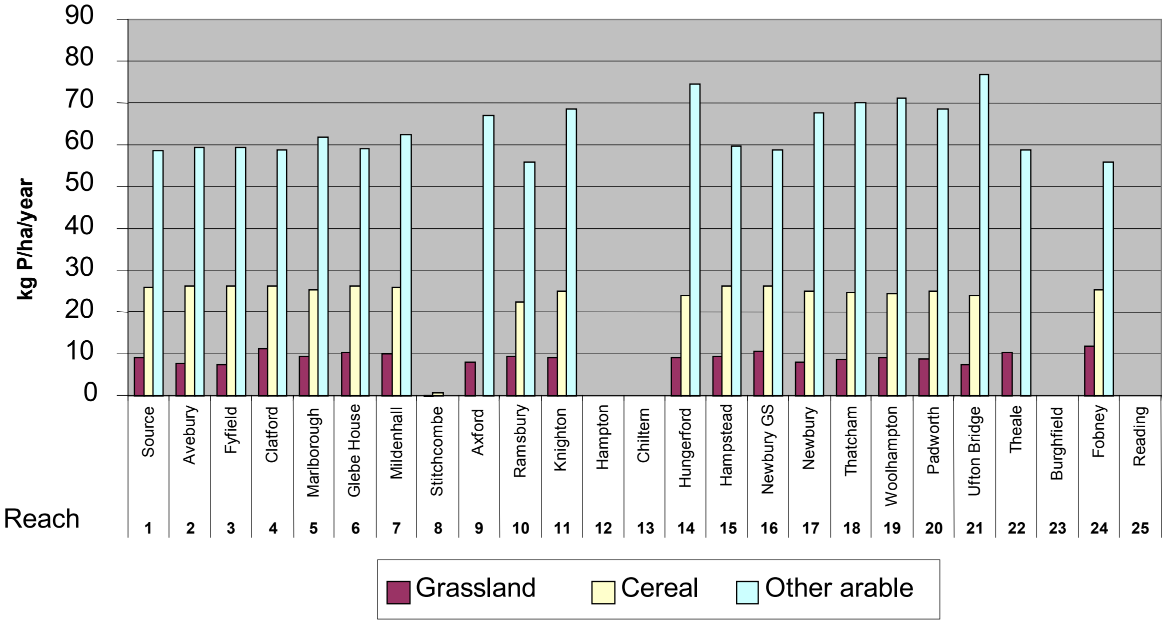


Figure 37 **Annual input phosphorus rates (kg P/ha/year) of fertiliser to land uses in the Kennet catchment**

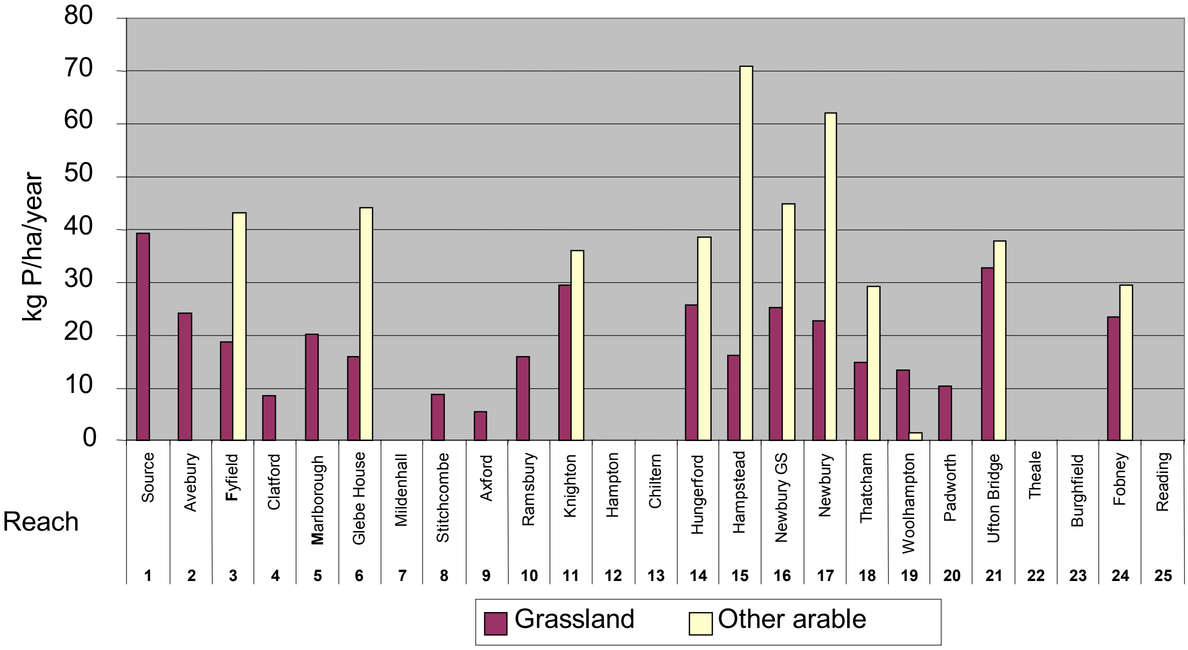


Figure 38 **Annual input phosphorus rates (kg P/ha/year) from livestock to land uses in the Kennet catchment**

The estimates of phosphorus inputs from fertiliser and livestock were calculated using the same method as for the River Lugg (see Sections 3.2.3 and 3.2.4). The calculated annual phosphorus inputs from fertiliser are shown in Figure 37. The largest phosphorus inputs are to the 'other arable' land use, which is reflected in the higher fertiliser input rates in the ECM scheme. The input rates from grassland and cereal are approximately constant through the catchment at 9 and 25 kg P/ha/year; these are similar to the Lugg. However, the input rate to 'other arable' varies between 55 and 75 kg P/ha/year, which is lower than for the Lugg catchment.

The annual phosphorus inputs per hectare from grazing livestock are shown in Figure 38. The higher inputs from livestock to 'other arable' in reaches 15 to 17 of the Kennet are caused by high numbers of pigs in the Dun, Lambourn and Enbourne sub-catchments. These sub-catchments also have relatively high numbers of cattle and sheep. The inputs to grassland very between approximately 5 to 450 kg P/ha/year, and those to 'other arable' between 2 and 70 kg P/ha/year. Again, these results are lower than for the Lugg application reflecting lower stocking densities.

4.2.4 Growing seasons

The estimates for MORECS square 259, which includes most of the Kennet system, were used (Table 33). The same assumptions used to define the growing systems for the Ant system were used in the application of INCA-P to the Kennet.

Table 33 Growing seasons used within the INCA-P application to the Kennet system

Land use	Planting or bud burst	Harvest or leaf fall	Assumptions
Spring barley	17 Mar	20 Aug	
Winter wheat	17 Mar	20 Aug	
Winter barley	7 Mar	30 Jul	
Cereal	**7 Mar**	**20 Aug**	
Early potatoes	15 Mar	18 Jun	
Main crop potatoes	10 Apr	5 Sep*	*Haulm (stems & stalks) destruction
Sugar beet	1 Apr	25 Oct	
Other arable	**15 Mar**	**25 Oct**	
Grassland	**1 Jan**	**31 Dec**	Roots active all year
Set-aside	**1 Jan**	**31 Dec**	Non-rotational, same as grass
Deciduous	12 Apr	17 Oct	
Orchards	27 Apr	27 Sep	
Coniferous	-	-	
Woodland	**1 Jan**	**31 Dec**	Coniferous roots may be active all year. SMD and soil temperature control phosphorus uptake.
Urban (parks and gardens)	**1 Jan**	**31 Dec**	All impermeable

*Dates are derived from input data used in the MORECS model for MORECS square 259. The dates in bold represent the range used for each INCA-P land class.

4.2.5 Calibration of system hydrology, hydrochemistry and ecology

The daily MORECS time-series describing the HER, SMD and air temperature from Marlborough were used to represent all reaches (Figure 39). The HER time-series shows that 1998 was wetter than 1997. The model was calibrated as described for the Ant calibration; the ‘a’ and ‘b’ parameters were 0.04 and 0.67, respectively. The other parameters are listed in Appendices E and F.

No flow was routed through the direct runoff box, so the application was effectively based on two stores: the soil water and the groundwater. Further work to be done on the Pang and Lambourn systems under the LOCAR programme and by the engineers Scott Wilson will help to identify the ‘a’ and ‘b’ parameters through tracer and flow manipulation studies. Moreover, the LOCAR programme will help to determine whether the simple two-box soil and groundwater conceptualisation is an adequate description of the hydrological response in a groundwater-dominated chalk system.

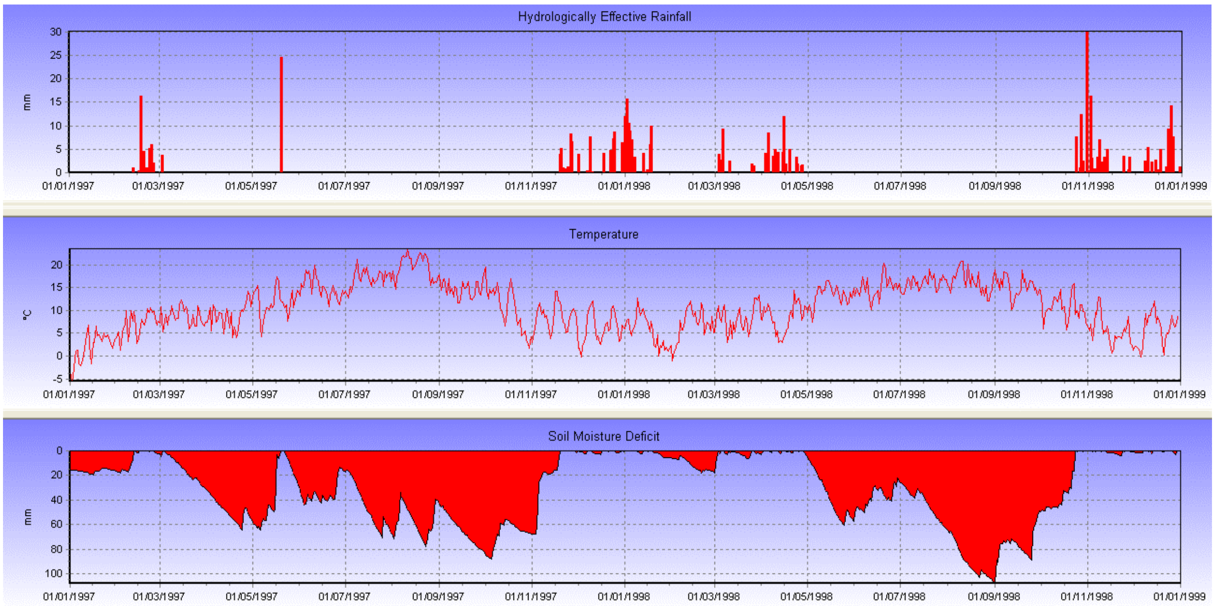


Figure 39 **MORECS derived HER, air temperature and SMD time-series from Marlborough for the period 1 January 1997 to 31 December 1998**

The initial TP and suspended sediment concentrations in the land phase of the model were set by calibration. The initial groundwater TP concentration of 1 µg P/litre is low (Table 34) compared with measurements of OP concentration in boreholes in the Kennet catchment (10–500 µg P/litre). Table 35 shows the initial suspended sediment concentrations for all six land use types.

Table 34 **Initial TP concentrations (µg P/litre in the land-phase of INCA-P applied to the Kennet**

Land use/pathway	**Soil water**	**Groundwater**
Grassland	10	1
Cereal	10	1
Other arable	10	1
Set-aside	10	1
Woodland	10	1
Urban	10	1

Table 35 **Initial sediment concentrations for all INCA-P land use types applied to the Kennet system**

Pathway	**Initial concentration (mg/litre)**
Soil water	50
Ground water	2

Table 36 **Input loads from STWs and trade effluents discharged directly into the main stem of the River Kennet**

Reach	Effluent name	Population Equivalent	Flow (m^3/s)	TP concentration (mg P/litre)	TP load (kg P/year)
4	Fyfield	1,700	0.0035	5.62	620
6	Marlborough*	7,500	0.063	2.67	5304

*Time-series of monthly effluent TP concentrations were used instead of mean values.

The effluent input from Fyfield STW was modelled as a constant input. The input from Marlborough was modelled as a time-series since weekly concentrations and daily flow data were available (Table 36). The model was also calibrated to the observed macrophyte and epiphyte biomass data in the Mildenhall reach. The terms relating to mineralisation and immobilisation were not adjusted as it was assumed that they were in equilibrium. The plant uptake parameters were adjusted until the simulated annual output load was within the range specified in the literature (see Section 2.3.3). The parameters controlling the transfer of phosphorus into firmly bound stores and vice-versa were adjusted to produce the best fit to the stream water TP concentrations.

4.3 Results

4.3.1 Hydrological simulation

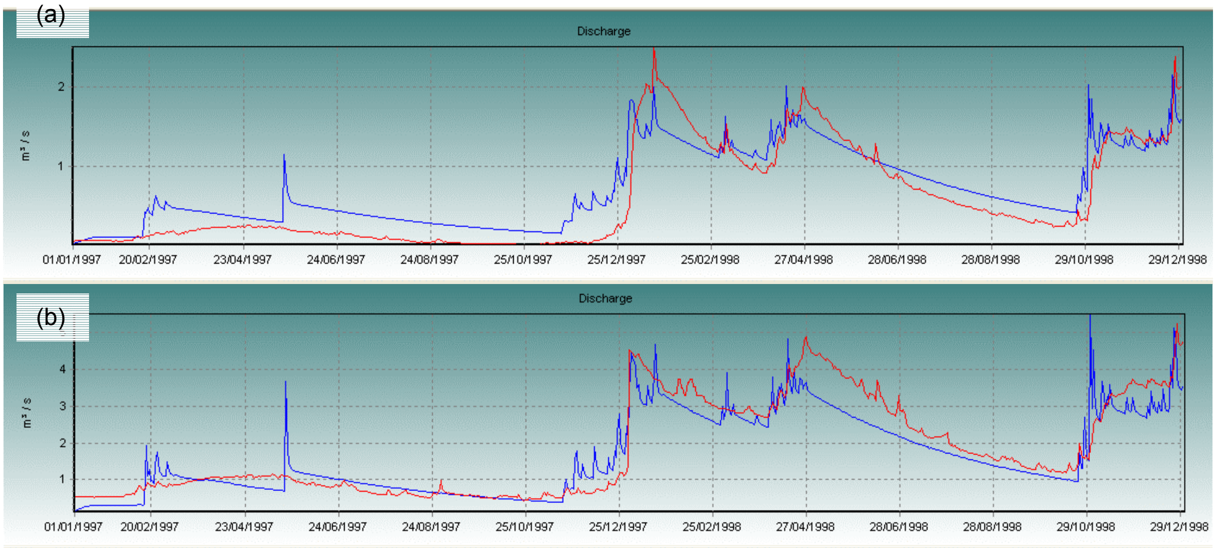


Figure 40 **Simulated and observed flows at (a) Marlborough and (b) Knighton**

The observed flows show that, during the winter and spring, the highest flows occur during the periods of high groundwater discharge into the river (Figure 40). The flows in 1997 are approximately four times lower than the corresponding flows in 1998. The shape of the hydrograph for 1997 is a generalised 'whale-back', although the influence of individual storm events can be seen as a series of super-imposed spikes. In 1998, the flows rose significantly in January, May and November. From May 1998 to early October 1998, the falling limb of the hydrograph decays slowly until mid-October, when the flow rises significantly. The simulated flow at Marlborough and Knighton is over-estimated in 1997 and under-estimated in 1998. The model can explain the first order changes – namely, the periods of increase and decrease are simulated, and the period of the recession of the falling limb represents that observed well.

4.3.2 In-stream phosphorus and suspended sediment concentrations

The observed total phosphorus concentrations decrease from maximum of around 1 mg P/litre in 1997 to around 0.1 mg P/litre in 1998 following the introduction of P stripping in September 1997 (Figure 41a). However, the lower TP concentrations observed in 1998 also coincide with the period of higher flows. In 1998, the observed concentrations exhibit peaks in January and November that correspond to periods of increasing flow. This suggests inputs of P from diffuse sources within the upper Kennet catchment are important controls in the streamwater P concentrations in the reach. During the summer months, the observed TP concentrations fall to an annual minimum, probably due to biological uptake of SRP. The simulated TP concentrations match with a reasonable degree of accuracy the dynamics of those observed. However, some of the peak concentrations either over-estimate or under-estimate the observed TP concentrations.

The observed SRP concentrations follow the same general pattern as the TP concentrations declining from around 0.6 mg P/litre in 1997 prior to P stripping to around 0.07 mg P/litre in 1998 following P stripping. Higher SRP concentrations are observed during the periods characterised by increasing flow, indicating a greater diffuse source contribution from agricultural land (Figure 41b). The simulated concentrations are similar to those observed with the dynamics being reproduced.

The observed suspended sediment concentrations range from around 0.2 to 120 mg/litre (Figure 41c). The higher flow conditions in 1998 do not produce higher sediment concentrations than 1997 and high sediment concentrations are recorded when the flows are relatively low. During the summer months, the suspended sediment concentrations are fairly constant around a value of 0.2 mg/litre. The simulated suspended sediment concentrations display a similar dynamic pattern to the observed concentrations, though the simulated peak sediment concentrations tend to underestimate those observed.

The observed Boron concentrations exhibit a decrease with flow, indicating that the major source of Boron within the reach is from the STW (Figure 41d). The simulated boron concentrations match those observed well, suggesting that the concentration of boron in the soils and groundwater is approximately 0.08 mg/litre.

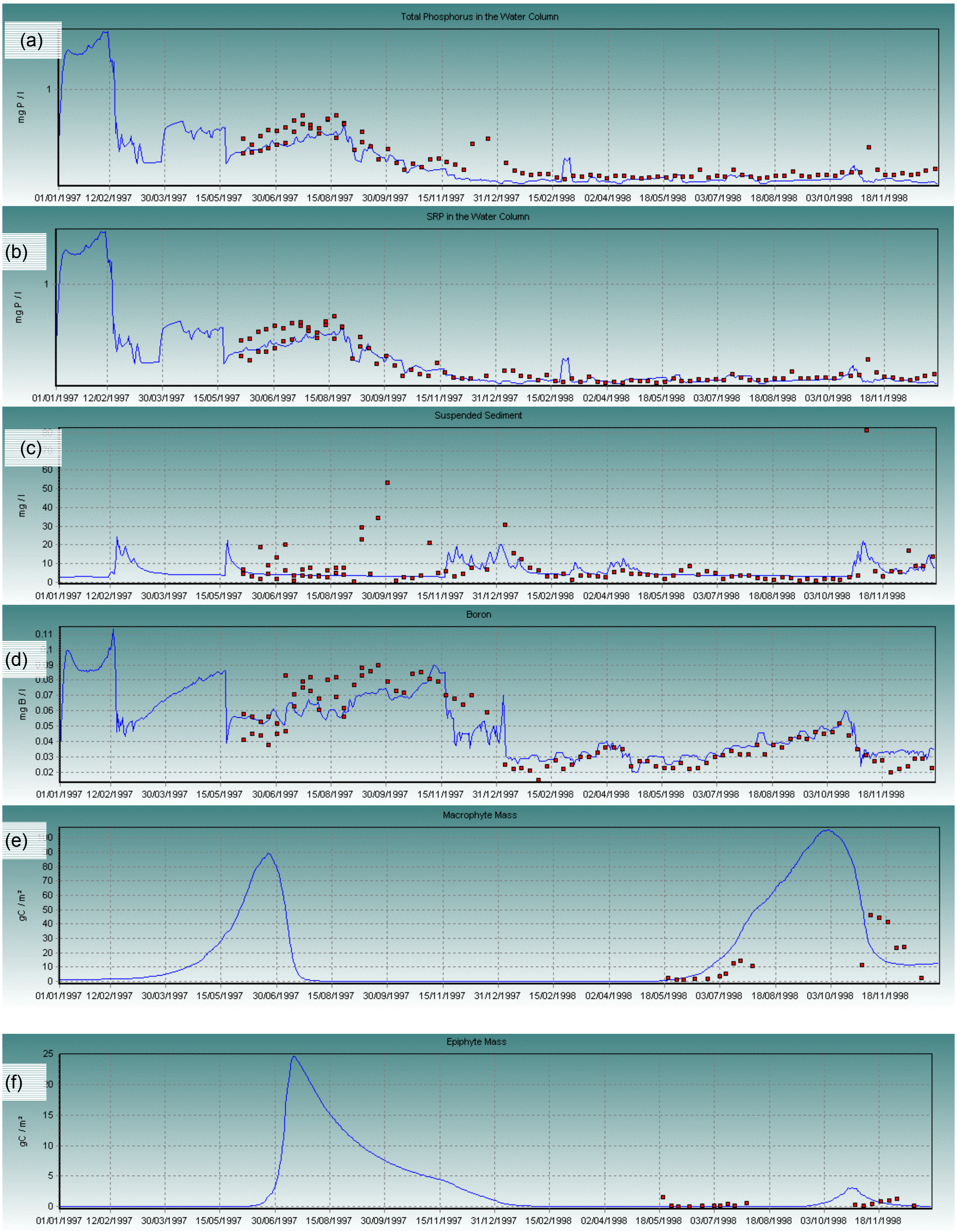


Figure 41 **Observed and simulated (a) TP (b) SRP (c) suspended sediment and (d) boron concentrations, and (e) macrophyte and (f) epiphyte biomass at Mildenhall (reach 7)**

The observed macrophyte growth pattern begins in March/April and peaks in August, before declining to zero by the end of November (Figure 41e). The simulated macrophyte biomass reaches a higher peak and occurs later in 1998 compared to 1997.

There is no clear pattern in the observed epiphyte biomass, perhaps indicating that the epiphytes are susceptible to the prevailing flow conditions (Figure 41f). The simulated epiphyte biomass is greater in the first year than the second, with the simulated biomass in 1998 within the range observed. Prior to effluent treatment, the simulated epiphyte peak is 6 times higher than that observed post treatment in 1998. Furthermore, the epiphytes persist in the reach for 8 and 2 months in 1997 and 1998 respectively. The reduction in epiphyte biomass corresponds to lower TP and SRP concentrations in the reach and to higher flow conditions.

Table 37 and Table 38 present the results of the same three goodness of fit tests that were used for the River Ant and River Lugg applications (see Section 2.2.12). These results demonstrate a very good hydrological fit at all three gauging stations and good results for total phosphate, ortho-phosphate and suspended sediment.

Table 37 Determination coefficient for flow, TP and SRP and suspended sediment in reaches along the Kennet system*

Reach	Flow(m^3/s)	TP(mg P/litre)	SRP(mg P/litre)	SS (mg/litre)
Marlborough	0.70 (0.84)	–	–	–
Mildenhall	–	0.67(0.82)	0.56 (0.75)	0.06 (0.25)
Knighton	0.81 (0.90)	–	–	–

*Correlation coefficient is given in brackets.

Table 38 Explained variance for flow, TP, SRP and suspended sediment in reaches along the Kennet system

Reach	Flow (m^3/s)	TP (mg P/litre)	SRP (mg P/litre)	SS (mg/litre)
Marlborough	0.78	–	–	–
Mildenhall	–	0.67	0.57	0.09
Knighton	0.82	–	–	–

4.4 Conclusions

The application of INCA-P to the Kennet is less well developed than either the application to the Ant or the Lugg, but the initial results build confidence in the structure of INCA-P. Namely, INCA-P can provide an adequate simulation of the diffuse delivery of phosphorus to the stream channel, which when combined with the effluent input, can explain the observed stream water TP, SRP, suspended sediment and boron concentrations, and the measured and anecdotal macrophyte and epiphyte growth. The simulation again suggests that phosphorus is stored within the system, although it is unclear if this is in the soil store, the groundwater or the river sediments. This application will be developed further under the LOCAR programme, in which INCA-N and INCA-P will be set up for the Lambourn and the Pang.

5. Sensitivity analysis

5.1 Introduction

Environmental models such as INCA-P contain parameters that cannot be measured directly but which have to be inferred by a trial-and-error process that adjusts the parameter values to match the observed data. This process is called ‘model calibration’. The aim of a model calibration is to reduce the uncertainty in the choice of parameter values (parameter uncertainty), while accounting for uncertainties in the measured input and output time series, and uncertainties in the structural ability of the model to simulate the processes of interest (Thiemann *et al.*, 2001). Ideally, model calibration will result in well-identified parameters with narrow uncertainty ranges around their optimum values.

In practice, the calibration of environmental models is a labour-intensive and cumbersome task, even for experienced modellers. As such, in recent years, modellers have sought automatic methods for model calibration. These methods, which take advantage of the speed and power of computers, are objective and relatively easy to implement. Although the modeller’s expertise remains ultimately important, automatic methods have become an indispensable tool for model calibration.

A recently developed, state-of-the-art automatic calibration method is the Shuffled Complex Evolution Metropolis (SCEM-UA) (Vrught *et al.*, 2003b), a search algorithm for the calibration of environmental model parameters. Recent studies have shown that this algorithm is both effective and efficient in determining optimum parameter values, and capable of dealing with complex calibration problems such as the simultaneous calibration of 15 or more parameters of an ecological model (Van Wink, unpublished results). One of the desirable properties of SCEM-UA is that it aims to describe parameter uncertainty. As such, SCEM-UA not only outputs a most suitable set of parameters, it also informs the modeller on how well parameters can be identified and how parameters are mutual correlated, and indicates parameter sensitivities.

As a first step towards automatic parameter optimisation and uncertainty analysis of the INCA-P model, three calibration studies using INCA-P were performed using the SCEM-UA algorithm. All three studies dealt with a one-year application of INCA-P to the river Ant, which was based on the manual calibration described in Section 2. The first case study (see Section 5.3) dealt with the calibration of the INCA-P water flow parameters using daily discharge observations at Honing Lock. The second and third studies (see Sections 5.4 and 5.5, respectively) focus on the calibration of phosphorus process parameters using observations of TP concentrations in six of the seven reaches of the River Ant.

5.2 INCA-P and SCEM-UA set-up

INCA-P was set up to track water and phosphorous through the first seven reaches of the River Ant catchment. Simulations ran from April 1999 to April 2000 and covered a total of 366 days. Hydrological and sewage input data, initial conditions and parameter values were copied from the application of INCA-P to the River Ant (Appendices A and B). However, to speed up INCA-P runs, the total number of land use types was reduced to just one for the water flow analysis and four for the phosphorus process analysis:

- grassland (LU1; predominantly fertilised with organic-P);
- cereal (LU2; inorganic-P fertilised);
- other arable (LU3; inorganic-P fertilised);
- other (LU4; not fertilised).

Daily fertiliser data were derived by assembling the original data used in this study. Daily discharge measurements at reach 5 (Honing Lock) were used to calibrate the water flow parameters. TP concentrations in the water column (TPwat) of six reaches were used in the phosphorus process analysis. One year of 12-hourly to daily data were available for reaches 3 (Swafield), 5 and 7 (Hunsett Mill). Biweekly data were available for reaches 1 (Lower Street), reach 2 (South Repps Common) and reach 6 (Wayford Bridge). TPwat calibration data summed up to a total of 2,071 observations.

For all calibrations performed, SCEM-UA was set to simultaneously optimise all parameters of interest with – depending on the number of parameters to calibrate – 12 to 20 complexes and a population size of 250 to 1,200. We assumed non-informative prior, i.e. we expected the model error to be larger than errors made in our observations. Convergence to a stationary posterior distribution was assumed when the scale reduction factor $\sqrt{SR}$ dropped below 1.2 (Gelman and Rubin, 1992). All INCA-P runs generated after convergence were defined as ‘acceptable simulations’. The parameter distribution intervals were calculated from these simulations, together with the prediction uncertainty ranges associated with the INCA-P simulated discharge and TP concentrations, respectively.

5.3 Case study 1: modelling of stream discharge with and without direct flow

The original INCA-N model (Wade *et al.*, 2002a) simulates water flow using two flow components:

- soil water flow (SWF), with a relatively fast respond to rainfall;
- the slow responding groundwater flow (GWF).

From the literature, however, it is known that a rapid responding overland flow is an important pathway for the transport of phosphorus. Residence times for overland flow are in the order of 15 to 60 minutes, which is a lot shorter then SWF residence times (2–10 days, depending on the type of catchment). As such, compared with the original INCA-N model, INCA-P applies a third, very quick flow component to simulate the flow of water, named direct flow (DF).

In this case study, we compared the identity of model parameters when modelling stream discharge with and without DF, and tested whether including DF as a water flow path would improve the simulation of stream discharge. As such, two calibrations were performed. In the first calibration, without DF, five parameters where calibrated:

- initial soil water (iniSWF) and groundwater flow (iniGWF);
- soil water and groundwater residence times (TrSWF and TrGWF);

- base flow index (BFI), which determines the proportions of soil water flowing to the groundwater reservoir and directly to the stream.

In the second calibration, with DF, the same five parameters plus four additional parameters were calibrated. These additional parameters were:

- initial direct flow (iniDF);
- direct flow residence time (TrDF);
- delta – the value of the flow threshold which, if exceeded by the flow in the soil water box (SWF), triggers DF flow;
- alpha – divides the water draining directly to the stream (as opposed to draining to the groundwater reservoir) in two flow paths, namely DF and SWF.

By definition, alpha + BFI ≤ 1. Instead of directly calibrating alpha, a derivative of alpha was calibrated. This derivative, named alpha*, was related to alpha such that alpha = alpha* (1 – BFI).

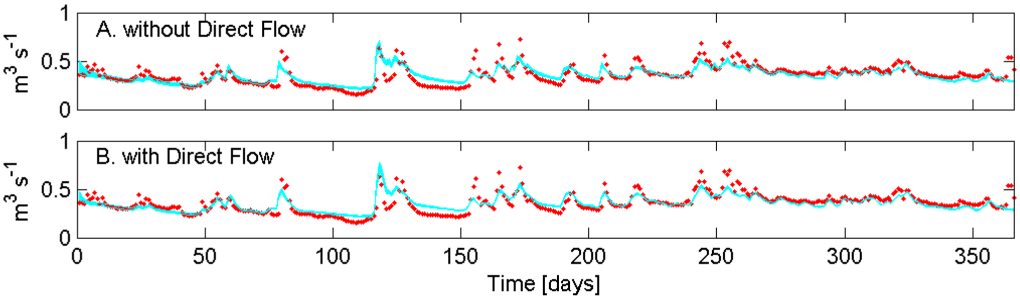


Figure 42 **Observed versus simulated stream discharge at reach 5 (Honing Lock) for INCA-P applications (A) without DF and (B) with DF***

*Day 1 = 15 April 15 1999

The calibration of INCA-P water flow parameters without using DF was successful, both in terms of parameter identification and the matching of modelled with observed stream discharge. Except for iniSWF, all parameters were confined effectively, with narrow ranges around the optimum values (Table 39, third column). iniSWF was not confined at all, indicating that simulations were not sensitive to changes in iniSW. Figure 42 shows the generally good agreement between observed and simulated stream discharge for Honing Lock.

At first sight, the ‘with DF’ calibration also appeared to be successful, with narrow ranges around optimum values for almost all parameters. However, a closer look at the parameter ranges (*, last column) revealed some curiosities. First, optimum values for delta are quite low, indicating that DF is almost always triggered. Secondly, alpha* has high optimum values (0.82–1.0), indicating that when DF is triggered (and it almost always is), most of the fast draining water is following the DF flow path and only 10– 20 per cent is following taking the SW route. In short, it seems as if SWF is not used as a water flow path – effectively transforming the model to use two instead of three flow paths. (Though with shorter residence times for the quick flow component than in the ‘without DF’ calibration!) Figure

42b shows that the simulated stream discharge is almost identical for simulations with and without DF; only the peak flows are slightly higher when using DF.

Table 39 **Calibrated parameter distribution intervals of INCA-P water flow parameters for applications without and with direct flow**

Parameter	Prior interval	Calibrated interval without DF	Calibrated interval with DF
IniDF	0.0005– 0.03	N/A	0.0006–0.018
IniSWF	0.0005–0.03	0.0005–0.03	0.0005–0.030
IniGWF	0.0005–0.03	0.0062–0.0089	0.0068–0.0085
TrDF	0.01–4	N/A	0.46–1.6
TrSWF	1–20	2.3–5.1	1.0– 2.5
TrGWF	20–300	64–118	69–110
BFI	0–1	0.78–0.86	0.82–0.87
alpha*	0–1	N/A	0.82–1.0
Delta	0–0.03	N/A	0– 0.003

*Daily stream discharge observations at Honing Lock were used for calibration (April 1999– April 2000).

N/A = not applicable

In conclusion, these two calibrations show that, when modelling stream discharge with INCA-P, there is no need to incorporate DF as a third, and very quick, flow path for water. As such, from a pure hydrologic viewpoint, the River Ant catchment can be modelled using only SWF and GWF. Secondly, these calibrations show that, with the current data, it is hard to distinguish between DF and SWF, making calibration of TrDF and TrSWF difficult. Thus, when making use of DF as a third flow path in an INCA-P application, i.e. when aiming to simulate phosphorus transport, good estimates for these residence times are more likely to be obtained from expert knowledge than from 'blind' automatic calibration.

5.4 Case study 2: organic-P and inorganic-P initial concentrations

In the second case study, we investigated whether acceptable simulations with INCA-P can be obtained when setting the 'firmly bound' organic-P and inorganic-P inputs and outputs to zero, and calibrating only the organic-P and inorganic-P initial concentrations. Zero firmly bound inputs indicate that there is no retention or storage of phosphorus in the soils. The intention of this case study is to identify how dependent the simulation results are on the initial conditions.

A total of 25 parameters were calibrated simultaneously. These included, for each of the four land use types, the initial organic (iniOP) and inorganic (iniIP) phosphorous concentrations in direct flow (DF), soil water (SW) and groundwater (GW). The 25th parameter was the initial TP concentration in the reaches' pore water and water column (iniTP). For each parameter, the feasible parameter space prior to the calibration was a uniform distribution between 0 and 10 mg P/litre, meaning that SCEM-UA searched for feasible parameter values only within these limits. Values for the water flow parameters were taken from the earlier INCA-P application in this study.

Table 40 **Calibrated parameter distribution intervals of INCA-P initial organic-P and inorganic-P concentrations in direct flow, soil water and groundwater, and initial total-P concentrations in the reaches' pore water and water column**

	Calibrated parameter interval			
Parameter	**Grassland**	**Cereal**	**Other arable**	**Other**
iniOP_DF	0–2.0	0–5.0	3.0–5.9	5.1–8.4
iniOP_SW	0–1.6	3.1–7.2	0–0.9	0–0.8
iniOP_GW	0–0.5	~ 0	~ 0	~ 0
iniIP_DF	6.0–9.8	2.8–5.5	0–2.5	6.6–8.9
iniIP_SW	0–1.8	0–1.1	0–0.8	0–0.7
iniIP_GW	~ 0	~ 0	~ 0	~ 0
IniTP	0–5.3			

All values in mg P/litre. Prior parameter interval was 0–10 mg P/litre for all parameters.

SCEM-UA converged to a stationary posterior distribution ($\sqrt{SR} < 1.2$) after approximately 8,000 model runs, which is relatively fast given the large number of parameters calibrated. Distribution intervals of the parameters are given in Table 40. Prior parameter intervals were effectively confined for all parameters, although not all choices in optimum parameter ranges are easily explained. For example, high values were assigned to iniOP and iniIP in the direct flow of land use type 'other', whereas it is known that this type contributes little to the phosphorus export to the River Ant. The calibration results demonstrate the importance of a quick flow mechanism in phosphorus export, as shown by the initial phosphorus concentrations assigned to direct flow. For all land use types, iniOP and iniIP concentrations were highest in direct flow, intermediate in soil water and very low (~ 0 mg P/litre) in groundwater.

Figure 43 presents the observed versus simulated TP concentrations in the water column. Simulations are very poor even after only two or three days. In particular, peaks in TP concentrations are simulated that were not observed. The results also show that the simulated stream water TP concentrations are only influenced by the initial concentrations of the direct runoff, soil water and groundwater and in-stream end members for approximately three days. After this period, the simulated output is predominantly governed by the driving data, and the factors and processes simulated.

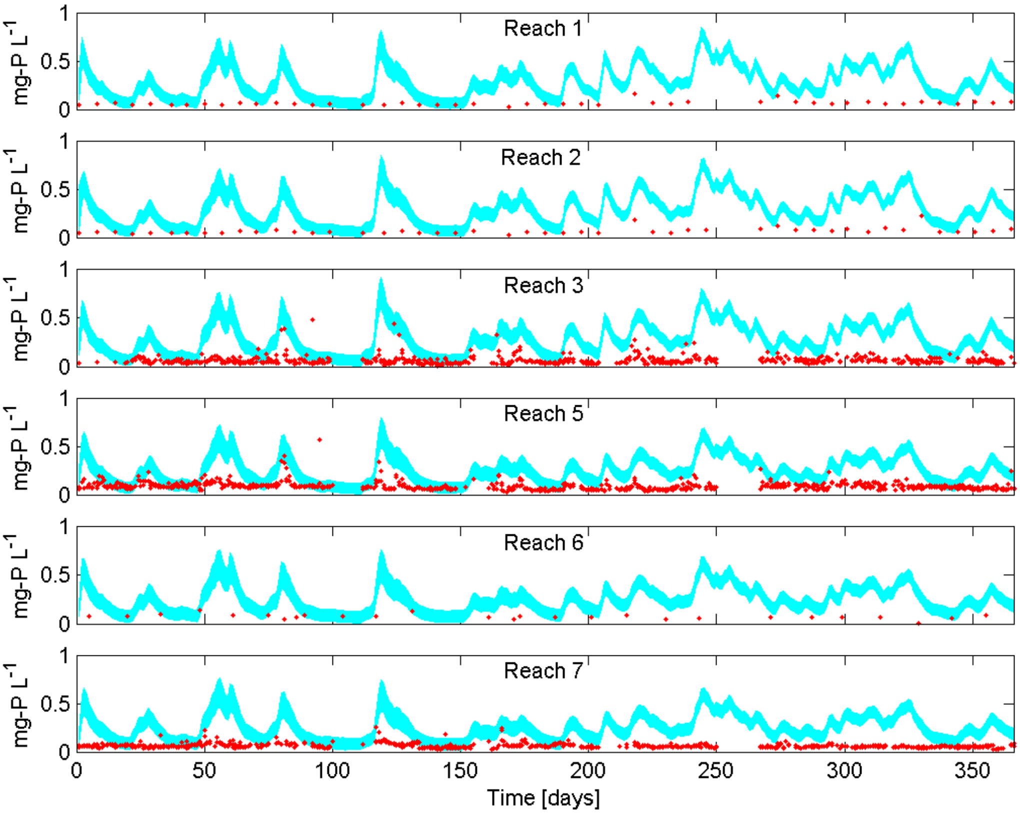


Figure 43 **Observed versus simulated TP in stream water after calibration of organic-P and inorganic-P initial concentrations***

*Day 1 = 15 April 1999

5.5 Case study 3: firmly bound organic-P and inorganic-P parameters

In this last INCA-P application, we included phosphorus retention and release mechanisms. Values for water flow parameters and initial organic-P and inorganic-P concentrations were taken from the earlier INCA-P application described by Wade *et al*. (2002b) Twenty-four parameters were calibrated, i.e. for every land use type:

- the initial condition for firmly bound organic-P (fbiniOP) and inorganic-P (fbiniIP);
- the firmly bound organic-P input (fbOPin) and output (fbOPout);
- the firmly bound inorganic-P input (fbIPin) and output (fbIPout).

The purpose of this case study is to identify the importance of phosphorus retention and release. If acceptable simulations can be obtained, it implies that TP in river water can be simulated simply by mixing different water types and that therefore the basic structure of the model is sound.

SCEM-UA converged to a stationary posterior distribution after approximately 13,000 model runs, indicating that this optimisation problem was more difficult than in case study 2. Table 41 lists the final distribution intervals calculated from SCEM-UA generated runs after convergence. A few clear trends can be deduced from these intervals. First, the firmly bound input and output parameters of land use type 'other' were hardly confined, indicating that the current TPwat observation holds very little information on these parameters. Secondly, firmly bound input and output parameters are alike for the remaining three land use types except for fbOPin and fbOPout of ‘cereal’. For all three land uses, for example, optimum fbIPin ranges were between approximately 0.7 and 2.0. Thirdly, for these three land use types, firmly bound input parameters were generally higher than the corresponding output parameters. This indicates that phosphorus is retained in the system.

Table 41 **Calibrated parameter distribution intervals of INCA-P firmly bound organic-P and inorganic-P initial conditions, firmly bound organic-P input and output, and firmly bound inorganic-P input and output**

		Calibrated parameter interval			
Parameter	**Prior range**	**Grassland**	**Cereal**	**Other arable**	**Other**
FbiniOP	0–10	6.5–10	0–0.6	0–3.9	0–0.9
FbiniIP	0–10	3.6–8.5	0–7.0	0.7–8.7	0.5–2.9
FbOPin	0–2	0.3–2.0	1.2–2.0	0.6–2.0	0.3–2.0
FbOPout	0– 2	~ 0	0.7–2.0	~ 0	0–2.0
FbIPin	0–2	0.7–2.0	0.9–2.0	0.7–2.0	0–2.0
FbIPout	0–2	~ 0	~ 0	~ 0	0–2.0

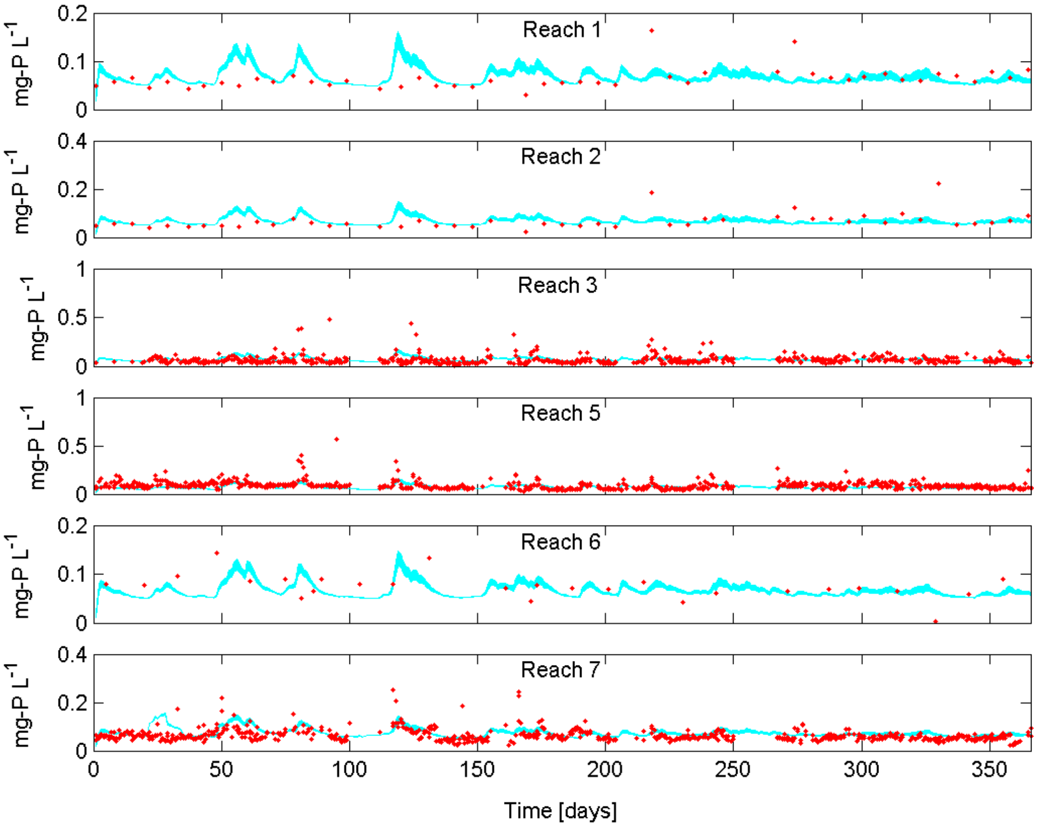


Figure 44 **Observed versus modelled TP in stream water after calibration of firmly bound organic-P and inorganic-P parameters***

*Day 1 = 15 April 1999

The effect of phosphorus retention is shown in Figure 44 by the absence of the erroneous peaks in simulated TP that were so characteristic of Figure 43. TP is generally simulated adequately by the current run – especially for reach 7 (Hunsett Mill).

5.6 Conclusions

These three simple calibration case studies illustrate the added value of using an automatic optimisation and uncertainty analysis tool in INCA-P applications. The SCEM-UA analysis helps modellers by providing insight in both the functioning of the INCA-P model and the worth of the available observations for parameter calibration. The first study demonstrated that, when making use of direct flow as a third flow path in an INCA-P application, i.e. when aiming to simulate phosphorus transport, good estimates for the direct flow residence times are more likely to be obtained from expert knowledge than from calibration to the available data. The second study showed that direct flow is indeed an important mechanism for phosphorus export and that phosphorus concentrations are likely to be higher in direct flow than in soil water and groundwater. Finally, the last study made it clear that good simulations of TP in the River Ant can only be obtained when incorporating phosphorus retention mechanisms.

6. Discussion

This discussion focuses on the issues of:

- collating the required data to apply INCA-P;
- the robustness of the model's ability to simulate the hydrology, hydrochemistry and hydroecology of contrasting UK river systems;
- the utility of the model as a research and operational tool.

The implications of the sensitivity analysis (see Section 5) for the model structure and the proposed revision of the in-stream component to model SRP concentrations are also discussed.

6.1 Data resolution and availability

INCA-P was successfully applied to the Ant, Lugg and Kennet catchments with datasets of differing spatial and temporal resolution that described the hydrology, water quality, ecology, and land use and management. The hydrological data describing daily hydrologically-effective rainfall, soil moisture deficit and air temperature were all derived from the MORECS model, using data from single sites. These data were purchased from the Met Office via ADAS. The actual data sent included the observed daily precipitation; this allows other rainfall runoff models such as IHACRES to be applied to derive other HER time-series.

The Ant and the Kennet had the most frequent water quality measurements; daily and weekly measurements of total phosphorus were available in the Ant and Kennet, respectively and at least weekly samples of soluble reactive phosphorus concentrations were available in each. In contrast, monthly streamwater samples of total phosphate and ortho-phosphate were available for the Lugg, but for a longer period. The Agency data used in the Lugg covered six years, whereas the more frequent data where collected for one and two years in the Ant and Kennet, respectively.

Each dataset was originally collected for a different purpose and therefore covers different spatial and temporal scales. Data collected primarily for research purposes tends to be for shorter periods, but at a higher frequency than data collected for routine monitoring to check effluent-consent compliance and the general water quality status. This work has shown that it is possible to set up INCA-P with water quality datasets of different frequency and period without any change to the model code. Moreover, the results of this study show that INCA-P can simulate the in-stream dynamics of different phosphorus forms (i.e. total phosphorus, total phosphate and orthophosphate). However, further work is required to improve the simulations of soluble reactive phosphorus – especially in systems such as the Ant, where concentrations are low and governed by diffuse sources.

The availability of data describing the flow and water quality of final effluent is, at best, daily flow measurements and weekly concentration measurements but, more typically, only estimates of the population equivalent and monthly concentrations are available. As with the water quality data, typically it is the larger effluent inputs or those considered to be of greatest concern that are most intensively monitored. The weekly – and daily for short periods – monitoring of phosphorus concentrations in the Marlborough STW effluent during 1997 and 1998 is atypical and resulted from a specific research interest in this works. As input data, INCA-P was successfully able to accept time-series of effluent data if available, or use constant effluent flow and concentration inputs that related to the whole simulation period, or use a mixture of time-series and constant inputs.

The model was also applied with different datasets describing land use and management practices:

- a detailed farm and fertiliser survey was available for the Ant;
- the Lugg applications utilised ADAS MAGPIE and Defra data to determine land use, livestock numbers and phosphorus inputs;
- Defra data were used to determine phosphorus inputs from fertiliser and livestock, and the land use and livestock numbers in the Kennet.

All three datasets required redistribution of observed land use and livestock information. In the case of the Ant, this was to infill missing data in the farm survey. In the case of the Lugg and the Kennet, redistribution was required to transform the farm level data into either 1 km^2 grid squares (MAGPIE) or sub-catchments (Defra). This data manipulation together with the assumptions made regarding the magnitude, timing and phosphorus form of the fertiliser (i.e. inorganic or organic) create uncertainty in the input load. If funds and time allow, a survey will provide the best information on land use and fertiliser practice. Alternatively, given the assumptions necessary to redistribute the Defra data, then it would be preferable to use the ADAS MAGPIE data where the assumptions have been standardised for the whole of England and Wales, thereby allowing comparability between model applications.

INCA-P simulates macrophyte and epiphyte biomass and, from this study, it is apparent that such data are not widely available but limited to a few research studies in southern England. Further work is needed to determine the model's capability to simulate the concentrations of stream water chlorophyll *a* or other readily available indices of macrophyte and epiphyte cover and growth. Stream water chlorophyll *a* is routinely monitored by the Agency and, from current studies in the River Lambourn, it may be possible to create a relationship between macrophyte biomass and the indices measured by the Agency.

Given that INCA-P was adaptable to different datasets, it is a very powerful tool. It is capable of integrating all pre-existing knowledge about a system in a user-friendly way such that the data and the functioning of the system can be explored in a modelling environment. The data collation exercise is non-trivial and there are costs associated with purchasing the input MORECS data and the derivation of the sub-catchment boundaries by CEH. Furthermore, ADAS will charge a fee for the retrieval of the MAGPIE land use information. In the case of the sub-catchment boundaries and the MAGPIE data, these costs are small – the former being a £140 administration charge plus £9 per boundary (+ VAT) and the latter £250 (+ VAT) handling charge. The MORECS data are more expensive, costing £460 (+VAT) for a single-site for two years. MORECS has now been replaced by MOSES (Met Office Surface Exchange Scheme), which has improved process representation – particularly of soil moisture – and improved spatial resolution.

Unless alternative data sources can be found, these costs must be factored into any future applications of the model together with those for data collation and analysis. Based on the three applications reported, the process of data collation and analysis typically took 2–3 months. However, this time may fall significantly following the development of the Agency's GIS front-end to its datasets. Furthermore, the University of Reading has started work to develop on some simple tools to automate the data collation process to create INCA-P parameter sets.

The collation and analysis of the pre-existing data are an important part of the modelling process, and has been shown in this study and elsewhere to be an invaluable method of analysing the hydrochemical functioning of large river systems and providing initial mass balances. It is recommended that this analysis of the spatial and temporal patterns in the hydrochemistry and hydroecology should precede any model development and application to maximise the understanding of the uniqueness of the system studied.

To apply INCA-P, it is suggested that the minimum data required are:

- daily mean flows
- monthly stream water TP or SRP or TPh or OP concentrations
- land use area
- a delineation of the area drainage into each reach.

Such data are generally collected by the Agency throughout England and Wales. Data describing the phosphorus in sediment and the macrophyte biomass are also useful to constrain the model, and essential to determine the phosphorus contribution from this pathway and the macrophyte growth response, respectively. The model can be run without macrophyte data and information on the phosphorus in sediment, but such a set-up does not allow the phosphorus load transported with in-stream sediment, the bed sediment phosphorus stored or the macrophyte growth to be estimated with confidence.

6.2 Model structure

INCA-P is based on ideas of the simple mixing of waters from different land use types and flow pathways. The initial phosphorus concentrations are set in the direct runoff, soil water and groundwater stores, and in the stream. These stores are then mixed together in proportions based on the prevailing hydrological conditions and the proportion of land use. The concentrations of the stores change over time in response to coincident factors and processes such as fertiliser input or plant uptake.

Given the reasonable simulations of flow and stream water phosphorus and suspended sediment concentrations, this representation of catchment phosphorus dynamics appears sufficient to explain the first order spatial and temporal variations in TP concentrations. Moreover, the equations describing the macrophyte and epiphyte growth are able to reproduce a sine-wave response, with a peak in macrophyte growth in the spring/summer period. Such a response has been observed in other UK rivers for which data are available. The model was unable to simulate the SRP concentrations observed in the Ant, which has relatively low concentrations compare to the Kennet. Improvements to the model are suggested (see Section 6.6).

The choice of model structure, based on this mixing approach, is supported by the results of the sensitivity analysis (see Section 5), which highlight the importance of simulating a phosphorus store in the soil to maintain the correct soil phosphorus to enable good estimates of the in-stream concentrations. Moreover, the sensitivity analysis results show that the simulated output depended on the initial values used but, as the simulation progressed, there was a shift away from these initial conditions to a dependency on the driving input data and the simulated model processes.

In addition, the sensitivity analysis showed that to simulate the catchment hydrology, a third store describing the direct runoff component may be unnecessary. This finding was not unexpected, as INCA-N is built on a two store conceptual model. However, the manual calibrations of INCA-P to the Lugg and the Kennet suggest that phosphorus dynamics can also be explained with a two-box model; however, the Ant application required all three boxes for a good calibration – either manual (see Section 2) or automated (see Section 5.6). This is an interesting result, and the explanation is unclear.

The Lugg and the Kennet represent the two extremes in terms of Base Flow Index – the values being 0.63 and 0.95, respectively (compared with 0.87 for the Ant). In the Lugg system, more of the water in flow is sourced from the soil; while the Kennet hydrograph is dominated by the groundwater input with superimposed storm event ‘spikes’. In contrast, the Ant is relatively flat and possibly has a more well developed system of field drains than the other catchments. As such, it is possible that three boxes are required to simulate the field drains, soil and groundwater of the Ant, but only two boxes are required to simulate the hydrology of the Lugg and Kennet catchments. The latter are dominated by a simpler, two store, quick and slow flow components – albeit with different residence times to describe the difference between a groundwater-dominated system and one more controlled by water from the soil store. Further model applications in other systems are expected to help resolve this issue.

6.3 Uncertainty

Within this study, it became apparent that there are six main sources of uncertainty within the model, of which the key four are:

- the sampling frequency of the observed data used for model set-up and calibration;
- the model structure;
- the equifinality of the model parameters;
- the scaling problem: relating the observations typically made at single points in space and time, to model parameters representing an a spatial and temporal mean, often over broad landscape types.

The discussion below considers the sampling frequency, parameter equifinality and scaling. The issue of model structure is discussed in Section 6.2, which also considered the results of the sensitivity analysis. The other sources of uncertainty relating to sampling and analytical methods are not considered; the implications of these two error sources are thought to be relatively minor compared with the other four.

6.3.1 Sampling frequency

A comparison of the daily and weekly phosphorus data sampled in the Ant system shows that the weekly data missed 20 storm events (Johnes *et al.*, 2003). This finding and other recent studies highlight the need for high-frequency and long-term monitoring studies of catchment input and output hydrochemical fluxes (Kirchner *et al.*, 2000). Coupled with this is a need for commensurate hydroecological modelling (Neal *et al.*, 2002). Ideally as much data describing the driving hydrological inputs, the land use and phosphorus management practices, the soil phosphorus fluxes, the stream water phosphorus concentrations and the in-stream sediment phosphorus and biomass should be used to apply INCA-P. This is because the longer the time-series, the higher the sampling frequency and the greater the spatial resolution, the more the model can be constrained and thought of as being representative of the place modelled and, thus, the greater the confidence in the model's ability to characterise the system (Kirchner *et al.*, 2001; Raat *et al.*, in press).

The infrequent or lack of effluent flows and concentration observations means that assessment of the point source contribution to the phosphorus load in the river is uncertain. This is particularly important as it affects the calculation of the catchment mass balance and a lack of effluent data makes the modelling apportionment of the river load to diffuse and point sources difficult. In the Lugg, the importance of the point sources controlling the in-stream dynamics was particularly apparent in the lower reaches, with the stream water TPh concentrations displaying a clearly defined concentration of point sources during the summer months. Thus, it is recommended that point sources be monitored more frequently. Such a detailed study is planned by CEH as part of the LOCAR study of the Pang and Lambourn catchments.

In all three INCA-P applications described in this report, only those effluents discharging directly into the main channel of each river system were included. In the Ant application, calibration of the model with (a) the observed effluent inputs from four STWs and (b) the loads derived from the ECM provided contrasting results, with the calibrations based on (a) providing a better fit to the observed stream water TP concentrations. The calibration based on (b) tended to over-estimate the observed stream water TP concentrations in all reaches. Good simulations of stream water phosphorus concentrations were also achieved for the Kennet and in all but the lowest reaches of the Lugg, where an over-estimate of the flow may have caused an underestimation of the simulated in-stream phosphorus concentrations.

These results suggest this strategy is reasonable: within INCA-P the point sources discharging to tributaries are represented in the general 'diffuse' input to the main channel from each sub-catchment. Consequently, in the Ant application, although Ross Foods is an important local source of phosphorus, it was not included explicitly within the model because it does not discharge directly into the main stem of the River Ant. The validity and implications of this description of the point source inputs require further assessment. Such an assessment will be performed when INCA-P is applied to the Pang and Lambourn catchments as part of LOCAR. These applications will also include the simulation of the relationship between phosphorus and boron, which can be used to establish the influence of effluent inputs on the in-stream phosphorus load (Neal *et al.*, 2000a; Neal *et al.*, 2000b).

6.3.2 Up-scaling model input data to represent a catchment

For applications of INCA-P to large (> 500 km^2) river systems or those that encompass a broad altitudinal range, the hydrological input data need to describe the spatial variations in the precipitation input, soil moisture deficit and air temperature. To achieve this, it may be necessary to use more than one input time-series – as in the case of the Lugg application. A good simulation of the river flow is important to simulate the correct dilution of the in-stream phosphorus concentrations and the correct timing of phosphorus delivery from the land to the river channel.

The input phosphorus loads to all three catchments are uncertain given the assumptions that have been made regarding the estimation of land use areas and management practices. In particular, broad classifications have been made of land use types so that estimates of fertiliser applications and inputs from livestock can be calculated. Given this uncertainty in the inputs, it is necessary when simulating the observed stream water phosphorus concentrations to adjust the model so that it simulates phosphorus being stored in the soil. The results from the Lugg application also tentatively suggest that phosphorus is stored in the stream bed; the storage of phosphorus in the stream bed for the Ant and Kennet was not calculated explicitly. Based on a mass balance calculation up to reach 12 in the Lugg, only approximately 1 per cent of the phosphorus input to the land enters the river. This figure is similar to other estimates of phosphorus retention (Johnes, 1996).

6.3.3 Parameter equifinality

Even with daily time-series of in-stream phosphorus concentrations, derivation of the optimum model parameter set was difficult due to equifinality. Given that it is hard to determine if the calibrated parameter set really does allow the model to represent reality, the model output should only be viewed as one component of a wider, data-driven, analysis. For example, of the phosphorus held within the catchment it is not known how much is stored in the soil water, groundwater or stream bed, or how much is removed as crop uptake. However, calculations suggest that, based on current estimates of crop uptake, it is unlikely that the phosphorus is all removed through crop growth and harvest in the three systems studied.

Despite the caveat regarding equifinality to the modelling assessment, the model and modelling assessment are still useful because the model can be used as a learning tool to understand how the catchment might behave. The modelling assessment also allows the modeller to test ideas regarding hydrochemical functioning and the likely effects of perturbations to the system. To aid model set-up in future applications, the parameters used in each application and the composite ranges are presented in Appendices A–H.

6.4 Utility of INCA-P for research and catchment management

The three model applications demonstrate the utility of INCA-P as a research and catchment management tool. Specifically, the model has been used to:

- calculate the relative contribution of point and diffuse sources in the Ant and the Lugg;
- investigate the upland/lowland contrast in the Lugg;
- investigate scenarios of effluent phosphorus stripping in the Lugg;
- calculate the land phase and in-stream mass balance in the Lugg;
- reproduce the effects of phosphorus stripping at the Marlborough STW in the Upper Kennet.

In addition, previous applications of the in-stream component of INCA-P at a single location downstream of the STW have been used to investigate the possible effects of flow and in-stream phosphorus concentrations on the macrophyte growth (Wade *et al.*, 2002c; Wade *et al.*, 2002d).

The modelling assessment of the Ant system suggests a 1:3 ratio between the point and diffuse source contribution to the in-stream load. In the Lugg, this ratio is 1:9 in the upper reaches dominated by a rural landscape, and 1:1 in the lower reaches which receive effluent inputs from six major STWs. Thus, it is apparent that point sources can make a significant impact on the in-stream load, although further work is required to establish if this affect is localised. In particular, it is proposed to:

- compare the estimates of sediment phosphorus uptake and release with those measured in the PSYCHIC study to determine if phosphorus is up taken in all reaches of the Lugg, or if the reach lengths used within INCA are to long to identify any localised effects (of effluent inputs);
- simulate the SRP:boron ratios in the Pang and Lambourn systems.

Such work will improve understanding of the point source contribution to phosphorus concentrations and loads in the stream water.

The results of the effluent phosphorus scenarios indicate that stripping all the effluents discharging to the main channel of the Lugg to a concentration of 1 mg P/litre results in a simulated mean concentration ranging from 63 to 68 µg P/litre in the lower reaches. Consequently, the modelling assessment suggests that further stripping will reduce the in-stream phosphorus concentrations to values similar to those found in the rural upper reaches, i.e. approximately 50 µg P/litre. Given the current problems of parameter equifinality and uncertainty in the estimates of the effluent inputs, it is recommended that this modelling assessment should be compared with others carried out using SIMCAT and PSYCHIC. It is also recommended that all three be considered in the context of an analysis of historic and new data collected as part of the PSYCHIC programme to determine if further tertiary treatment will benefit the ecology of the Lugg and Wye.

6.5 Agency use of INCA-P

It is recommended that INCA-P be used within a hierarchy of modelling approaches within the Agency. INCA-P represents an intermediate complexity model capable of simulating the daily variations in the flow and phosphorus concentrations along the main river channel, based on readily available data. However, the data requirements mean that the model will take some effort to set up and application on a national scale is probably impractical. It is suggested that INCA-P would provide the most benefit by application to a specific catchments for a modelling assessment of a possible environmental impact. Simpler steady-state approaches such as the Export Coefficient Method or Phosphorus Indicators Tool (PIT) (Heathwaite *et al.*, 2003) could be applied at a national scale to identify phosphorus 'hot-spots'; the application of the INCA-P could then be targeted appropriately.

Training in the set-up, calibration and scenario testing was provided at an INCA training day held at the Agency's Reading office in June 2004. Free copies of the INCA-P executable will be made available to Agency staff and additional support will be available.

6.6 Structural changes

6.6.1 In-stream component

In the original version of INCA-P, all the in-stream parameters controlling the phosphorus and ecological dynamics were constant between reaches. During the applications of INCA-P in this study, it became apparent that some of these parameters must be reach dependent and that three structural changes were required. While these changes necessarily introduced more degrees of freedom, they were necessary to describe the spatial and temporal variations observed in the stream water TP and suspended sediment concentrations.

First, the SUP fraction of the in-stream TP was made reach dependent. Data collected in the 1999–2000 Ant study and studies of the phosphorus dynamics in the Lambourn system indicate that the SUP fraction of the TP load can vary between river systems from 4 to 25 per cent. In addition, the SUP fraction can exhibit a seasonal pattern, with SUP forming a greater fraction of the TP load during winter and spring (possibly due to slower rates of mineralisation in response to the lower temperatures). This may be due to the input of animal manures or desorption of phosphorus from bed sediments. Thus, the original assumption that SUP formed 25 per cent of the TP load was a clear over-simplification given the observed differences between river systems (Wade *et al.*, 2002b).

Secondly, the suspended sediment K_d value, the macrophyte and epiphyte growth and death rates, and bed sediment depth reach were also made reach dependent. The K_d value, which controls the amount of phosphorus sorbed to suspended sediment, needed to be spatially variable to explain some of the variation in the observed SRP concentrations. Within INCA-P, the macrophyte and epiphyte death rates are multiplied by flow to build in a flow dependency. Given that flow accretes along the length of the River Ant, then the death and consequently the growth rates were made reach dependent to account for:

- the heterogeneous relationship between flow and macrophyte and epiphyte wash-out;
- spatial variations in the factors that affect macrophyte and epiphyte growth, such as shading and dredging.

Thirdly, the structure of INCA-P was changed so that the bed sediment depth could vary between reaches rather than being a fixed parameter for all reaches (it was incorrect to maintain the same bed sediment depth for all reaches). The user-defined initial condition for the bed sediment mass was also removed, since it is possible to calculate the initial value from other parameters already specified within the model using the following equation:

$$x_{28,i} = \rho_s (1-\Phi) C_{21,i} \qquad [11]$$

where:

x_{28} = bed sediment mass in reach i

ρ_s = sediment particle density

Φ = porosity

$C_{21,i}$ = bed sediment depth.

Within this application, the particle density was 2.65 kg/m^3 and the porosity was set to 0.3.

To obtain the correct range of simulated SRP concentrations, the K_d value relating the SRP and TP concentrations was set to approximately 10^6 dm^3/kg P in the Ant calibration, but to 800 and 200 dm^3/kg P in the Lugg and Kennet, respectively. Measures of K_d for bed sediments in the Rivers Kennet and Yorkshire-Ouse are typically in the order of 10^2–10^3 dm^3/kg P. The K_d values in the Ant seem high and, while it is possible that the K_d value for suspended sediment could be greater than that for bed sediment due to the greater surface area per specific mass, further work is required to test this finding.

Additional work is required to improve the simulation of the SRP dynamics in the Ant, where the observed SRP data show a peak in summer. Stepwise regression showed that 50 per cent of the variation in SRP concentrations was explained by the TP concentrations, the flow and the (air) temperature. The latter described the seasonality in the observed SRP concentrations, which alone accounted for 43 per cent of the variation. All three factors are already included in INCA-P. The results suggest inadequate simulation of either a temperature control on the SRP fraction, increased stream water concentrations caused by a lower dilution of inputs from STWs during the summer months, or that release from bed sediment.

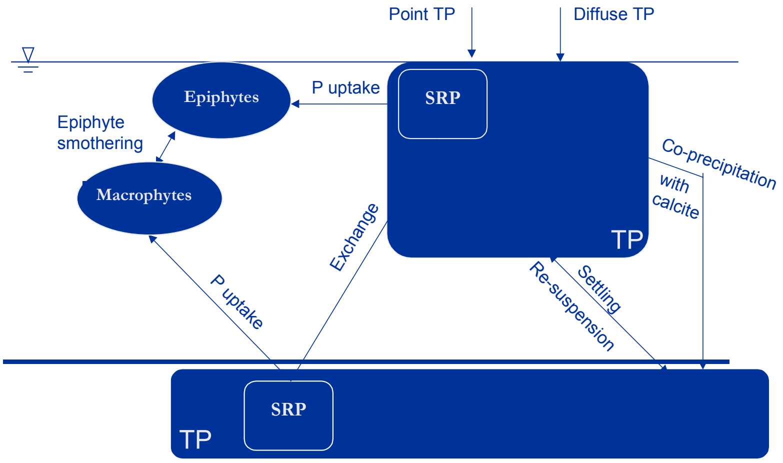


Figure 45 **Current structure of the in-stream component of INCA-P**

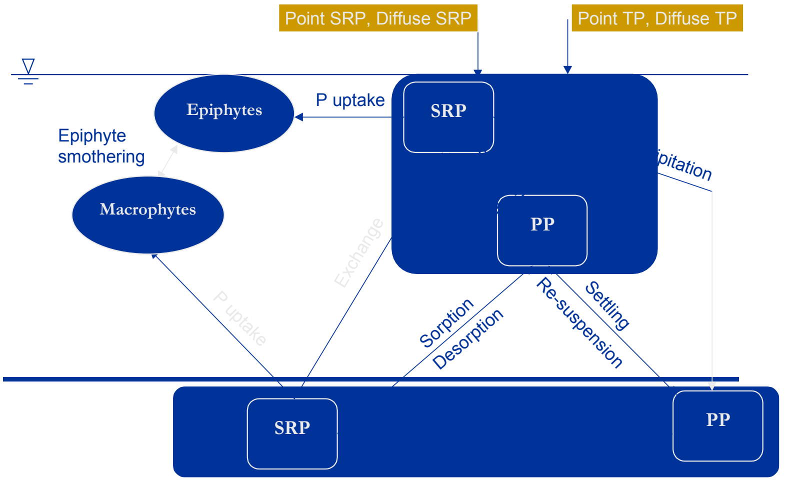


Figure 46 **Proposed structure for the in-stream component of INCA-P**

INCA-P currently tracks the transport and storage of TP in both the water column and pore water; the stream water SRP concentration is calculated at the end of each day based on the stream water TP concentration and the K_d value (Figure 45). The philosophy of this approach is that:

- it is simpler to track the total amount of phosphorus rather than each fraction (i.e. PP, SUP and SRP);
- the thermodynamic equilibrium between particulate and soluble P forms adjusts rapidly (sub-daily).

Specifically, the SRP concentration is calculated from the TP concentration using the following equations:

In the water column:

$$a_{11} = \frac{0.75a_8}{1+10^{-6}K_D^{Sus}a_7} \qquad [12]$$

where:

a_{11} and a_7 = stream water SRP and TP concentrations, respectively (mg P/litre)

a_8 = stream water suspended sediment concentration (mg/litre)

K_d^{Sus} = K_d value for suspended sediment (dm^3/kg).

In the pore water:

$$a_{12} = \frac{0.75a_{10}}{1+\frac{10^{-3}K_D^{Bed}x_{28}}{(n-1)C_{21}}} \qquad [13]$$

where:

a_{12} and a_{10} = pore water SRP and TP concentrations, respectively (mg P/litre)

x_{28} = reach bed mass (kg)

K_d^{Bed} = K_d value for the bed sediment (dm^3/kg)

C_{21} = sediment depth (m)

n = bed porosity (Ø)

All the parameters in equations [12] and [13] can be varied by reach.

To improve the simulations of stream water SRP concentrations, INCA-P will be modified to track the TP and SRP separately, both in the water column and in the stream bed (Figure 46). Tracking TP in the stream bed is more conceptually appealing than the current model structure, which tracks pore water TP. In addition, the model will be adapted to incorporate the EPC$_0$ concept of phosphorus sorption to sediment pioneered by House and Dension (1998).

6.6.2 Fully distributed version

It is also planned to create a fully distributed version of INCA-P. Model applications using INCA-N and INCA-P have demonstrated a need to adjust the some of the land phase model parameters (e.g. residence times and crop growth) according to the position within the catchment rather than by land use type. For example, in large river systems spanning contrasting upland and lowland regions or geological types, the residence times might be quite different in the two regions. A fully distributed version would also allow routing between land use units, providing a more realistic simulation of phosphorus transport through the land phase.

A fully distributed version would also allow the simulation of tributaries and the point source inputs on those tributaries.

At the same time, the nitrogen equations from INCA-N would be integrated into INCA-P to form a unified catchment model of nitrogen and phosphorus dynamics. Part of the appeal of the INCA framework of models is the execution speed and the user-friendly interface. A careful assessment is therefore required of whether the extra computation time and data preparation are warranted, or whether structural or parameter uncertainty make the additional complexity redundant. Moreover, new high frequency measurements may lead environmental modelling in a completely new direction away from the linking inputs and component processes into one of deriving solute travel time distributions from spectral analysis.

7. Conclusions

This study has met the original aims and objectives set out in Section 1.4. INCA-P was developed and applied within three major UK river systems to simulate the phosphorus dynamics and fractionations in the land phase, the in-stream water-column and pore waters. The SCEM-UA technique was applied to investigate the suitability of the model structure and the operational potential of the model was tested.

The detailed monitoring of the stream water chemistry and the farm survey within the three systems studied provided a key data resource with which to test and develop INCA-P. Where available, daily data proved invaluable in assessing the model's ability to simulate the dynamics of the system and provided a means to constraint the model. Equally valuable are the long-term Agency water quality archives, which allowed INCA-P to simulate a six-year period covering a range of hydrological conditions in the Lugg system, and the data from small-scale research studies focussed on single perturbations to the river system such as the stripping of phosphorus from Marlborough STW in the Upper Kennet.

Within the three systems, the spatial and temporal variations in the observed stream water phosphorus and suspended sediment concentrations exhibited complex patterns and a highly heterogeneous response (Jarvie *et al.*, 2002). These patterns represent the complex interaction between the factors and processes controlling the transport and retention of phosphorus within the land and in-stream phases. In particular, different phosphorus source areas become active depending on antecedent soil wetness, and phosphorus transport is dependent on the pathway invoked (which changes between storms).

The results also indicate that simulating phosphorus behaviour is likely to be more difficult than simulating that of nitrate. Patterns in stream water nitrate concentrations in the UK tend to exhibit a sine-wave, with a minimum in summer and a maximum in spring. This pattern reflects the sine-waves evident in the factors and processes that control the transport and retention of nitrate within the system:

- fertiliser inputs are usually greatest in autumn and winter;
- mineralisation, nitrification and de-nitrification are highest under the wet and warmer conditions found in spring and autumn;
- the wetting of the soils during autumn is likely to flush the nitrate built up in the soils during the summer into the stream during the autumn;
- plant uptake from both the soil and the stream is greatest during summer.

Phosphorus dynamics are more complex because of the sorption and desorption to and from sediment, and the dependence on sediment transport (unlike nitrate, which is soluble).

Data analysis of pre-existing and contemporary datasets formed an integral part of all three model applications and it is recommended that such analysis should precede applications of the model to understand the uniqueness of each system. Such an analysis highlights the key issues within the catchment, data availability and quality, and the general patterns of hydrochemical functioning. It can also allow simple mass balance calculations.

INCA-P is based on ideas of simple mixing of waters from different land use types and flow pathways. Given the reasonable simulations of flow and stream water phosphorus and suspended sediment concentrations, this representation of catchment phosphorus dynamics appears sufficient to explain the first order spatial and temporal variations in TP concentrations. Moreover, the equations describing the macrophyte and epiphyte growth are able to reproduce a sine-wave response, with a peak in macrophyte growth in the spring/summer period. Such a response has been observed in other UK rivers for which data are available.

Further work is required to improve the model's simulations of SRP concentrations and the detailed phosphorus dynamics for individual storm events. With the current model structure, the mass of TP associated with the stream bed is tracked; however, conceptually it is unclear whether the TP is associated with the sediment, or with the pore water, or both. The equations will be rewritten to:

- make the transfer of phosphorus between the bed and pore water more explicit;
- make it possible to determine the mass of phosphorus per mass of sediment (kg P/kg sediment) – a measure that is often made in studies of in-stream phosphorus transport (House and Denison, 1998).

In addition, the SRP fraction will be explicitly tracked in the water column to account for the seasonal variations in the dilution of STW inputs.

Given the need to understand the impact of water quality on the in-stream biota, it is also recommended that biological data corresponding to the water quality data are gathered. Advances in relating the MTR and the TDI to the percentage cover and biomass measures may be possible through work currently being carried out as part of the LOCAR project and by CEH, which is investigating remote sensing techniques for monitoring macrophyte growth in the Lambourn. Furthermore, the MTR and TDI are also being developed under the Water Framework Directive to produce reference-based diatom and macrophyte classification tools, which should be ready for implementation in 2006.

The application of the INCA-P model highlighted the lack of detailed information regarding point source phosphorus inputs. This lack of data must be addressed if confidence is to be placed in the estimated partition of inputs from point and diffuse sources. If the Agency needs to decide whether to target point or diffuse inputs for Asset Management Plans (AMP) or national or international environmental policy, then more detailed sampling of point sources is recommended. Without such data it is difficult to establish if the partition of the in-stream phosphorus load between point and diffuse sources by INCA-P (or any other model) is meaningful. Therefore, no firm conclusions about the management of diffuse or point sources can be made based on model applications alone.

At present, it is unclear how information measured at the point-scale (e.g. soil water TP concentrations) can be transformed to a meaningful parameter value representative of the catchment. This problem is not confined to this study but is true of most, if not all, model applications to real systems. At present, the only way to gain confidence in a model is to test it against high temporal resolution data most likely measured in-stream, for a range of different climatic conditions and land use types. Namely, the model provides a hypothesis about how the system works and is then applied with high-resolution data to test that hypothesis. If the model is able to reproduce the dynamics, then it can be kept ready for testing with the next dataset. If it fails, then it must be rejected or refined.

Uncertainty analysis is useful as it aids the identification of the parameters and aspects of model structure controlling the model behaviour (Wade *et al.*, 2001). In this study, the sensitivity analysis confirmed the appropriateness of the end-member mixing approach to simulating the in-stream phosphorus concentrations and loads, and demonstrated that the model simulated output was only dependent on the initial conditions for the first three days – thereafter, the model output was controlled by the driving input data and the simulated processes.

To develop the next generation of water quality models capable of simulating the full range of flow related phosphorus dynamics, it is recommended that state-of-the-art in situ monitoring equipment capable of high-frequency (sub-hourly) measurements for a broad range of determinands is used in research studies. The data must be 'multi-channel', i.e. they must cover the key water quality determinands and not just the nutrient species and fractions, because such data provide the background description of the water quality functioning of the system. For example, chloride or boron data could be used within the Ant catchment to determine whether the SRP stream response is linked to point or diffuse sources (Neal *et al.*, 2000a). High frequency measurements are required to further understand the solute retention times in catchments and the factors controlling the concentrations, including the biological effects which may occur at the sub-daily time-scale (e.g. respiration and photosynthesis).

The INCA-P model is available from the AERC free-of-charge to the Agency. A short description of this project has been added to the UK-ADAPT (UK Agicultural Diffuse Aquatic Pollution Toolkit) website (www.uk-adapt.org.uk).

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9. List of acronyms

ADAS	Agricultural Development and Advisory Service
AERC	Applied Environmental Research Centre
AMP	Asset Management Plan
BFI	Base Flow Index
CEH	Centre for Ecology and Hydrology
ds	downstream
ECM	Export Coefficient Method
FYM	farmyard manure
HER	hydrologically effective rainfall
IHACRES	Identification of Unit Hydrographs and Component Flows from Rainfall, Evaporation and Stream flow data model
INCA	Integrated Nitrogen in Catchments model
INCA-P	Integrated Catchments Model of Phosphorus dynamics
LOCAR	NERC Lowland Catchment Research project
MORECS	Meteorological Office Rainfall and Evapotranspiration Calculation System
MTR	mean trophic rank
OP	orthophosphate
PE	population equivalent
PIT	Phosphorus Indicators Tool
PP	particulate phosphorus
SAC	Special Area of Conservation
SCEM-UA	Sheffield Complex Evolution Metropolis algorithm
SMD	soil moisture deficit
SPA	Special Protection Area
SRP	soluble reactive phosphorus
SS	suspended sediment
STWs	sewage treatment works
SUP	soluble unreactive phosphorus
TDI	trophic diatom index
TP	total phosphorus
TPh	total phosphate

A. Ant: Land phase initial and parameter values

Table A1 Land phase initial conditions

Initial conditions	Units	Grassland	Cereal	Other arable	Set-aside	Woodland	Urban
Direct runoff							
Initial flow	m^3s^{-1}	0.001	0.001	0.001	0.001	0.001	0.001
Organic P	mg P l^{-1}	2	1	1	0.5	0.05	0.05
Inorganic P	mg P l^{-1}	4	2	3.5	1	0.05	0.05
Volume	m^3	1000	1000	1000	1000	1000	1000
Soilwater							
Initial flow	m^3s^{-1}	0.05	0.05	0.05	0.05	0.05	0.05
Organic P	mg P l^{-1}	2	1	1	0.5	0.05	0.05
Inorganic P	mg P l^{-1}	4	2	3.5	1	0.05	0.05
Volume	m^3	50000	50000	50000	50000	50000	50000
Groundwater							
Initial flow	m^3s^{-1}	0.008	0.008	0.008	0.008	0.008	0.008
Organic P	mg P l^{-1}	0.01	0.01	0.01	0.01	0.01	0.01
Inorganic P	mg P l^{-1}	0.01	0.01	0.01	0.01	0.01	0.01
Volume	m^3	10^7	10^7	10^7	10^7	10^7	10^7
Firmly bound							
Organic P	mg P l^{-1}	0.0	0.0	0.0	0.0	0.0	0.0
Inorganic P	mg P l^{-1}	0.0	0.0	0.0	0.0	0.0	0.0
Diffuse							
Boron	mg B l^{-1}	0	0	0	0	0	0
Suspended sediment							
Direct runoff	mg l^{-1}	150	150	150	150	150	150
Soilwater	mg l^{-1}	10	10	10	10	10	10
Groundwater	mg l^{-1}	3	3	3	3	3	3

Parameter	**Units**	**Grassland**	**Cereal**	**Other arable**	**Set-aside**	**Woodland**	**Urban**
			Processes				
Immobilisation	m day^{-1}	0	0	0	0	0	0
Mineralisation	m day^{-1}	0	0	0	0	0	0
			Firmly bound				
Organic P input	m day^{-1}	0	0	0.03	0.05	0.05	0.05
Organic P output	m day^{-1}	0	0	0	0	0	0
Inorganic P input	m day^{-1}	0	0.02	0.02	0.02	0.02	0.02
Inorganic P output	m day^{-1}	0	0	0	0	0	0
			Plant growth				
Start day	day	1	69	67	1	1	1
Period	day	365	166	263	365	365	365
Organic P uptake rate	m day^{-1}	0.1	0.08	0.01	0.01	0.01	0.01
Inorganic P uptake rate	m day^{-1}	0.1	0.08	0.025	0.01	0.01	0.01
Maximum uptake	Kg P ha-1 a^{-1}	100	100	100	100	100	100
			Hydrology				
Soil retention volume per km^2	m	0.2	0.2	0.2	0.2	0.2	0.2
Max soil moisture deficit	mm	150	150	150	150	150	150
Max temp difference	^{o}C	0	4.5	4.5	4.5	4.5	4.5
			Residence time				
Direct runoff	days	0.01	0.01	0.01	0.01	0.01	0.01
Soilwater	days	1	1	1	1	1	1
Groundwater	days	70	70	70	70	70	70

B. Ant: In-stream phase initial and parameter values

Table B1 Land distribution and reach dimensions and effluent inputs

Parameter*	**Units**	**Reach**						
		1	**2**	**3**	**4**	**5**	**6**	**7**
Sub-catchment area								
Area	km^2	7.15	1.95	16.49	10.59	8.31	35.51	6.79
Sub-catchment hydrology								
Base flow index	Ø	0.87	0.87	0.87	0.87	0.87	0.87	0.87
Alpha	Ø	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Delta	Ø	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Land use								
Grassland	per cent	2	0	6	9	13	14	16
Cereal	per cent	48	64	36	29	58	53	47
Other arable	per cent	26	28	29	29	16	24	34
Set-aside	per cent	9	5	6	9	9	3	3
Woodland	per cent	1	0	0	8	1	2	0
Urban	per cent	14	3	23	16	3	4	0
Reach characteristics								
Length	m	2,000	1,250	3,000	4,000	4,250	4,500	1,750
Width	m	1.5	1.5	5.0	5.0	5.0	7.0	10.0
Latitude	°	52.865	52.860	52.836	52.789	52.770	52.770	52.884
Longitude	°	1.361	1.372	1.396	1.459	1.481	1.481	1.521
In-stream flow								
A	m-^{2}	1.0	1.0	1.0	1.0	0.4	0.4	0.1
B	Ø	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Effluent								
Flow	m^{3}s^{-1}	0.0	0.0	0.0	0.0	0.0007	0.0001	0.0
TP	mg P l^{-1}	0.0	0.0	0.0	0.0	7.0	7.0	0.0
B	mg B l^{-1}	0.0	0.0	0.0	0.0	0.0	0.0	0.0

*Parameters are defined in Wade *et al.*, 2002.

Table B2 Reach-dependent in-stream parameters

Parameter*	Units	Reach						
		1	2	3	4	5	6	7
Temperature dependency								
Macrophyte	Ø	1.066	1.066	1.066	1.066	1.066	1.066	1.066
Epiphyte	Ø	1.066	1.066	1.066	1.066	1.066	1.066	1.066
Phytoplankton	Ø	1.066	1.066	1.066	1.066	1.066	1.066	1.066
Growth rate								
Macrophyte	day^{-1}	0.2	0.3	0.3	0.3	0.35	0.35	0.15
Epiphyte	m^{2} g C^{-1} day^{-1}	0.01	0.005	0.035	0.01	0.01	0.01	0.01
Death rate								
Macrophyte	s m^{-1} g C^{-1} day^{-1}	5.0	15.0	0.9	1.5	0.75	0.5	0.05
Epiphyte	s m^{-3} day^{-1}	0.15	0.15	0.1	0.01	0.03	0.01	0.03
Suspended sediment								
SUP proportion	Ø	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Suspended sed K_d	dm^{3} kg^{-1}	10^6	$8*10^5$	$2*10^6$	10^6	10^6	10^6	$3*10^5$
Bed suspended potential	Ø	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Bulk sediment density	kg m^{-3}	2.65	2.65	2.65	2.65	2.65	2.65	2.65
Porosity	Ø	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Bed sediment depth	m	0.3	0.5	0.3	0.3	0.3	0.3	0.3

*Parameters are defined in Wade *et al.*, 2002.

Table B3 Reach initial conditions

Parameter*	Units	Value
Flow	m^{3}s^{-1}	0.01
Suspended Sediment	mg l^{-1}	5
Sediment grain size	µm	500
Sediment suspended or resuspension	kg	0.1
Macrophyte mass	gC m^{-2}	1
Epiphyte mass	gC m^{-2}	0.01
Live phytoplankton	µg Chl ‘a’ l^{-1}	2.12
Dead phytoplankton	µg Chl ‘a’ l^{-1}	1
Water column TP	mg P l^{-1}	0.05
Pore water TP	mg P l^{-1}	0.1
Boron	mg B l^{-1}	0.0

*Parameters are defined in Wade *et al.*, 2002.

Table B4 In-stream parameters constant between reaches

Parameter*	Units	Value
Proportion of P in macrophytes	gP gC^{-1}	0.0054
Proportion of P in epiphytes	gP gC^{-1}	0.0054
P exchange (water column/pore water)	day^{-1}	1000
P precipitation	day^{-1}	0
Sediment suspension\resuspension	µm s m^{-3}	800
Bed sediment K_d (fraction of suspended sed K_d)	Ø	0.0005
Half saturation of P for macrophytes	mg P l^{-1}	0.01
Half saturation of P for epiphytes	mg P l^{-1}	0.01
Half saturation of P for algal growth	mg P l^{-1}	1
Macrophyte self-shading	g C m^{-2}	10
Phytoplankton growth rate	day^{-1}	0
Phytoplankton death rate	day^{-1}	0
Phytoplankton self-shading	µg Chl ‘a’ l^{-1}	1
Dead phytoplankton settling rate	day^{-1}	0

*Parameters are defined in Wade *et al.*, 2002

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C. Lugg: land phase initial and parameter values

Table C1 Land phase initial conditions

Initial conditions	Units	Grassland	Cereal	Other arable	Set-aside	Woodland	Urban
			Direct runoff				
Initial flow	m^3s^{-1}	0.001	0.001	0.001	0.001	0.001	0.001
Organic P	mg P l^{-1}	0.025	0.025	0.025	0.01	0.01	0.01
Inorganic P	mg P l^{-1}	0.025	0.025	0.025	0.01	0.01	0.01
Volume	m^3	1000	1000	1000	1000	1000	1000
			Soilwater				
Initial flow	m^3s^{-1}	0.005	0.005	0.005	0.005	0.005	0.005
Organic P	mg P l^{-1}	0.1	0.1	0.1	0.01	0.01	0.01
Inorganic P	mg P l^{-1}	0.1	0.1	0.1	0.01	0.01	0.01
Volume	m^3	$5x10^5$	$5x10^5$	$5x10^5$	$5x10^5$	$5x10^5$	$5x10^5$
			Groundwater				
Initial flow	m^3s^{-1}	0.008	0.008	0.008	0.008	0.008	0.008
Organic P	mg P l^{-1}	0.001	0.001	0.001	0.001	0.001	0.001
Inorganic P	mg P l^{-1}	0.001	0.001	0.001	0.001	0.001	0.001
Volume	m^3	$1x10^7$	$1x10^7$	$1x10^7$	$1x10^7$	$1x10^7$	$1x10^7$
			Firmly bound				
Organic P	mg P l^{-1}	0.01	0.01	0.01	0.01	0.01	0.01
Inorganic P	mg P l^{-1}	0.01	0.01	0.01	0.01	0.01	0.01
			Diffuse				
Boron	mg B l^{-1}	0	0	0	0	0	0
			Suspended sediment				
Direct runoff	mg l^{-1}	150	150	150	150	150	150
Soilwater	mg l^{-1}	80	80	80	80	80	80
Groundwater	mg l^{-1}	10	10	10	10	10	10

Parameter	**Units**	**Grassland**	**Cereal**	**Other arable**	**Set-aside**	**Woodland**	**Urban**
Processes							
Immobilisation	m day^{-1}	0	0	0	0	0	0
Mineralisation	m day^{-1}	0	0	0	0	0	0
Firmly bound							
Organic P input	m day^{-1}	0.07	0.01	0.22	0.0	0.0	0.0
Organic P output	m day^{-1}	0.07	0.01	0.22	0.0	0.0	0.0
Inorganic P input	m day^{-1}	0	0	0	0.1	0.1	0.1
Inorganic P output	m day^{-1}	0	0	0	0.1	0.1	0.1
Plant growth							
Start day	day	1	70	77	1	1	1
Period	day	365	160	221	365	365	365
Organic P uptake rate	m day^{-1}	0.08	6	0.18	0	0	0
Inorganic P uptake rate	m day^{-1}	0.08	6	0.18	0	0	0
Maximum uptake	kg P ha^{-1} a^{-1}	100	100	100	100	100	100
Hydrology							
Soil retention volume/km^2	m	0.2	0.2	0.2	0.2	0.2	0.2
Max soil moisture deficit	mm	150	150	150	150	150	150
Max temp difference	^{o}C	0	4.5	4.5	4.5	4.5	4.5
Residence time							
Direct runoff	days	0.01	0.01	0.01	0.01	0.01	0.01
Soilwater	days	1	1	1	1	1	1
Groundwater	days	70	70	70	70	70	70

D. Lugg: In-stream phase initial and parameter values

Table D1a **Land distribution and reach dimensions and effluent inputs**

Parameter*	Units	Reach										
		1	2	3	4	5	6	7	8	9	10	11
							Sub-catchment area					
Area	km^2	30	71	13	86	28	21	54	37	24	3	292
							Sub-catchment hydrology					
Base flow index	Ø	0.65	0.65	0.65	0.65	0.7	0.7	0.7	0.7	0.63	0.63	0.63
Alpha	Ø	0	0	0	0	0	0	0	0	0	0	0
Delta	Ø	0	0	0	0	0	0	0	0	0	0	0
							Land use					
Grassland	per cent	81	72	63	70	65	52	51	54	33	26	64
Cereal	per cent	1	5	16	11	17	14	24	28	28	23	17
Other arable	per cent	1	2	4	2	5	4	9	8	16	11	8
Set-aside	per cent	0	0	0	0	0	0	0	0	1	0	0
Woodland	per cent	17	20	10	15	10	28	10	5	8	0	7
Urban	per cent	0	1	7	2	3	2	6	5	14	40	4
							Reach characteristics					
Length	m	9,200	11,000	4,300	3,500	2,000	8,000	11,500	500	700	1,500	3,000
Width	m	5	10	10	10	10	10	15	20	20	25	25
Latitude	°	52.865	52.865	52.865	52.865	52.865	52.865	52.865	52.865	52.865	52.865	52.865
Longitude	°	1.361	1.361	1.361	1.361	1.361	1.361	1.361	1.361	1.361	1.361	1.361
							In-stream flow					
A	m^{-2}	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
B	Ø	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67
							Effluent					
Flow	m^3 s^{-1}	0.0003	0.0	0.0059	0.0	0.0	0.0	0.0019	0.0	0.0	0.033	0.0
TP	mg P l^{-1}	4.69	0.0	4.57	0.0	0.0	0.0	3.63	0.0	0.0	4.92	0.0
B	mg B l^{-1}	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

*Parameters are defined in Wade *et al.*, 2002.

Table D1b Land distribution and reach dimensions and effluent inputs

Parameter*	Units	Reach										
		12	13	14	15	16	17	18	19	20	21	22
						Sub-catchment area						
Area	km^2	8	48	27	48	8	22	48	8	184	2	15
						Sub-catchment hydrology						
Base flow index	Ø	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63
Alpha	Ø	0	0	0	0	0	0	0	0	0	0	0
Delta	Ø	0	0	0	0	0	0	0	0	0	0	0
						Land use						
Grassland	per cent	48	51	44	44	48	45	44	45	49	34	36
Cereal	per cent	25	26	30	22	29	25	30	27	25	39	13
Other arable	per cent	10	8	10	13	15	19	15	17	11	17	9
Set-aside	per cent	0	0	1	0	0	0	0	0	0	0	0
Woodland	per cent	11	8	8	15	2	5	4	1	5	0	39
Urban	per cent	6	6	7	6	6	6	7	10	10	10	3
						Reach characteristics						
Length	m	2,500	2,100	3,000	10,000	3,700	3,500	1,400	2,000	3,200	2,000	500
Width	m	30	25	25	25	25	25	25	25	25	25	25
Latitude	°	52.865	52.865	52.865	52.865	52.865	52.865	52.865	52.865	52.865	52.865	52.865
Longitude	°	1.361	1.361	1.361	1.361	1.361	1.361	1.361	1.361	1.361	1.361	1.361
						In-stream flow						
A	m^{-2}	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
B	Ø	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67
						Effluent						
Flow	$m^3\ s^{-1}$	0.0637	0.0	0.014	0.0	0.0072	0.0	0.0	0.0	0.0	0.0003	0.0
TP	$mg\ P\ l^{-1}$	5.42	0.0	7.71	0.0	9.45	0.0	0.0	0.0	0.0	15.6	0.0
B	$mg\ B\ l^{-1}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Parameters are defined in Wade *et al.*, 2002.

Table D2a Reach-dependent in-stream parameters

Parameter*	Units	Reach										
		1	2	3	4	5	6	7	8	9	10	11
Temperature dependency												
Macrophyte	Ø	1.066	1.066	1.066	1.066	1.066	1.066	1.066	1.066	1.066	1.066	1.066
Epiphyte	Ø	1.066	1.066	1.066	1.066	1.066	1.066	1.066	1.066	1.066	1.066	1.066
Phytoplankton	Ø	1.066	1.066	1.066	1.066	1.066	1.066	1.066	1.066	1.066	1.066	1.066
Growth rate												
Macrophyte	day^{-1}	0	0	0	0	0	0	0	0	0	0	0
Epiphyte	m^2 g C^{-1} day^{-1}	0	0	0	0	0	0	0	0	0	0	0
Death rate												
Macrophyte	S m^{-1} g C^{-1} day^{-1}	0	0	0	0	0	0	0	0	0	0	0
Epiphyte	s m^{-3} day^{-1}	0	0	0	0	0	0	0	0	0	0	0
Suspended sediment												
SUP proportion	Ø	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Suspended sed K_d	dm^3 kg^{-1}	800	800	800	800	800	800	800	800	800	800	800
Bed suspended potential	Ø	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Bulk sediment density	kg m^{-3}	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65
Porosity	Ø	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Bed sediment depth	m	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3

*Parameters are defined in Wade *et al.*, 2002.

Table D2b Reach-dependent in-stream parameters

Parameter*	Units	Reach										
		12	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**
						Temperature dependency						
Macrophyte	Ø	1.066	1.066	1.066	1.066	1.066	1.066	1.066	1.066	1.066	1.066	1.066
Epiphyte	Ø	1.066	1.066	1.066	1.066	1.066	1.066	1.066	1.066	1.066	1.066	1.066
Phytoplankton	Ø	1.066	1.066	1.066	1.066	1.066	1.066	1.066	1.066	1.066	1.066	1.066
						Growth rate						
Macrophyte	day^{-1}	0	0	0	0	0	0	0	0	0	0	0
Epiphyte	m^{2} g C^{-1} day^{-1}	0	0	0	0	0	0	0	0	0	0	0
						Death rate						
Macrophyte	s m^{-1} g C^{-1} day^{-1}	0	0	0	0	0	0	0	0	0	0	0
Epiphyte	s m^{-3} day^{-1}	0	0	0	0	0	0	0	0	0	0	0
						Suspended sediment						
SUP proportion	Ø	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Suspended Sed K_d	Dm^{3} kg^{-1}	800	800	800	800	800	800	800	800	800	800	800
Bed suspended potential	Ø	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Bulk sediment density	kg m^{-3}	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65
Porosity	Ø	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Bed sediment depth	m	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3

*Parameters are defined in Wade *et al.*, 2002.

Table D3 Reach initial conditions

Parameter*	Units	Value
Flow	m^3s^{-1}	0.01
Suspended sediment	mg l^{-1}	5
Sediment grain size	µm	100
Sediment suspended or resuspension	kg	0.1
Macrophyte mass	gC m^{-2}	1
Epiphyte mass	gC m^{-2}	0.01
Live phytoplankton	µg Chl 'a' l^{-1}	2.12
Dead phytoplankton	µg Chl 'a' l^{-1}	1
Water column TP	mg P l^{-1}	0.01
Pore water TP	mg P l^{-1}	0.01
Boron	mg B l^{-1}	0.0

*Parameters are defined in Wade *et al.*, 2002.

Table D4 In-stream parameters constant between reaches

Parameter*	Units	Value
Proportion of P in macrophytes	gP gC^{-1}	0.0054
Proportion of P in epiphytes	gP gC^{-1}	0.0054
P exchange (water column/pore water)	day^{-1}	1000
P precipitation	day^{-1}	0
Sediment suspension\resuspension	µm s m^{-3}	8
Bed sediment K_d (fraction of suspended sediment K_d)	Ø	0.6
Half saturation of P for macrophytes	mg P l^{-1}	0.02
Half saturation of P for epiphytes	mg P l^{-1}	0.02
Half saturation of P for algal growth	mg P l^{-1}	1
Macrophyte self-shading	g C m^{-2}	10
Phytoplankton growth rate	day^{-1}	0
Phytoplankton death rate	day^{-1}	0
Phytoplankton self-shading	µg Chl 'a' l^{-1}	1
Dead phytoplankton settling sate	day^{-1}	0

*Parameters are defined in Wade *et al.*, 2002.

E. Kennet: land phase initial and parameter values

Table E1 Land phase initial conditions

Initial conditions	Units	Grassland	Cereal	Other arable	Set-aside	Woodland	Urban
			Direct runoff				
Initial Flow	m^3s^{-1}	0.0	0.0	0.0	0.0	0.0	0.0
Organic P	mg P l^{-1}	0.0	0.0	0.0	0.0	0.0	0.0
Inorganic-P	mg P l^{-1}	0.0	0.0	0.0	0.0	0.0	0.0
Volume	m^3	$6x10^7$	$6x10^7$	$6x10^7$	$6x10^7$	$6x10^7$	$6x10^7$
			Soilwater				
Initial Flow	m^3s^{-1}	0.001	0.001	0.001	0.001	0.001	0.001
Organic P	mg P l^{-1}	0.005	0.005	0.005	0.005	0.005	0.005
Inorganic-P	mg P l^{-1}	0.005	0.005	0.005	0.005	0.005	0.005
Volume	m^3	10000	10000	10000	10000	10000	10000
			Groundwater				
Initial Flow	m^3s^{-1}	0.001	0.001	0.001	0.001	0.001	0.001
Organic P	mg P l^{-1}	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005
Inorganic-P	mg P l^{-1}	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005
Volume	m^3	$1.38x10^6$	$1.38x10^6$	$1.38x10^6$	$1.38x10^6$	$1.0x10^6$	$1.38x10^6$
			Firmly bound				
Organic P	mg P l^{-1}	0.0	0.0	0.0	0.0	0.0	0.0
Inorganic-P	mg P l^{-1}	0.0	0.0	0.0	0.0	0.0	0.0
			Diffuse				
Boron	mg B l^{-1}	0.08	0.001	0.001	0.001	0.001	0.001
			Suspended sediment				
Direct runoff	mg l^{-1}	150	150	150	150	150	150
Soilwater	mg l^{-1}	50	50	50	50	50	50
Groundwater	mg l^{-1}	10	2	2	2	2	2

Parameter	Units	Grassland	Cereal	Other arable	Set-aside	Woodland	Urban
			Processes				
Immobilisation	m day^{-1}	0.1	0.1	0.1	0.1	0.1	0.1
Mineralisation	m day^{-1}	0.25	0.25	0.25	0.25	0.25	0.25
			Firmly bound				
Organic P input	m day^{-1}	5.0	5.0	5.0	5.0	5.0	5.0
Organic P output	m day^{-1}	5.0	5.0	5.0	5.0	5.0	5.0
Inorganic P input	m day^{-1}	0.1	0.1	0.1	0.1	0.1	0.1
Inorganic P output	m day^{-1}	0.1	0.1	0.1	0.1	0.1	0.1
			Plant growth				
Start day	day	1	66	74	1	1	1
Period	day	364	166	224	364	364	364
Organic P uptake rate	m day^{-1}	2	2	2	2	2	2
Inorganic P uptake rate	m day^{-1}	1	1	1	1	1	1
Maximum uptake	kg P ha^{-1} a^{-1}	70	40	45	105	95	0
			Hydrology				
Soil retention volume/km^2	m	0.45	0.45	0.45	0.45	0.45	0.45
Maximum soil moisture deficit	mm	150	150	150	150	150	150
Maximum temperature difference	^{o}C	4.5	4.5	4.5	4.5	4.5	4.5
			Residence time				
Direct runoff	days	0.01	0.01	0.01	0.01	0.01	0.01
Soil water	days	0.5	0.5	0.5	0.5	0.5	0.5
Groundwater	days	100	150	150	150	150	150

F. Kennet: In-stream Phase initial and parameter values

Table F1 Land distribution and reach dimensions and effluent inputs

Parameter*	Units	Reach										
		1	2	3	4	5	6	7	8	9	10	11
Sub-catchment area												
Area	km^2	24	34	51	1	24	77	1	2	2	24	57
Sub-catchment hydrology												
Base flow index	Ø	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
Alpha	Ø	0	0	0	0	0	0	0	0	0	0	0
Delta	Ø	0	0	0	0	0	0	0	0	0	0	0
Land use												
Grassland	Per cent	28	14	29	56	24	27	27	55	87	29	26
Cereal	Per cent	48	59	47	29	43	47	47	29	0	34	50
Other arable	Per cent	6	5	5	3	5	5	5	0	4	8	6
Set-aside	Per cent	15	20	17	6	12	14	14	10	0	12	9
Woodland	Per cent	3	2	2	7	6	3	3	7	9	11	6
Urban	Per cent	0	0	0	0	11	3	3	0	0	6	2
Reach characteristics												
Length	m	6,250	4,500	8,000	1,750	3,000	2,250	500	1,500	1,000	4,000	2,500
Width	m	10	10	10	10	10	10	10	10	10	10	10
Latitude	^{o}	51.467	51.427	51.411	51.415	51.415	51.421	51.424	51.423	51.425	51.439	51.437
Longitude	^{o}	-1.855	-1.859	-1.782	-1.777	-1.73	-1.7	-1.692	-1.672	-1.663	-1.608	-1.585
In-stream flow												
a	m^{-2}	0.01	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
b	Ø	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67
Effluent												
Flow	m3 s^{-1}	0.0	0.0	0.0035	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TP	mg P l^{-1}	0.0	0.0	5.96	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
B	mg B l^{-1}	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

*Parameters are defined in Wade *et al.*, 2002.

Table F2 Reach-dependent in-stream parameters

Parameter*	Units	Reach										
		1	2	3	4	5	6	7	8	9	10	11
Temperature dependency												
Macrophyte	Ø	1.066	1.066	1.066	1.066	1.066	1.066	1.066	1.066	1.066	1.066	1.066
Epiphyte	Ø	1.066	1.066	1.066	1.066	1.066	1.066	1.066	1.066	1.066	1.066	1.066
Phytoplankton	Ø	1.066	1.066	1.066	1.066	1.066	1.066	1.066	1.066	1.066	1.066	1.066
Growth rate												
Macrophyte	day^{-1}	0.25	0.25	0.25	0.25	0.25	0.25	0.225	0.25	0.25	0.25	0.25
Epiphyte	m2 g C^{-1} day^{-1}	0.0077	0.0077	0.0077	0.0077	0.0077	0.0077	0.0077	0.0077	0.0077	0.0077	0.0077
Death rate												
Macrophyte	S m^{-1} g C^{-1} day^{-1}	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Epiphyte	S m^{-3} day^{-1}	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035
Suspended sediment												
SUP proportion	Ø	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Suspended sed K_d	dm^3 kg^{-1}	200	200	200	200	200	200	200	200	200	200	200
Bed suspended potential	Ø	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Bulk sediment density	kg m^{-3}	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65
Porosity	Ø	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Bed sediment depth	m	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3

*Parameters are defined in Wade *et al.*, 2002.

Table F3 Reach initial conditions

Parameter*	Units	Value
Flow	$m^3 s^{-1}$	0.01
Suspended sediment	mg l^{-1}	5
Sediment grain size	µm	500
Sediment suspended or resuspension	kg	0.1
Macrophyte mass	gC m^{-2}	1
Epiphyte mass	gC m^{-2}	0.01
Live phytoplankton	µg Chl ‘a’ l^{-1}	2.12
Dead phytoplankton	µg Chl ‘a’ l^{-1}	1
Water column TP	mg P l^{-1}	0.02
Pore water TP	mg P l^{-1}	0.05
Boron	mg B l^{-1}	0.0

*Parameters are defined in Wade et al., 2002.

Table F4 In-stream parameters constant between reaches

Parameter*	Units	Value
Proportion of P in macrophytes	gP gC^{-1}	0.0054
Proportion of P in epiphytes	gP gC^{-1}	0.0054
P exchange (water column/pore water)	day^{-1}	1000
P precipitation	day^{-1}	0
Sediment suspension\resuspension	µm s m^{-3}	800
Bed sediment K_d (fraction of suspended sediment K_d)	Ø	1
Half saturation of P for macrophytes	mg P l^{-1}	0.01
Half saturation of P for epiphytes	mg P l^{-1}	0.01
Half saturation of P for algal growth	mg P l^{-1}	1
Macrophyte self-shading	g C m^{-2}	30
Phytoplankton growth rate	day^{-1}	0
Phytoplankton death rate	day^{-1}	0
Phytoplankton self-shading	µg Chl ‘a’ l^{-1}	1
Dead phytoplankton settling rate	day^{-1}	0

*Parameters are defined in Wade *et al.*, 2002.

G. Land Phase initial and parameter value ranges

Table G1 Land phase initial conditions

Initial conditions	**Units**	**Minimum**	**Maximum**	**Mean**
Direct runoff				
Initial flow	m^3s^{-1}	0	0.001	0.0005
Organic P	mg P l^{-1}	0	0.1	0.05
Inorganic P	mg P l^{-1}	0	1	0.5
Volume	m^3	1,000	$6x10^7$	$2.999x10^7$
Soil water				
Initial flow	m^3s^{-1}	0.001	0.005	0.003
Organic P	mg P l^{-1}	0.005	0.1	0.0525
Inorganic P	mg P l^{-1}	0.005	1	0.5025
Volume	m^3	10000	500000	246000
Groundwater				
Initial flow	m^3s^{-1}	0.001	0.008	0.0045
Organic P	mg P l^{-1}	0.001	0.015	0.008
Inorganic P	mg P l^{-1}	0.001	0.015	0.008
Volume	m^3	10^6	10^7	$5.5x10^6$
Firmly bound				
Organic P	mg P l^{-1}	0	0.01	0.005
Inorganic P	mg P l^{-1}	0	0.01	0.005
Diffuse				
Boron	mg B l^{-1}	0	0	0
Suspended sediment				
Direct runoff	mg l^{-1}	150	150	150
Soilwater	mg l^{-1}	10	80	45
Groundwater	mg l^{-1}	2	10	6

Parameter	**Units**	**Minimum**	**Maximum**
Processes			
Immobilisation	m day^{-1}	0	0.1
Mineralisation	m day^{-1}	0	0.25
Firmly bound			
Organic P input	m day^{-1}	0	5
Organic P output	m day^{-1}	0	5
Inorganic P input	m day^{-1}	0	0.1
Inorganic P output	m day^{-1}	0	0.1
Plant growth			
Start day	day	1	77
Period	day	160	365
Organic P uptake rate	m day^{-1}	0	2
Inorganic P uptake rate	m day^{-1}	0	6
Maximum uptake	Kg P ha^{-1} a^{-1}	0	105
Hydrology			
Soil retention volume/km^2	m	0.2	0.45
Maximum soil moisture deficit	mm	150	150
Maximum temperature difference	^oC	0	4.5
Residence time			
Direct runoff	days	0.01	0.01
Soil water	days	0.5	1
Groundwater	days	70	150

H. In-stream phase initial and parameter value ranges

Table H1 Land distribution and reach dimensions and effluent inputs

Parameter*	**Units**	**Minimum**	**Maximum**
Sub-catchment area			
Area	km^{2}	1	292
Sub-catchment hydrology			
Base flow index	Ø	0.63	0.95
Alpha	Ø	0	0.03
Delta	Ø	0	0
Reach characteristics			
Length	m	500	11,500
Width	m	1.5	30
In-stream flow			
a	m-^{2}	0.04	1
b	Ø	0.67	0.7
Effluent			
Flow	m^{3}s^{-1}	0	0.033
TP	mg P l^{-1}	0	15.6
B	mg B l^{-1}	0	0

*Parameters are defined in Wade *et al.*, 2002.

Table H2 Reach-dependent in-stream parameters

Parameter*	**Units**	**Minimum**	**Maximum**
Temperature dependency			
Macrophyte	Ø	1.066	1.066
Epiphyte	Ø	1.066	1.066
Phytoplankton	Ø	1.066	1.066
Growth rate			
Macrophyte	day^{-1}	0	0.35
Epiphyte	m^{2} g C^{-1} day^{-1}	0	0.01
Death rate			
Macrophyte	s m^{-1} g C^{-1} day^{-1}	0	15
Epiphyte	s m^{-3} day^{-1}	0	0.15
Suspended sediment			
SUP proportion	Ø	0.05	0.25
Suspended sed K$_{d}$	dm^{3} kg^{-1}	200	10^{6}
Bed suspended potential	Ø	0.1	0.1
Bulk sediment density	kg m^{-3}	2.65	2.65
Porosity	Ø	0.3	0.3
Bed sediment depth	m	0.3	0.3

*Parameters are defined in Wade *et al.*, 2002.

Table H3 Reach initial conditions

Parameter*	Units	Minimum	Maximum
Flow	m^3s^{-1}	0.01	0.01
Suspended sediment	mg l^{-1}	5	5
Sediment grain size	μm	100	500
Sediment suspended or resuspension	kg	0.1	100
Macrophyte mass	gC m^{-2}	1	1
Epiphyte mass	gC m^{-2}	0.01	0.01
Live phytoplankton	μg Chl 'a' l^{-1}	2.12	2.12
Dead phytoplankton	μg Chl 'a' l^{-1}	1	1
Water column TP	mg P l^{-1}	0.01	0.05
Pore water TP	mg P l^{-1}	0.01	0.1
Boron	mg B l^{-1}	0	0

*Parameters are defined in Wade *et al.*, 2002.

Table H4 In-stream parameters constant between reaches

Parameter*	Units	Minimum	Maximum
Proportion of P in macrophytes	gP gC^{-1}	0.0054	0.0054
Proportion of P in epiphytes	gP gC^{-1}	0.0054	0.0054
P exchange (water column/pore water)	day^{-1}	1000	1000
P precipitation	day^{-1}	0	0
Sediment suspension\resuspension	μm s m^{-3}	8	800
Bed sediment K_d (fraction of suspended sediment K_d)	Ø	0.0005	1
Half saturation of P for macrophytes	mg P l^{-1}	0.01	0.02
Half saturation of P for epiphytes	mg P l^{-1}	0.01	0.02
Half saturation of P for algal growth	mg P l^{-1}	1	1
Macrophyte self-shading	g C m^{-2}	10	30
Phytoplankton growth rate	day^{-1}	0	0
Phytoplankton death rate	day^{-1}	0	0
Phytoplankton self-shading	μg Chl 'a' l^{-1}	1	1
Dead phytoplankton settling rate	day^{-1}	0	0

*Parameters are defined in Wade *et al.*, 2002.

I. Comparison of observed and simulated flow, stream water phosphorus and suspended sediment concentrations in the River Ant

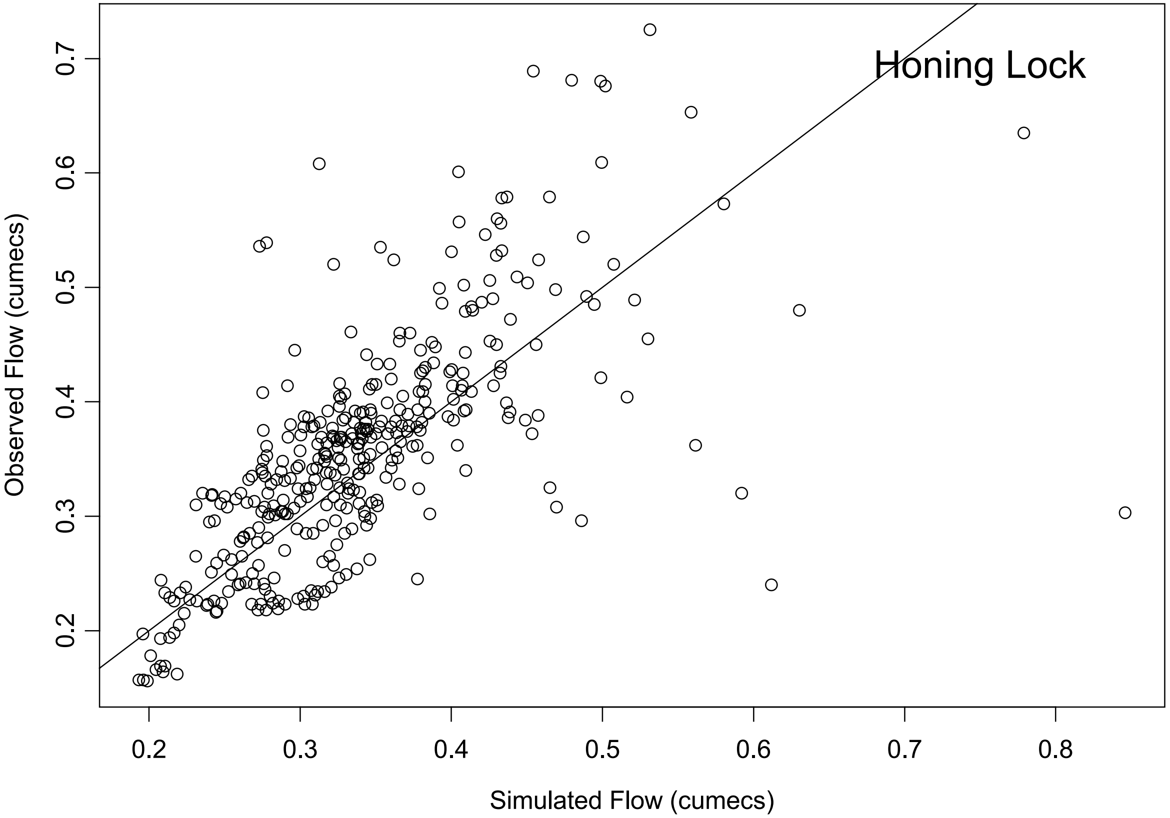

Figure I1 **Comparison of observed and simulated flow at Honing Lock, River Ant**

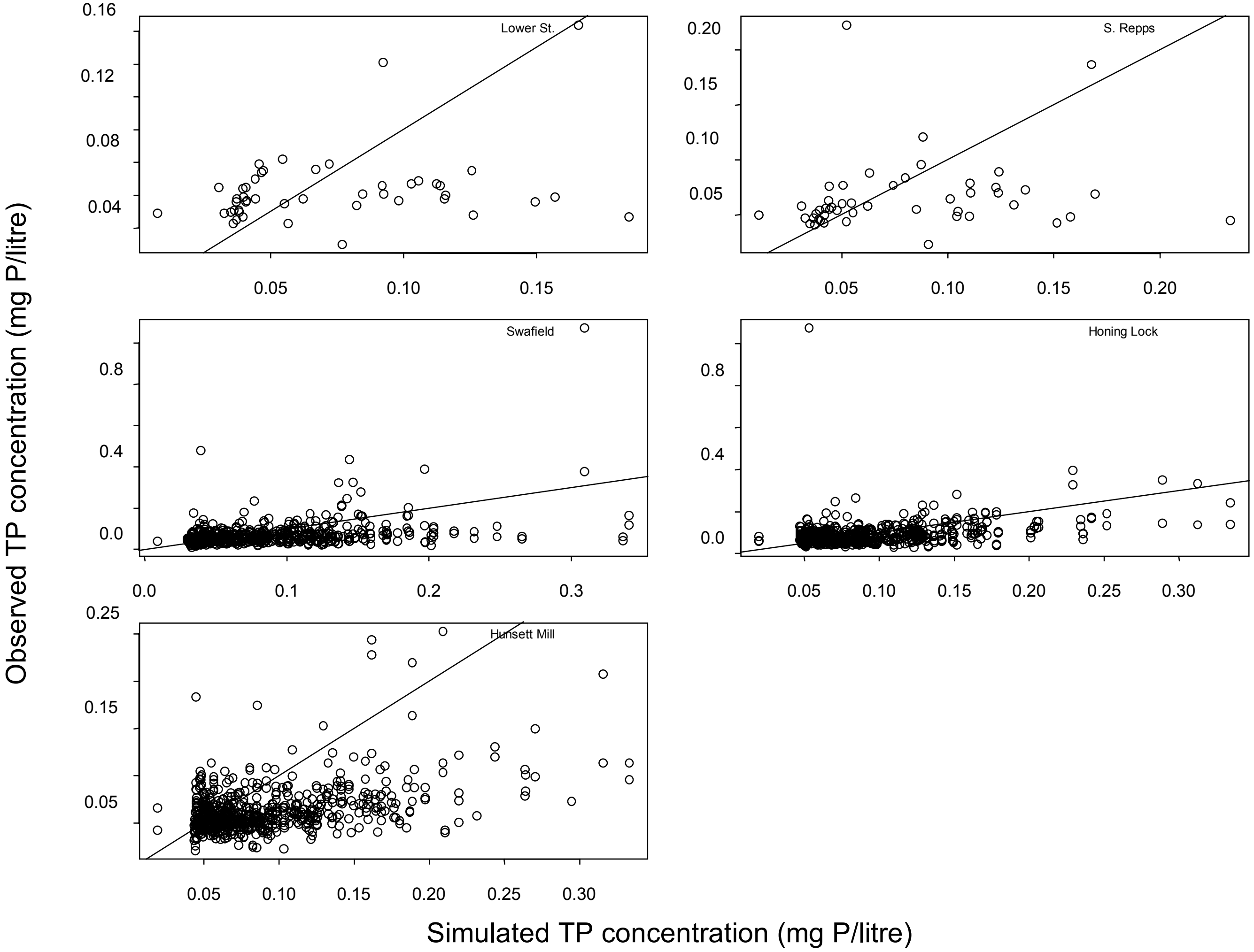

Figure I2 **Comparison of observed and simulated stream water TP concentrations in the River Ant**

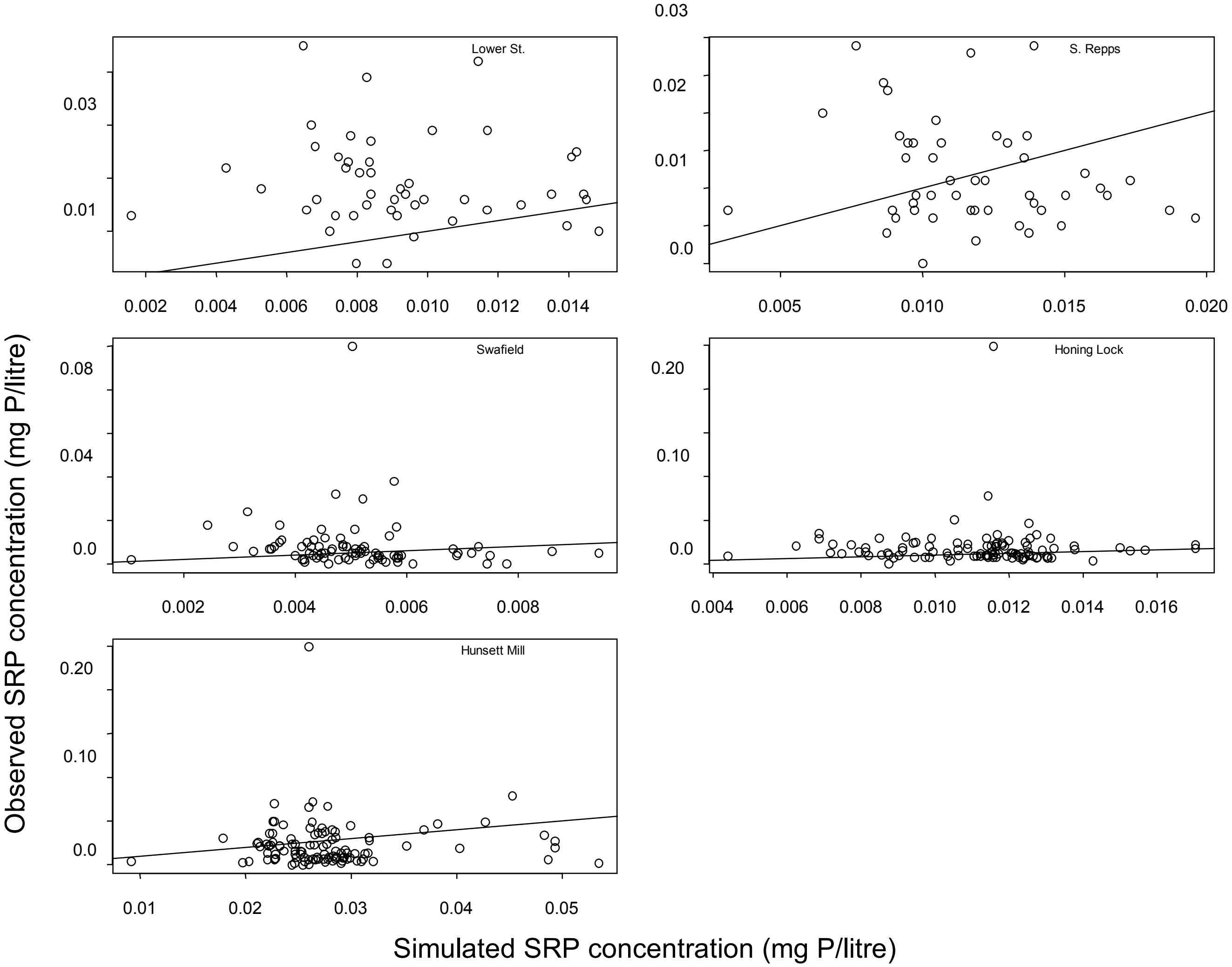

Figure I3 Comparison of observed and simulated stream water SRP concentrations in the River Ant

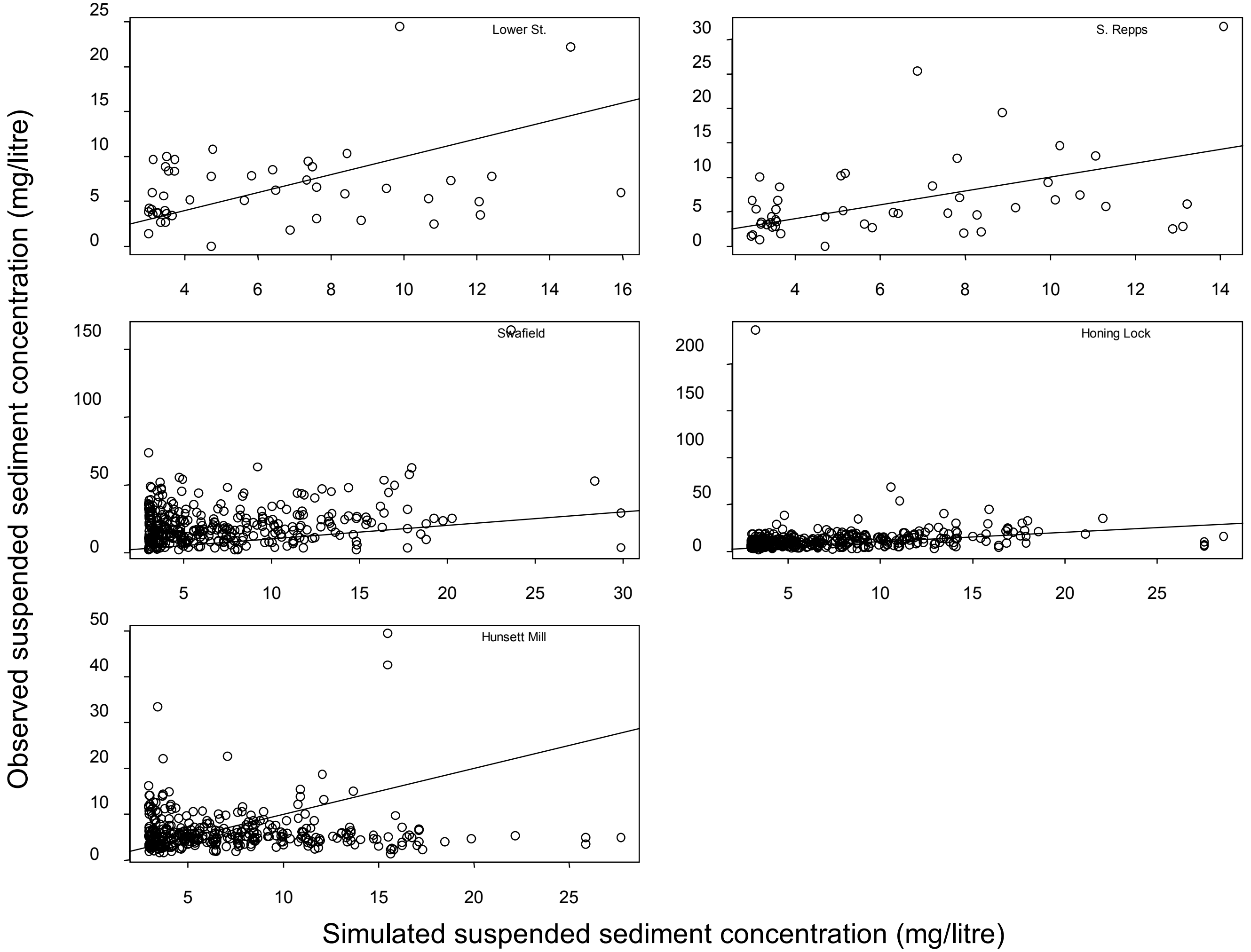

Figure I4 **Comparison of observed and simulated stream water suspended sediment concentrations in the River Ant**