Article (refereed)

Howden, Nicholas J. K.; Bowes, Michael J.; Humphries, Neil; Neal, Colin. 2009 Water Quality, nutrients and the European Union's Water Framework Directive in a lowland agricultural region: Suffolk, south-east England. *Science of the Total Environment*, 407 (8), 2966-2979. doi:10.1016/j.scitotenv.2008.12.040

Water Quality, nutrients and the European Union's Water Framework Directive in a lowland agricultural region: Suffolk, south-east England.

Nicholas J K Howden[1*], Michael J Bowes[2], Neil Humphries[1,3] and Colin Neal[2]

[1]National Soil Resources Institute, Natural Resources Department, School of Applied Sciences, Cranfield University, Cranfield, Bedfordshire, MK43 0AL;

[2]Centre for Ecology and Hydrology, Wallingford, Oxfordshire, OX10 9BB;

[3]URS Corporation Ltd, The Derwent Business Centre, Clarke Street, Derby, DE1 2BU.

Abstract

The water quality of 13 rivers in the lowland, agricultural county of Suffolk is investigated using routine monitoring data for the period 1981 to 2006 collected by the Environment Agency of England and Wales (EA), and its predecessors, with particular emphasis on phosphorus (as total reactive phosphorus, TRP) and total (dissolved and particulate) oxidised nitrogen (TOxN – predominantly nitrate NO_3). Major ion and flow data are used to outline fundamental hydrochemical characteristics related to the groundwater provenance of base-flow waters. Relative load contributions from point and diffuse sources are approximated using Load Apportionment Modelling for both TRP and TOxN where concurrent flow and concentration data are available. Analyses indicate a mixture of point and diffuse sources of TRP, with the former being dominant during low flow periods, while for TOxN diffuse sources dominate.

Out of 59 sites considered, 53 (90%) were found to have annual average TRP concentrations greater than 0.05 mg P l^{-1}, and 36 (61%) had average concentrations over 0.120 mg P l^{-1}, the upper thresholds for 'High' and 'Good' ecological status, respectively. Correspondingly, for TOxN, most of the rivers are already within 70% of the 11.3 mg N l^{-1} threshold, with two rivers (Wang and Ore) being consistently greater than this.

It is suggested that the major challenge is to characterise and control point-source TRP inputs which, being predominant during the late spring and summer low-flow period, coincide with the peak of primary biological production, thus presenting the major challenge to achieving 'good' ecological status under the Water Framework Directive. Results show that considerable effort is still required to ensure appropriate management and develop tools for decision-support.

keywords: Suffolk rivers, nutrients, Water Framework Directive, nitrate, phosphate, Load Apportionment Modelling

*corresponding author: nicholas.howden@cranfield.ac.uk tel: 01234 750 111

Introduction

Here, the water quality of the rivers draining to the eastern part of Suffolk are examined. Information is drawn from the extensive Environment Agency (EA) database to characterise long-term patterns in water quality and to examine spatial coverage and long-term patterns of change for Total Oxidised Nitrogen (TOxN) and total reactive phosphorus (TRP) across the region. This study area has a relatively low human population density (176 people per km^2 compared with 379 and 430 people per km^2 for England and SE England respectively (Office of National Statistics, 2008)), and this study will provide an important contrast to previous studies of highly urbanised catchments that are typical of southern Britain.

There are five strategic reasons for this study. (1) It is this type of region with high agricultural coverage where the UK debate on farming, regional economics and the aquatic environment is critical. (2) Intensive agricultural areas in this part of the UK have received little attention. (3) The Water Framework Directive (WFD) requires a basin-wide integrated approach and the study of these coastal Suffolk rivers provides a representative example and at an appropriate scale to consider this approach. (4) There are requirements for ongoing monitoring to support both understanding of catchment function and management of water quality; the utility of existing data must be assessed in order to inform and target future monitoring requirements. (5) The coastal context of these rivers makes their catchment areas of ecological significance in respect of freshwater, inter-tidal and coastal habitat provision of national and international significance (Howden et al., 2006).

Background

In recent decades there has been a major research effort to determine nutrient concentrations and fluxes from agricultural areas and their impact on surface waters (Neal and Heathwaite, 2005), largely due to the European Community Water Framework Directive (WFD: EA, 2002) which is designed to foster improving the ecology and amenity value of UK surface waters (e.g. Hilton et al., 2006). For the UK, phosphorus (P) rather than nitrogen (N) is generally considered to be the limiting nutrient in rivers

(Mainstone and Parr, 2002; Withers and Lord, 2002) and much attention is focussed on the lowlands, where nutrient inputs are greatest due to high population densities and intensive/extensive agriculture. A central water quality issue is the impact of nitrogen (nitrate) and phosphorus (phosphate) on eutrophication (EA, 2000, Withers and Lord, 2002, Mainstone and Parr, 2002 and DEFRA, 2004), both of which derive primarily from sewage and agricultural sources. Knowledge of the relative contributions of nutrients from these sources is vital for effective river catchment management (Withers and Sharpley, 2008).

In addressing nutrient sources, the WFD requires the control of both point and diffuse inputs into water bodies, which might well prove costly; in the case of farming, large changes may be required to lower nutrient concentrations below ecologically significant thresholds. As point sources of pollution are increasingly controlled, non-point or diffuse sources of pollution become relatively more important. However, given the complexity of agricultural landscapes, managing the risk of diffuse pollution is not straightforward (Burt and Pinay, 2005), because diffuse pollution varies considerably as a complex function of soil type, climate, topography, hydrology, land use and management (Heathwaite et al., 2005). This can create widespread, intermittent and poorly defined contaminant sources that degrade water quality in a way that makes their control difficult. Most research on diffuse pollution has involved surface and near-surface flow paths, but in catchments with high groundwater baseflow contributions, there is an added complexity because of the long pathways and residence times involved in nutrient transfer through the aquifer (Mathias et al., 2007). Major sources of inorganic P, are often associated with high population density and sewage treatment work (STW) discharges and even in agricultural areas, inputs from habitation and local STWs cannot generally be ignored (Muscutt and Withers, 1996; Neal et al., 1998c, 2004b, 2006a, 2008a,b; Bowes et al., 2005a; Neal and Jarvie, 2005; Jarvie et al., 2006a). Thus, catchments that are defined in terms of “rural” or “agricultural” are a misnomer: such catchments are a mix of rural farming, rural settlement and in some cases peri-urban components (Neal et al., 2006a). Hence the system needs to be considered in a more “holistic” way that in some respects is much fairer to the farming community in terms of pollutant sources and impacts.

For NO_3, agriculture is considered the predominant source (Johnes and Burt, 1993; Neal et al., 2006b), but leaching from farmland is linked to many factors such as fertilisation, soil texture, land use, disturbance, crop rotation and effluent disposal (Vinten and Smith, 1993).

For environmental management purposes it is essential to assess the levels of their inputs and provide focussed measures for amelioration strategies (Neal and Jarvie, 2005); and in the lowlands where agriculture often provides the dominant inputs of nitrate, and there are clear measures in place for remediation such as the introduction of nitrate vulnerable zones (DoE, 1993; Jordan and Smith, 2005).

For phosphate, there is often a more balanced mix of fluxes from agricultural and various effluent sources across many parts of the British lowlands (Mainstone and Parr, 2002; Smith et al., 2005a; Wood et al., 2005). Point effluent sources are of particular importance in terms of eutrophication risk, as dilution potential is low during summer low-flows, while biological activity is high (Neal and Jarvie, 2005; Jarvie et al., 2006).

In many lowland areas in the UK, and the south of England in particular, there are growing pressures for increased housing in rural and agricultural 'green belt' areas (Evans et al., 2003). Increased habitation density will lead to increased nutrient loading to rivers from increased STW requirements unless more stringent control on nutrient fluxes is introduced. This increasing pressure will be exacerbated by reduced dilution resulting from increased abstraction of water from the river and groundwater sources. Further, with increased global warming and predicted reduction in rainfall for the lowland UK (UKCIP, 2008), the problem of low flows and increased water usage requirements will compound the problem.

Study area

General

The data presented here cover the river catchment areas of Suffolk between Southwold in the north to the Alde-Ore estuary in the south (Figure 1). The landscape is predominantly rural in character, largely used for arable farming. Spatial land-use data (NRFA, 2008) show that predominant land use is arable and horticulture (74 to 76%, England average 34.1%), with grassland (12 to 15%, England average 38.1%), woodland (4.4 to 7%, England average 11.0%) and built-up areas (4 to 5%, England average 11.2%).

The main rivers draining the area are the Blyth to the north, and the Alde-Ore system to the south, with recorded average annual rainfall (1961-1990) of around 600 mm (Blyth 591 mm; Alde 592 mm; Ore 597mm). General characteristics of the main river catchments are given in Table 1.

The rivers considered here are small (mean flow 1961 to 2006 <0.5 m^3s^{-1}), flow from west to east, and are close to the coast, and so are recognised for their ecological significance: for example the Easton Broad River (see Figure 1), is designated as a Site of Special Scientific Interest (SSSI) for most of its length, and the lower reaches form part of the Benacre to Easton Bavents Lagoons, designated as a Special Area of Conservation (SAC) under the EU habitats directive (Howden et al., 2006).

Data Sources

Water quality data were provided by the Environment Agency of England and Wales (EA) for 60 sample sites for the period between August 1981 and October 2005. This included: sets of major ion data for the River Blyth at Blyford, the River Alde at Langham and the River Ore at Beversham; around 60 sites sampled on a minimum of 40 occasions over the period for the following determinands: alkalinity at pH 4.5 (as $CaCO_3$); ammonia (as N); chloride (as Cl); chlorophyll-a; nitrite (as N); TOxN; TRP or orthophosphate (as P); pH; dissolved reactive silica (as SiO_2); suspended solids at 105°C; water temperature; and turbidity. It is important to note that the data presented by the EA as SRP concentration is actually total reactive phosphorus, as the sample is unfiltered (Mainstone et al., 2000). Conversions were used to express alkalinity at pH 4.5 as bicarbonate (HCO_3), which was then also used to calculate the excess partial pressure of carbon dioxide ($EpCO_2$) using the method outlined by Neal et al.(2000). The hydrometric data used came from the National River Flow Archive (NRFA) datasets (www.ceh.ac.uk/data/nrfa/index.html) for catchment stations (see Figure 1) ref. 35003 (River Alde at Farnham), 35004 (River Ore at Beversham) and 35013 (River Blyth at Holton), are also used to investigate relationships between concentrations and flow.

Methods

The long-term monitoring data were summarised in a GIS-framework and used to support three sets of analyses, the salient points of which are presented here:

1. Major ion concentrations, inter-determinand relationships and relationships with flow to support interpretation of catchment hydrological and hydrochemical functioning.

2. Spatial distributions of nutrient concentrations over the region and relationships with biological indicators such as pH and $EpCO_2$

3. Where sufficient data were available, decomposition of nutrient concentration time series into diffuse- and point-source inputs, to provide an indication of the importance of different source-types and their relative contribution to N and P loading.

For items 1, and 2, the information is presented in the form of panel plots for determinands, summary tables and regional maps, while for item 3 the following methodology was used.

The relationships between nutrient concentration and flow at each study site were assessed using the Load Apportionment Model (Bowes et al., 2008). The model is based on the fundamental difference in the timing of point and diffuse nutrient inputs. Point source inputs from sewage treatment works are relatively constant through the year, and will be unrelated to river flow. Therefore, if a river received all of its nutrient input from STW effluent, the nutrient load would remain constant, and concentrations would decrease reciprocally with increasing river flow. Diffuse sources are predominantly rainfall dependant, and therefore a river receiving only diffuse nutrient input would receive increasing nutrient load with increasing river flow. The Load Apportionment Model quantifies these constant (approximating to point source) inputs and rain / flow-dependent (approximating to diffuse source) inputs using a simple power-law function, to parameterise empirical fits to paired flow and nutrient concentration observed at each study site. The model also determines the flow, Q_e, at which point and diffuse inputs to the river are equal, which is of great value when considering nutrient management options (Bowes et al., 2008).

The Load Apportionment Model requires that the empirical data set of phosphorus and flow for each site covers the full river flow conditions observed at the site. The data sets used in this study are based on monthly sampling interval, which can greatly under-represent high flow events and their related phosphorus exports (Jordan et al., 2005). However, due to the long period of monthly monitoring used in this study, each data set consists of relatively large numbers of observations (River Blythe, n = 120; River Alde, n = 270; River Ore, n = 224) which will capture the full range of river flows.

Results

General

Water quality data from the period 1981 to 2005 are summarised in Table 3. Major ion data (alkalinity, calcium, chloride, magnesium, potassium, sodium, and sulphate) are available at three sites: the River Fromus at Gromford, the River Blyth at Blyford and the River Alde at Farnham (Table 2). These data are plotted to show inter-ion relationships (Figure 2). Examples of relationships between major ions and flow are shown for the River Alde in Figure 3.

Water Quality

The waters are generally of a Ca HCO_3 type and they are also Na, Cl and SO_4 bearing. Of the cation charge Ca has 51 to 83% (Blyth: 51-82%; Alde: 68-83%; Fromus 59-78%) and Na 11 to 41% (Blyth: 11-41%; Alde: 11-22%; Fromus: 14-28%). Of the anion charge, HCO_3 (alkalinity) has 35 to 72% (Blyth: 35-65%; Alde: 50-72%; Fromus: 50-68%), Cl 10 to 36% (Blyth: 10-36%; Alde: 12-18%; Fromus: 13-23%) and SO_4 9 to 38% (Blyth: 9-35%; Alde: 12-38%; Fromus: 19-28%).

Inter-determinand correlations (and with flow, where available) for the three rivers show the following:

River Blyth Positive correlations occur between Cl and Mg ($r = 0.848$, $p<0.0001$). Cl and Na ($r = 0.829$, $p<0.0001$). and Mg and Na ($r = 0.874$, $p<0.0001$). Negative correlations with flow for alkalinity($r = -0.431$, $p<0.05$), Mg ($r = -0.467$, $p<0.05$) and SO_4 ($r = -0.549$, $p<0.01$).

River Fromus Positive correlations occur between: alkalinity and Ca ($r = 0.491$, $p<0.05$), Cl ($r = 0.391$, $p<0.05$), Mg ($r = 0.721$, $p< 0.0001$) and SO_4 ($r = 0.643$, $p<0.001$); Ca and Cl ($r = 0.544$, $p<0.01$), Mg ($r = 0.575$, $p<0.01$) and SO_4 ($r = 0.615$, $p<0.001$); Cl and Mg ($r = 0.452$, $p<0.05$), Na ($r = 0.801$, $p<0.0001$) and SO_4 ($r = 0.543$, $p<0.01$); Mg and SO_4 ($r = 0.713$, $p<0.0001$); and K and Na ($r = 0.464$, $p<0.05$).

River Alde Positive correlations between: Cl and Mg ($r = 0.518$, $p<0.01$), K ($r = 0.550$, $p<0.001$) and Na ($r = 0.722$, $p<0.001$); K and Na ($r = 0.403$, $p<0.05$) and SO_4 ($r = 0.413$, $p<0.05$). Negative correlations between: flow and alkalinity ($r = -0.613$, $p<0.0001$), Cl ($r = -0.496$, $p<0.01$), Mg ($r = -0.431$, $p<0.01$), Na ($r = -0.625$, $p<0.0001$) and SO_4 ($r = -0.365$, $p<0.05$).

Alkalinity shows limited variability (164 to 295 mg $CaCO_3$ l^{-1}), with lower values corresponding to those areas where tidal influence is of importance (e.g. in the Ore/Alde Estuary, River Tang). Chloride concentrations are higher for sampling sites close-to or below the tidal limit with extremely high concentrations in some places (i.e. >10,000 mg Cl l^{-1} on a regular basis).

Regional long-term TRP / TOxN monitoring

Concentrations of total oxidised nitrogen (TOxN) vary (Figure 4a): average concentration for the region is 7.85 mg N l^{-1}, with a range in average of 0.59 to 15.07 mg N l^{-1}. Lowest average concentrations (0.59 mg N l^{-1}) are observed in the Dunwich River (which also tends to have high Cl - average 78 mg l^{-1}), and the highest average concentrations are observed in the River Wang to the north (15.07 mg N l^{-1}).

For the purposes of water quality management within the Nitrates Directive, the maximum allowable concentration for drinking water is 11.3 mg N l^{-1}, which would most likely be an assessment criterion for surface waters, excepting heavily modified water bodies. With the exception of the Rivers Wang and Ore, where average TOxN concentrations already exceed this threshold (133 and 105% respectively) and the Dunwich River where concentrations are very low (5% of the threshold limit), the remainder are presently at between 29 and 91% of this limit, with the Lothingland Hundred River (91%), Easton Broad River (72%), Minsmere River (71%), River Alde (86%), River Fromus (77%) and Black Ditch (72%) all at more than 70% of the limit.

The average TRP concentration across the region is 0.73 mg P l^{-1}, with the range of averages for component rivers lying between 0.05 and 4.47 mg P l^{-1} (Figure 4b). There remains some uncertainty as to what threshold will be set for environmental management purposes, but two emerging values are used as targets for annual averages. For high alkalinity waters, such as those encountered in this study, values of 0.120 and 0.05 mg P l^{-1} are suggested (WFD UK TAG, 2006): the respective values classify the rivers in terms of 'Good' and 'High' ecological status. With the exception of samples from the Ore/Alde Estuary and the River Tang (0.07 and 0.05 mg P l^{-1}) which lie within the 'Good' ecological status range, all other rivers have annual averages above the higher of the two thresholds; in the best case (Dunwich River average 0.14 mg P l^{-1}) the exceedence is only marginal (115%), but in the worst case (River Wang 4.47 mg P l^{-1}) the exceedence is around 3729% above the threshold for 'Good' ecological status. There are no indications of a one-off pollution event skewing these data, rather consistently high P concentrations over the period of record. Out of 59 sites considered here, 53 (90%) were found to have annual average TRP concentrations greater than the 0.05 mg P l^{-1} threshold, and 36 (61%) had average concentrations over 0.120 mg P l^{-1}.

TRP / TOxN and flow relationships

General

The relationship between TRP and TOxN concentrations with river volumetric flow are shown for the Alde at Farnham in Figure 5a and 5b, Ore at Beversham Figure 5c and 5d and the Blyth at Holton in Figures 5e and 5f, with the associated solutions from the Load Apportionment modelling shown in Figure 6, and parameter values produced from the modelling are given in Table 4.

Concentration-flow relationships (TRP and TOxN)

TRP relationships with flow show that the highest TRP concentrations occur at low flows, indicating a point source input at each site. These point sources are of particular relevance, as they will tend to occur during the summer periods when biological activity/response is at a maximum (Neal et al., 2005; Jarvie et al., 2006). The TRP concentrations are relatively high at high flows for the River Alde at Farnham and the River Ore at Beversham, and therefore the TRP load increases with increasing river discharge, indicating that there is a significant, rainfall-dependant input of phosphorus. TOxN relationships with flow at all three sites show a pattern typical of diffuse source dominance, with a positive gradient in the concentration / flow relationship at low to intermediate flows. At higher flows the TOxN concentrations either remained constant (for the Rivers Alde and Ore) at high flows, but decreased for the River Blyth, indicating a possible depletion of TOxN within the catchment during major storm events.

Source apportionment - TRP

The Load Apportionment modelled fits to the concentration / flow data are shown in Figure 6, and the load coefficient values are given in Table 4. For the River Alde at Farnham, the model estimated that flow-dependent (approximating to diffuse source) inputs contributed 88.4 % of the total annual TRP load, indicating that agriculture was the predominant source of phosphorus to the river. However, constant phosphorus inputs (approximating to point sources) are dominant at flows of up to 0.14 $m^3 s^{-1}$ (the calculated Q_e value) which, according to the available flow records, equated to 59% of the sampling period. Above this flow, diffuse sources become dominant with total load apportionment results suggesting 11.6 % contribution from point source inputs and the remaining 88.4 % coming from diffuse sources.

For the River Ore at Beversham, results are presented for three discrete periods as they show contrasting patterns of behaviour.

Period 1 (1983 to November 1992): constant (point source) inputs are dominant up to a volumetric flow rate of 0.37 $m^3 s^{-1}$, which accounts for around 91% of the flow record, with estimated total TRP load contributions of 41.4 % and 58.6 % for point and diffuse sources respectively.

Period 2 (1993 to November 1996): The model was unable to produce a satisfactory solution, as the data set during this period did not include any high – flow data points, due to the large sampling interval. This highlights the problems associated with the existing EA data sets, and shows that efforts should be made to sample UK rivers at a much higher temporal resolution in the future, so that true nutrient load estimates can be made and new methodologies such as the Load Apportionment Model can be applied to them.

Period 3 (1997 to November 2003): constant TRP contributions are dominant at flows of up to 0.31 $m^3 s^{-1}$, which accounts for around 72 % of the period of record, leading to estimated TRP load contributions of 36.7% and 63.3% for constant (point) and flow dependent (diffuse) sources respectively.

For the River Blyth at Holton, constant (point source) inputs are dominant at flows of up to 0.177 $m^3 s^{-1}$, which accounts for around 58% of the period of record, and leads to an estimated TRP load apportionment of 30.6% and 69.4% for point and diffuse sources respectively.

The model appears to have produced realistic apportionments in these predominantly rural catchments. The River Ore and River Blyth receive point source inputs from sewage treatment works serving the towns of Framlingham and Halesworth respectively, and this 'constant input' signal is clearly detected by the Load Apportionment Model. The River Alde catchment has no sewage treatment works upstream of Farnham, which explains why the model identified the river as being dominated by flow-dependent inputs. However, the model still detected a clear continuous input, despite this lack of STWs in the catchment. This could be indicative of significant numbers of septic tank inputs that are leaking or are directly connected to the river rather than soak-aways.

<u>Source apportionment - TOxN</u>

For all three rivers, the Load Apportionment Model was unable to detect a constant input signal indicating that there is no point source input of TOxN, and concentrations in the river are dominantly controlled by diffuse source inputs, provided that within-river TOxN denitrification or biological uptake is not large during the low-flow months when dilution potential and water volumes are low while point source inputs will be most influential in terms of concentration.

Discussion

General water quality

The waters are generally Ca-HCO_3 bearing as a result of soil and bedrock weathering where calcite ($CaCO_3$) is present, and they tend to be moderately alkaline and oversaturated with respect to CO_2, which reflects dissolution of calcite by atmospheric/soil CO_2 and a net excess of respiration over photosynthesis.

Patterns of decreasing major ion concentrations with flow indicate a groundwater source that becomes diluted at intermediate and high flows – notably alkalinity, Mg and SO_4 reflecting the Crag and Palaeogene aquifer sources contributing to baseflow in the River Blyth, and alkalinity, Cl, Mg, Na and SO_4 reflecting the Chalk, Crag and Palaeogene water contribution to the River Alde.

Strong linear inter-determinand correlations most likely indicate a lack of chemical reactivity, with net conservative mixing processes between high-flow and low-flow endmember concentrations (Jarvie et al., 2000).

TRP

The River Ore at Beversham and the River Blythe at Holton have estimated diffuse TRP inputs of *ca.* 60 and 70 % of the total load respectively (Table 4), indicating the dominance of agriculture as a source of P in these largely arable catchments with low human population density. However, in terms of controlling eutrophication, it is the nutrient concentrations (rather than loads) during the plant and algae growing seasons that control nuisance epiphytic algal growth, and so are critical for catchment managers to consider (Hilton et al., 2006). The maximum TRP concentrations observed in the River Blyth and River Ore occur at flows that are below the calculated Q_e value (i.e the flow at which point and diffuse inputs are equal) (Figure 6), and so are mostly point source in origin. Also, most of the data points observed during the algae and plant growing periods also occur at times of point source dominance. This indicates that even in these predominantly rural catchments with low population density, it is clear that to reduce eutrophication risk and improve the ecology and water quality at these sites, most phosphorus mitigation efforts need to be targeted at sewage inputs.

The River Alde at Farnham receives an estimated 88.4% of its annual TRP load from diffuse sources. The majority of the highest TRP concentrations (around 400 µg l^{-1}) occur at flows > Q_e (Figure 6), but those occurring during the algae growing season occur in equal numbers at flows greater and less than Q_e. This implies that catchment managers should target both sewage and agricultural inputs in this catchment.

Nitrate

The long-term average nitrogen concentration for the Suffolk rivers (7.85 mg/l) is similar to, and slightly lower than, that for other agriculturally-impacted eastern UK rivers such as the Great Ouse and Thames (average 8.4 and 8.2 mg N l^{-1} respectively, Neal and Robson, 2000) and for rivers in the Humber Basin (average 9.6 mg N l^{-1}, Neal et al., 2008)). The importance of this agricultural component is well-established and is illustrated for the eastern UK rivers by lower average NO_3-N concentrations in the low intensity agricultural catchments of the north-eastern UK rivers and the low intensity agricultural and industrial Humber catchments (averages 1.9 and 5.9 mg N l^{-1} respectively) compared with the agricultural catchments of East Anglia (average 10.5 mg N l^{-1}) (Robson and Neal, 2000; Neal et al., 2008b).

There are consistent flow and seasonal patterns for TOxN with higher concentrations during the autumn and winter months occurring across all the Suffolk rivers, which most likely reflects a combination of two processes: (1) within-river uptake during biologically-active periods of the spring and summer (Bowes et al., 2005b) and (2) flushing of nitrogen from agricultural lands during the autumn and winter periods, which is largely related to the hydrobiogeochemical processing of N within the catchment, and the timing and nature of local farming practices.

Nutrient status and biological water quality

General Quality Assessment (GQA) data published by the EA (available at www.environment-agency.gov.uk) for biological status, N and P concentrations is shown in Figure 7. For the period 1990 to 2000, the percentage length of rivers attaining 'very good' biological status doubles, a change which also corresponds to a more than 50% reduction (40.1 to 13.7%) in river reaches classified as having 'very high' (> 1.0 mg P l^{-1}) phosphorus concentrations. Over the same period, there are increases in the percentages of river lengths with 'high' or 'very high' nitrate concentrations (30 to 40 or > 40 mg NO_3 l^{-1}

respectively), which suggests that, as found elsewhere (e.g. Neal et al., 2008b), the limiting nutrient is phosphorus and that reductions in concentrations released from both agricultural and other (i.e. sewage discharge) point and diffuse sources is of crucial importance to maintain and improve the ‘good’ biological status, as the most recent assessments indicate a decline over the period 2004 to 2006.

Conclusions

The high concentrations of TRP and TOxN found in most of the Suffolk rivers considered here pose a clear challenge for water quality management. Within this context, there are a number of factors which will ultimately determine what management strategies may be required, and how they will be implemented.

Although some successful source-decomposition has enabled a view of the relative contribution of point and diffuse TRP sources at different volumetric river flow rates to be made, the present monitoring data is not ideal to define the exact sources, but some conclusions are none-the less evident:

(1) For TRP, point sources are dominant at low flows, with diffuse sources becoming dominant at intermediate to high flow;

(2) For TOxN, diffuse sources are dominant irrespective of the flow conditions.

In order to further improve understanding of the relative importance of TRP sources and links with flow conditions, monitoring should continue and be improved to cover a wider range of flow conditions throughout the seasonal cycle, either by introducing storm sampling or increasing the sampling frequency. Consideration should also be given to identifying the relative contributions of agricultural and population-based TRP point sources. Given such sources control streamwater-TRP during low flow periods, coinciding with periods of primary production, it is essential that attention be focussed on understanding the nature and extent of such sources, enabling development of appropriate strategies to mitigate and reduce their influence.

For N, reduction in fertiliser applications will not necessarily translate into a rapid of proportional reduction in TOxN concentrations in the streams and rivers (e.g. Boorman, 2003) and there are complex within-catchment processes for both the nutrients and hydrology in relation to the soil, unsaturated and saturated zones (Smettem, 1986; Parker et al., 1991; Jackson et al., 2006).

It is of crucial importance that long-term monitoring of such agriculturally-impacted river systems continues, particularly where that builds on existing data-rich monitoring sites. However, given the ongoing multi-faceted challenge of managing resources to maintain ecological quality, it is essential that this is primarily based on detailed understanding and management of the underlying water quality, and the land-management strategies required to maintain and improve this quality, such that WFD ambitions to benefit the aquatic environment may be realised.

Acknowledgements

We are grateful to the Environment Agency of England and Wales, and the National River Flow Archive (NRFA) for supplying the data used in this paper.

References

Boorman, D.B., LOIS in-stream water quality modelling. Part 2. Results and scenarios. Science of the Total Environment, 2003, 314-316, 397-409.

Bowes, M.J., Hilton, J., Irons, G.P. and Hornby, D.D. The relative contribution of sewage and diffuse phosphorus sources in the River Avon catchment, southern England: implications for nutrient management, Science of the Total Environment, 2005a, 344, 67–81.

Bowes M.J., Leach D.V., House W.A. Seasonal nutrient dynamics in a chalk stream: the River Frome, Dorset, UK. Science of the Total Environment, 2005b, 336, 225-241.

Bowes M.J., Smith J.T., Jarvie H.P., Neal C. Modelling of phosphorus inputs to rivers from diffuse and point sources. Science of the Total Environment; 2008, 395, 125-138.

Burt, T.P. and Pinay, G.. Linking hydrology and biogeochemistry in complex landscapes. Progress in Physical Geography, 2005, 29(3), 297-316.

DEFRA (2004) Developing measures to promote catchment-sensitive farming. A joint Defra-HM Treasury Consultation. http://www.defra.gov.uk/environment/water/dwpa/index.htm.

DoE Methodology for identifying sensitive areas (Urban Wastewater Directive) and designating vulnerable zones (Nitrates Directive) in England and Wales. Department of the Environment, Ministry of Agriculture Fisheries and Food, Welsh Office. Consultation Document, 1993.

EA Aquatic Eutrophication of England and Wales: A Management Strategy, Environment Agency, Bristol, 2000, p. 32.

EA The Water Framework Directive: Guiding Principles on the Technical Requirements. Environment Agency, Rio house, Waterside Drive, Aztec West, Almondsbury, Bristol, BS32 4UD, 2002, 84pp.

Evans, S.G., Spillett, P.B. and Colquhoun K. South-east housing development – the quest for sustainability: water and sewerage needs, Journal of Water and Environmental Management, 2003, 17, 257–261.

Heathwaite, A.L., Quinn, P.F. and Hewett, C.J.M. Modelling and managing critical source areas of diffuse pollution from agricultural land using flow connectivity simulation. Journal of Hydrology, 2005, 304, 446-461.

Hilton, J., O'Hare, M., Bowes, M. J. and Jones, J. I. How green is my river? A new paradigm of eutrophication in rivers, Science of the Total Environment, 2006, 365, 66–83.

Howden, N. J. K., Humphries, C. E. L., Humphries, R. N. Coastal Squeeze & Maintenance – Pilot Study. A Report to English Nature, Peterborough, 2006.

Jackson, B.M., Wheater, H.S., Mathias, S.A., McIntyre, N. and Butler, A.P. A simple model of variable residence time flow and nutrient transport in the Chalk. Journal of Hydrology, 2006, 330, 221-234.

Jarvie, H.P., Neal, C. and Withers, P.A. Sewage-effluent phosphorus: a greater risk to river eutrophication than agricultural phosphorus? Science of the Total Environment, 2006, 306, 243–253.

Johnes, P.J. and Burt, T.P. Nitrate in surface water. In: Burt, T. P., Heathwaite, A. L. and Trudgill, S. T. (editors), Nitrate: Processes, Patterns and Management, John Wiley & Sons, Chichester, 1993, 269-317.

Jordan, C. and Smith, R.V. Methods to predict the agricultural contribution to catchment nitrate loads: designation of nitrate vulnerable zones in Northern Ireland, Journal of Hydrology, 2005, 304, 316–319.

Jordan P, Arnscheidt J, McGrogan H, McCormick S. High-resolution phosphorus transfers at the catchment scale: the hidden importance of non-storm transfers. Hydrology and Earth System Sciences 2005; 9: 685-691.

Mainstone, C.P. and Parr, W. Phosphorus in rivers – ecology and management. Science of the Total Environment, 2002, 282-283, 25-48.

Mainstone CP, Parr W, Day M. Phosphorus and river ecology. Tackling sewage inputs. English Nature and Environment Agency, Peterborough, 2000, pp. 46.

Mathias, S. A., Butler, A. P., Ireson, A. M., Jackson, B. M., McIntyre, N. and Wheater, H. S. Recent Advances in modelling nitrate transport in the Chalk unsaturated zone. Quarterly Journal of Engineering Geology and Hydrogeology, 2007, Volume 40, Part 4, November 2007, Geological Society, London.

NRFA (2008), National River Flow Archive, CEH Wallingford, < http://www.ceh.ac.uk/data/nrfa/catchment_spatial_information.html>

Neal, C. and Heathwaite, A.L. Nutrient mobility within basins: a European perspective. Journal of Hydrology, 2005, 304, 477-490.

Neal, C. and Jarvie, H.P. Agriculture, community, river eutrophication and the Water Framework Directive, Hydrological Processes, 2005, 19, 1895–1901

Neal, C., House, W.A. , Jarvie, H.P. and Eatherall A. The significance of dissolved carbon dioxide in major lowland rivers entering the North Sea, Science of the Total Environment, 1998, 210/211, 187–203.

Neal, C. , Jarvie, H.P., Wade, A.J., Neal, M., Wyatt, R.,Wickham, H. Hill, L. and Hewitt, N. The water quality of the LOCAR Pang and Lambourn catchments, Hydrology and Earth System Sciences, 2004, 8, 614–635.

Neal, C., Jarvie, H.P., Neal, M., Love, A.J., Hill, L. and Wickham, H. Water quality of treated sewage effluent in a rural area of the upper Thames Basin, southern England, and the impacts of such effluents on riverine phosphorus concentrations. Journal of Hydrology, 2005, 304(1-4), 103-117.

Neal, C., Neal, M., Hill, L. and Wickham, H. River water quality of the River Cherwell: an agricultural clay-dominated catchment in the upper Thames Basin, southeastern England, Science of the Total Environment, 2006a, 306, 272–289.

Neal, C., Jarvie, H.P., Neal, M., Hill, L. and Wickham, H. Nitrate concentrations in river waters of the upper Thames and its tributaries, Science of the Total Environment, 2006b, 365, 15–32.

Neal, C., Jarvie, H.P., Love, A., Neal, M., Wickham, H. and Harman, S. Water quality along a river continuum subject to point and diffuse sources and canal water interchange, Journal of Hydrology, 2008a, 350 (3–4), 154–165.

Neal, C., Davies, H. and Neal, M. Water quality, nutrients and the water framework directive in an agricultural region: The lower Humber Rivers, northern England, Journal of Hydrology, 2008b, 350, (3-4), 232-245.

Office for National Statistics Census 2001: the most comprehensive survey of the UK Population <http://www.statistics.gov.uk/census2001/census2001.asp>, Details taken on 10th August 2008.

Parker, J.M., Young, C.P. and Chilton, P.J. Rural and agricultural pollution of groundwater.In Applied Groundwater Hydrology (eds. R.A. Downing and W. B. Wilkinson) Clarendon Press (Oxford, UK), 1991, 149-163.

Smettem, K.R.J., Solute movement in soils. In Solute Processes (ed. S.T. Trudgill) John Wiley (Chichester, UK), 1986, 141-165.

Smith, R.V., Jordan, C. and Annett, J.A. A phosphorus budget for Northern Ireland: inputs to inland and coastal waters, Journal of Hydrology, 2005, 304, 193–202.

Vinten, A.J.A. and Smith K.A. Nitrogen cycling in agricultural soils. In: T.P. Burt, A.L. Heathwaite and S.T. Trudgill, Editors, Nitrate: Processes, Patterns and Management, John Wiley, Chichester, 1993, pp. 29–73.

Wood, F.L., Heathwaite, A.L. and Haygarth, P.M. Evaluating diffuse and point contributions to river transfers at different scales in the Taw catchment, Devon, UK, Journal of Hydrology, 2005, 304, 118–138.

WFD UK TAG, UK Environmental Standards and Conditions (Phase 1). Draft provided to groups and organisations for review and comment. UK Technical Advisory Group on the Framework Directive. <www.wfduk.org>, 2006.

Withers, P.J.A. and Lord, E.I. Agricultural nutrient inputs to rivers and groundwaters in the UK: policy, environmental management and research needs. Science of the Total Environment, 2002, 282-283, 9-24.

Withers P.J.A., Sharpley A.N. Characterization and apportionment of nutrient and sediment sources in catchments. Journal of Hydrology, 2008, 350, 127-130.

Figure 1: Location of catchments and sampling sites.

Figure 2: Major ion concentrations for the River Alde at Farnham (red), River Blyth at Blyford (blue) and River Fromus at Gromford (green), showing inter-determinand relationships.

Figure 3: Relationship between major ion concentrations and flow on the River Alde at Farnham.

Figure 4: Regional variations in Total Oxidised Nitrogen (TOxN) and TRP for rivers in Suffolk.

Figure 5: Concentration-flow relationships for: the River Alde at Farnham (a) TRP, (b) TOxN; the River Ore at Beversham (c) TRP, (d) TOxN; and the River Blyth at Holton (e) TRP, (f) TOxN.

Figure 6: Load apportionment modelling results showing: samples taken during the main plant and algae growing season (1st April to 30th September) and samples taken during the winter (1st October to 31st March); model solution; and the Q_e value (i.e. the flow at which diffuse and point source contribution to observed concentrations are equal). (a) River Ore at Beversham Bridge (1983 to 1992); (b) River Ore at Beversham Bridge (1996 to 2006); (c) River Alde at Farnham (1981 to 2006) and (d) River Blyth at Holton (1981 to 2006).

Figure 7: Environment Agency (EA) General Quality Assessment (GQA) of rivers in Anglian Region for: (a) biological status; (b) nitrate concentrations; and (c) phosphorus concentrations.