EVALUATION OF THE WATER INFRASTRUCTURE AND TREATMENT ENGINEERING (WITE) PROGRAMME

INTERIM REPORT GR/N26074/01

The SEAL Project

Strategic Management of Non-point Source Pollution from SEwAge Sludge

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INTRODUCTION

The environmental risk linked to soil P saturation is recognised in the UK *Code of Good Agricultural Practice for the Protection of Water* (MAFF 1998), which sets an advisory standard that limits sludge application to land on fields at or above ADAS Soil P Index 3. This standard is applied on a field-by-field basis. We suggest that such potential restrictions on sludge recycling to land are based on limited information and may not optimise the available capacity of the agricultural system. The SEAL research programme aims to show that not all land has an equal risk of contributing diffuse contaminants to receiving waters. We believe high risk is associated with *critical source areas* of diffuse pollution where source and transport risks coincide (Heathwaite & Sharpley, 1999). Where connectivity does not exist between source and receiving waters, a high nutrient source does not necessarily constitute a high nutrient risk. Essentially, the export of phosphorus (P) from agricultural land depends on the coincidence of source and transport controls.

Phosphorus source areas have a high potential to contribute P but they are often spatially limited and may include land of high soil P status or reflect agricultural land uses which increase surface P concentrations, for example, intensively grazed grassland, certain arable crops and land receiving excess nutrient applications. Transport factors describe the hydrological processes, which translate P source areas into P loss areas. Not all catchment areas are equally vulnerable to P loss; certain areas contribute runoff (both surface and subsurface) more readily than others. For example, hillslope hollows become saturated through the confluence of subsurface water with the consequent rise in the local water table and increased risk of saturation-excess surface runoff. In terms of P transport, such areas do not pose a risk unless they are *coincident* with P source areas. This means that within an agricultural catchment it is possible to have areas with a high potential to contribute P but no transport if the hydrological connectivity does not exist; conversely we may have areas with high hydrological connectivity but no P transport because they do not link to P source areas.

Evaluating the environmental risk of sludge to land recycling is integral to our research programme. Policy decisions regarding the efficacy of sludge to land need to be made at the catchment scale but current knowledge draws largely on small-scale empirical data. Our project integrates nested field experiments with hillslope to catchment scale models to evaluate the risk of land to stream contaminant transport that is scaled to account for the variation in contaminant contributing areas within a catchment.

The specific project objectives are:

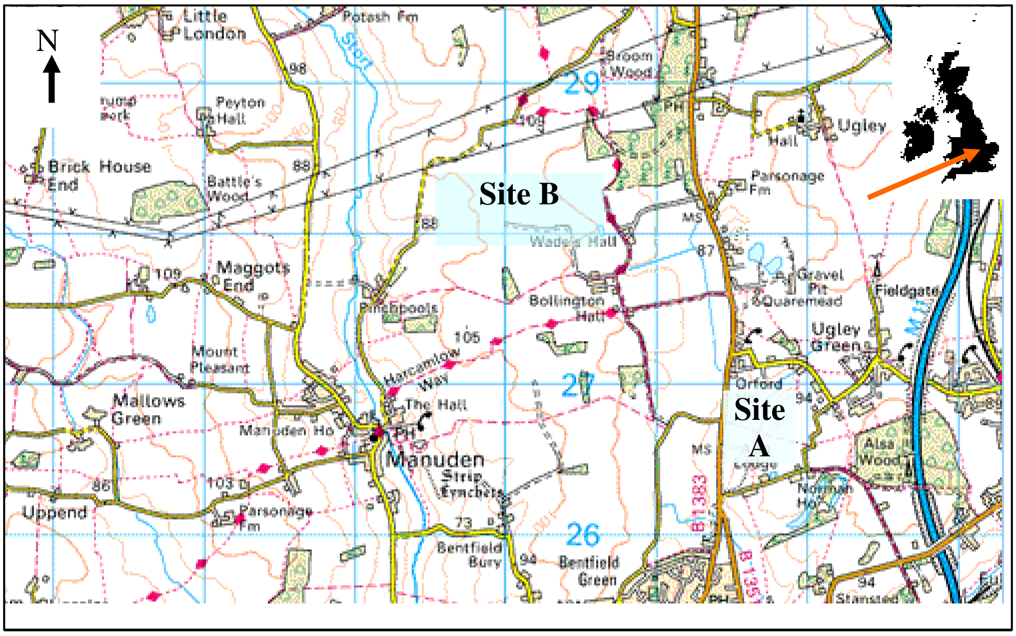
1. *To develop an advice matrix for end-users to promote environmentally sensitive sludge recycling to land.*
2. *To produce a transferable, semi-distributed model predicting the environmental impact of nutrient export from non-point sources at the catchment scale.*
3. *To evaluate whether inclusion of critical source areas (CSAs) in predictive models can improve mapping of risk areas for sludge-amended land.*
4. *To derive spatially-sensitive nutrient export coefficients to validate modelling of surface and subsurface flowpaths of nutrient loss from sludge-amended land.*
5. *To advance understanding of the form and fate of nutrients derived from sludge applied to land.*

The research reported forms part of an integrated multi-scaling field and modelling programme, the end product of which is a predictive and spatially-sensitive semi-distributed model of critical thresholds for biosolids recycling to land. In order to align the research output to the needs of end-users such as the water industry, environmental agencies and land managers the research output from this research is being synthesised into a risk advice matrix: the Nutrient Export Risk Matrix or NERM. The NERM will help determine the most appropriate form and frequency of spatially-sensitive biosolids application to land to achieve sustainable biosolids management without detriment to the environment and receiving water quality, whilst being of net benefit to land managers. The basis of the NERM is the assessment of environmental risk: this has advantages over other decision support systems, which are wholly agronomic, for example, the ADAS Safe Sludge Matrix[3] (SSM). The SSM has only two criteria: crop uptake (potential contaminant end-point) and sludge type (potential contaminant hazard). For sludge-derived nutrients, we suggest that as the receptors are water bodies then crop uptake is not a useful risk indicator. Our work is focussed on deriving a more environmentally-sensitive risk tool for sludge-derived pollutants.

We devised a series of work packages (WPs) to meet the objectives of the project: Sheffield, field experimentation, WP1-sludge characterisation and WP2-field contaminant flowpath tracing. WP3-Newcastle flow connectivity modelling. WP4-Reading catchment scenario modelling, and WP5-Sheffield decision support matrix for sustainable sludge loading strategies.

FIELD EXPERIMENTATION

Figure 1 shows the locations of the individual sites in the research area undergoing trials (NGR TL:5077:2777) located near Stansted Mountfitchet, Essex, UK. Two sites (Site A and B) have been chosen due to differing hydrology and different sludge application dates within this main area. Catchment geology is dominated by glacial sands and gravels which overly the Upper Chalk. The soils range from sandy loam to clay loam with boulder clay present to the east of the site. The area receives an annual rainfall of around 600mm with a gently undulating topography.



1 mile

Figure 1 Locations of the individual sites

Figure 2 shows the layout of Site A with the instrumentation identified. A total of 31 piezometers have been installed along with 2 flumes, a Delta-T weather station, 1 Sigma 900 automatic water samplers, 3 TDRs at depths of 0.3, 0.6 and 0.9m, 15 Teflon samplers and five zero tension samplers. A multi-level approach was taken with the piezometer installation with depths ranging from 1 to 15m. However due to changing field conditions some of the equipment has been removed from the ditch at Site A.

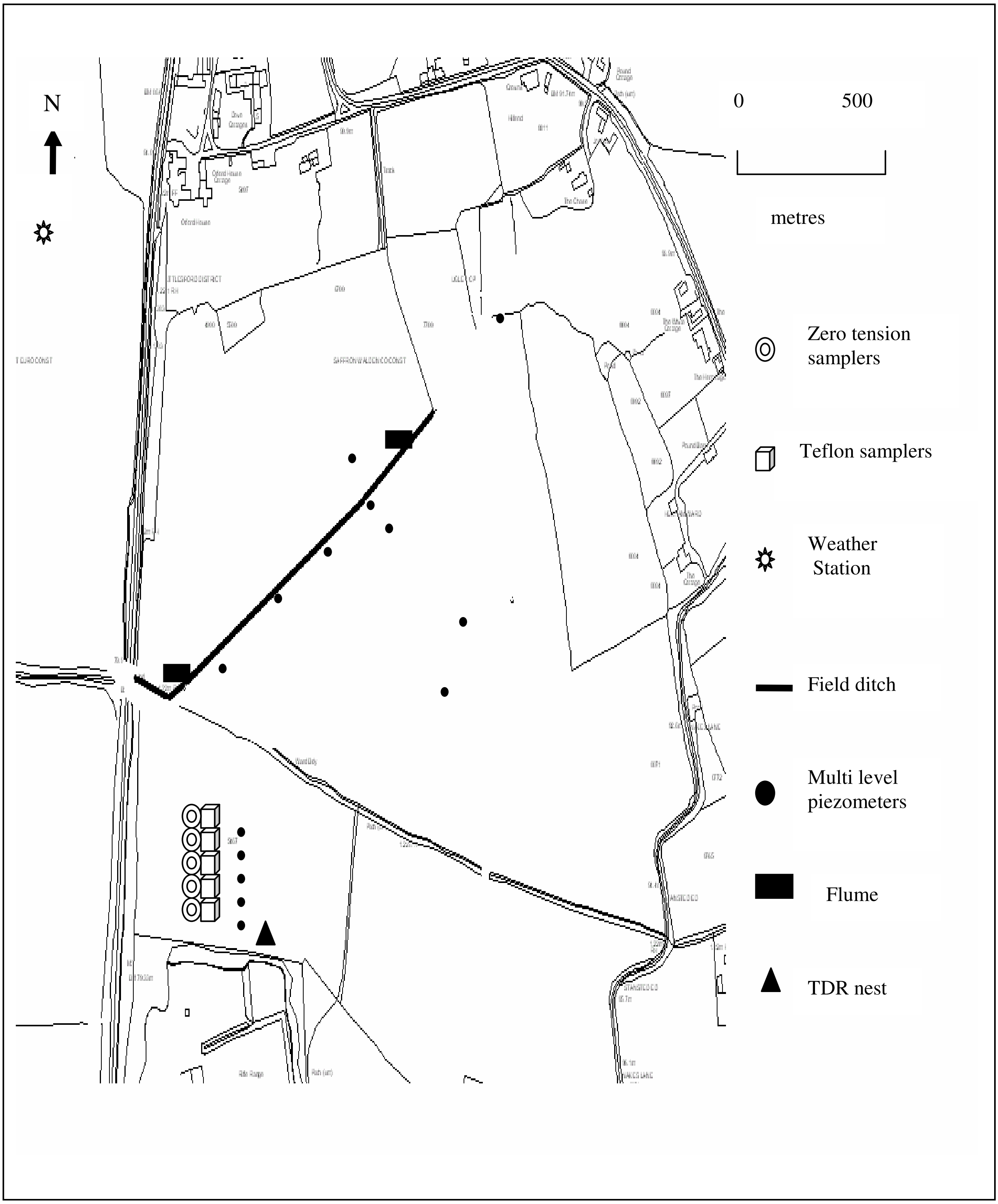


Figure 2 The general layout of Site A

with an average width of 2 metres and depth of 1 metre runs from the south west to the north east of the site.

To asses the flow rates within the ditch two flumes were installed which continuously logged water depth at 15 minute intervals using solnest pressure transducers. Five piezometers were also nstalled with solnest pressure transducers again logging water depth (cm) at 15 minute intervals. The site received a sludge application of digested sludge and lime stabilised sludge in October 2001. Digested sludge was applied at 50 t ha and lime stabilised sludge was applied at 25 t ha, equivalent to 1100 mg total P kg $^{-1}$ and 7000 mg total N kg $^{-1}$ for the digested sludge cake and 9000 mg total P kg $^{-1}$ sludge and 15000 mg total N kg $^{-1}$ sludge for the lime stabilised sludge.

Water samples were collected and analysed from the piezometers on a fortnightly interval and from the ditch when it was flowing November 2001. The samples were pre-filtered through a 0.45μm millipore filter on-site and stored around 4^{o} C before analysis within 24 hours of sample collection. Laboratory analyses for PO_4^{3-}, NO_3^- and NH_4^- was carried out using Flame Injection Analysis (FIA); pH, temperature, redox potential and total dissolved solids were determined on site using a Camlab ultra-meter. Soil samples were collected using a randomised grid selector from selected locations at surface and 30 cm depth from the site prior to the sludge being applied and post sludge application. The soil samples were analysed for moisture content, pH, TP, TN, and selected cations (Al, Fe and Ca). Samples for total P and TN were digested using the TKN method developed by Foss with the selected cations determined by an acidic digest.

A Digital Terrain Map (DTM) was also constructed of a section of Site A (Figure 3) using. The DTM map illustrates the varied topography of the site and the likely locations of any critical source areas where source zones are present. The field drain is also identified within the DTM.

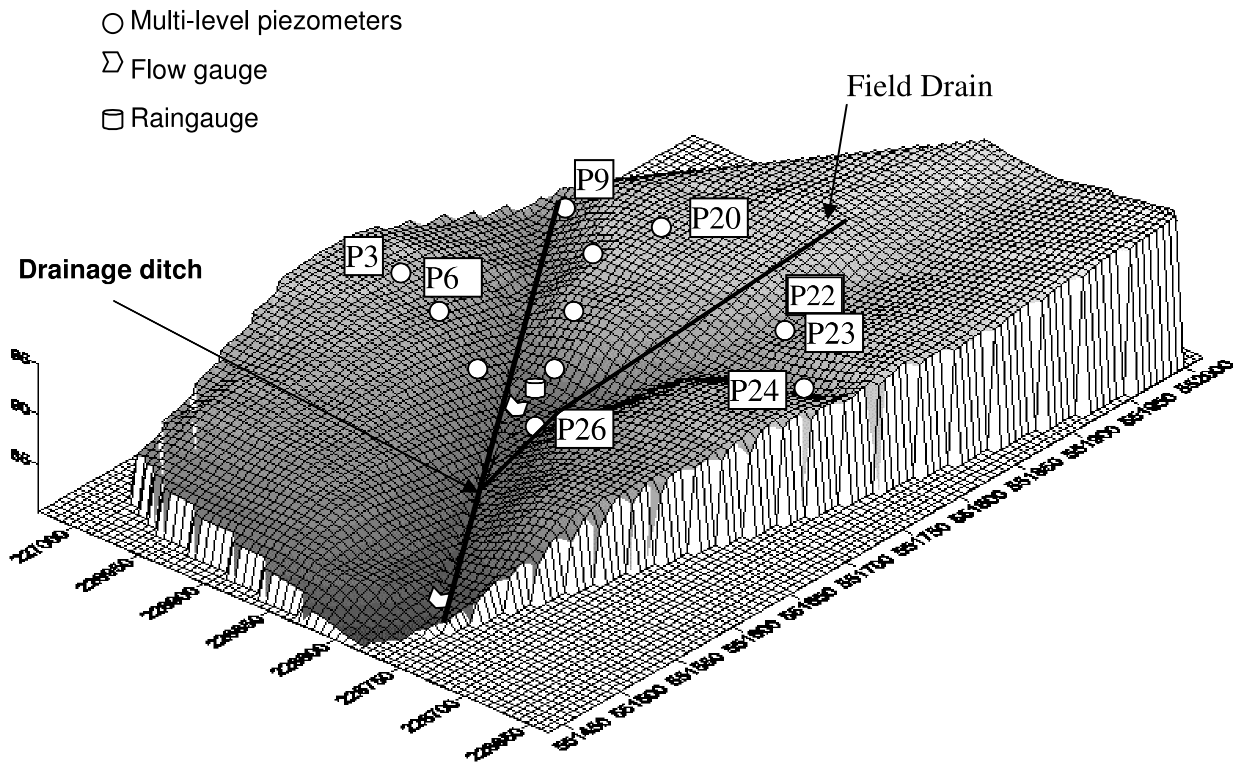


Figure 3 A Digital Terrain Map (DTM) of the site

Site B

The 80 ha site (NGR: TL 5170 2680) (Fig 4) is used primarily for the production of winter fodder and consists of an artificially drained plot with subsurface tile drains. The hydrology of site B is likely to be dominated by the artificial drainage system, running in an easterly direction into a shallow ditch. Site B was amended with anaerobically digested sewage sludge on the 2nd of November 2003 and has previously received applications of digested sludge cake during October and November of 1997. The most recent agricultural use of the study sites was for the production of winter barley (2000), since which time both plots have remained unused. Pre and post sludge application levels of nitrogen (NO_3-N), phosphate (PO_4-P) and ammonium (NH_4^+) were measured using background samples of soil and water.

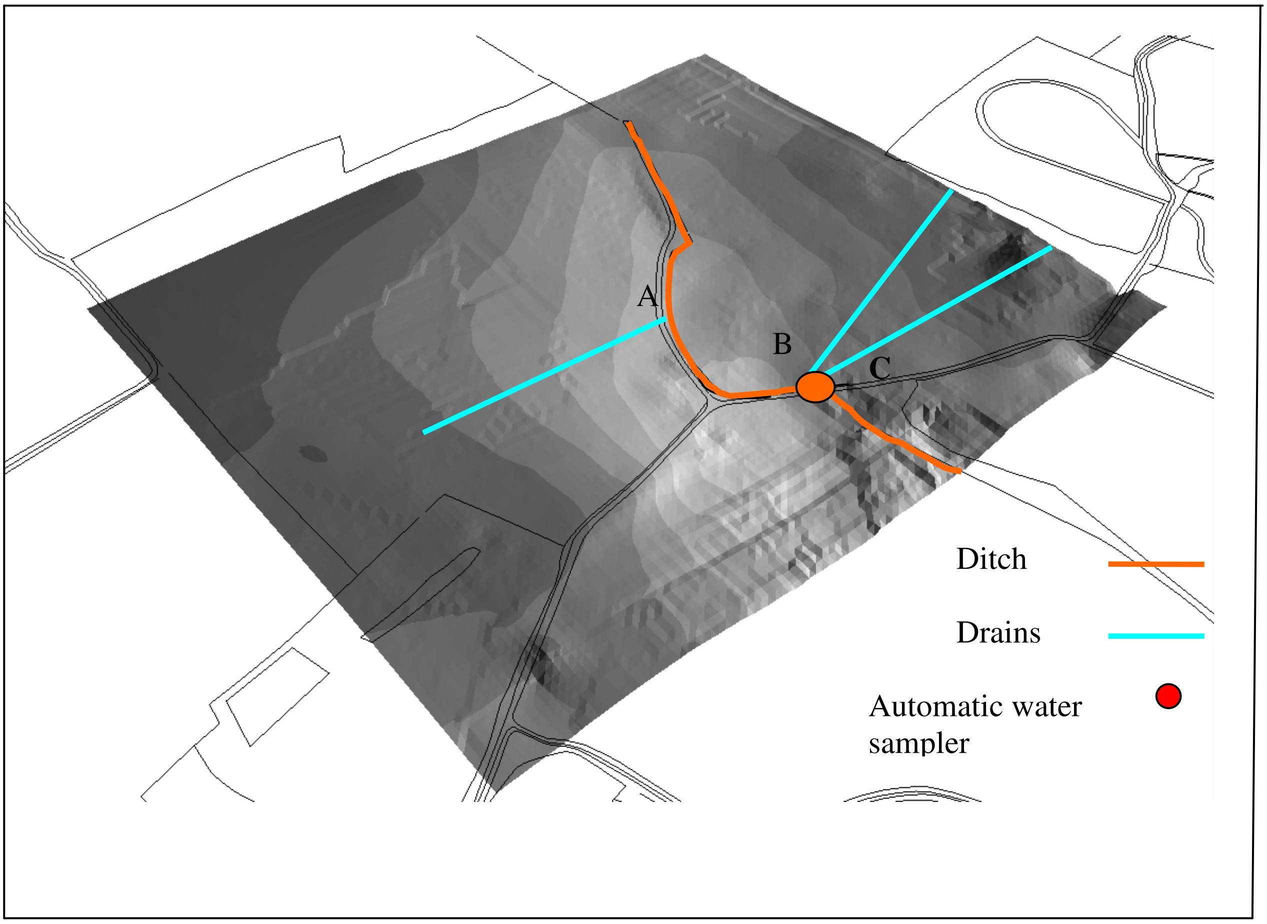


Figure 4 DTM of Field B with individual sampling points identified A,B, and C

Three individual sampling points were identified where grab samples were taken when possible. These sampling points are identified in Figure 3 where A was a non recent sludge applied field with B and C corresponding to recent sludge application points. A automatic water quality sampler was also installed (Fig 3).

RESULTS

Due to the large amount of data collected , it is intended to present only a summary of the results from the SEAL project within this section. Initially selected soil data will be presented for Site A, followed by water quality data. The data collected form Site B will then be presented which will include soil and water quality data.

Site A

Figure 5 shows the pre sludge concentrations at Site A. It highlights the variability of the P concentration within the site. The P Index of the site ranges from 1 to 4.

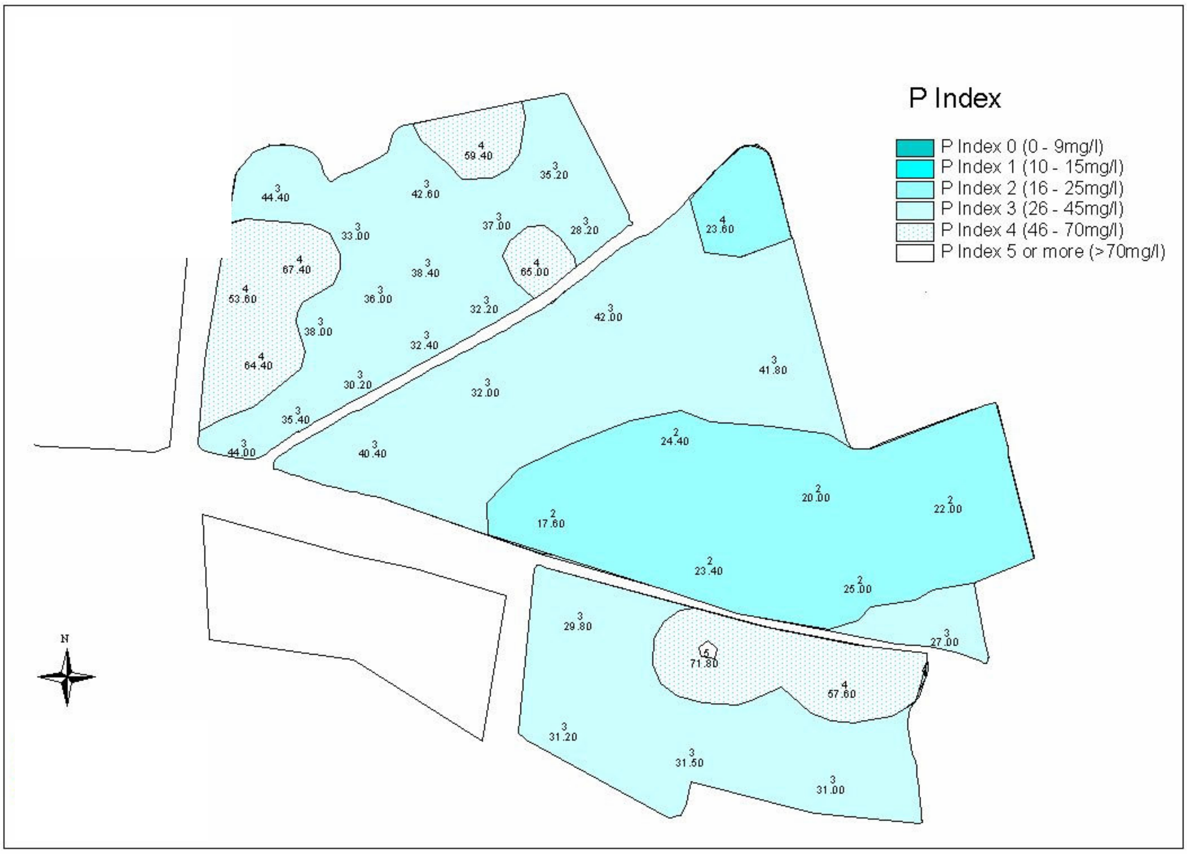


Figure 5 Pre sludge concentrations at Site A (Thames Water)

Figure 6 shows the total P (TP) and dissolved reactive P (DRP) concentrations (mg l^{-1}) recorded in the shallow multi-level piezometers that are installed in the perched water tables at the field site. The piezometers are located at depths of 1 and 2 meters. The results shown in Figure 6 highlight the range of variation in P concentrations across the 14 ha site and the relatively small concentration range for the DRP fraction in comparison with TP. The DRP concentrations recorded in the piezometers were consistently below 0.1 mg l^{-1}. The TP concentrations, however, exceeded 1 mg l^{-1} at one location, with the majority of samples demonstrating TP concentrations above 0.2 mg l^{-1}. The elevated TP and DRP in the piezometers indicate a source of P, however, the 20 meter unsaturated zone will significantly reduce the connectivity to the groundwater and it is anticipated that P sorption may limit transfer to groundwater unless hydrological conditions change, i.e. the unsaturated zone is reduced.

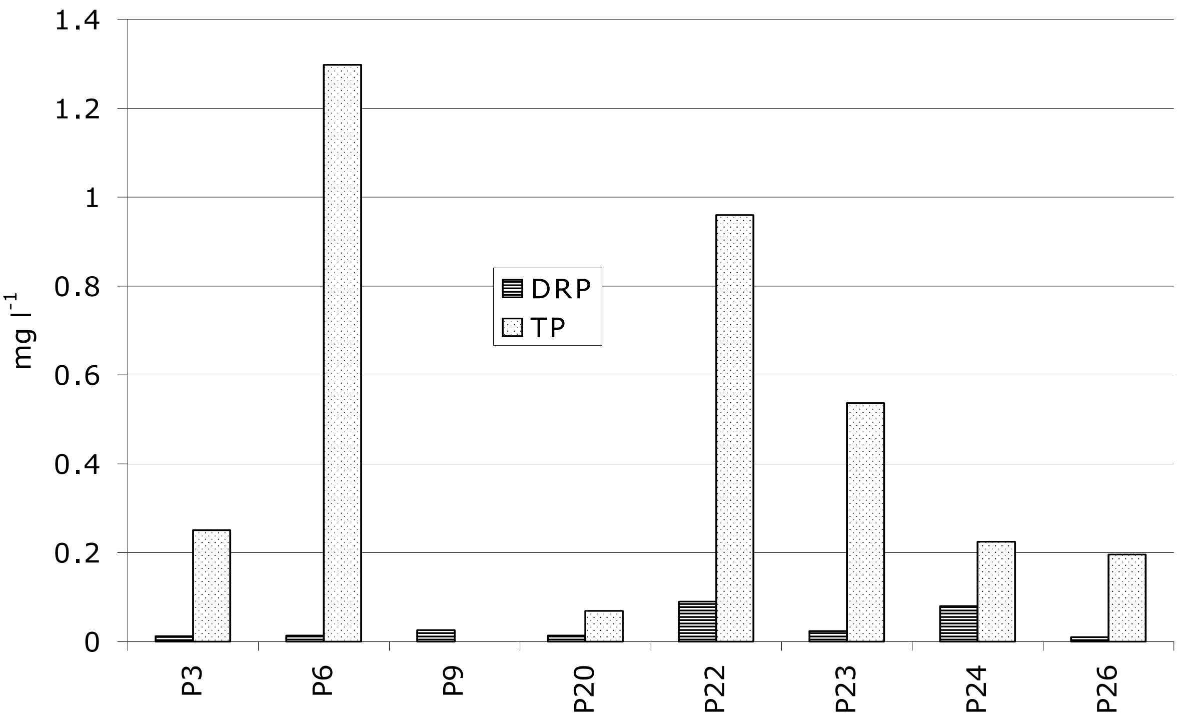


Figure 6 The variation in dissolved reactive P (<0.45 µm) and TP (mg l^{-1}) at a range of locations across Site B (see Fig 3 for location of sampling points).

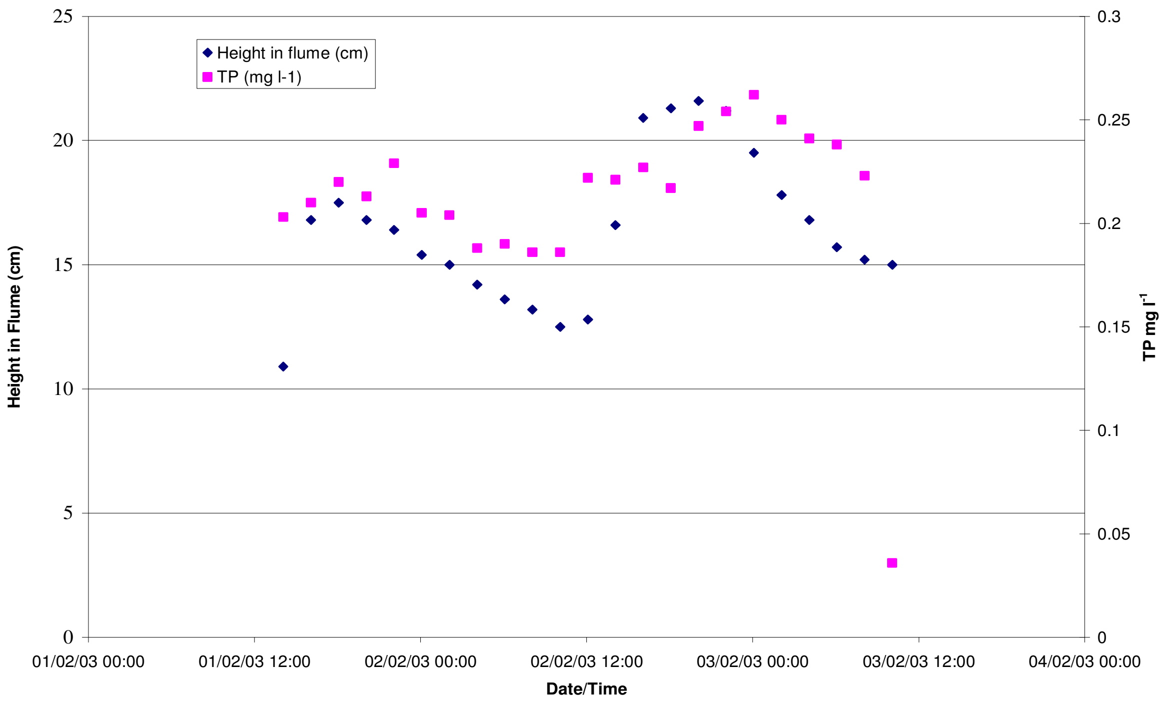


Figure 7 TP with height of water in the downstream flume at Site B.

Figure 7 shows the relationship between TP and height of water in the flume over a three day period where water height was collected at 10 minute intervals and TP samples collected at 2 hourly intervals. It suggests that as ditch flow increases it coincides with a corresponding increase in TP with TP values ranging from 0.036 to 0.262 mg l^{-1}.

Site B

Figure 8 shows the soil P concentrations at various locations at Site B for pre sludge and post sludge application. Comparison of pre and post application soil pH for the site reveals no significant difference between the sample means at the 5% level (p=0.061). Furthermore, samples demonstrated a high degree of within-site variation both before and after treatment. The most feasible explanation lies with the natural spatial variability of soils coupled with uneven application and mixing of sludge during amendment and ploughing stages.

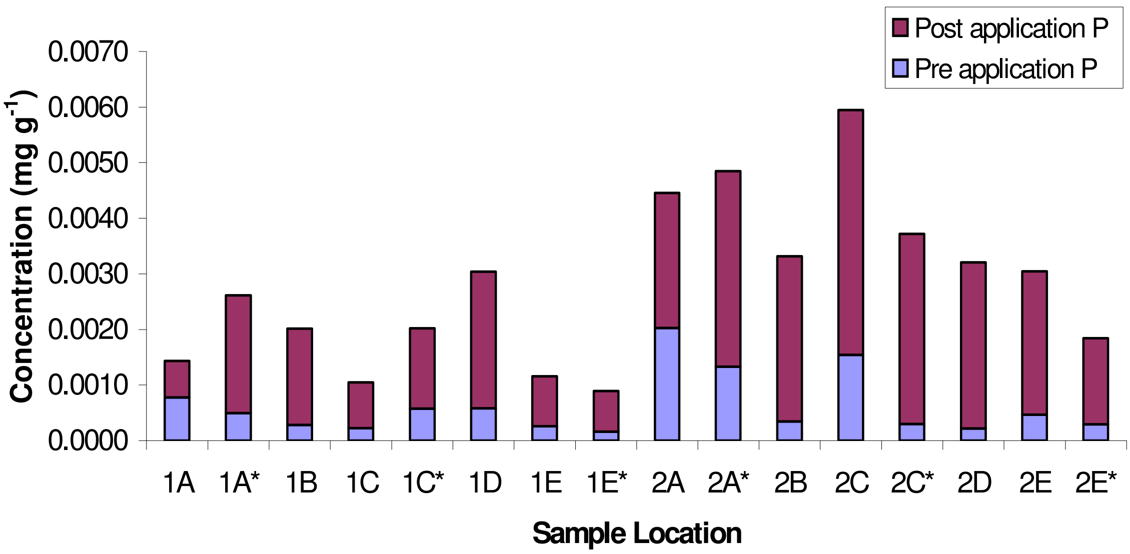


Figure 8 Soil P concentrations from selected locations around Site B

Figure 9 shows the TP concentrations plotted with rainfall for a field drain draining Site A. and appears to suggest that high rainfall events are characterised by subsequent high TP losses with the values ranging from 0.046 mg l^{-l} to 8.14 mg l^{-1}. However, with the first rainfall event after the first sludge application there appears to be a gradual decline in the concentration of TP with subsequent rainfall events.

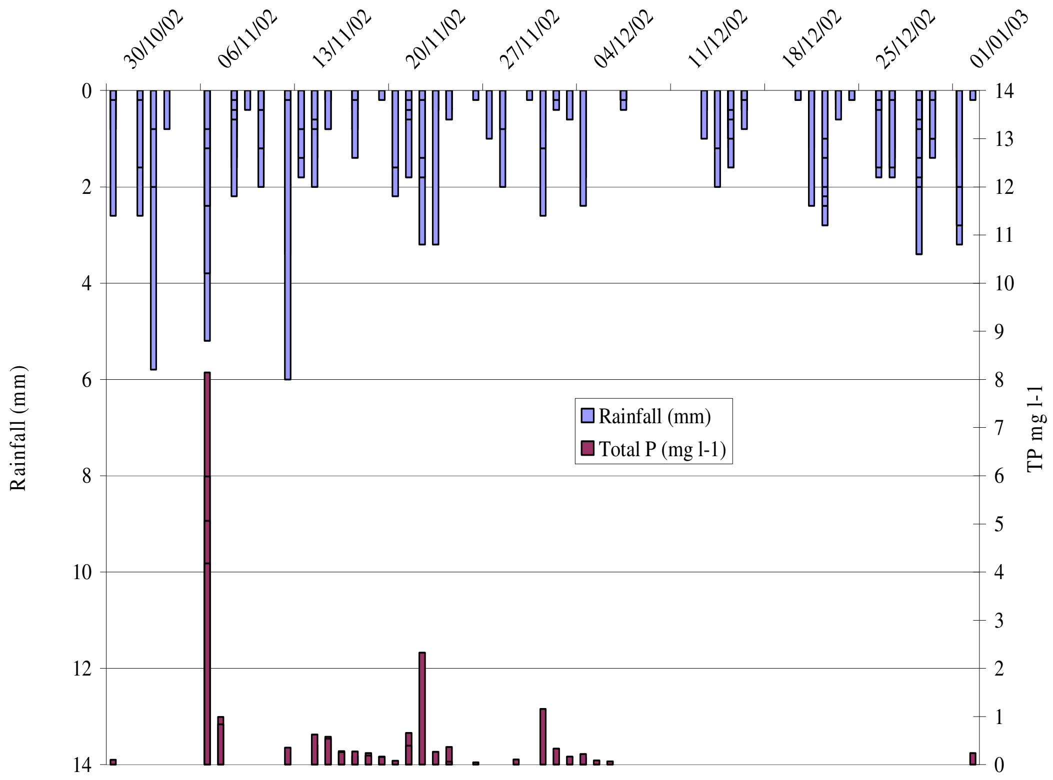
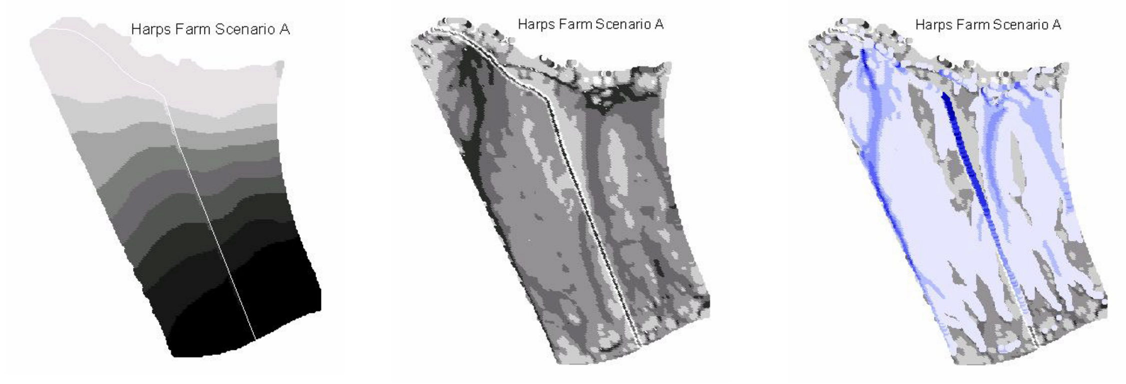


Figure 9 Rainfall with TP concentrations from a field drain draining Site B.

FIELD SCALE CONNECTIVITY MODELLING

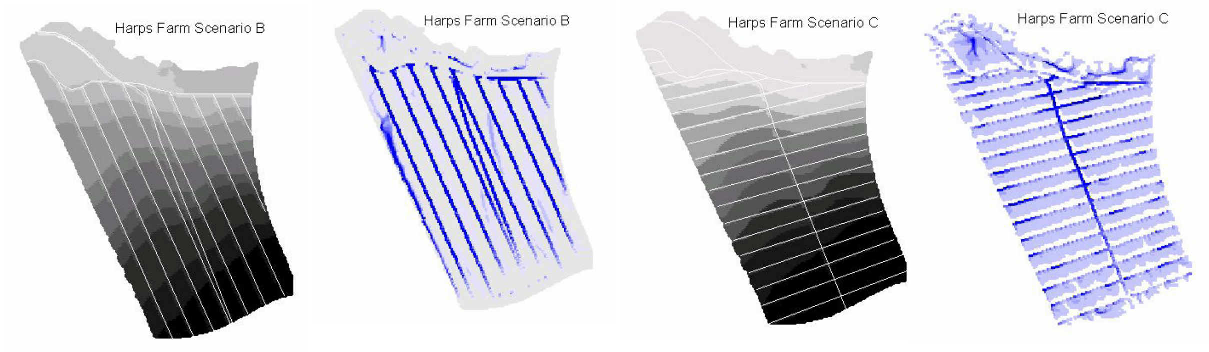
Two tools have been used to investigate flow connectivity at the study sites, TopManage and TOPCAT. TopManage (www.ncl.ac.uk/wrgi/TOPCAT/TopMan.html) is a high resolution digital terrain analysis (DTA) tool designed to help farmers and land managers visualise the effect of different management practices on hydrology. Used in conjunction with a Geographical Information System (GIS) such as ArcView, TopManage enables the user to assess what the effect would be of adding to, or removing from, the land topographic features. Starting from a digital terrain map of a particular field or area of farmed land, usually derived from Geographical Positioning System (GPS) measurement, maps can be input to the GIS, topographic features added, and augmented terrain maps analysed using TopManage. TOPCAT is a hydrological model that provides time series modelling of flow, N and P (www.ncl.ac.uk/wrgi/TOPCAT/TCTheory.html). High resolution maps have been made of Site A (Orford House) Site B (Bunny field) at Bollington Hall and an additional site Harps Farm, chosen to assist in the model development (Figure 10). Field experiments have revealed very different characteristics of these sites. The Orford House site is dominated by subsurface flow, Bunny field by overland flow and land drains and Harps Farm by overland flow only.

The characteristics of the Harps Farm field made it the best choice for a case study for overland flow management. A series of TopManage scenarios were run this field. The effect of introducing water storage features on the field and of different ploughing strategies demonstrates some general points which can be used as input to the NERM. Figures 11, 12 and 13 show five scenarios for the Harps Farm field. The blue maps indicate flow accumulation. Scenario A is the field with a road running down it, Scenarios B and C have tramlines running down and across the slope respectively, Scenario D represents managed



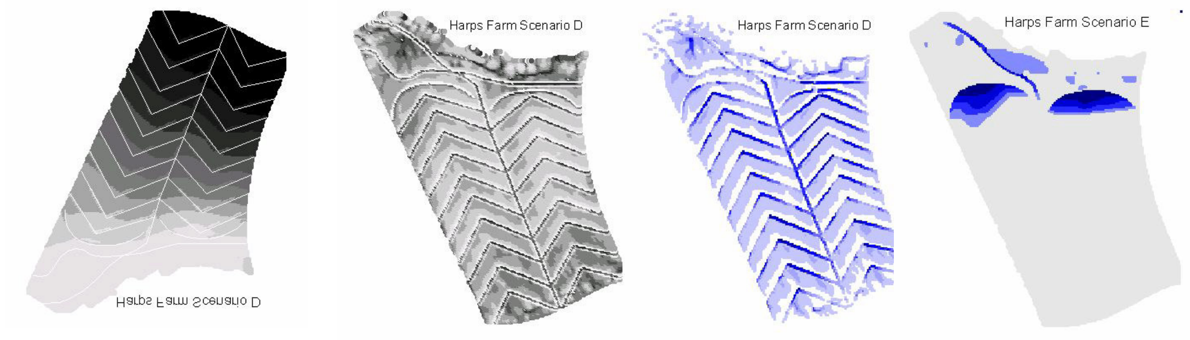
(a) slope (b) topographic index (c) flow accumulation

Figure 11 Scenario A – Harps Farm field with road



(a) tramlines down (b) flow (c) tramlines across (d) flow

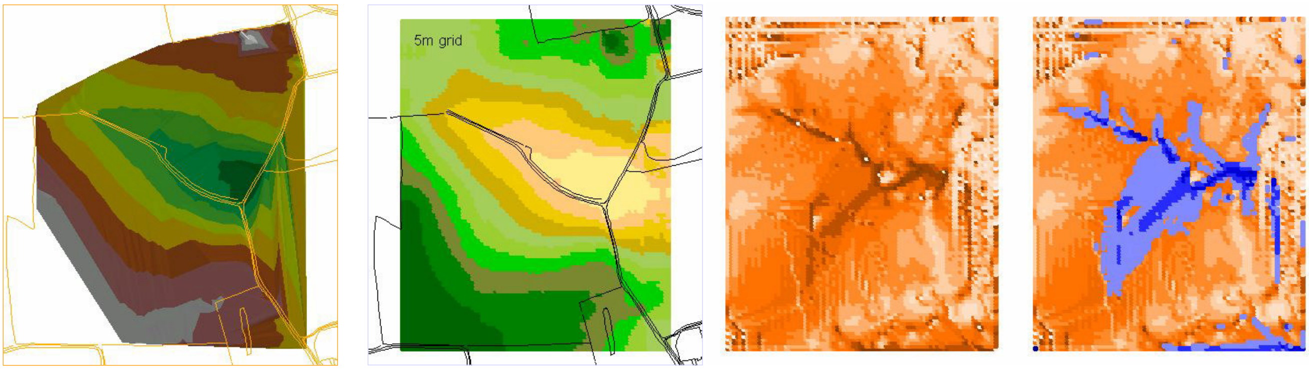
Figure 12 Scenarios B and C – tramlines down (B) and across (C) field slope



(a) managed tramlines down (b) topographic (c) flow accumulation (d) flow

Figure 13 Scenarios D and E – Managed; water storage areas with (D) and without (E) tramlines ploughing to feed water into two storage areas at the bottom of the slope and Scenario E is the case where water storage areas only have been introduced.

A Digital Terrain Map (DTM) was constructed of Bollington (Figure 14 (a) and (b)). TopManage was then used to examine the topography and flow accumulation of the field considering surface flow only, (Figures 14 (c) and (d). Land drains were then superposed onto the field, (Figure 15 (a)) and the TopManage analysis was performed again. The results for the 5m grid are show in Figures 15 (b) and (c). Figures 15 (c) is of particular interest as it demonstrates the flow connectivity created by the presence of land drains – the whole field is effectively transformed into a critical source area (CSA).



(a) TIN based on GPS mapping (b) 5m grid (c) topographic (d) flow accumulation

Figure 14 – Bunny field – surface only

(a) 5m grid with drains (b) topographic index (c) flow

Figure 15 – Bunny field with land drains

Field experiments at the Bollington Hall site have shown that it is dominated by subsurface flow and some interesting baseflow effects. Thus two analyses were performed for this site.

1. an analysis of subsurface flow accumulation using a course scale (10m cells) and estimates of the general gradient of the water table towards the ditch. The results of this analysis are shown in Figure 16.

Figure 16 - Bollington Hall subsurface flow accumulation

2 TOPCAT was used to model the site – the model was calibrated and comparisons made between simulations of flow, nitrates and total phosphorus and the measured time series data (Figures 17, 18,19) for the period December 2002 to March 2003.

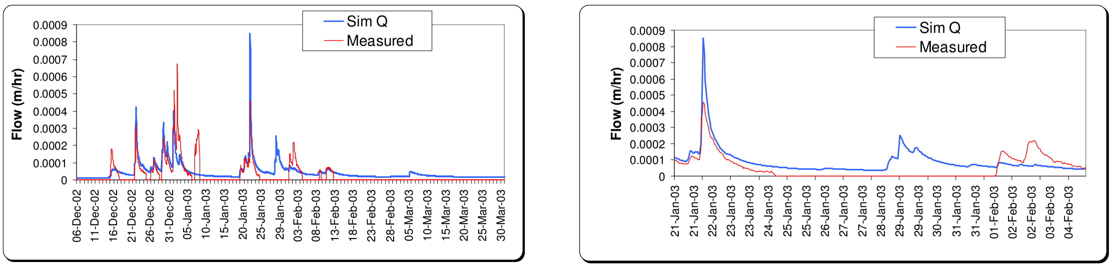


Figure 17 – Measured and simulated flow for Bollington field A

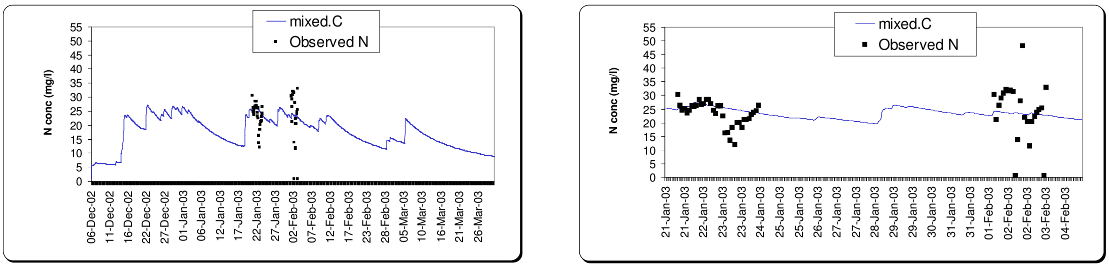


Figure 18 Measured and simulated nitrate concentrations for Bollington field A

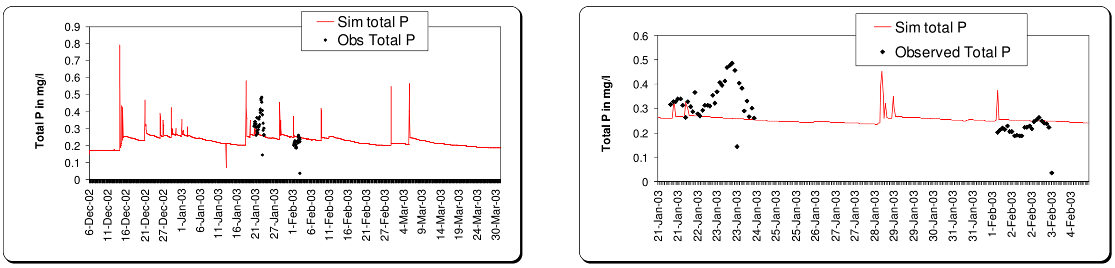


Figure 19 Measured and simulated total phosphorus concentrations for Bollington field A

CATCHMENT MODELLING USING THE INCA MODEL

Work has progressed with the further development of the INCA model and its application to the catchment system. Further refinements of the Nitrogen and Phosphorus models have been undertaken to incorporate an improved soil temperature equation so the soil temperatures are correctly modelled. This is important because N and P concentrations in the soils depend on a range of biochemical reactions which are temperature dependant and thus an accurate estimate of the soils temperature is crucial. Also there has been considerable work on refining the instream components of the models to incorpoate further processes such as biological uptake of N and P.

Model application has focused on the Bollington sub -catchment and the River Stort that Bollington flows into. Several years of daily hydrological, temperature and soil moisture data has been obtained for the Stort as well as all the EA water quality and flow data along the river. Land use maps have been used to proportion land use within all the sub- catchments of the Stort . The INCA-N and P models have been set up for the whole of the Stort catchment and good simulations of N have been achieved. The P model is currently being calibrated. The INCA model has also been applied in a preliminary study to the Bollington site.

THE NERM

The research carried out so far suggests that where agricultural land is subjected to nutrient loadings for agricultural benefit this may not immediately transpire to a nutrient problem unless the nutrient is in a form to be transported and connectivity exists to a receptor. Figure 10a shows the NERM (Nutrient Export Risk Matrix). This helps identify where nutrient source and connectivity meet. Axis 1: P availability (Figure 10a) - is a synthesis of all possible P application forms, crop covers, tillage and husbandry regimes into a single estimate of how much of the P is actually available for direct mobilisation by overland, drain or subsurface flow. Even if a rough estimate is made, a comparative understanding of the surplus

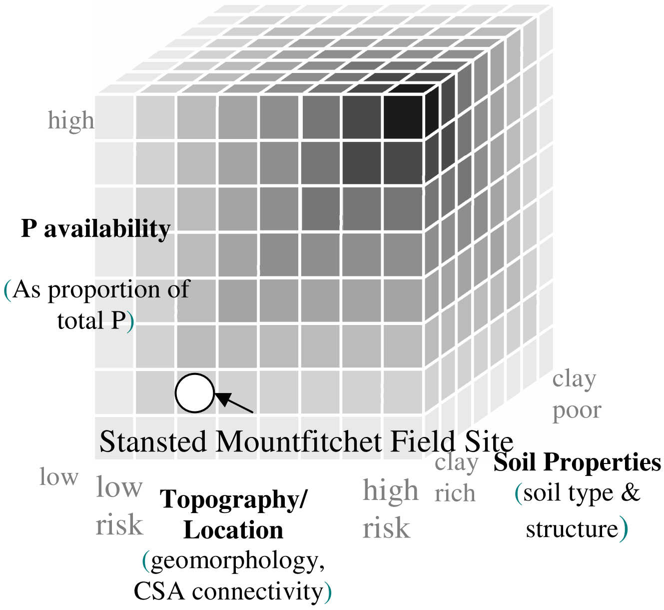
P available in certain sludge/FYM and bag fertiliser forms can be represented along with the total P loading of the field. This is essentially an estimate the P surplus per unit area.

Axis 2: (Figure 10a) Soil type reflects the propensity of a certain soil, under certain cultivation to lose P due to overland flow (in sediment attached and soluble forms), to retain P or to lose P to subsurface P (when the soil becomes P saturated; Heathwaite & Dils, 2000; Heckrath et al, 1995). In this case it allows an estimate of the portion of flow that is lost to the surface water o be compared with the loss to the groundwater

Axis 3: (Figure 10a) flow connectivity - assesses surface topography and the typical landscape features created by farmers, such as tyre tracks and land drains, but also the potential benefits of environmental features such as buffers strips and wetlands. Thus both natural and human influenced features are assessed together. These aspects of P loss are difficult to assess accurately but there is often clear evidence of how chronic and acute P losses can be made relatively quickly. Visual evidence of active flow connectivity can be seen during storms with discoloured water, rich in sediment being lost across fields, within tyre tracks and exiting land drains. The strongest evidence usually lies in the hands of farmer, thus the farmer often plays a key role of acquiring locally derived information. More semi-quantitative evidence can be accrued through a study of the terrain (especially if high resolution terrain map is constructed, (Figure 3) and a set of rudimentary, inexpensive, portable hydrological field instrumentation are performed. For example, understanding the infiltration rate of the soil reflects the likely overland flow risk. Some measurement of flow in local ditches also points towards the operation of local land drains or subsurface flow in storm events. Shallow piezometer activity is also a vital indicator of the rapid response subsurface flow paths. For the case shown here it is clear to see the dominance of deeper groundwater processes and hence the need install a range of piezometers to asses/ confirm that this is the dominant process.

Thus the third axis in Figure 10a reflects the flow connectivity aspects of P loss. It also points towards many possible, cheap land management options that will reduce P. The first is obviously lowering surplus P in hydrological active zones. Secondly there is the possibility to manage runoff at key locations within the landscape, such as within field and local ditches if required.

In Figure 10b and 10c we show a typical question and answer session that the farmer and the land manager can perform to: (i) estimate the risk of their fields to P loss, and (ii) estimate the likely improvement to P reduction if a series of simple land management options are performed. The position of this research site is shown within the NERM in Figure 10a where surface CSA are few and therefore there is low P export risk in terms of near surface ‘quick’/acute runoff processes and with the large unsaturated zone and associated sorption processes connectivity to the groundwater is reduced in respect of nutrient transfer.



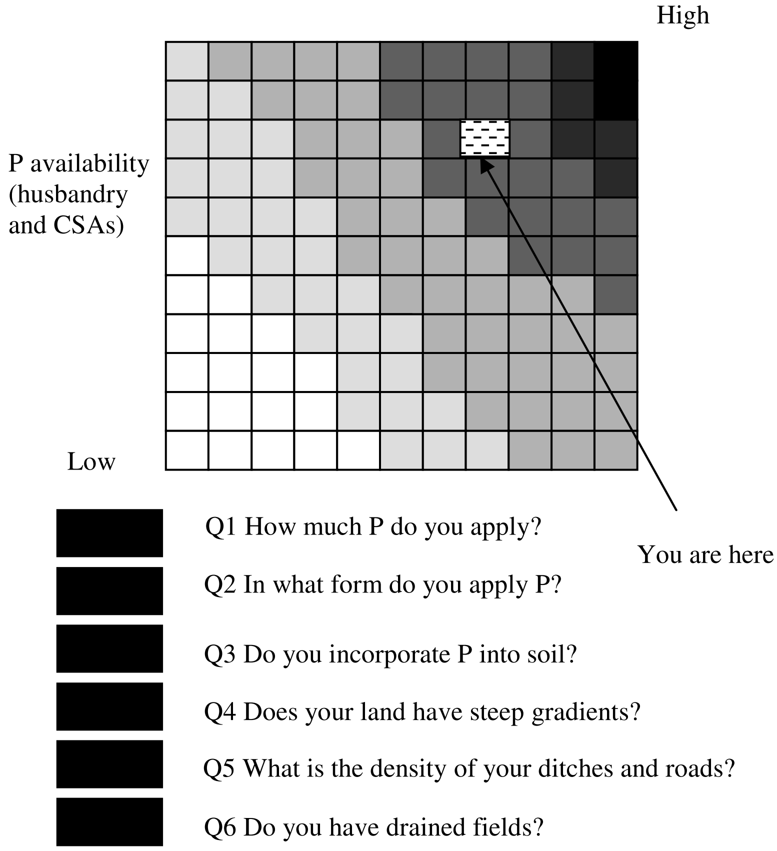


Figure 10a

Figure 10b

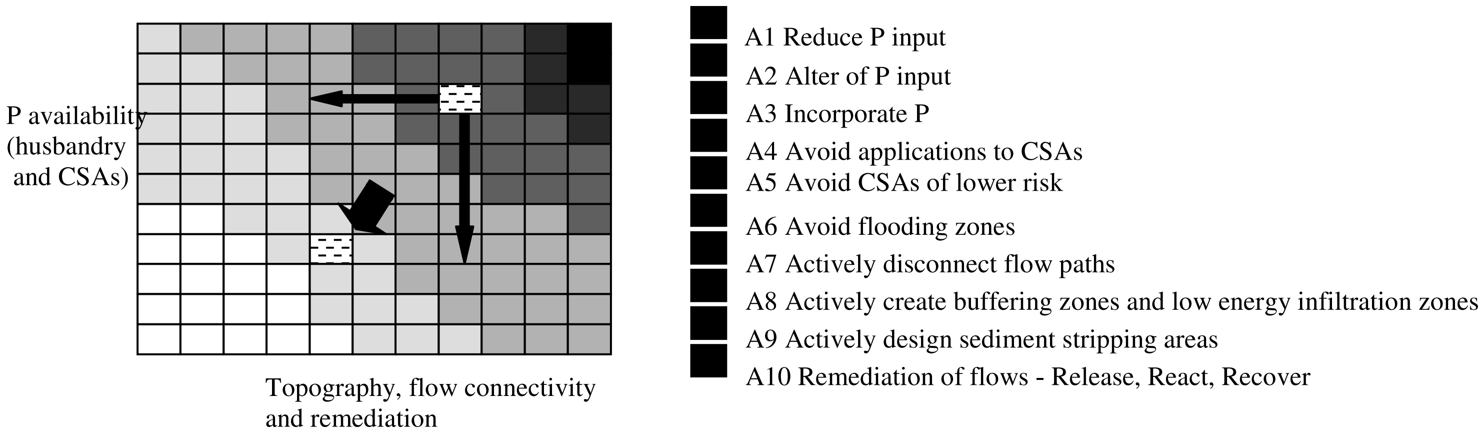


Figure 10c

PROGRESS SUMMARY

The cutting edge of our research is interfacing of field and modelling approaches by combining our research expertise to address real problems that are both generic (e.g. scaling-up) and specific (e.g. sludge recycling to land). WP1 is completed. Field experimentation under WP2 is ongoing but was seriously impacted by the foot and mouth (F&M) outbreak WP3/4 are using the material from WP1 plus the preliminary data from WP2 to develop the models. We have focussed our steering group meetings on WP5 (the decision support framework, DSF) to bring onboard the needs of our end-users from the start of the project. This means we have the criteria for our DSF, the NERM (Nutrient Export Risk Matrix) already agreed and awaiting validation using input from our field and modelling work.