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# The effectiveness of agricultural stewardship for improving water quality at the catchment scale: experiences from an NVZ and ECSFDI watershed

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## Abstract

Agriculture is estimated to be responsible for 70 % of nitrate and 30-50 % of phosphorus pollution, contributing to ecological and water treatment problems. Despite the fact that significant gaps remain in our understanding, it is known that agricultural stewardship can be highly effective in controlling water pollution at the plot and field scales. Knowledge at the catchment scale is, to a large extent, entirely lacking though and this is of paramount concern given that the catchment is the management unit used by regulatory authorities. The few studies that have examined the impact of agricultural stewardship at the catchment scale have found that Nitrate Vulnerable Zones (NVZs) in the UK have resulted in little improvement in water quality which concurs with the current catchment study. In addition to NVZs, there was little evidence to suggest that the England Catchment Sensitive Farming Delivery Initiative had impacted water quality and suggestions have been made for improvements, such as ensuring that stewardship measures are used in key pollution source areas and their implementation and impacts are monitored more closely. This will be essential if agricultural catchment management schemes are going to provide the benefits expected of them. Nevertheless, more intensive monitoring than that carried out by regulators showed a significant trend in decreasing winter nitrate peaks in some streams which is hypothesised to be due to recent reduced inorganic fertiliser application as a result of increasing prices. It was concluded that, collectively, these findings indicate that agricultural stewardship measures have the potential to improve water quality at the catchment scale but that voluntary schemes with insufficient financial reward or regulatory pressure are unlikely to be successful.

**Keywords:** Nitrate Vulnerable Zones; Catchment Sensitive Farming; nutrients; agriculture; water quality.

## 1. Introduction

Nutrient (nitrate (N) and phosphorus (P)) pollution of waterbodies has been a recognised problem for a number of decades, first becoming a major concern during the 1950's and 1960's as eutrophication increased dramatically. This was largely attributed to the intensification of agriculture and, specifically, the increased use of fertilisers, following the food shortages experienced during and after the second world war (Withers et al., 2003; Macgregor and Warren, 2006). Other contributing factors include runoff from farmyards (Edwards and Withers, 2008), increases in the growth of winter-sown cereals (Chamberlain et al., 1999), conversion of grassland to arable production (Herzog et al., 2006), the installation of under-drainage in agricultural soils (Hooda et al., 1999) and leakage from septic tanks (Edwards and Withers, 2008). It is estimated that agricultural land receives an excess of 125 kg N $ha^{-1}$ $yr^{-1}$ (MAFF, 2000) and that 70-80 % of nitrate in English rivers comes from agricultural sources (Ferrier et al., 2001; Defra, 2004; Neal et al., 2006). Over the past decade, nitrate concentrations have continued to increase in many rivers due to continued fertiliser use and the long residence times of nitrate in groundwaters (Heathwaite et al., 1996; Lord et al., 1999; Neal et al., 2006). The annual average nitrate increase in waters is estimated to be 0.1-0.2 mg N $l^{-1}$ (MacDonald et al., 1994) and average nitrate concentrations in a number of English rivers are now approaching 9 mg N $l^{-1}$ (Neal et al., 2006). Peak concentrations frequently exceed the drinking water limit of 11.3 mg N $l^{-1}$ (MAFF, 1993). Losses are greatest during the autumn/winter period, when runoff generation is relatively high and crop/grass uptake is limited (Withers and Lord, 2002). Due to nutrient concentrations in waterbodies (P more so than N (Correll, 1999)), eutrophication is now widespread in the UK (Environment Agency, 2000). Elevated nitrate concentrations in drinking water have been associated with impacts in humans, including methemoglobinemia and reproductive and developmental problems (Fan and Steinberg, 1996). The water industry must therefore remove nitrate from water which costs an estimated £16M per annum. Treatment of phosphorus (and sediment) costs an additional £55M (Pretty et al., 2000).

In an attempt to deal with nutrient pollution, the Nitrates Directive (91/676/EEC) (EC, 1991) was introduced in 1991, which requires Member States to take action to ensure that nitrate concentrations are below 11.3 mg N $l^{-1}$ in streams, rivers and groundwaters. As a result, 68 Nitrate Vulnerable Zones (NVZs) were designated in England in 1996 (NVZ legislation came into force in 1998), covering an area of approximately 600,000 ha (Edwards et al., 2003) where concentrations in rivers exceeded 11.3 mg N $l^{-1}$ or where a eutrophication problem had been identified (Lord et al., 2007). The area designated as NVZ was subsequently expanded in 2002 and again in 2009, to cover 70 % of the land area. Prior to NVZs, actions to control nitrate pollution from agricultural land had been voluntary, under the Nitrate Sensitive Areas (NSA) scheme. The general aim of the NVZ regulations is to reduce N inputs to catchments and improve the timing of applications to reduce the likelihood of N losses in runoff. Recently, the Water Framework Directive (WFD) (2000/60/EC) (EC, 2000) has placed further emphasis on the reduction of N and P pollution to ensure that good ecological status is achieved. At present, more significant nitrate pollution than ever before is ensuring major emphasis is still being placed on the control of its delivery to rivers from agricultural land (Neal et al., 2006) whilst agriculturally derived P represents just as significant a problem (Jarvie et al., 2007).

It has previously been postulated that, whilst some progress has been made in reducing pollution from point sources, diffuse pollution, particularly that from agriculture, still represents as large a problem as ever (Skinner et al., 1997; Defra, 2004). Recent work has suggested that agricultural stewardship could help to control this problem at source but that, whilst there is scientifically robust evidence to show the effectiveness of some measures for reducing nutrient pollution, a dearth of data exists to describe and explain the effects of many (Kay et al., 2009; Deasy et al., 2010). Moreover, these papers and others (Krutz et al., 2005) highlighted the almost complete lack of evidence at the catchment scale which is particularly important given that this is the unit employed in the management of rivers (e.g. EC, 2000). Some studies have examined the impacts of NVZs. Neal et al. (2006) have hypothesised that NVZs may be one of the reasons for decreasing nitrate concentrations in the Thames at Howberry Park although Lord et al. (2007) found that the overall impact of NVZ measures was small, with only a 3 % reduction in nitrate leaching losses and nitrate levels still exceeding 11.3 mg N $l^{-1}$ in many of the monitored catchments. Worrall et al. (2009) found little impact at the catchment scale. Despite the England Catchment Sensitive Farming Delivery Initiative (ECSFDI) now being the main mechanism by which farm advice is delivered in England no studies have measured its impact on water quality.

The current study was undertaken to aid our understanding of the impacts of operational agricultural stewardship schemes on nutrient pollution at the catchment scale. Furthermore, despite the fact that much of the NVZ area in England comprises of upland farms, relatively little is known about nutrient pollution in headwater streams (Edwards and Withers, 2008), let alone the effectiveness of NVZs and the ECSFDI. The specific objectives of the project were to:

- Use long-term Environment Agency data to assess the effect of NVZ legislation on nutrient pollution in an upland catchment.
- Deliver additional farm advice as part of the England Catchment Sensitive Farming Delivery Initiative (ECSFDI).
- Undertake more intensive monitoring of N and P concentrations in waters to begin to determine the efficacy of the ECSFDI for improving water quality.

- Use these findings to inform an overall synthesis of the impacts of agricultural stewardship on nutrient pollution at the catchment scale and make suggestions as to how research and management may proceed.

## 2. Methodology

### 2.1 Field site

The current study was undertaken in the Ingbirchworth catchment in South Yorkshire, UK, which is an 11 km$^2$ headwater subcatchment of the River Don (Figure 1). The catchment was designated an NVZ in 2002 and an ECSFDI Associate catchment in 2006. The basin comprises a range of land uses; improved (13 % of land area) and semi-improved (49 %) grassland dominate and this is used to rear cattle (dairy and beef) and sheep. Cattle numbers ranged between 105 and 175 on individual farms. There is also a limited area of arable land (1.3 %), used for whole crop silage and fodder beet production. A number of manure heaps (approximately 3-5 at any one time) existed in the catchments although none of these were within several hundred metres of a water course. In addition to individual farms (28), the only urban area is Ingbirchworth village, on the eastern watershed. Small areas of moorland are also present that have not been improved for agriculture. The highest parts of the catchment are at almost 400 m elevation above Ordnance Datum (a.o.d.) while the lower reaches remain above 200 m a.o.d. Solid geology comprises Coal Measures rocks (sandstones and shales), whilst a soil survey of the catchment during the current project showed a variety of soil series, dominated by clay loams. Relatively impermeable soils such as these are a common feature of NVZ areas (Lord et al., 2007). The Ingbirchworth catchment can be divided into the subcatchments of the four reservoirs present; Broadstones, Royd Moor, Ingbirchworth itself, and Scout Dyke. The first three are impoundment reservoirs (i.e. used to supply drinking water) while the latter provides compensation flow to the downstream watercourse which has its confluence with the River Don approximately 1.25 km downstream. As is the case for many upland water supply catchments in Yorkshire, engineering works have manipulated the natural hydrology and water is transferred into both Broadstones and Royd Moor reservoirs from moorland areas outside the catchment. Water from Royd Moor is fed into Ingbirchworth reservoir via an underground conduit. Although some of the water in Broadstones is pumped to a Water Treatment Works (WTW) outside the catchment overflow from the reservoir moves downstream to Ingbirchworth reservoir. Specific measurements of quantities of water being pumped into these reservoirs, remaining in the catchment and being exported elsewhere are not measured by Yorkshire Water.

### 2.2 Water quality monitoring

Environment Agency (EA) General Quality Assessment Scheme data was available for two monitoring sites in Ingbirchworth and Scout Dykes (Figure 1) and covers the previous three decades, although very few data were available for nitrate during the 1980-90 period. Water quality was monitored more intensively throughout the catchment during the period 2006-09 (Figure 1; Table 1) by taking grab samples on a fortnightly basis in a range of flow conditions. The actual number of samples collected was lower than this regime would result in though due to many sites being inaccessible during flood events, particularly during 2007. The actual number of samples collected at each site was therefore approximately fifty. These were supplemented by samples collected using ISCO 6712 autosamplers (Teledyne Isco, Lincoln, US), coupled with ISCO 4250 area-velocity modules which monitored stream discharge, at sites A1-3.

### 2.3 Chemical analysis

On return to the laboratory, a 15 ml aliquot from each water sample was filtered through a cellulose nitrate 0.45 µm membrane (Whatman, Maidstone, UK) for analysis of aqueous nutrients, while total concentrations of these nutrients were measured on an unfiltered aliquot. These samples were frozen prior to analysis in vials which had been rinsed with a discarded volume of the sample to saturate adsorption sites. Nutrient analysis was carried out using an Aqua 800 Advanced Quantitative Analyser, with N being measured at 520 nm and P at 724 nm. Total P was first converted to molybdate reactive phosphorus by hydrolysis with di-potassium peroxodisulphate (potassium persulphate), absorbance being proportional to the concentration of orthophosphate in the sample. Limits of quantification were 0.2 mg N $l^{-1}$ and 2 µg P $l^{-1}$ for nitrate and phosphorus respectively. The remainder of each 500 ml sample was filtered through a 0.45 µm membrane using a vacuum filtration method to determine the concentration of suspended sediment. A 15 ml aliquot of the original sample was also preserved using nitric acid for analysis of boron as an indicator of sewage pollution (Jarvie et al., 2007) using a Perkin Elmer (Massachusetts, USA) 5300DV ICP-OES.

### 2.4 NVZ checks and farm advice

Farmers in the catchment were checked for compliance with NVZ regulations by Environment Agency (EA) staff who considered practises carried out on individual fields as well as the entire farm. The whole farm assessments took account of the N output of livestock, the land area available for grazing and manure/slurry applications. An application rate of less than 250 kg N $ha^{-1}$ $yr^{-1}$ resulted in a pass. Assessments of individual fields considered the total N application from manure/slurry, which should not exceed 250 kg N $ha^{-1}$ $yr^{-1}$ for grassland and 170 kg N $ha^{-1}$ $yr^{-1}$ on arable, as well as applications of inorganic fertiliser. An agronomic report was assessed for each field, which included information such as previous and current cropping as well as existing soil N. Farm records were also checked to ensure that organic amendments had not been applied to any sandy or shallow soils between 1 August and 1 November for arable land and 1 September to 1 February for grass.

Records were checked to ensure that N had not been applied when land was saturated or to steeply sloping areas. Spreader calibrations were also assessed.

Further farm advice delivery was undertaken between 2006 and 2008 as part of the ECSFDI, comprising farmer meetings, workshops, farm walks, demonstration days and one-to-one visits. A range of land management practices were discussed during these events, including entry into agri-environment schemes and the options that these contain, manure, fertiliser and soil management plans, manure and slurry application techniques and pasture reseeding methods. The one-to-one visits focussed on the preparation of plans for individual farms.

## 3. Results

### 3.1 NVZ checks and ECSFDI advice

Farm assessments by the Environment Agency found that all farmers within the catchment were fully compliant with current NVZ regulations. Between 6 and 30 individuals attended the ECSFDI group events and eleven farms received one-to-one visits from which succinct reports were prepared which detailed actions that could be taken to improve environmental quality. These included recommendations on the placement of in-field manure heaps, soil and manure nutrient content analysis, leaving buffer zones next to water courses when spreading manure and reseeding grassland, installing stream fencing to exclude livestock, and entry to the Entry Level Stewardship (ELS) scheme, for example. Four manure and fertiliser management plans were produced (Figure 1) which required a detailed understanding of the farm and laboratory analyses of soil nutrient levels. These plans highlighted the risk to water quality of applying manures and fertiliser to specific areas of each farm in order for this to be minimised in the future. Although farmers agreed to follow these best practise guidelines none implemented specific measures, such as those included in ELS. Any improvements in land management were therefore of a diffuse nature throughout the catchment encompassing a variety of the fields on farms that took up advice.

## 3.2 Nutrient concentrations

### 3.2.1 Long-term data

The long-term Environment Agency dataset demonstrates that nitrate concentrations have changed little over the previous 2-3 decades, with linear regression giving low $R^2$ values (Table 2). The median nitrate concentration in Ingbirchworth Dyke between 1990 and 2007 was 3.78 mg N $l^{-1}$ with a peak of 23.7, whilst the respective figures for the period 1980-2008 in Scout Dyke were 2.94 and 12.5 mg N $l^{-1}$. Orthophosphate concentrations were occasionally above 0.1 mg P $l^{-1}$, particularly in Ingbirchworth Dyke, up to a peak value of 0.34 mg P $l^{-1}$. Whilst concentrations have varied, little change has occurred in the general trend.

### 3.2.2 2006-09 monitoring

Median nitrate values in streams in the period 2006-09 were generally close to 5 mg N $l^{-1}$ or below, although peak concentrations were as high as 36 mg N $l^{-1}$ (Figure 2a). The 11.3 mg N $l^{-1}$ limit was exceeded in a number of streams (Maze Brook, Annat Royd Beck, Brown’s Edge Beck, Ingbirchworth Dyke and Slack Beck), although individually only on between one and three occasions. Concentrations in groundwater (site G2) were routinely below 1 mg N $l^{-1}$. Over the 2006-09 period significant reductions in nitrate concentrations were observed in the Royd Moor sub-catchment (Annat Royd Beck and Maze Brook) and Ingbirchworth Dyke at all sites (Table 3). In contrast, no significant change was recorded in Slack Beck, Blackwater Dyke, Brown’s Edge Beck and groundwater. The recent monitoring showed total P concentrations to be as high as 0.87 mg P $l^{-1}$ with peak values above 0.1 mg P $l^{-1}$ at all sites and in some cases even the mean was greater than this (Figure 2b and c). The spatial pattern of dissolved P levels was similar to that for total P and concentrations were of the order measured in the long-term monitoring. Unlike N, P concentrations generally remained static over the 2006-09 period (Table 3). Boron was detected in less than 25 % of the stream water samples and only at low concentrations (usually <35 µg $l^{-1}$), indicating that inputs of sewage to the catchment were limited and therefore not a significant cause of nutrient pollution. On those occasions that boron was detected, however, a significant relationship did exist with dissolved P concentrations (Figure 3).

## 4. Discussion

Despite the fact that evidence exists to show that individual agricultural stewardship measures can be very effective in controlling nutrient pollution (Dorioz et al., 2006; Kay et al., 2009; Deasy et al., 2010), most of which has been collected at the plot scale, there exists a severe dearth of knowledge on the impacts of operational agricultural catchment management schemes, such as NVZs and the ECSFDI. It is imperative that this information is obtained if we are to manage nutrient pollution in rivers effectively given that the catchment is the management unit utilised (e.g. EC, 2000). Previous studies of the effects of NVZs have found little or no impact on water quality (Lord et al., 2007; Worrall et al., 2009), perhaps because NVZs have not been found to change farmers' behaviour (Barnes et al., 2009). This would indicate that they were already operating in a fashion to meet NVZ requirements or that policing of their implementation is not rigorous enough to require farmers to actually change. Despite being the key way in which agricultural stewardship has been delivered in the UK since 2005, no studies have previously assessed the impacts of the ECSFDI. It has been postulated that targeted advice and financial incentives could achieve promising results although the actions taken often depend on the personal relationships between farmers and advisors (Posthumus et al., 2011) and the intrinsic view of conservation held by the farmer (Robinson, 2006).

The current study has shown that during the previous 20-30 years N and P concentrations in the Ingbirchworth catchment have varied although the general trend has not changed. Based on the EA data NVZ regulations have, therefore, not had an obvious impact on water quality since their implementation in 2002. This concurs with some other recently published work that found the Environment Agency of England and Wales' (EA) work to reduce diffuse pollution has had little impact (National Audit Office, 2010; Howarth, 2011). Additional more spatially and temporally intensive monitoring, going well beyond that undertaken by regulators, has shown that nitrate concentrations have decreased in a number of streams between 2006 and 2009, however, whilst remaining static in others. This recent decrease is exemplified by the fact that the median nitrate concentration in Ingbirchworth Dyke during the long-term monitoring was 3.7 mg N $l^{-1}$ compared to 2.7 mg N $l^{-1}$ at the same site during the 2006-09 monitoring. The winter peak in nitrate concentrations, typical of intra-annual stream nitrate patterns (Heathwaite et al., 1996; Lord et al., 1999; Neal et al., 1996), decreased significantly in Maze Brook, for example, from approximately 11 to less 4 mg N $l^{-1}$ over the three year period (Figure 4).

The fact that the decrease in N concentrations was observed in some streams but not others (e.g. Brown's Edge Beck) may indicate that changes in biogeochemical cycling, due to the wet conditions of 2007-09 for instance, are not responsible for the observed decreases in nitrate concentrations. Even though stream temperatures were similar in 2007 and 2008, with median values of 11.9 and 10.1 ˚C and ranges of 17 and 15.3 ˚C for the respective years, ANOVA showed that a significant difference existed ($p=<0.001$) between the years for which full datasets were available. As 2008 was the cooler year, however, it is unlikely that increased plant uptake of N led to the decline in stream concentrations. Moreover, when the reported nitrate concentrations were adjusted to flow-weighted annual averages concentrations were actually 1.5

times greater in 2008 than 2007 and so differences in hydrology seem unlikely to be the cause. Elucidation of the impact of any land management changes on nutrient pollution is difficult as none of the farmers implemented specific measures such as buffer zones or wetlands. The plans produced focused on good agricultural practice on broad areas of land and individual sub-catchments also contained land managed by farmers who did not engage with the ECSFDI. Although no data was collected to describe inorganic fertiliser applications in the Ingbirchworth catchment, some farmers did comment that increasing prices had caused them to reduce applications and this may have had some influence on nitrate concentrations. A declining trend in inorganic fertiliser applications currently exists nation-wide, particularly to grassland (Defra, 2009). It remains a possibility that the decrease in nitrate pollution in some streams could be a delayed response to NVZ actions and/or ECSFDI associated improvements in agricultural practice or a general increase in farmers' awareness of environmental issues.

The current study indicated that many farmers are willing to listen to advice, such as that delivered under the ECSFDI, but less open to changing their practices, even where some financial savings may be made. This could be explained by the fact that Posthumus et al. (2011) found that the money available to farmers through Environmental Stewardship was often insufficient to allow them to change their practices. Moreover, the schemes were too inflexible to allow farmers to respond to changes in markets.

Further studies would be useful to help quantify if the observed reduction in N pollution is sustained in the streams where it was measured, if it has occurred in other catchments recently and the relationship with the potential reasons that have been identified. Explanation of changes in water quality at the catchment scale can be very difficult however due to the complexity of processes operating.

It is important that the current study has shown that more spatially and temporally intensive water quality monitoring can highlight some outcomes which the current standard in regulatory monitoring may miss (i.e. decreasing winter N concentrations in some streams). Furthermore, particular areas of the catchment were shown to contribute more to diffuse pollution than others in the intensive monitoring, which would allow regulatory actions to be targeted better. This would help to solve two recent criticisms made of the EA's work which were that it worked with a lack of information on diffuse pollution sources and struggled to provide evidence of the impacts of its actions. It should be recognised however that the EA itself believes that its legal power to control nutrient pollution is limited which highlights that policy reform may be needed in addition to improved scientific understanding to address the problem. Further work has also confirmed that farmers do not feel sufficiently threatened by prosecution to change to more environmentally friendly practices (Posthumus et al., 2011). In order to address problems in identified source areas it will be necessary to further convince farmers that they are part of the problem and need to help find the solution (Macgregor and Warren, 2006; Popp and Rodriquez, 2007; Barnes et al., 2009; National Audit Office, 2010; Howarth, 2011). Moreover, in future, the money spent on mitigation options could achieve much greater gains in terms of the health of the aquatic environment if it was targeted towards key areas of land contributing runoff to streams rather than spread over other areas of catchments (Davies et al., 2009).

The present study has highlighted that ascertaining the impact of agricultural stewardship at the catchment scale is difficult, due to the need to implement measures over greater areas and undertake larger monitoring schemes. Nevertheless, Posthumus et al. (2011) have stated that improved monitoring (in terms of spatial and temporal intensity and overall monitoring campaign length) is needed to fill knowledge gaps and, even though this may be expensive, it is likely to be cheaper than the costs of water pollution (Howarth, 2011). Carrying out this research in catchments where agricultural stewardship schemes are voluntary (e.g. ECSFDI and Defra demonstration catchments) may yield little in terms of scientific understanding as the implementation of measures can be disparate due to some farmers not engaging and others implementing particular measures only. Indeed, even where farmers have joined the ELS less than 2 % of agreements contain measures for protecting water resources (Howarth, 2011). The lack of entry of farmers into Environmental Stewardship in the current study is perhaps surprising given that the highest uptake of such schemes usually occurs on marginal land such as the Ingbirchworth catchment (Kleijn and Sutherland, 2003). Nevertheless, other work has found that these farmers may be uneasy about accepting government standards when they see their land as problematic (Davies and Hodge, 2006).

## 5. Conclusion

The severe lack of published data to describe and explain the impacts of agricultural stewardship at the catchment scale makes this a pressing research need. In particular, there is a requirement to assess the effectiveness of operational agricultural stewardship schemes on which large sums of public money have been spent, such as NVZs and the ECSFDI.

The current study has supported the two previously carried out to assess the impacts of NVZs on water quality (Lord et al., 2007; Worrall et al., 2009) in that this legislation appears to have had little impact. Furthermore, there is no evidence to-date that the ECSFDI is resulting in improvements to water quality. These findings support recent criticisms of operational agricultural catchment management schemes (National Audit Office, 2010; Howarth, 2011). In contrast though, the observed decrease in winter N peaks, hypothesised to be due to decreasing inorganic fertiliser applications, does indicate that measures can be implemented which will have an impact at the catchment scale. This is supported by the fact that we already know that many can be highly effective at improving runoff quality at the plot scale (e.g. Dorioz et al., 2006; Kay et al., 2009; Deasy et al., 2010).

It is important that we continue to improve our understanding of the impacts of agricultural stewardship at the catchment scale as this is the management unit employed by regulatory authorities to manage rivers (e.g. EC, 2000). It is also necessary to move agricultural catchment management forward by dealing with the criticisms levelled at current procedures. This will mean improving water quality monitoring by making it more spatially and temporally intensive so allowing better establishment of key pollution source areas in which to target stewardship measures and to measure the impacts of these. This will allow us to move beyond making assessments based on qualitative and anecdotal evidence (Posthumus et al., 2011). Better information is also needed to describe the actions taken by farmers as at present there is much debate about its accuracy and usefulness. Many farmers will need to be further incentivised to do this by greater financial rewards or an increased threat of prosecution. Furthermore, there is still a need to ensure that farmers recognise themselves as part of the problem and the solution.

In summary, there is a good deal of science undertaken at the plot scale to suggest that agricultural stewardship should improve water quality at the catchment scale and therefore help us to meet policy objectives, such as those required by the WFD. What the current study has suggested is that it is the implementation and regulation of these stewardship actions, rather than their inherent ability to alter water quality, that are likely to be the most important factors in the success of such measures or otherwise at the catchment scale.

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## References

Barnes, A.P., Willock, J. and Toma, L., 2009. Farmer perspectives and practices regarding water pollution control programmes in Scotland. Agricultural Water Management, 96, 1715-1722.

Chamberlain, D.E., Crick, H.Q.P., 1999. Population declines and reproductive performance of Skylarks Alauda arvensis in different regions and habitats of the United Kingdom. IBIS, 141(1), 38-51.

Correll, D.L., 1999. Phosphorus: A rate limiting nutrient in surface waters. Poultry Science, 78, 5, 674-682.

Davies, B., Biggs, J., Williams, P. and Thompson, S., 2009. Making agricultural landscapes more sustainable for freshwater biodiversity: a case study from southern England. Aquatic Conservation: Marine and Freshwater Ecosystems, 19, 439-447.

Deasy, C., Quinton, J.N., Silgram, M., Bailey, A.P., Jackson, B. and Stevens, C.J., 2010. Contributing understanding of mitigation options for phosphorus and sediment to a review of the efficacy of contemporary agricultural stewardship measures. Agricultural Systems, 103(2), 105-109.

Defra, 2004. Developing measures to promote catchment sensitive farming: A joint Defra-HM Treasury Consultation. Defra, London.

Defra, 2009. The British Survey of Fertiliser Practice, Fertiliser Use on Farm Crops for Crop Year 2008. Defra, London.

Dorioz, J.M., Wang, D., Poulenerd, J. and Trévisan, D., 2006. The effect of grass buffer strips on phosphorus dynamics – A review and synthesis as a basis for application in agricultural landscapes in France. Agriculture, Ecosystems and Environment, 117, 4-21.

EC, 1991. Council Directive 91/676/EEC concerning the protection of waters against pollution by nitrates from agricultural sources, OJ L375.

EC., 2000. Council Directive 2000/60/EC establishing a framework for community action in the field of water policy, OJ L327.

Edwards, A.C., Sinclair, A.H., Domburg, P., 2003. Identification, designation and formulation of an action plan for a nitrate vulnerable zone: a case study of the Ythan catchment, NE Scotland. European Journal of Agronomy, 20(1-2), 165-172.

Edwards, A.C., Withers, P.J.A., 2008. Transport and delivery of suspended solids, nitrogen and phosphorus from various sources to freshwaters in the UK. Journal of Hydrology, 350(3-4), 144-153.

Environment Agency., 2000. Aquatic Eutrophication in England and Wales, a Management Strategy. Environment Agency, Bristol.

Fan, A.M., Steinberg, V.E., 1996. Health implications of nitrate and nitrite in drinking water: An update on methemoglobinemia occurrence and reproductive and developmental toxicity. Regulatory Toxicology and Pharmacology, 23(1), 35-43.

Ferrier, R.C., Edwards, A.C., Hirst, D., Littlewood, I.G., Watts, C.D., Morris, R., 2001. Water quality of Scottish rivers: spatial and temporal trends. Science of the Total Environment, 265(1-3), 327-342.

Genereux, D., 1998. Quantifying uncertainty in tracer-based hydrograph separations. Water Resources Research, 34(4), 915-919.

Heathwaite, A.L., Johnes, P.J., Peters, N.E., 1996. Trends in nutrients. Hydrological Processes, 10(2), 263-293.

Herzog, F., Steiner, B., Bailey, D., Baudry, J., Billeter, R., Bukacek, R., De Blust, G., De Cock, R., Dirksen, J., Dormann, C.F., De Filippi, R., Frossard, E., Liira, J., Schmidt, T., Stockli, R., Thenail, C., van Wingerden, W., Bugter, R., 2006. Assessing the intensity of temperate European agriculture at the landscape scale. European Journal of Agronomy, 24(2), 165-181.

Hooda, P.S., Moynagh, M., Svoboda, I.F., Edwards, A.C., Anderson, H.A. and Sym, G., 1999. Phosphorus loss in drainflow from intensively managed grassland soils. Journal of Environmental Quality, 28, 1235-1242.

Howarth, W., 2011. Diffuse water pollution and diffuse environmental laws. Journal of Environmental Law, 23(1), 129-141.

Jarvie, H.P., Withers, P.J.A., Hodgkinson, R., Bates, A., Neal, M., Wickham, H.D., Harman, S.A. and Armstrong, L., 2007. Influence of rural land use on streamwater nutrients and their ecological significance. Journal of Hydrology, 350 (3-4), 166-186.

Kay, P., Edwards, A.C. and Foulger, M., 2009. A review of the efficacy of contemporary agricultural stewardship measures for addressing water pollution problems of key concern to the UK water industry. Agricultural Systems, 99, 67-75.

Kleijn, D. and Sutherland, W.J., 2003. How effective are European agri-environment schemes in conserving and promoting biodiversity? Journal of Applied Ecology, 40, 947-969.

Krutz, L.J., Senseman, S.A., Zablotowicz, R.M. and Matocha, M.A., 2005. Reducing herbicide runoff from agricultural fields with vegetative filter strips: a review. Weeds Science, 53, 353-367.

Leinweber, P., Turner, B.L. and Meissner, R., 2002. Phosphorus. In: Haygarth, P.M. and Jarvis, S.C. (eds.). Agriculture, Hydrology and Water Quality. Cabi, Wallingford, UK.

Leinweber, P., Meissner, R., Eckhardt, K.-U. and Seeger, J., 1996. Management effects on forms of phosphorus in soil and leaching losses. European Journal of Soil Science, 50(3), 413-424.

Lord, E., Shepherd, M., Silgram, M., Goodlass, G., Gooday, R., Anthony, S.G., Davison, P. and Hodgkinson, R., 2007. Investigating the effectiveness of NVZ Action Programme measures: development of a strategy for England. ADAS report for Defra project NIT18.

Lord, E.I., Johnson, P.A. and Archer, J.R., 1999. Nitrate Sensitive Areas: a study of large scale control of nitrate loss in England. Soil Use and Management, 15(4), 201-207.

MacDonald, A.M., Edwards, A.C., Pugh, K.B. and Balls, P.W., 1994. Soluble nitrogen and phosphorus in the River Ythan system: annual and seasonal trends. Water Research, 29, 837–846.

Macgregor, C.J. and Warren, C.R., 2006. Adopting sustainable farm management practices within a Nitrate Vulnerable Zone in Scotland: The view from the farm. Agriculture, Ecosystems and Environment. 113(1-4), 108-119.

MAFF, 2000. England Rural Development Plan, 2000-2006, Appendix A3, Yorkshire and the Humber Region. MAFF Publications, London, UK.

MAFF, 1993. Solving the nitrate problem: progress in research and development. MAFF report PB 1092.

National Audit Office, 2010. Environment Agency: Tackling Diffuse Water Pollution in England. Comptroller and Auditor General, London.

Neal, C., Jarvie, H.P., Neal, M., Hill, L. and Wickham H., 2006. Nitrate concentrations in river waters of the upper Thames and its tributaries. The Science of the Total Environment, 365, 1-3, 15-32.

Popp, J. and Rodriguez, G., 2007. The role of stakeholders' perceptions in addressing water quality disputes in an embattled watershed. Journal of Environmental Monitoring and Restoration, 3, 225-263.

Posthumus, H., Deeks, L.K., Fenn, I. and Rickson, R.J., 2011. Soil conservation in two English catchments: linking soil management with policies. Land Degradation and Development, 22, 97-110.

Pretty, J.N., Brett, C., Gee, D., Hine, R.E., Mason, C.F., Morison, J.I.L., Raven, H., Rayment, M.D. and van der Bijl, G., 2000. An assessment of the total external costs of UK agriculture. Agricultural Systems, 65(2), 113-136.

Robinson, G.M., 2006. Ontario's Environmental Farm Plan: evaluation and research agenda. Geoforum, 37, 859-873.

Skinner, J.A., Lewis, K.A., Bardon, K.S., Tucker, P., Catt, J.A. and Chambers, B.J., 1997. An Overview of the Environmental Impact of Agriculture in the U.K. Journal of Environmental Management, 50(2), 111-128.

Soulsby, C., Petry, J., Brewer, M.J., Dunn, S.M., Ott, B. and Malcolm, I.A., 2003. Identifying and assessing uncertainty in hydrological pathways: a novel approach to end member mixing in a Scottish agricultural catchment. Journal of Hydrology, 274, 1-4, 109-128.

UK TAG, 2008. UK Environmental Standards and Conditions (Phase 1). UK Technical Advisory Group on the Water Framework Directive report.

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

Withers, P.J.A., Ulén, B., Stamm, C and Bechmann, M., 2003. Incidental phosphorus losses - are they significant and can they be predicted? Journal of Plant Nutrition and Soil Science, 166(4), 459 – 468.

Withers, P.J.A., Hodgkinson, R.A., Bates, A. and Withers, C.M., 2006. Some effects of tramlines on surface runoff, sediment and phosphorus mobilization on an erosion-prone soil. Soil Use and Management, 22(3), 245 – 255.

Wood, P.J. and Armitage, P.D., 1997. Biological effects of fine sediment in the lotic environment. Environmental Management, 21, 203-217.

Worrall, F., Spencer, E. and Burt, T.P., 2009. The effectiveness of nitrate vulnerable zones for limiting surface water nitrate concentrations. Journal of Hydrology, 370(1-4), 21-28.

## Captions

### Figures

Figure 1. Water quality monitoring sites in the Ingbirchworth catchment, South Yorkshire, UK. Hatched areas indicate agricultural land for which manure and fertiliser management plans were produced during the Associate England Catchment Sensitive Farming Delivery Initiative project. Other, more generic, advice was delivered throughout the catchment. Table 1 provides further details for the sampling sites.

Figure 2. Boxplots showing nitrate (a), total phosphorus (b) and dissolved phosphorus (c) concentrations in the main stream channels and groundwater in the Ingbirchworth catchment, 2006-09 (□=mean, centre line in box=median, lower and upper ends of box=lower and upper quartiles, whiskers=5 and 95 percentiles, ×=minimum and maximum value).

Figure 3. Correlation between dissolved phosphorus and boron on those occasions that the latter was detected (<25% of samples) in stream water samples.

Figure 4. Decreasing nitrate concentrations in Maze Brook (sampling site A1) in the Ingbirchworth catchment during the period 2006-09.

## Tables

Table 1. Description of water quality monitoring sites. EA=Environment Agency monitoring site. A=monitoring site with autosampler (grab samples also collected). G=grab samples only collected.

Table 2. $R^2$ values (p value in parenthesis) describing changes in nitrate and orthophosphate concentrations at two sites in the Ingbirchworth catchment during the period 1980-2009. Minus sign indicates a negative relationship between concentrations and time, otherwise a positive correlation exists.

Table 3. $R^2$ values (p value in parenthesis) describing changes in nitrate, total and dissolved phosphorus concentrations over the period 2006-09 in the Ingbirchworth catchment. Minus sign indicates a negative relationship between concentrations and time, otherwise a positive correlation exists.

Figure 1.

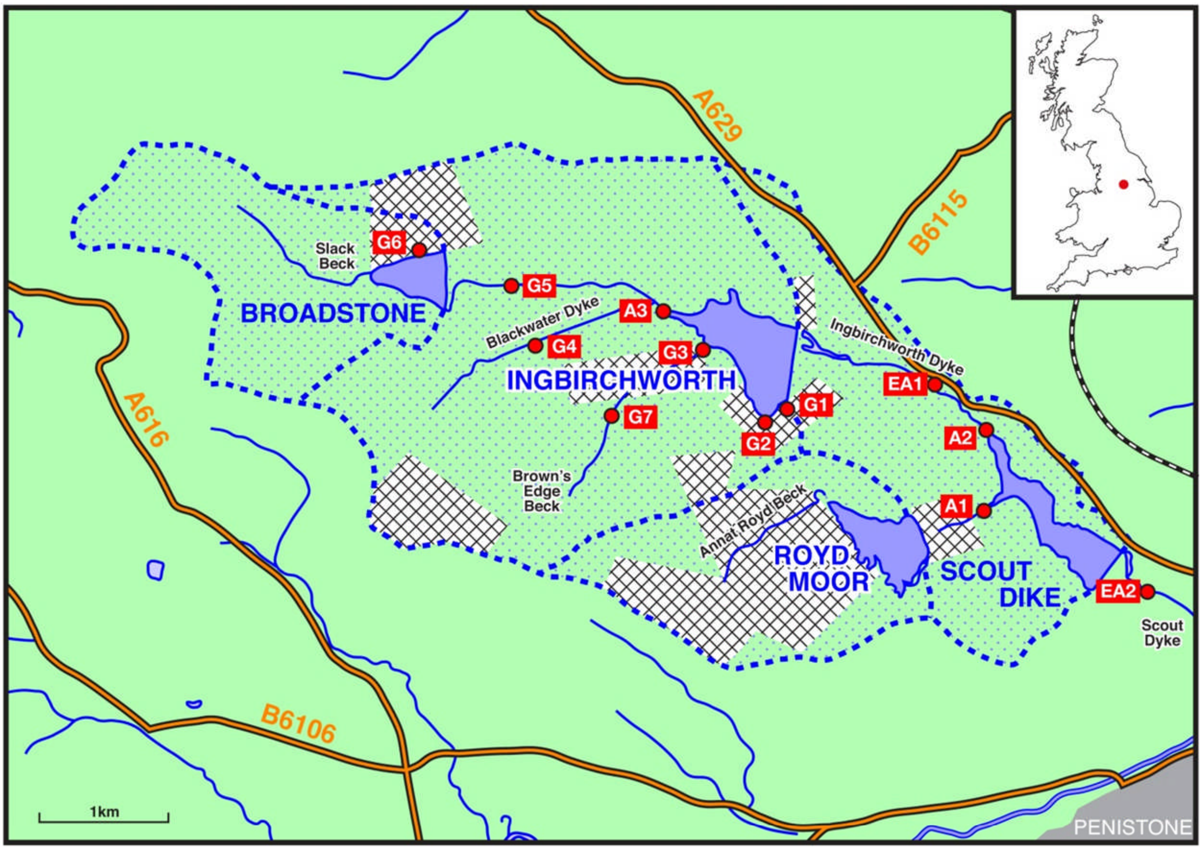
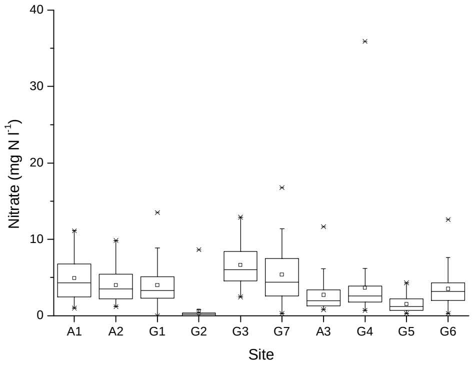
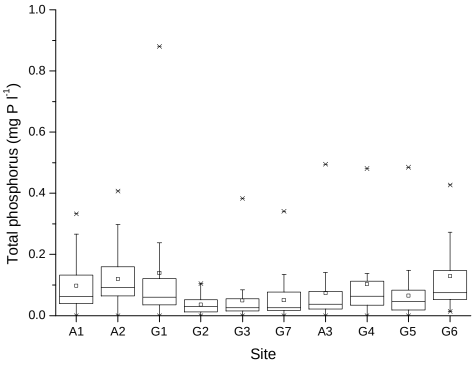

A629
B6115
A616
B6106
Slack Beck
G6
G5
BROADSTONE
A3
Blackwater Dyke
G4
G3
INGBIRCHWORTH
Ingbirchworth Dyke
EA1
G1
G2
G7
A2
Brown's Edge Beck
Annat Royd Beck
A1
ROYD MOOR
SCOUT DIKE
EA2
Scout Dyke
1km
PENISTONE

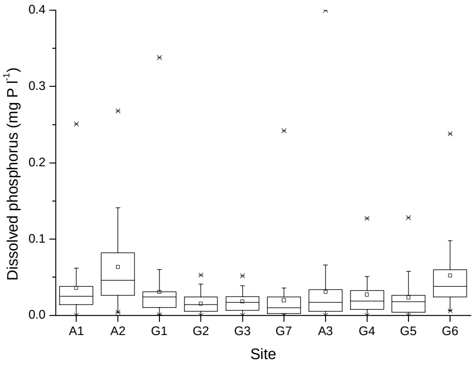
Figure 2.


Nitrate (mg N l$^{-1}$)
40
30
20
10
0
A1
A2
G1
G2
G3
G7
A3
G4
G5
G6
Site

(a)

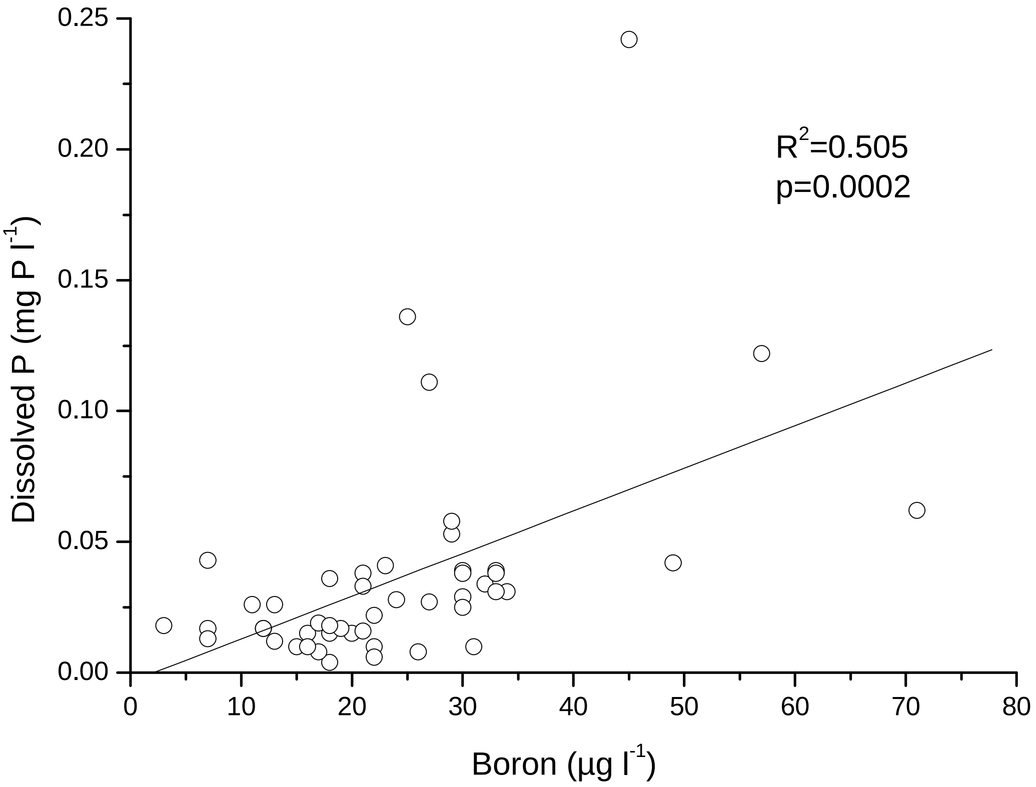

Total phosphorus (mg P l$^{-1}$)
1.0
0.8
0.6
0.4
0.2
0.0
A1
A2
G1
G2
G3
G7
A3
G4
G5
G6
Site

(b)


Dissolved phosphorus (mg P l$^{-1}$)
0.4
0.3
0.2
0.1
0.0
A1
A2
G1
G2
G3
G7
A3
G4
G5
G6
Site

(c)

624 Figure 3.



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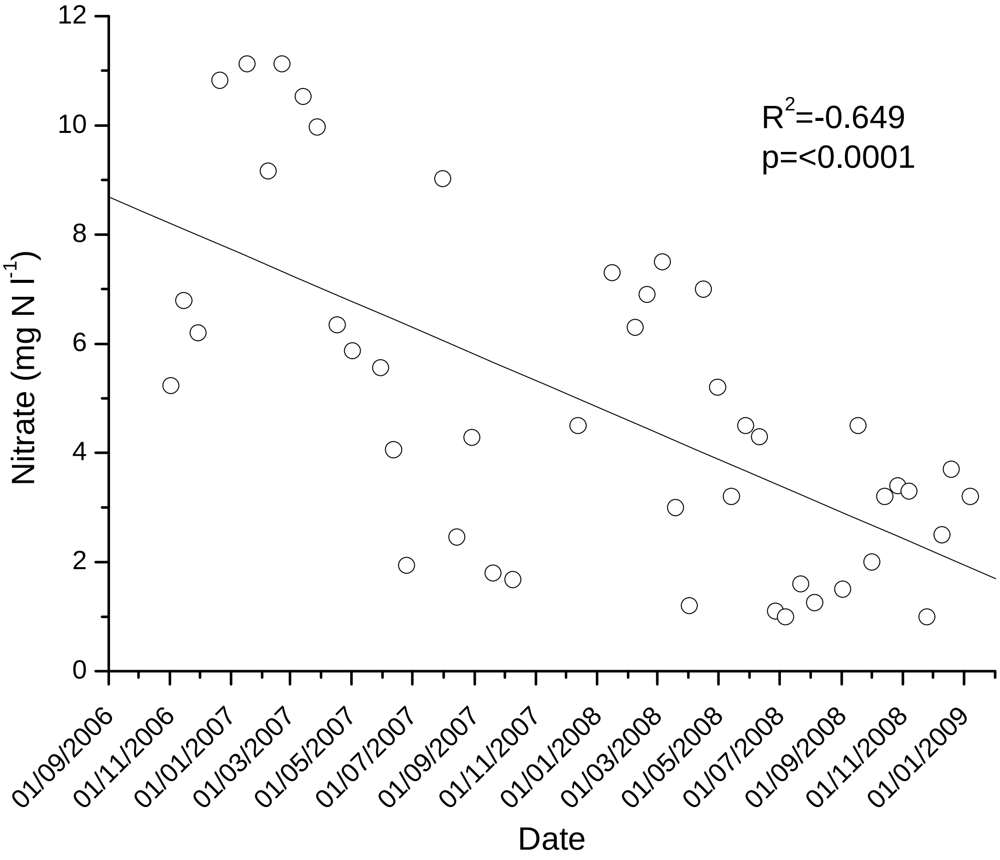
628 Figure 4.



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632 Table 1.

| Monitoring site | Description |
|---|---|
| EA1 | Environment Agency monitoring site on Ingbirchworth Dyke |
| EA2 | Environment Agency monitoring site on Scout Dyke |
| A1 | Maze Brook. |
| A2 | Ingbirchworth Dyke upstream of Scout Dyke reservoir. |
| A3 | Ingbirchworth Dyke upstream of Ingbirchworth reservoir. |
| G1 | Conduit transferring water from Annat Royd Beck (before entry to Royd Moor Reservoir) to Ingbirchworth Reservoir. |
| G2 | Groundwater sampled from borehole (151 m depth) discharging to Ingbirchworth Reservoir. |
| G3 | Brown’s Edge Beck before entry to Ingbirchworth Reservoir. |
| G4 | Blackwater Dyke. |
| G5 | Ingbirchworth Dyke downstream of Broadstone Reservoir. |
| G6 | Ingbirchworth Dyke sampled from bypass channel around Broadstone Reservoir. The Reservoir receives water pumped in from out side of the catchment which is then transferred to a water treatment works also outside of the catchment. Broadstone Reservoir does occasionally overflow into Ingbirchworth Dyke immediately downstream of monitoring site G8. |
| G7 | Upper Brown’s Edge Beck |

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Table 2.

| Stream and monitoring site | Nitrate | Orthophosphate |
|---|---|---|
| Ingbirchworth Dyke | | |
| EA1 | -0.0676 (0.418) | 0.2329 (0.001) |
| Scout Dyke | | |
| EA2 | -0.0589 (0.424) | 0.011 (0.871) |

Table 3.

| Stream and monitoring site | Nitrate | Total P | Dissolved P |
|---|---|---|---|
| Slack Beck | | | |
| G6 | -0.2630 (0.085) | 0.0304 (0.850) | -0.1207 (0.435) |
| Ingbirchworth Dyke | | | |
| G5 | -0.5089 (0.001) | 0.2068 (0.189) | -0.0777 (0.616) |
| A3 | -0.4688 (0.001) | -0.2079 (0.204) | 0.0904 (0.5600) |
| A2 | -0.5103 (0.001) | 0.0385 (0.806) | 0.1450 (0.3477) |
| Blackwater Dyke | | | |
| G4 | -0.0892 (0.560) | 0.1248 (0.437) | -0.1298 (0.3954) |
| Brown’s Edge Beck | | | |
| G7 | 0.0918 (0.594) | 0.1002 (0.592) | 0.0960 (0.5895) |
| G3 | -0.2259 (0.140) | 0.0759 (0.651) | -0.2934 (0.0626) |
| Royd Moor sub-catchment | | | |
| G1 | -0.4795 (0.001) | 0.2222 (0.174) | -0.0570 (0.7201) |
| A1 | -0.6491 (0.001) | 0.1635 (0.295) | 0.0117 (0.9400) |
| Groundwater | | | |
| G2 | -0.2856 (0.060) | 0.0349 (0.828) | -0.4223 (0.0048) |