Nutrient Monitoring, Simulation and Management within a Major Lowland UK River System: The Kennet

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Abstract: This paper describes an assessment of the nitrogen and phosphorus dynamics of the River Kennet in the south east of England. The Kennet catchment (1200 km^2) is a predominantly groundwater fed river impacted by agricultural and sewage sources of nutrient (nitrogen and phosphorus) pollution. The results from a suite of simulation models are integrated to assess the key spatial and temporal variations in the nitrogen and phosphorus chemistry, and the influence of changes in phosphorous inputs from a Sewage Treatment Works on the macrophyte and epiphyte growth patterns. The models used are the Export Co-efficient model, the Integrated Nitrogen in Catchments model, and a new model of in-stream phosphorus and macrophyte dynamics: the 'Kennet' model. The paper concludes with a discussion on the present state of knowledge regarding the water quality functioning, future research needs regarding environmental modelling and the use of models as management tools for large, nutrient impacted riverine systems.

Keywords: Modelling; Nitrogen; Phosphorus; Basin management; Macrophytes.

1. INTRODUCTION

In lowland UK river systems dominated by intensive agriculture, enhanced nitrogen (N) and phosphorus (P) inputs can have a detrimental impact on river ecology since both are linked to problems of eutrophication at local, catchment and regional scales. Most freshwater systems are P limited and hence there are concerns that increased P loads to a water body can affect the composition and diversity of aquatic plant species and attached algae and phytoplankton by changing the competitive balance. Nitrate is of concern because elevated concentrations render water unsuitable for drinking and many of the permeable catchments of south and east England are subject to rising nitrate concentrations in both surface waters and groundwater. In such catchments, nitrate is derived predominantly from diffuse (agricultural) sources. In contrast, Soluble Reactive Phosphorus (SRP) is derived from both point and diffuse sources, the relative contributions of which are highly variable in space and time [Jarvie et al., In press]

As part of European Union legislation that includes the Water Framework Directive, it is necessary to regulate the N and P loads entering lake and river systems considered sensitive to nutrient inputs [EC, 2000]. Given the costs involved in reducing N and P loads, mathematical models are commonly used to aid the understanding of freshwater N and P dynamics and to make predictions of future changes in the water quality and ecology under likely scenarios. In lowland areas of the UK, of major concern is the balance between sewage inputs and river flow which is likely to change due to increasing urbanisation, groundwater abstraction and climate variability, which is currently predicted to cause more extreme low-flow conditions [Neal et al., In press].

Problems arise when trying to simulate the transfer of water, and the associated pollutant load, through the landscape because of two factors: (a) the structure and parameters of current models do not adequately represent the spatial and temporal variability observed in water chemistry data and (b) some current water quality models are based on small (< 10 km^2) scale research studies and may be inappropriate for simulating large catchments. To overcome these problems, increasingly it is being recognised that a range of modelling approaches must be used, and that these should be employed with data collected at appropriate spatial and temporal scales. As such, the work presented in this paper investigates the potential of using a range of water quality models together with a substantial database, to form a modelling framework appropriate for the study and management of a large river system with a perceived ecological deterioration.

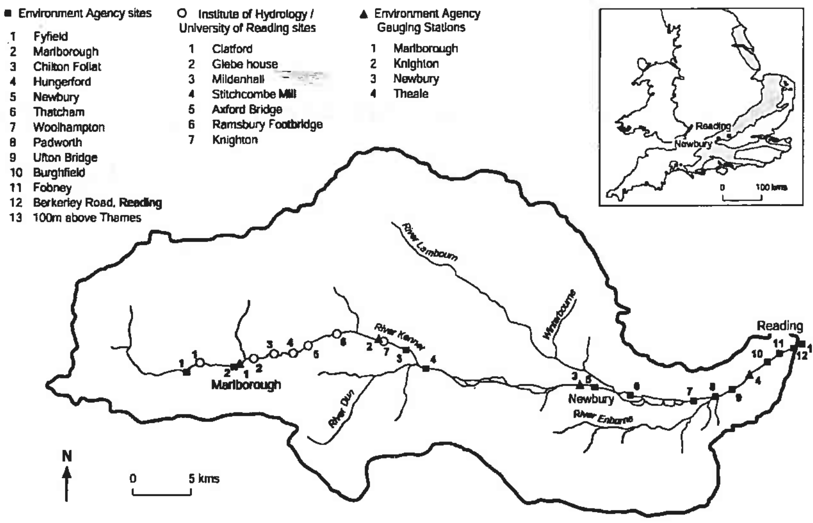

Figure 1. The River Kennet catchment. The inset map shows the location of Cretaceous Chalk in England.

2. THE KENNET SYSTEM AND THE DATABASE

2.1 Study Area

The River Kennet (1200 km^2) is typical of Cretaceous Chalk catchments in southern England (Figure 1). Rising from a source at 190 m, the Kennet flows broadly eastwards for about 40 km before entering the River Thames at Reading. Cretaceous Chalk underlies approximately 80% of the total area. The relief is dominated by gently sloping valleys, with the altitudinal range spanning 32 m at the confluence with the Thames, to 294 m at the highest point on the Marlborough Downs.

The long-term average annual precipitation over the catchment is 774 mm, with approximately 38% ultimately apportioned to river flow and 62% to evapotranspiration. Much of the precipitation percolates into the Chalk aquifer, and consequently the flow response in the Kennet is highly damped. The long-term mean annual flow at Theale, the lowest gauging station on the Kennet is 9.6 m^{3}s^{-1} (or 294 mm of runoff). The catchment is mainly rural, with arable agriculture being the predominant land-use. There are several large towns along the main channel, from which treated sewage is discharged directly into the Kennet. The catchment provides water for public and industrial supply by means of direct surface and groundwater abstractions.

The upper River Kennet is designated a Site of Special Scientific Interest (SSSI), in recognition of its outstanding chalk river plant and animal communities, and therefore there is keen interest in protecting the high conservation value of the river. In the last decade, there have been increasing concerns about perceived ecological deterioration of the River Kennet, particularly poor growth of *Ranunculus* downstream of Marlborough, accompanied by unsightly growth of epiphytes. Concerns have focused on the protracted droughts that occurred in 1991-2 and 1996-7, water abstraction pressures and declines in water quality associated with reduced capacity for dilution of effluent from Marlborough STW.

2.2 Monitoring Program

Weekly water samples were taken from seven sites upstream of Knighton gauging station between June 1997 and December 1998 [Jarvie et al., In press; Figure 1.] The water quality samples were analysed for a broad range of determinands including SRP and Total Phosphorus (TP). TP concentrations in the STW discharge at Marlborough were also available from Thames Water plc for the period January 1997 to December 1998. These data cover periods before and after the onset of P removal from the STW effluent. Monthly nitrate and ammonium concentration data were available at the 13 Environment Agency (EA) routine monitoring sites along the main stem of the Kennet for the period January to December 1998. The macrophyte and epiphyte biomass was monitored in the reach between Glebe House (site 2) and Mildenhall (site 3) bi-weekly between May and December 1998 when the river conditions permitted safe access to the water.

2.3 Other Data

Daily flow data are available from the EA for four gauges along the main channel. Daily solar radiation and water temperature data were measured in the reach between Glebe House and Mildenhall using an Automatic Weather Station and Hydrolab respectively. Other data collated for the application of the models included: land cover data describing the land-use in 1 km^2 cells stored as a Geographical Information System coverage; parish statistics describing crop areas and livestock numbers; fertiliser application rates; hydrologically effective rainfall; soil moisture deficit and air temperature data from the MORECS model; and an estimation of dry and wet, nitrate and ammonium deposition within the catchment derived from MATADOR-N [Whitehead et al., In press].

3. THE MODELLING FRAMEWORK

Detailed descriptions of the models and their applications, including calibration and testing are reported in Whitehead et al., In press and Wade et al., In press (a). Briefly, The Export Co-efficient model was used to determine the long-term (decadel) changes in streamwater N and P concentrations [Johnes, 1996; Whitehead et al., In press]. The estimates of the annual concentration changes are based on historical records of land use: the parish statistics.

The Integrated Nitrogen Model for Catchments [INCA, Whitehead et al., 1998] was used to determine the spatial and seasonal variations in N loads. INCA is a process-based model of both the plant/soil system and in-stream N dynamics, developed to assess multiple sources of N in catchments. The model simulates surface and sub-surface flow pathways and is semi-distributed, thereby accounting for land-use variations. Operating on a daily time-step, INCA provides load and concentration time series at key sites along the main stem of a river, and the load leached from individual land use types.

The 'Kennet' model provided a first assessment of the effects of changing flow and P concentrations due to point source remediation on macrophyte and epiphyte biomass [Wade et al., In press a and b]. The Kennet model is a mathematical representation of the major stores in the aquatic P cycle, and the in-stream processes that determine the transfer of P between those stores. At present, the model, which is dynamic and operates on a daily time step, is designed to simulate a single reach. It simulates the mean daily flow, (TP – dissolved plus particulate P), soluble reactive P (SRP – effectively inorganic monomeric P sometimes known as orthophosphate) concentrations and the effects of P concentrations on the growth of the macrophyte and epiphyte populations within the reach. The Kennet model was applied to the reach between Glebe House and Mildenhall, thereby utilising the TP and SRP measurements, the STW TP data and the measured macrophyte and epiphyte biomass.

4. AN ASSESSMENT OF THE NUTRIENT STATUS OF THE RIVER KENNET

4.1 Spatial Variations

Arable agriculture is a major source of nitrate in the Kennet [Figure 2], and the INCA simulations suggest that arable land provides at least 80% of the nitrate load along the main stem. The contribution from point sources, which are mainly STWs, is greater in the upper reaches of the system where the effluent concentrations are higher and the lower flows provide less dilution. The relative importance of pasture and urban sources increases downstream, as the more of land is used for grazing and the towns become larger. Upstream of site 7 where the main work has been undertaken, there is only one important market town (Marlborough), but near the source areas, small (e.g. septic tank inputs) may be important in relation to nutrient concentration owing to the lack of dilution.

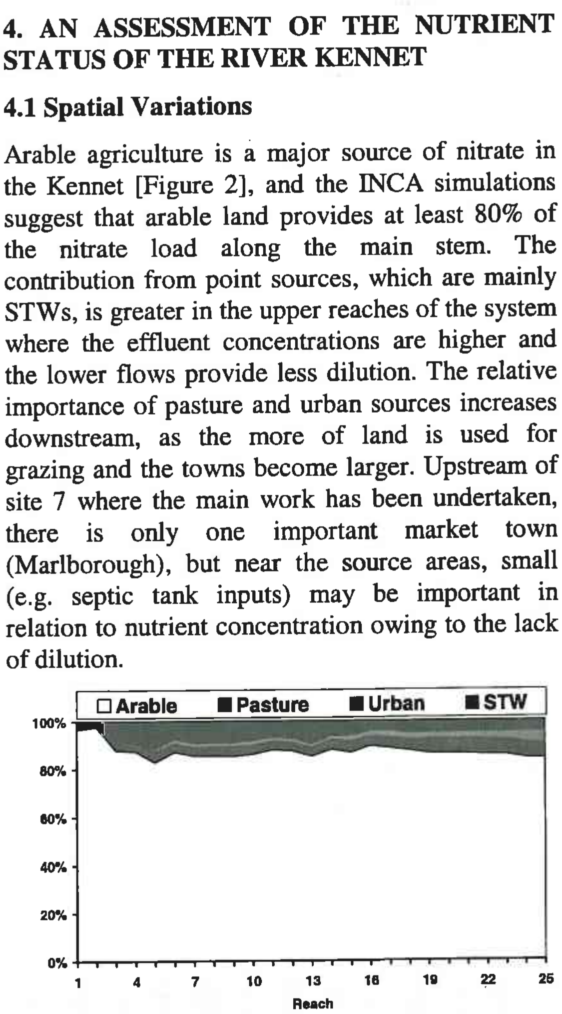

Figure 2. The relative contribution from each land use to the nitrate load in the Kennet system derived from INCA simulations (Reach 5 = Marlborough, 11 = Knighton, 14 = Newbury and 21 = Theale).

4.2 Long Term Changes

Simulation of the long-term changes in the Total Nitrogen (TN) and TP concentrations using the Export Co-efficient model show a 2.5 fold increase in both the TN and TP from 1931 to 1991. These changes correspond to human population increases, increased stocking densities for cattle and poultry and increased fertiliser applications associated with more intensive cereal production (Figure 3).

4.3 Seasonal Variations

The seasonal pattern of the INCA simulated N loads in the main stem is dominated by diffuse inputs from arable agriculture (Figure 4). The input from arable land is broadly constant throughout the year probably due to the application of fertiliser top dressing throughout crop growth. The inputs from STW are more important during the summer months of August and September when the flows are usually lowest.

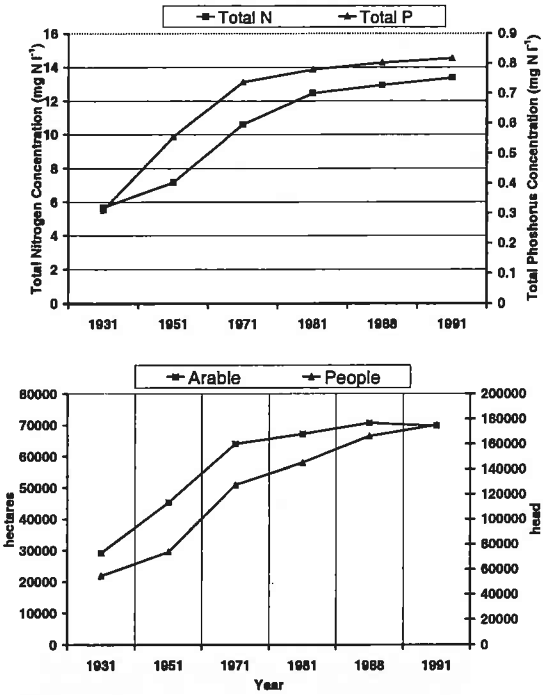

Figure 3. Long-term changes in nitrogen and phosphorus concentrations, the area of arable land and the head of population in the River Kennet system between 1931 and 1991. This data was derived from the Export Co-efficient Model.

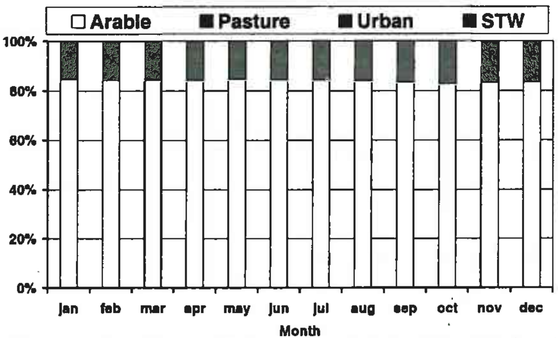

Figure 4. The relative simulated NO_3-N load leached each month from the land use units in the River Kennet, 1998. The simulated data were derived from INCA.

4.4 Daily Variations

The Marlborough hydrograph shows a seasonal pattern typical of a river dominated by groundwater inputs (Figure 5). The shape of the hydrograph for 1997 is a generalised 'whale-back', though the influence of individual storm events on the river flow can be seen as a series of super-imposed spikes. The flows in 1997 are approximately one quarter of the corresponding flows in 1998.

In the reach between Glebe House and Mildenhall, the observed TP concentrations decrease from maximum of around 1 mg P l^{-1} in 1997 to around 0.1 mg P l^{-1} in 1998 following the introduction of P-stripping in September 1997 at the Marlborough STW which is located immediately upstream of Glebe House (Figure 5). The lower TP concentrations observed in 1998 also coincide with the period of higher flows. By using Boron as a tracer, Neal et al., [In press] have shown that the reduction in TP can be attributed to the P-reduction in the STW effluent. 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 TP concentrations, simulated using the Kennet model, 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.

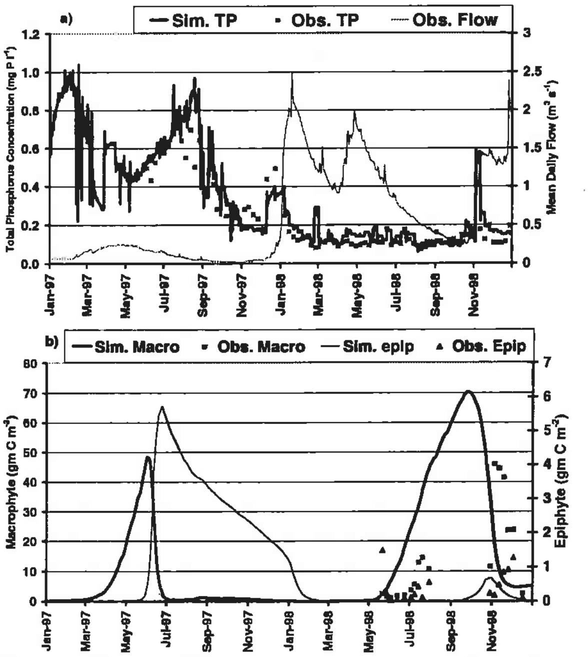

Figure 5. (a) Observed mean daily flow at Marlborough and simulated and observed TP concentrations and (b) simulated and observed macrophyte and epiphyte biomass during 1997 and 1998 for the reach between Glebe House and Mildenhall. The simulated data were derived from the Kennet model.

The macrophyte growth pattern observed in 1998 began in May and declined to zero by the end of December. This onset and decline of growth is later than for 1999, where growth began in April/May and peaked in August before declining to zero by November [Flynn et al., In press]. 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, suggesting that the epiphytes are susceptible to the prevailing flow conditions. Though the model predicts the correct magnitude of the epiphyte biomass, the simulation of the epiphyte growth dynamic is poor. 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 at Marlborough STW, the simulated epiphyte peak is 6 times higher than that observed post treatment in 1998. The reduction in epiphyte biomass corresponds to lower TP concentrations in the reach and to higher flow conditions.

5. DISCUSSION

The models used in this study cover a range of spatial and temporal scales, as is necessary for the scientific study and management of complex natural systems such as the Kennet. The study has demonstrated the utility of using different modelling approaches to identify the key nutrient management issues within a river system. The results indicate that the nutrient water chemistry is a result of a mixture of diffuse and point-source inputs, with arable agriculture the dominant input of N to the River Kennet throughout the year. Results from the Export Co-efficient model suggest that arable agriculture and point source inputs are important sources of P, and that the relative contribution from point sources may increase if population expansion continues within the catchment. Whilst the long-term increases in streamwater TN concentrations remain a concern given the possibility of reduced flows due to climate change, the streamwater NO_3 (as N) concentrations are currently below the EU drinking water limit of 11.3 mg N l^{-1}, and therefore the immediate management issue is the *Ranunculus* deterioration [Whitehead et al., In press].

The model applications may be viewed as a hierarchy based on the spatial and temporal scale of interest. At the top of the hierarchy was the Export Co-efficient model that provided a rapid assessment of the long-term average annual N and P exports from parishes in the catchment. Below this in the hierarchy was INCA that provided estimates for the daily N leaching loads in the plant/soil system and in-stream N loads, and then the 'Kennet' model that provided an assessment of in-stream phosphorus cycling and ecological response. INCA and the 'Kennet' model are more data intensive than the Export Co-efficient model, requiring daily hydrological data. INCA also requires detailed data on the fertiliser application rates and timing, and the onset and duration of growing season, and the 'Kennet' model also requires solar radiation, water temperature and input TP concentration data. Thus, to address specific management issues, models need to be selected that operate at temporal and spatial scales appropriate to the management issue and the data available.

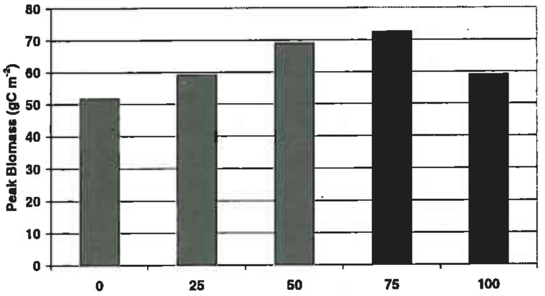

Figure 6. Peak macrophyte biomass as a function of percentage reduction in TP in Sewage effluent, derived from the Kennet model.

Due to the problems of structural and parameter uncertainty and the need to improve the simulation of epiphyte growth in the Kennet model, the simulation results of this study remain tentative. However, the results of the Kennet model still have utility for catchment management as they represent initial estimates of the likely impacts of pollution control policies to meet in-stream compliance and ecological status conditions. For example, the Kennet model was applied to assess the likely increases in macrophyte biomass following reductions in the P loads in STW effluent (Figure 6) [Wade et al., In press (b)]. The results suggest that as the STW effluent P load is reduced the macrophyte biomass increases due to reduced epiphyte biomass, and alteration of the timing of the epiphyte growth: if the epiphytes grow during periods of high flow then they maybe washed from the system, thereby reducing the restriction of the macrophyte growth. Where 100% of the P is removed from the effluent then macrophyte growth is restricted possibly due to P limitation. By 1998 and 1999, after the introduction of effluent phosphorus-treatment at Marlborough STW, considerably higher river flow conditions have prevailed and spectacular regrowth of Ranunculus was recorded [Wright et al., In press]. It is, however, difficult to unravel the extent to which low flows and phosphorus-enrichment contributed to the proliferation of epiphytes and reduction in Ranunculus growth during 1997 due to the uncertainty in the models. Though the initial results from the 'Kennet' model simulations suggest that the epiphyte biomass flow dependency was more important in controlling the macrophyte biomass, than the in-stream phosphorus concentrations that were elevated due to agricultural diffuse sources [Wade et al., In press (b)].

The model applications highlighted the need to collect and interpret long-term water chemistry and ecological datasets. In many cases, ecological monitoring is not routinely undertaken alongside hydrochemical studies, but since the aim of many water quality programmes is ultimately to assess the ecological affects of water quality changes, then ecological data are of upmost importance. Such data sets are needed to describe the changes in response to land management and climatic changes that may occur over several decades. Without such data it will be impossible to verify the accuracy of model results and thereby make any necessary changes to a model's structure. New process measurements offer the prospect of improved understanding of the relative importance of the plant/soil, in-stream processes and biological interactions (e.g. Jarvie et al., [In press]). The iterative steps of data gathering, model creation and hypothesis testing are likely to increase process understanding, leading to more structurally sound models. This interplay between modelling and measurement demonstrates new and interdisciplinary developments in water quality and ecological sciences which are providing new opportunities to advance our understanding of river system functioning, particularly biological responses to chemical and hydrological perturbations.

6. ACKNOWLEDGEMENTS

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