The Nutrient Export Risk Matrix (NERM) for strategic application of biosolids to agricultural land

LOUISE HEATHWAITE, SEAN BURKE
Department of Geography, University of Sheffield, Sheffield, UK
a.l.heathwaite@sheffield.ac.uk

PAUL QUINN
School of Civil Engineering and Geosciences, University of Newcastle, Newcastle, UK

Abstract Diffuse phosphorus (P) export from biosolids application to agricultural land above specified soil P thresholds or incidental losses of nutrients applied as manure or fertilizers during high risk periods, may be linked to deteriorating surface or groundwater quality. However, our research suggests that not all land has an equal risk of contributing diffuse contaminants to receiving waters, either via surface or groundwater delivery routes, and that high risk is associated with critical source areas of diffuse pollution where source and transport risks coincide. We report the initial output from a research programme examining the environmental risk of biosolids recycling to agricultural land, which is being synthesized into a risk advice matrix: the Nutrient Export Risk Matrix or NERM for end-users in the water industry. The intention is that 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.

Key words agriculture; biosolids; diffuse pollution; nutrients; phosphorus; sewage sludge

INTRODUCTION

The recycling of livestock waste and biosolids to agricultural land benefits soil quality owing to the increased supply of major plant nutrients (N and P); provision of some essential micro-nutrients (Zn, Cu, Mo and Mn); and improvement in soil physical properties, primarily soil structure, increased soil water capacity, and improved soil transmissivity (Snyman et al., 2000). Recent research has sought to quantify whether excess biosolids application to agricultural land (McGrath et al., 2000; Wong et al., 2000); or incidental losses of nutrients applied as manure or fertilizers during high risk periods (Preedy et al., 2001), is linked to deteriorating surface or groundwater quality. Such research is motivated by knowledge that diffuse phosphorus (P) export from land is a key driver of the eutrophication of surface waters (Edwards & Withers, 1998; Dils & Heathwaite, 2000; Environment Agency, 2000) and may contaminate groundwater resources (Withers & Lord, 2002).

Of particular concern is the growing evidence for the accumulation of P in soils receiving biosolids (see Fig. 1), and the possible risk such accumulation poses for groundwater resources (Barry et al., 1995; Kyle & McClintock, 1995; Siddique et al.,
2000). Part of the explanation of the current UK P surplus of ~10 kg ha$^{-1}$ year$^{-1}$ may lie in P enrichment of surface soils because applications to land (e.g. livestock manure P) are undervalued (Sharpley & Withers, 1994). Soil P saturation across Europe is already well-documented (e.g. Leinweber et al., 1999) and may further elevate diffuse P losses to surface and groundwater (e.g. Hughes et al., 2001; Jordan et al., 2000). The environmental risk linked to soil P saturation is recognized in the *UK Code of Good Agricultural Practice for the Protection of Water* (MAFF, 1998), which sets an advisory standard that restricts P application (including biosolids) to land where fields are at or above guidelines recommended in the *Code of Good Agricultural Practice* at soil P Index 3 (MAFF, 1998). This standard is applied on a field-by-field basis and has no sensitivity to the hydrological connectivity of fields in the landscape to receiving waters. We suggest that such restrictions on biosolids recycling to land are based on limited information and may not optimise the available capacity of the agricultural system. The research presented here aims to show that not all land has an equal risk of contributing diffuse contaminants to groundwater but that high risk is associated with critical source areas of diffuse pollution where source and transport risks coincide (Heathwaite & Sharpley, 1999). Furthermore, not all receiving waters are of equal sensitivity to P inputs. A holistic approach matching landscape risk to receiving water sensitivity is needed. Within any agricultural catchment it is possible to have areas with a high potential to contribute P but no P transport if the hydrological connectivity does not exist. Where connectivity does not exist between source and receiving waters, a high nutrient source does not necessarily constitute a high nutrient risk. The theoretical basis to the critical source area concept has been examined recently by Endreny & Wood (2003).

The preliminary research reported here forms part of an integrated multi-scaling field and modelling programme examining the environmental evidence for non-point source pollution from agricultural land receiving biosolids applications (see: *The Seal Project*: www.shef.ac.uk/seal). The end product of this research programme will be a predictive and spatially-sensitive semi-distributed model of critical thresholds for biosolids recycling to land. The integrated approach used in the project goes beyond traditional “end-of-pipe” or “edge-of-field” modelling, to include hydrological delivery to receiving waters from diffuse sources at the catchment scale. 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 synthesized 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 (SSM). The SSM has only two criteria: crop uptake (potential contaminant end-point) and sludge type (potential contaminant hazard). For biosolids-derived nutrients, we suggest that as the receptors are water bodies then crop uptake is not a useful risk indicator. Our work is focused on deriving a more environmentally-sensitive risk tool for biosolids-derived pollutants.

The NERM seeks to offer farmers and land managers the opportunity to assess the relative risk of their field/hillslopes to contributing to an overall P loss (P export to the environment). The NERM is based on quantitative evidence for P loss processes from land (e.g. Heathwaite & Dils, 2000) combined with the interpretation of information regarding local soil processes, historical evidence of P loss, local topographic controls on hydrological flow paths, and current farmer practices that may exacerbate the P loss (through land drainage, ditching and surface flow along tyre racks and tramlines) that really allows us to assess the realistic P loss risk. The SEAL project is calibrating the NERM with fully worked field applications. Moreover the NERM brings together the key P loss terms in a simple 3-dimensional (3-D) visual format, that allows:

(a) A rough estimate of the P loss risk for any site and the uncertainty of that estimate.
(b) The likely impacts of a range of land use management options, i.e. in the control of P surplus and the connectivity of that P surplus to the receiving waters.

SITE DESCRIPTION

Figure 2 shows the layout of the field site located near Stansted Mountfitchet, Essex, UK. Catchment geology is dominated by glacial sands and gravels overlying the Upper Chalk with an unsaturated zone of around 20 m, emphasizing the predominance of groundwater pathways at the site, although the heterogeneity of the sands and gravels results in locally perched water tables. The soils range from sandy loam to clay loam, with boulder clay present on the eastern edge of the site. The area receives an annual rainfall of around 600 mm. A total of 31 piezometers were installed along with two flumes, a Delta-T weather station, three TDRs at depths of 0.3, 0.6 and 0.9 m, 15 Teflon samplers and five zero tension samplers. A multi-level approach was taken with the piezometer installation with depths ranging from 1 to 15 m. Five piezometers were also installed with Solnest pressure transducers logging water depth (cm) at 15-min intervals. The water levels in the piezometers do not respond significantly to rainfall and indicate the groundwater nature of the site. A field drain drains the northeastern section of the site.

Digested sludge cake and lime stabilized sludge was applied to the field site in October 2001. Lime stabilized sludge was applied at 25 t ha⁻¹ with digested sludge...
Fig. 2 Layout of the experimental field site for the SEAL Project (Strategic Management of Non-point source pollution from Sewage Sludge) field site, Essex, UK.

applied at 50 t ha\(^{-1}\), equivalent to around 9000 mg total P kg\(^{-1}\) sludge and 15 000 mg total N kg\(^{-1}\) sludge for the lime stabilized sludge, and 1100 mg total P kg\(^{-1}\) and 7000 mg total N kg\(^{-1}\) for the digested sludge cake.

A Digital Terrain Map (DTM) was constructed based on a detailed field survey for a section of the field site using equipment supplied by the CHASM programme (www.ncl.ac.uk/chasm). Water samples were collected from the piezometers every 14 days from November 2001 to date. The samples were pre-filtered through a 0.45-\(\mu\)m Millipore filter on-site and stored around 4°C before analysis within 24 h of sample collection. Laboratory analyses for PO\(_4^{3-}\), NO\(_3^-\) and NH\(_4^+\) were carried out using Flame Injection Analysis (FIA); pH, temperature, redox potential and total dissolved solids were determined on site using a Camlab ultra-meter.

RESULTS AND DISCUSSION

The DTM shown in Fig. 3 was constructed to identify any likely critical source areas (CSAs) within the field site and to gain an understanding of the local hydrology of the site. The DTM illustrates the varied topography of the site and the likely locations of
**Nutrient Export Risk Matrix (NERM) for strategic application of biosolids to agricultural land**

**Fig. 3** Digital Terrain Model (DTM) at 2 m resolution for the southern field of the SEAL experimental site (= Site B, Fig. 2) showing the hydrological instrumentation including piezometer locations sampled to generate the data shown in Fig. 4 and the likely positions of critical source areas (CSAs) within the field site.

**Fig. 4** The variation in dissolved reactive P (DRP) (<0.45 μm, mg l⁻¹) and total P (TP) (mg l⁻¹) at a range of locations across the field site.

any critical source areas. For example, flow contribution via the field drain is a likely source area for a surface CSA and therefore has important implications for the position
of a site within the NERM. The existence of the drain within the field was confirmed by locating and sampling at the drain outfall to the drainage ditch. For this particular field, a single large concrete drain outfall had been installed. At other nearby fields, field drains have been installed to 65 cm depth and at a 20 m drain spacing in order to drain a perched water table (see later and Fig. 5(a)). Figure 4 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 m. The results shown in Fig. 4 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\(^{-1}\); whereas the TP concentrations ranged from 0.2 to 1 mg l\(^{-1}\) with the majority of samples having TP

![Diagram](image)

**Fig. 5** The Nutrient Export Risk Matrix (NERM): (a) conceptual basis for the NERM; (b) identification of pre-mitigation risk locations within the NERM; and (c) approaches available to change the risk position within the NERM.
concentrations above 0.2 mg l\(^{-1}\). The elevated TP concentrations in the piezometers indicate a source of P. However, the 20 m 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. Currently, work is being undertaken to partition the flow from the field through lateral flow paths linked to the perched water table, relative to vertical percolation to the underlying chalk aquifer. The assumption is that lateral flow paths are only important for a limited period of time when drain flow and ditch flow are recorded in the winter months. However, such flows are probably disproportionately important for P delivery from land to receiving waters.

The research presented above suggests that where agricultural land is subjected to nutrient loadings that are in balance with crop off-take and soil nutrient concentrations, this may not necessarily lead to a nutrient loss risk unless the nutrient is present in a form that is readily transported and connectivity exists to a receptor. The NERM shown in Fig. 5(a) helps identify where nutrient source and connectivity meet:

**AXIS 1: P AVAILABILITY** 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 mobilization by overland, drain or subsurface flow. Even if a rough estimate is made, a comparative understanding of the surplus P available in certain sludge/farm yard manure and bag fertilizer forms can be represented along with the total P loading of the field. This is essentially an estimate of the P surplus per unit area.

**AXIS 2: SOIL TYPE** reflects the propensity of a soil, under different cultivation practices 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; Heckrath *et al.*, 1995; Heathwaite & Dils, 2000). In this case it allows an estimate of the portion of flow that is lost to the surface water to be compared with the loss to the groundwater.

**AXIS 3: FLOW CONNECTIVITY** assesses surface topography and the typical landscape features created by farmers, such as cultivation 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 qualitative evidence of the relative balance between chronic and acute P losses that may be made relatively quickly. Visual evidence of active flow connectivity can be observed during storms with discoloured water, rich in sediment, often being generated in surface flow paths across fields, within tyre tracks and exiting land drains. The strongest evidence is usually derived from the day to day observations of the farmer or site manager, who can play a key role in acquiring local site information. Added to this subjective information is semi-quantitative evidence accrued through a study of the terrain—especially if high resolution (approx. 2–5 m) terrain maps are constructed (Fig. 3) and used alongside rudimentary observations made using temporary installations of inexpensive, portable hydrological field instruments. For example, evaluation of 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 to install a range of
piezometers to assess/confirm that this is the dominant process.

The third axis shown in Fig. 5(a) reflects the flow connectivity aspects of P loss. It
also points towards a number of feasible and cheap land management options that may
reduce P loss from land. The first is obviously lowering surplus P in hydrological
active zones. Although it should be acknowledged that while the scientific case for this
action might be obtained via GPS-related precision agriculture techniques or through
more traditional soil P balance analyses, this is not the same as convincing a farmer not
to apply to these zones. Here the dialogue set-up between the farmer and researchers in
obtaining qualitative evidence for sediment and associated P transport is important in
defining the extent of the problem and discussing practical measures to reduce it.
Secondly there is the possibility to manage runoff at key locations within the
landscape, such as within field and local ditches if required.

In Fig. 5(b) and (c) we show a typical question and answer session that the farmer
and the land manager can perform to: (a) estimate the risk of their fields to P loss, and
(b) 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 Fig. 5(a) 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.

CONCLUSIONS

The preliminary research reported here describes a simple risk-based matrix approach
for evaluating sediment and associated P losses from critical source areas in the
landscape. The matrix combines use of technologically-advanced, but now widely
available GPS systems to produce high-resolution digital terrain maps at the field
scale, with simple field measurements of potential hydrological flow paths and soil
physico-chemical characteristics. The matrix has been successfully applied to a site
with complex hydrology and has been shown to identify areas of greatest risk from P
losses. At such locations strategic land management advice might consider recommend­
ing reduced P applications or different land uses. Equally, the matrix can be used to
identify land areas where the risk of P loss is low and hence the application of, for
example, biosolids to the land surface is not of environmental risk to receiving waters.

REFERENCES

metal and phosphorus sorption characteristics of soil. Water Res. 29(9), 2031–2034.
Manage. 14, 124–130.
Nutrient Export Risk Matrix (NERM) for strategic application of biosolids to agricultural land


