IS CATCHMENT MANAGEMENT FEASIBLE FOR IMPROVING QUALITY OF PUBLIC GROUNDWATER SUPPLIES?

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ABSTRACT

This paper presents the outcome of the study of 44 catchments to public groundwater supply boreholes in the Midlands and North West of England. Land use and nitrate loading to each catchment was characterised and a trend model was fitted to concentration data. Predictions of concentrations in 25 years' time were used to inform the feasibility of catchment management to improve abstracted groundwater quality. In many of the catchments, measures would not be required because a better understanding of the system demonstrated that drinking water quality is not at risk. In many others, concentrations are too high to be controlled effectively by catchment management measures. In the remainder, a spectrum of different levels of stewardship would be required to achieve desired outcomes. Catchment management is most suited to achieving marginal (<20%) reductions in nitrate concentrations in these catchments. At this level of loading reduction, some land use change would be required. Where the reduction in concentration required is 8% or less measures may be cost beneficial for the farmer and may not need incentivisation for their adoption.

INTRODUCTION

At the last five-yearly price review the UK's water industry regulator, Ofwat, allowed water companies to include elements of catchment management activity in their Asset Management Plans to reduce diffuse water pollution. Ofwat signed off £60M of stewardship activity, which despite the large figure, represented a small proportion of budget assigned to water quality programmes overall.

For the next price review targeted catchment management will take a far more prominent role in water companies' proposals for 2015 and beyond. In December 2011, Defra published a White Paper which outlined a commitment to a new 'catchment-based approach' to water quality and diffuse pollution control (Defra, 2011a). A couple of months earlier, Ofwat published 'Catchment to Customer' (Ofwat, 2011), which highlighted a National Audit Office finding that diffuse water pollution from agriculture is one of the biggest challenges to improving water quality. Water utilities are now seriously reviewing targeted agricultural land stewardship as an alternative to treatment and blending.

Water companies, however, still face a simple reality: catchment management has to be at least as cost-effective as industrial treatment solutions or else Ofwat will not approve their water quality plans for funding. There can also be resistance from farmers to adopt required new practices because of cost, reduced profitability or the extra workload that new methods place on their businesses. Therefore the challenge for water companies is to provide compelling evidence that interventions work, that they are cost-effective (for water companies and for farmers) and that they are sustainable. Most evidence to date arises from schemes that improve surface water quality, there has been some success with limiting nutrient (ADAS, 2011; Wessex Water, 2011) and pesticide (Wessex Water, 2011) concentrations in groundwater catchments.

This paper discusses the findings of a review of the feasibility of catchment management in about 44 catchments to groundwater abstractions in the English Midlands and North West (Figure 1). All of these catchments were put forward for detailed assessment because nitrate concentrations are rising towards critical target concentrations. Target concentrations vary depending on installed capacity for downstream treatment or blending. Based on simple linear fits to recent data it appeared that abstraction concentrations would exceed targets within about twenty years. Catchment management was to be considered as an option to limit concentrations to below the target, or at least to slow the rate of rise and therefore extend the lifespan of the current arrangements. Feasibility studies reported here were used to assess which of the 44 catchments were likely to respond positively to nitrate reduction measures.

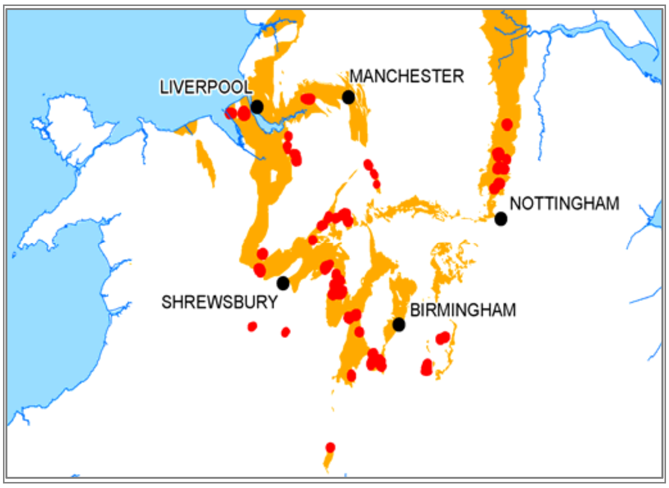

Figure 1. Catchment locations (red) on the Midlands and North West England Permo-Triassic sandstone outcrop (orange).

PREDICTIVE MODELLING

Linear trends, used in the initial screening of the sites, are too pessimistic for prediction and have no conceptual justification or physical relationship with historical nitrogen inputs. A conceptually informed model, for predicting nitrate concentrations, was therefore developed and calibrated to:

- demonstrate that the conceptual understanding of the hydrogeological system and assumptions about land use were robust; and if not, to identify when concentrations deviate from the expected trend, to help identify unanticipated hydrogeological mechanisms or land use change; and,
- to predict what concentrations would be without intervention (the do-nothing scenario), and the timing of any peaks in concentration; and to predict future concentrations and likely timescales for scenarios with reduced future N loading.

CATCHMENT DELINEATION

Land use within the historical catchment area – where the recharge came from, and therefore where the diffuse nitrate pollution came from – is a key input to the models. Accurate delineation of catchments is important in obtaining representative land use parameters and it is essential to identify where measures are to be implemented – otherwise any scheme would have limited credibility and may not work as intended.

Catchments to public water supply boreholes are delineated in England and Wales as part of defining Source Protection Zones (SPZ). The total catchment, or SPZ3, is the estimated area within which recharge contributes to the licensed maximum borehole yield, but

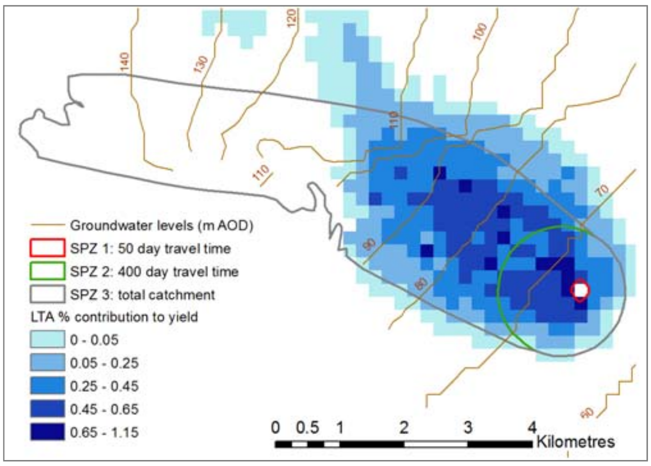

Figure 2. Comparison of two methods for groundwater catchment delineation. Source Protection Zones are derived from particle tracking using the maximum (licensed) annual abstraction rate. Distributed historical contribution of borehole yield from each cell (using FlowSource post-processing software) is shown as a blue colour gradient.

abstractions are seldom operated at their licensed rate, so this is larger than the catchment that will have contributed yield historically. Historical catchments may be derived manually by scaling SPZ catchments, by using existing SPZ delineation models or, lately, groundwater model post-processing tools have become available to define catchments (Whiteman, 2013). FlowSource, for example, uses results from transient groundwater model runs to compute the amount of historical yield contributed by each model cell. Figure 2 shows a comparison of the SPZ and FlowSource outputs for a typical groundwater catchment in the Nottinghamshire Permo-Triassic sandstone aquifer. Historically, abstraction has been at about 50% of the licensed rate, which is clear from the extent of the modelled catchment. These results also make it clear that the greatest contribution of abstraction yield comes from closer to the borehole, so it is obvious where nitrate mitigation measures should be focused.

SOURCE TERM

All of the groundwater catchments in these studies comprised >50% agricultural land, whilst only 14 had >10% urban land. The National Environment and Agricultural Pollution Nitrate (NEAP-N) dataset (Lord and Anthony, 2000) is a national scale tool for predicting concentration of nitrate in leachate from agricultural land. Crop and animal data in the model are obtained from parish-scale census data. NEAP-N assumes that nitrogen is applied at the correct rate for the crops given in the agricultural census. It does not include the effects of non-compliance with official fertiliser recommendations, good agricultural practice or Nitrate Vulnerable Zone (NVZ) limits; nor sludge spreading, or point sources, all of which will may contribute excess N to the catchments. NEAP-N data, from the 1980 and 2010 datasets, therefore gives two well-constrained snapshots of diffuse agricultural nitrate loading in the catchments. National fertiliser use (Defra, 2011b) and county scale livestock numbers (Defra, 2013) were used to interpolate between the two NEAP-N snapshots of 1980 and 2010, and to hindcast pre-1980 loading. Loadings were turned to soil leachate concentrations by dilution from annual recharge (estimated from regional rainfall data at *data.gov.uk*) to output concentrations. Urban loading was estimated (as a constant input) using parameters from Wakida and Lerner (2005).

SUB-SURFACE TRANSPORT

Water and nitrate move slowly through the hydrogeological system so the soil zone inputs are subject to significant delay before they reach the abstraction. Conservative solute transport rates may be estimated using generic data on unsaturated zone velocity, and Darcy’s Law for the saturated zone. But heterogeneity in the subsurface such as marl bands and bypass flow, and order-of-magnitude uncertainty in hydraulic parameters, makes it difficult to estimate travel times with confidence. In the trending model a combined unsaturated and groundwater travel time is estimated by fitting a modelled trend to the data. Hydrodynamic dispersion is not simulated in the model at present. In the unconfined Permo-Triassic aquifers of the English Midlands, nitrate is not subject to retardation or biodegradation (Rivett *et al.*, 2007).

IN-BOREHOLE DILUTION AND MIXING

Additional processes that affect abstracted concentrations occur near to, or within, the abstraction boreholes. Each is simply accounted for in the model to fit the data, by defining a concentration and a percentage of abstraction yield contributed. Deep, unpolluted, groundwater entering at the bottom of deep boreholes dilutes concentrations from the near-surface polluted layers of aquifers. Ingress of surface water from rivers passing close to the borehole may dilute or increase concentrations in the abstracted water, depending on the relative concentrations. Point sources of pollution close to the borehole, such as manure heaps, leaking slurry pits, septic tanks, etc. can provide additional sources of pollution. Finally, blending with water from other sources at treatment works or in service reservoirs is used to operationally lower concentrations to public water supply.

MODELLING METHODOLOGY

Catchment land use, nitrate loading and rainfall determine the results from the soil zone model. Delay, dilution and mixing processes modify the soil zone model results into the results from the groundwater trend model. Model parameters are calibrated within reasonable limits, informed by the conceptual understanding, and to achieve the best fit to concentration data. A typical example of the quality of fit to data, for a catchment in the Cheshire Permo-Triassic sandstone aquifer, is shown in Figure 3. There are two boreholes close together: BH3 is 91 m deep, BH 4 is 244 m deep. The model trend line (solid black) for the catchment is fitted closer to the BH 4 data because that is the borehole that provides most yield. This model suggests a 35 year travel time and suggests that concentrations may not peak for another 10-20 years or so.

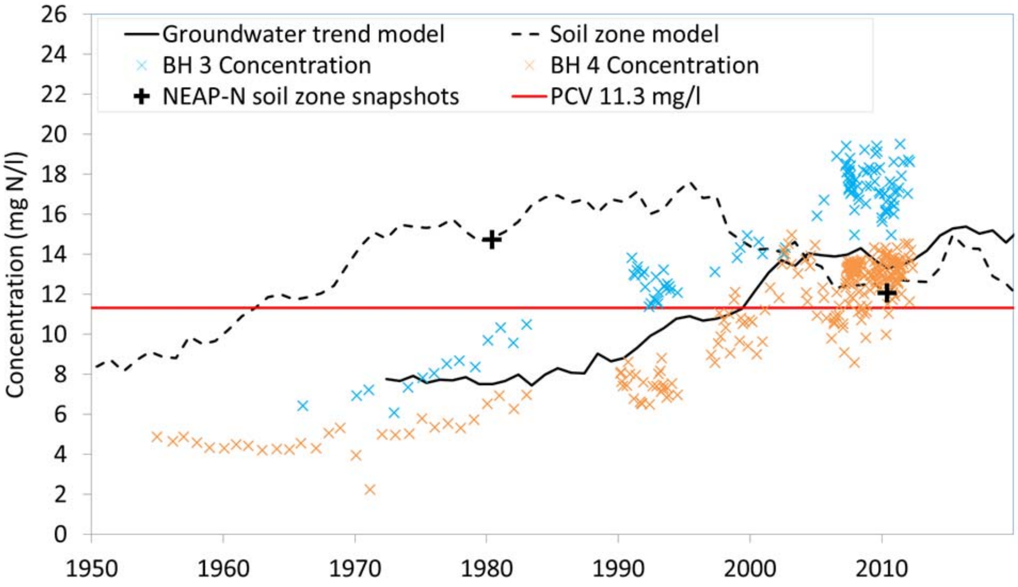

Figure 3. Soil zone model and groundwater trend model for a dominantly dairy farming area of Cheshire.

INSIGHTS

Catchments, land use and hydrogeology of 44 public water supply groundwater abstractions were modelled and the trends compared with data to assess deviations from the expected trend. These deviations were examined and conceptual justification was sought, to demonstrate that the model was robust. All but three catchments are in the unconfined Permo-Triassic sandstone aquifer. Based on these analyses the following insights were gained.

- **Typical transport times, from the base of the soil zone to the abstraction, are in the range 15 to 35 years.** Without reviewing correlations in detail, modelled delay time seems to relate most strongly to:

  a) **Presence/absence of marl layers.** The Nottinghamshire Permo-Triassic sandstone aquifer is mostly free of marl bands unlike the sandstone aquifers further west. This is believed to be the reason that in most of the Nottinghamshire abstractions, concentrations have remained relatively stable at elevated concentrations since the 1990s. Concentrations further west are still increasing, or have been stable for only five years. This is despite lower recharge rates, and therefore slower rates of movement in the unsaturated zone, in east England.

  b) **Thickness of the unsaturated zone.** Where similar sized catchments are compared, in aquifers with similar development of marl bands, those with the thickest unsaturated zones have the longest apparent travel times. This is not a surprise, of course, but highlights that the lithology of the aquifer (above) is more significant than the overall distance travelled.

  c) **Area of the catchment zone / time of travel within groundwater.** Of the Cheshire sources, all are constructed within a similar aquifer and have a similar unsaturated zone thickness. While larger catchments have longer travel times, these are not in proportion to the area. Delay times imply a consistent unsaturated zone travel time about 24 years, across c. 50 m of aquifer, or c. 2 m/year. Travel velocities in the saturated zone are around 0.5 km/year.

- **Travel times of 15 to 35 years imply that the 1980s peak N loading has passed**, or is passing imminently, in Permo-Triassic sandstone aquifers. A relatively stable trend is often seen in the latest five years' data. Seen in isolation any of these might be assumed to be fluctuation on a general rising trend. However, the weight of evidence from calibrated model results, and the combined review of 44 sets of data, gives confidence that many trends are levelling out. Except for the few catchments in which nitrate loading has increased over the last thirty years, further risk of a significant increase in nitrate concentrations therefore appears small.
- **There is stratification of concentration with depth below the water table.** Where there are multiple boreholes on site of significantly different depths the deepest borehole consistently shows a lower concentration (e.g. the catchment in Figure 3: BH 3 is 91 m deep; BH4 is 243 m deep). This stratification is also observed in many single boreholes where, when abstraction rates and therefore drawdowns increase, then concentrations decrease. Exceptions are noted where there are multiple boreholes connected by adits, which have complex water quality responses to drawdown.
- **Interaction with nearby rivers is important in many unconfined catchments.** Smaller river catchments normally have similar land use to the groundwater catchment. In this instance surface water has a similar concentration to soil leachate and may not affect borehole concentrations. Larger rivers may have upland catchments, resulting in lower nitrate concentrations to dilute concentrations in the borehole. But also these larger rivers may have significant N loading from upstream sewage treatment works, so may act as a source of excess N.
- **Point sources, that significantly increase concentrations above those predicted by the soil zone model, appear uncommon**. Where this has been seen, field surveys have identified varied potential sources (none have yet been investigated and verified as causing an issue): open water with significant wildfowl activity, poorly constructed slurry stores, poorly managed farm runoff, and dense cropping of particularly leaky crops (e.g. potatoes and salads) near the boreholes.
- **Ploughing-up permanent pasture has occurred in some catchments and has caused considerable spikes in nitrate concentration,** sometimes increasing the concentration at the borehole by 5 mg N/l, for more than a decade. This is seen particularly clearly in data from in smaller Cheshire catchments. In the early 1980s the local dairy industry was restructured, with a reduction in the number of dairy farms and an increase in the size of the remaining farms. There was then greater reliance on housing animals with a consequent increase in the requirement for fodder; in part supplied by maize, hence replacement of pasture by arable land.
- **Catchments with significant amounts of urban area are characterised by very flat trends**, sometimes with a minor rise from outlying agricultural loading. Trends could not be fitted well in any of the urban catchments and it is thought that Wakida and Lerner (2005) underestimate nitrate loading from urban areas, and/or the numerical models used in assessing recharge inputs may underestimate urban recharge.

FEASIBILITY OF CATCHMENT MANAGEMENT

Models were parameterised that best fitted historical data. Future concentrations were forecast to predict how abstraction concentrations are likely to change up to 2037. A 25-year planning horizon was chosen as this is, firstly, a requirement for long term planning from OFWAT, and secondly, a time at which catchment management interventions starting now might be significantly realised.

Uncertainty analysis was undertaken on model parameterisation to identify more pessimistic predictions, albeit with the model still being a reasonable fit to historical data. Scenario analysis was also undertaken to test the potential risk posed by climate change, or by changing agricultural practice. Predictive model scenarios were used with 20% less recharge (a reasonably pessimistic case for the English Midlands from UKCP09 modelling – Christierson *et al.*, 2012) and 20% higher N loading.

MODELLING RESULTS

Results from all 44 sites are tabulated in Figure 4. This table shows the predicted annual peak concentration in 2037 (accounting for parameter uncertainty) compared with water company targets (which take into account blending and treatment to provide a potable supply at customers' taps). Headroom is presented as a percentage change needed to comply with the target (negative headroom means that groundwater concentrations would need to be reduced to meet the target). Vulnerability to climate change or land use change (scenario uncertainty) is also presented as a percentage of the target concentration. Terms used for the "assessment of feasibility" are explained in the next sub-section.

		Best estimate + parameter uncertainty		Best estimate + parameter uncertainty + scenario uncertainty		
Source ID	Peak target mg N/l	Peak concentration in 2037 (mg N/l)	Headroom	Peak concentration in 2037 (mg N/l)	Headroom	Assessment of feasibility
1	8.5	15.6	-46%	17.4	-51%	Feasible with considerable land use change
2	8.5	15.5	-45%	17.6	-52%	Feasible with considerable land use change
3	8.5	15.5	-45%	17.4	-51%	Feasible with considerable land use change
4	9.5	16.1	-41%	17.8	-47%	Feasible with considerable land use change
5	8.5	14.1	-40%	16.2	-48%	Feasible with considerable land use change
6	8.5	14.0	-39%	17.0	-50%	Feasible with considerable land use change
7	13.5	20.5	-34%	23.4	-42%	Feasible with considerable land use change
8	6.5	9.7	-32%	12.6	-48%	Feasible with considerable land use change
9	8.5	12.0	-29%	14.0	-39%	Feasible with considerable land use change
10	8.5	10.9	-22%	12.7	-33%	Feasible with considerable land use change
11	9.5	11.8	-20%	13.8	-31%	Feasible with considerable land use change
12	10.2	12.6	-19%	14.4	-29%	Feasible with limited land use change
13	12.4	15.2	-19%	18.0	-31%	Feasible with limited land use change
14	7.9	9.3	-15%	10.4	-24%	Feasible with limited land use change
15	9.5	10.8	-12%	12.3	-23%	Feasible with limited land use change
16	13.5	14.6	-7%	16.7	-19%	Feasible with light touch measures
17	11.3	12.0	-6%	13.7	-17%	Feasible with light touch measures
18	9.5	9.7	-2%	11.2	-15%	Feasible with light touch measures
19	11.6	11.7	-1%	12.7	-9%	Unfeasible (urban catchment)
20	8.5	8.4	1%	9.9	-14%	Feasible with light touch measures
21	16.3	16.1	1%	17.8	-9%	Feasible with light touch measures
22	8.5	7.7	10%	8.8	-4%	Probably robust, ensure no deterioration
23	16.5	14.9	10%	16.4	1%	Probably robust, ensure no deterioration
24	14.7	13.1	12%	15.8	-7%	Probably robust, ensure no deterioration
25	15.8	14.0	13%	15.7	1%	Probably robust, ensure no deterioration
26	8.5	7.3	16%	8.1	5%	Probably robust, ensure no deterioration
27	17.6	15.0	17%	16.7	6%	Probably robust (urban catchment)
28	14.9	12.7	17%	14.3	4%	Probably robust, ensure no deterioration
29	17.6	14.8	19%	18.6	-5%	Probably robust, ensure no deterioration
30	14.0	11.1	26%	12.2	14%	Probably robust, ensure no deterioration
31	20.3	14.5	40%	16.6	23%	Probably robust
32	19.0	13.2	44%	16.0	18%	Probably robust, ensure no deterioration
33	22.6	15.6	45%	17.9	26%	Probably robust
34	13.3	9.1	47%	10.8	23%	Probably robust
35	8.5	5.5	54%	6.0	41%	Probably robust
36	14.0	8.7	60%	10.2	37%	Probably robust (urban catchment)
37	14.9	9.3	61%	11.7	28%	Probably robust
38	20.3	12.5	62%	14.5	40%	Probably robust
39	12.6	7.8	63%	8.7	45%	Probably robust
40	24.8	15.2	63%	19.3	29%	Probably robust
41	27.1	16.5	64%	19.2	41%	Probably robust
42	8.5	5.1	66%	5.7	49%	Probably robust (urban catchment)
43	8.5	5.1	66%	5.9	44%	Probably robust
44	17.4	7.5	131%	8.3	110%	Probably robust

Figure 4. Assessment of catchment management feasibility.

MEASURES TO REDUCE CATCHMENT NITRATE LOADING

Diffuse pollution mitigation measures aimed at mitigating leaching of nitrate to groundwater are identified in Newell-Price *et al.* (2011). While precise selection of measures to implement in a catchment requires individual assessments of the local farm-scale context, some generic mitigation strategies were considered. Light touch measures, or those that require no fundamental change to farming operations, are preferred as farmers' business models would not be substantially affected.

- For arable-dominated land, light touch measures might include: use of cover crops before spring cereals; use of a fertiliser recommendation system; and integration of fertiliser and manure nutrient supply. In combination, these may achieve a reduction in nitrate losses to groundwater of up to 8%. Where outdoor pigs are part of the rotation, low N and P foods can be used to reduce nitrate loading by 10% to fields where manure is applied.
- For pasture-dominated land, light touch measures might include: reduction of field stocking rates when fields are wet; avoiding spreading manufactured fertiliser at high risk times; use of clover in place of fertiliser N; use of a fertiliser recommendation system; and integration of fertiliser and manure nutrient supply. In combination, these may achieve a reduction in nitrate losses to groundwater of up to 10%. Where dairy cattle are farmed, low N and P foods can also be used to reduce nitrate loading by 10% to fields where manure is applied.

Some of these measures proposed above are cost beneficial for the farmer, and others are required for farms in an NVZ – so they may be current practice in the catchment and the anticipated reduction may not be achieved. On the other hand, if they are not practised, then the changes will lead to more profitable farm businesses and therefore there should be little resistance to change.

More significant changes to the farming systems might be required to achieve reductions in N loading of more than about 8%. These might include: undersowing of spring crops (c. 10% reduction in the catchment); reduction in stocking densities; or reversion of some or all arable land to extensive grazing (c. 80% reduction on land reverted) or woodland (up to a 95% reduction). However losses of income incurred would need compensation, and schemes would inevitably meet with some resistance.

FEASIBILITY OF CATCHMENT MANAGEMENT

Based on the likely effectiveness of mitigation measures presented above, the following statements of catchment management feasibility can be made:

- **Light touch measures** are recommended in the first instance for catchments with predicted headroom between, say, -8% and +5%. Perhaps, however, many of the measures are in current practice, and a judgement would have to be made whether to encourage more significant change. If the measures have been recently adopted then it is likely that there will be some improvement in concentrations anyway.
- **Limited land use change** would be recommended if headroom is between, say, -20% and -8%. Reversion to extensive grazing of, perhaps, the 10% of land in the catchment nearest the borehole(s) would be beneficial both because of an additional 8% reduction of nitrate loading, but also it would tend to reduce the magnitude of variability in monitored concentrations at the abstraction. Since abstraction yield is mostly obtained from areas closest to the borehole(s) (Figure 2) there is a disproportionate gain in water quality if inputs in this area are controlled.
- **Considerable land use change** would be at the scale of reversion of arable land use on the scale of whole farms or catchments. While this often still appears to be cost effective compared to construction of a nitrate treatment plant, it is likely to meet considerable resistance, and other high-level pressures begin to become significant (such as local jobs, and food security). It is expected that this level of land use change could not be widely achieved in the UK.
- **Ensuring no deterioration of water quality** is recommended for catchments where the headroom is insufficient to cope with additional inputs of N from changing crop types, say +5% to +20%. In these catchments it is recommended that some of the light touch measures might be encouraged (where they are cost beneficial to the farmer) and contact be maintained to ensure that the water company has early warning of, for example, ploughing up permanent pasture, or an increase in the amount of maize or potatoes grown.

From Figure 4 it is clear that, of the 44 sources in the studies, it would not be possible to achieve targets without considerable land use change in 11 catchments (25%), and in 13 catchments (30%) the headroom is sufficient that there is little risk of drinking water quality being compromised. In four catchments (9%) the nitrate inputs are dominated by urban influences, for which effective measures are not yet defined. Of the remaining 16 catchments (36%) some level of stewardship is recommended and catchment management should be a feasible solution to protecting drinking water quality.

CONCLUSIONS

Compelling evidence for the effectiveness of catchment management needs support from catchment-specific data sets and modelling. Calibrating a predictive model to historical data, in which upward trends are the result of historical increased nitrate loading, provides confidence that the model can predict the effects of reduced nitrate loading. Use of a nationally-validated soil zone model (NEAP-N) in a nitrate trending model removes further uncertainty. Review of data, conceptualisation and modelling of nitrate trends in 44 catchments from the English Midlands and North West provides insights into the nature of catchment-scale nitrate transport and near-borehole effects. With a few exceptions, deviations from expected soil zone concentrations can be explained by a few hydrogeological influences.

Predictions of future nitrate concentration, when compared with water company targets, can be used to assess feasibility of catchment management. In many of the catchments studied, measures would not be required because a better understanding of the system demonstrates that drinking water quality is not at risk. In many others, concentrations are too high to be managed effectively. In the remainder, a spectrum of stewardship schemes would be required to achieve desired reductions in nitrate loading.

Catchment management is most suited to achieving marginal (<20%) reductions in nitrate concentrations in the catchments studied. At this level of loading reduction, some land use change would be required. Where the reduction in concentration required is 8% or less measures may be cost beneficial for the farmer and may not need incentivisation for their adoption.

Calibrated and conceptually-justifiable models can provide compelling evidence that can be used to design mitigation strategies and to persuade stakeholders of the effectiveness of proposed measures. With this evidence, practical interventions needed to reduce pollutants entering groundwater are far more likely to be adopted, maintained and assimilated into everyday farming practice. This is crucial to maintain the long-term sustainability of catchment management programmes and will provide the value for money sought by both water companies and Ofwat.

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