INCORPORATING UNCERTAINTY INTO PREDICTIONS OF DIFFUSE-SOURCE PHOSPHORUS TRANSFERS (USING READILY AVAILABLE DATA)

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ABSTRACT
Phosphorus (P) is a limiting nutrient in many freshwater ecosystems and increases in its availability can lead to eutrophication. Effective management of P in freshwaters requires quantitative estimates of P supply from all significant sources. A simple GIS-based model, capable of predicting total diffuse source phosphorus export from catchments using readily available data, has been developed. The model is based on the idea of export coefficients but includes the effects of topography (slope and cumulative area), soil type (using the UK Hydrology of Soil Types (HOST) classification) and climate (hydrologically effective rainfall) as well as land use. Uncertainty in key model parameters is accounted for using Monte Carlo simulation which involves random sampling from probability density functions in a large number of iterations. This reduces the need for subjective optimisation of export coefficients. The model has been applied to the Greens Burn catchment, Scotland and predicts P exports within the confidence limits of the measured values.

Keywords : Phosphorus Export, GIS, Modelling, Monte Carlo

INTRODUCTION
There is wide concern relating to the eutrophication of surface waters and the associated enhanced growth of algae and aquatic macrophytes (e.g Vollenweider, 1968). Research indicates that phosphorus (P) is often the main limiting nutrient in freshwaters (e.g. Foy & Bailey-Watts, 1998) and consequently efforts have been concentrated on reducing P transfers to susceptible water bodies. Point sources are relatively easy to quantify, given information on flow rates and concentrations or the number of people served by a particular sewage treatment plant. In addition, point sources can be treated with end of pipe abatement measures. As a result, there is now a focus on diffuse sources, of which agriculture can be the most important contributor. The influence of agriculture can be divided into P additions (fertiliser and animals) and soil management (e.g. tillage regime and crop type), both of which can affect P transfer.

Numerical models allow the prediction of surface water nutrient concentrations and loads on the basis of the most important controlling factors (e.g. land use, climate and soil type). Many different approaches (of varying complexity) have been developed, ranging from simple empirical models to distributed physically-based models. The problem with more complex models is that they have high data requirements and sometimes give little, if any, improvement on the predictions of simpler models. In this paper we describe a model which attempts to capture the most important factors controlling diffuse source P transfer to surface waters whilst retaining low and readily available input requirements.

METHODS
Our approach is based on the export coefficient model (e.g. Johnes & O'Sullivan, 1989). This is probably the simplest description of P export available and assumes that present land use is the most significant control on nutrient export. Total annual nutrient (nitrogen and phosphorus) loading to surface waters is predicted by estimating export coefficients from each of the constituent land uses in the catchment, such that, for phosphorus

$$P = \sum_{i=1}^{n} c_i A_i + \sum_{j=1}^{m} \omega_j n_j \qquad (1)$$

where

P	=	estimated P load (kg a^{-1})
c_i	=	export coefficient for land cover type i (kg ha^{-1} a^{-1})
A_i	=	area of land cover type i (ha)
ω_j	=	export coefficient for animal type j (kg ca^{-1} a^{-1})
n_j	=	number of animals of type j
n	=	number of land cover types in catchment
m	=	number of animal types in catchment

The export coefficients represent all controls on nutrient transfer (edaphic, hydrological and management). For phosphorus, the coefficients are expressed as mass ha^{-1} a^{-1} rather than as a proportion of the amount of P applied because phosphorus transfer is often independent of input rate in the short term.

The simplicity of this model has made it popular with regulators and policy makers. However, there are a number of problems: Firstly, no account is taken of the uncertainty in the selected export coefficients. For any particular land use, phosphorus export will vary from year to year and from location to location. This is reflected in a wide range of measured values of phosphorus export reported in the literature (e.g. Table 1) and means that the basis for selecting a meaningful coefficient for each of the constituent land uses of a catchment will always be highly uncertain, particularly in the absence of site-specific measurements. A common approach is to invoke a calibration procedure, which involves adjusting the coefficients so as to obtain a good match between the observed and measured fluxes. However, this will be poorly constrained as several different combinations of export coefficients may generate equally good fits to measured data. Alternatively, the selection of coefficients may be achieved subjectively, with expert opinion being sought to ascertain the likely export for land uses in a specific catchment. With both these approaches, the model parameters are set for a specific catchment and hence are not universally applicable.

Secondly, the position of each field in relation to receiving watercourses is not explicitly considered. The P transferred from all fields with the same land use is assumed to be the same, regardless of where the fields are in the catchment. However, it is reasonable to expect that P exported from a field far from a watercourse is more likely to be retained in the catchment (by deposition of sediment-associated P or adsorption of dissolved P) compared with a field adjacent to the receiving waterbody. Likewise, a field on a steep slope is more likely to export P than an otherwise identical field on a shallow slope. Finally, since P export is predicted solely on the basis of land use, the model cannot predict inter-annual variations in P losses due to changes in hydrological processes, although it is known that more phosphorus will generally be transferred in wet years than in dry years (e.g. Heathwaite, 1997).

In the model described here we have modified the export coefficient model by attempting to address these limitations. In addition to land use, the model requires information on topography (slope and cumulative area from the divide), soil type, annual precipitation and annual actual evapotranspiration, which are used to adjust export coefficients and to produce uncalibrated, catchment-specific predictions.

Table 1. Range of export coefficients for crops and animals

Land Use	**Export kg P ha^{-1} a^{-1}**		
	Average	**Minimum**	**Maximum**
Grass	0.52	0.02	4.90
Arable/Cereals	1.40	0.06	5.67
Row Crops	1.68	0.02	5.77
Animal	Input kg P ca^{-1} a^{-1}		
	Average	Minimum	Maximum
Cattle	10.4	3.13	17.6
Sheep	1.59	1.47	1.80
Humans (Septic Tank)	0.65	0.30	1.00

(compiled from Vollenweider, 1968; Kolenbrander, 1972; SAC, 1992; Johnes et al, 1994; Smith et al, 1998; Brady & Weil, 1999; Turner & Haygarth, 2000; McGechan, in press). For animals, the export is calculated as: input * proportion applied to land * proportion estimated to reach surface waters. The proportion applied to land is assumed to be 70 – 100% for cattle and 100% for sheep (after Richardson, 1976 and Gostick, 1982 in Johnes et al, 1996). The proportion estimated to be lost to surface waters is 1 – 5% (after Vollenweider, 1968). Where slurry and hen manure are applied to the land, the inputs are taken as 10 kg P tonne^{-1} hen manure and 7 kg P 1000 L^{-1} slurry (after SAC, 1986).

Catchments are represented, using a Geographical Information System (GIS), as a raster grid with boundaries defined using the digital elevation model (DEM). Each cell in the grid is characterised by its land use, soil type and its topographic attributes (slope and cumulative area drained from the divide).

In order to account for the uncertainty in the export coefficients selected for each land use, Monte Carlo simulation is employed. This involves making a large number of iterations of the deterministic model core. In each iteration, a value for each export coefficient is randomly selected from a probability distribution constructed from the range of published coefficients for that land use (see Table 1). Although calculations are made for each grid cell, the same export coefficient is used for cells of the same land use in each iteration. This is superior to the alternative technique of sampling from the relevant export coefficient distributions on a cell by cell basis as it results in a wider distribution of predicted P transfers which better reflects the constituent uncertainties. In the absence of information to suggest otherwise, uniform distributions, with ranges defined in Table 1, are currently used for all export coefficients.

In addition to cropping, the contribution of animals to the total phosphorus (TP) load is included. To do this it is assumed that (1) animals are evenly distributed in all cells suitable for grazing (i.e. grass and rough grazing); (2) manure is spread evenly on all land use types and (3) where information on the position of sewage outlets (e.g. septic tanks) is not available, P resulting from humans is uniformly distributed over the catchment. Animal export coefficients are also selected randomly from probability distributions constructed using measured data.

In each iteration, the combined P export (cropping and animal) from each cell is corrected for topography (slope and cumulative area), soil type and annual hydrologically effective rainfall (*HER*). Slope is important in the erosion of sediment (e.g. Nash *et al*, 2000) so that, with all other factors remaining constant, steeper slopes pose a greater erosion risk and hence an elevated likelihood that sediment-associated phosphorus will be exported. Greater drainage area will result in greater surface and sub-surface discharge with more risk of erosion and a greater chance of both sediment-associated and dissolved P being transported. In addition, since upslope area increases as cells get closer to the channel network, it can also be used as an inverse surrogate for distance to streams. Topographic controls are included in the model using generic empirically-based equations summarised by Rustomji & Prosser (2001), i.e.:

$$q_S = k_1 . q^b . S^g$$

where $q = k_2 . a^l$

i.e. $q_S = k_1 (k_2 a^l)^b S^g$ (2)

where
$\mathbf{q_s}$ = sediment flux per unit width of slope
$\mathbf{q}$ = discharge per unit width
$\mathbf{S}$ = local gradient
a = hillslope area per unit width of contour
$\mathbf{k_1}$, $\mathbf{k_2}$, **b**, **g**, **l** = constants

The following parameter values were chosen for hillslope hydrological conditions in humid temperate climates, such as Britain (i.e. dominated by subsurface throughflow and the development of variable source areas) based on guidelines given by Rustomji & Prosser (2001): $k_1 = k_2 = \lambda = 1$; $\beta = \gamma = 1.4$. Since it is difficult to predict absolute sediment and phosphorus fluxes using a generic model, we have defined the relative flux (*RF*, 0-1) as:

$$RF = \frac{\ln(q_s + 1)}{\max[\ln(q_s + 1)]} \quad (3)$$

Soil properties (e.g. texture and organic matter content) are potentially important in the transfer of phosphorus (e.g. Morgan, 1997; Brady & Weil, 1999). To incorporate the effect of soil type into the model, we have adopted a well-tested and readily available soils classification system. The UK Hydrology of Soil Types (HOST) classifies UK soils into 29 classes on the basis of hydrology and geology (Boorman *et al*, 1995). Soils from different HOST classes will respond differently to rainfall, producing varying degrees of runoff. HOST predicts a standard percentage runoff (*SPR*) value for each HOST class. For each soil series, which may contain a number of different HOST classes, a weighted average for *SPR* can be calculated. These *SPR* values are used in the model to further adjust the export coefficients such that soils with greater *SPR* will have a greater likelihood of transferring dissolved and sediment-associated phosphorus than otherwise similar cells. The soil weighting factor (*SWF*) describing the relative transfer of P is defined as:

$$SWF = \left(\left[\frac{\max SWF - \min SWF}{\max SPR - \min SPR} \right] * SPR \right) + SWFi \quad (4)$$

where

max*SWF*	= maximum *SWF*, as defined by the model user; default = 0.8
min*SWF*	= minimum *SWF*, as defined by the model user; default = 1.2
max*SPR*	= maximum *SPR* value in catchment
min*SPR*	= minimum *SPR* value in catchment
SPR	= *SPR* value for specific cell
SWFi	= *SWF* intercept, defined by max*SWF*, min*SWF*, max*SPR*, min*SPR*

In addition to affecting hydrological response, soil type can also influence erosivity (the propensity of soil to erode). Whilst we recognise that this may be important in many circumstances, we believe that other factors probably outweigh erosivity in much of the UK and consequently it has not been included in the model for the sake of simplicity.

Climatic controls on the transfer of phosphorus to surface waters are incorporated using hyrdologically effective rainfall (*HER*) for the catchment under consideration in each year. This is calculated by subtracting the actual evapotranspiration (*AET*) from the annual rainfall total. *AET*, which includes interception losses, is derived from predictions made by the Meteorological Office Rainfall and Evapotranspiration Calculation System - MORECS (Thompson *et al*, 1981). For each year a relative weighting factor is calculated by dividing the *HER* for that year by the average *HER* for all years. This is based on the reasonable assumption that annual P flux (although not necessarily concentrations) will be directly proportional to *HER* (see for example Figure 3b).

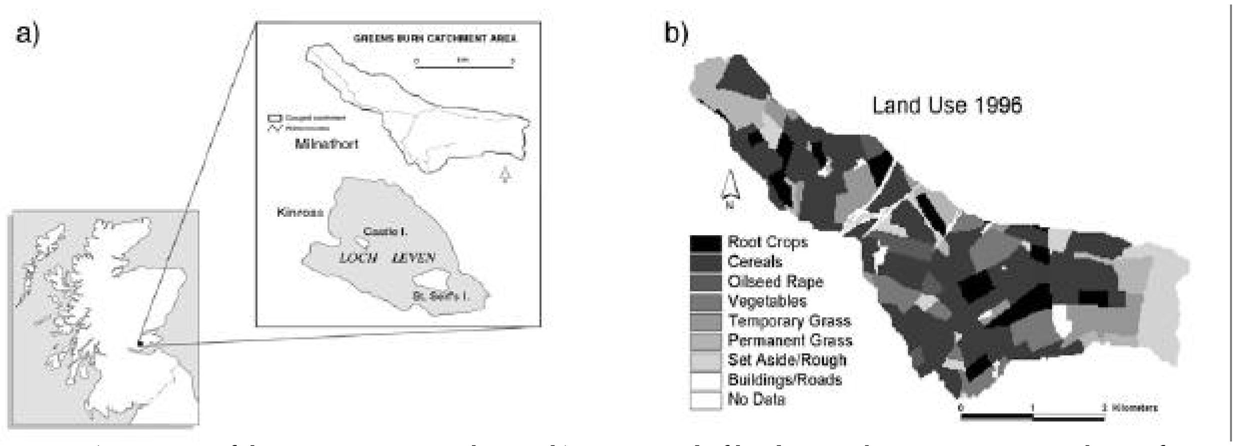

Figure 1. *a) Location of the Greens Burn catchment, b) Raster grid of land use in the Greens Burn catchment for 1996.*

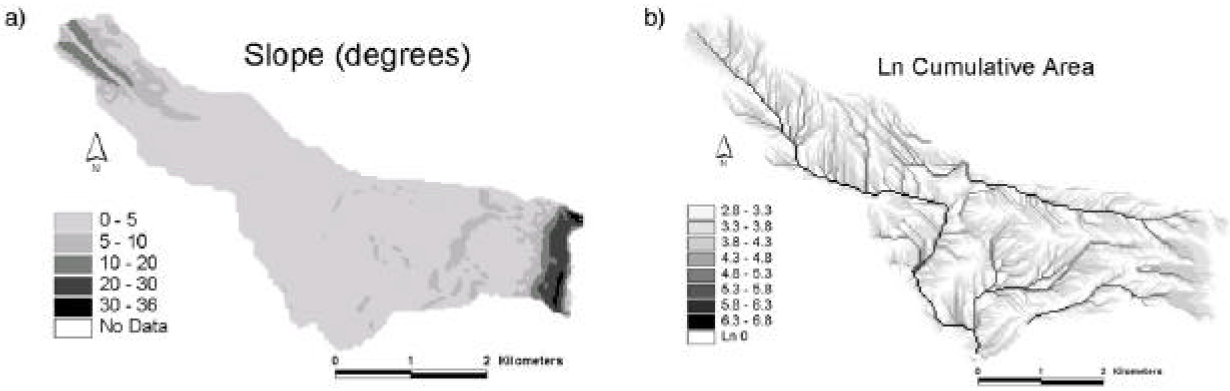

Figure 2. *a) Slope and b) Natural Log of Cumulative Area for the Greens Burn catchment.*

Soil type for the Greens Burn catchment is detailed in the Soil Survey of Scotland, 1:250,000. Using HOST, a map of weighted SPR *values for the catchment was created (Figure 3a). Soils in the centre of the catchment are predicted to produce less runoff than those to the east and west, all other factors remaining constant.*

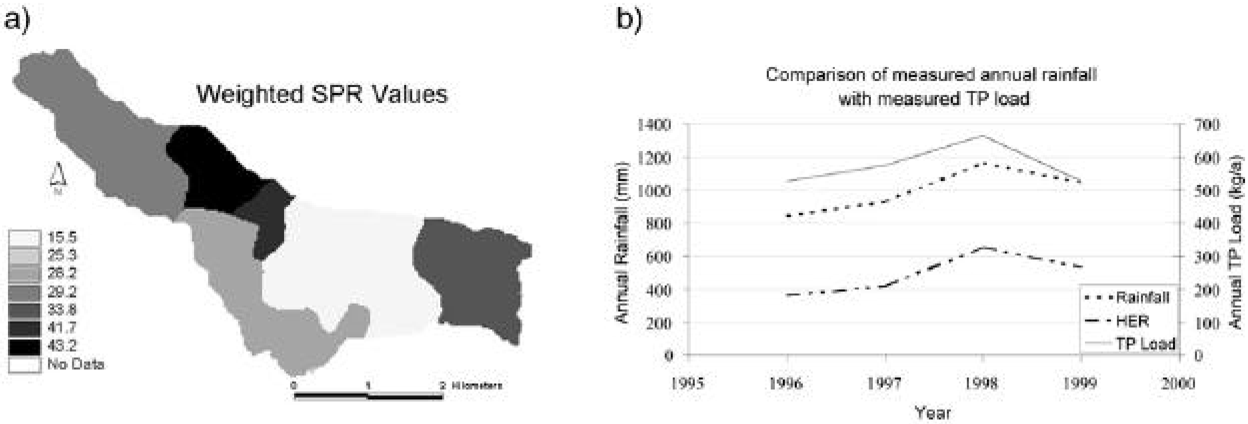

Figure 3. *a) Weighted* SPR *coefficients for each soil class (as defined by the Soil Survey of Scotland, 1:250,000, The Macaulay Inst. for Soil Research, Aberdeen, 1982), derived from HOST. b) Comparison of measured average annual rainfall and* HER *with measured average annual TP loading, 1996 – 1999, for the Greens Burn catchment. Correlation between TP and* HER *is 0.997 (p-value = 0.003).*

MODEL APPLICATION

The model was applied to the Greens Burn catchment, Scotland, UK (location shown in Figure 1a). The gauged catchment is approximately 10 km^2 and drains into Loch Leven. The loch has historically shown signs of eutrophication, which led to the establishment of the Loch Leven Area Management Advisory Group (LLAMAG) in 1992. Since then, major reductions in point sources of phosphorus have been achieved (LLCMP, 1999) and an appraisal of measures to reduce diffuse sources is currently being carried out.

Land use data and stocking densities for the catchment were obtained by interviewing farmers (shown for 1996 in Figure 1b). Slope and cumulative area were derived from a raster grid DEM with a 25m grid cell resolution (Figure 2) using standard routines in ArcView GIS (ESRI, 1996).

RESULTS AND DISCUSSION

Figure 4 shows the frequency distribution of predicted P transfer produced for the Greens Burn catchment from 500 iterations for 1996. The distribution is approximately symmetrical with a mean flux of 486 kg a^{-1} (0.45 kg ha^{-1} a^{-1}) and a standard deviation of 111 kg a^{-1} (0.10 kg ha^{-1} a^{-1}). The graph also shows the load estimated from measured concentration and discharge data (± 1 SEM) for 1996. The high uncertainty in the measured load arises as a consequence of the high variability in measured concentrations and the low number of samples taken (n=14). It is important to recognise that the observed data with which the model output is compared is, itself, an estimate with a potentially high error. From the graph, the similarity between the range of predicted loads and the measured load is evident.

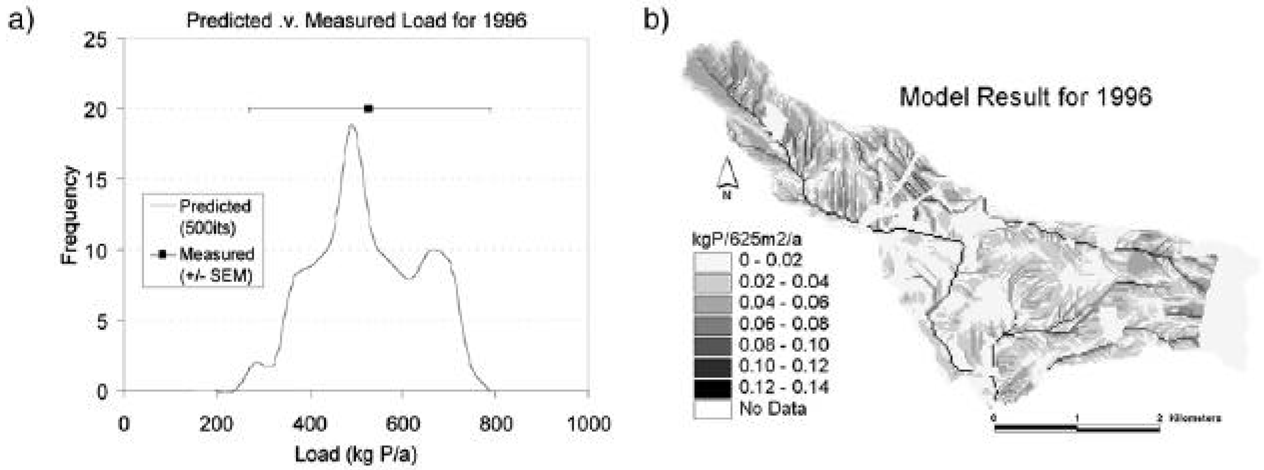

Figure 4. *a) Frequency distribution of predicted TP loads (500 iterations) compared with an estimate of the load derived from measured data (±1 SEM) for the Greens Burn catchment. b) Spatial distribution of P losses from the Greens Burn catchment for 1996.*

The spatial distribution of predicted phosphorus export from the Greens Burn catchment for 1996 is shown in Figure 4b. This shows the combined effects of land use, slope, proximity to watercourses and soil type. Such a visualisation can help to show up “hot spots” for P loss which can be targeted for special management measures. Worthy of note are the grassland areas in the northwest of the catchment. According to the basic export coefficient model these areas should export relatively little phosphorus compared to arable land. However, they become significant when adjusted for slope, cumulative area and soil type. Areas close to stream channels are also evident as disproportionately active sources of P due to high cumulative area. Again, this tallies with an expectation that P mobilised near to, or within, channels will be transported beyond the catchment outlet.

Table 2. Comparison of TP loads (1996-1999) from the Greens Burn catchment predicted by the basic export coefficient model and the modified model (Mean, Mean-1SD, Mean+1SD) with measured data (SEM).

Year	Measured (SEM) (kg P a^{-1})	Basic Model (kg P a^{-1})	Modified Model Mean (kg P a^{-1})	***Mean – 1SD (kg P a^{-1})***	Mean + 1SD (kg P a^{-1})
1996	527 (260)	1810	486	376	597
1997	574 (330)	1607	542	422	662
1998	664 (257)	1614	860	632	1087
1999	528 (224)	1639	678	459	898

Table 2 shows the model results for 1996-1999, along with the measured loads in these years. Also shown are the results from the original export coefficient model, applied using the mean value of export coefficients shown in Table 1. This model clearly over-predicts the measured loads. Although it can be argued that the result for the basic model could be improved by optimising the coefficients, there are too few measurements to justify a unique set of export coefficients, especially since changes in observed fluxes may be due to a number of factors other than land use (including sampling error). Incorporating the effects of topography, soil type and *HER* produces better predictions suggesting that these adjustments are sensible. Although the match between predicted and measured mean is not always good, there is always an overlap between the measured mean ±SEM and mean predicted flux ±1SD. Furthermore, the direction of change from year to year is captured by the modified model but not by the original export coefficient model.

CONCLUSIONS

The model presented is an improvement on the basic export coefficient model. The inclusion of additional controls (topography, soil type and *HER*) describing TP transfer and the use of Monte Carlo simulation (to preclude the need for poorly constrained optimisation or subjective selection of coefficients) greatly improves the utility of this approach for predicting phosphorus transfer, whilst retaining low, readily-available input data requirements. Although further testing of the model in other catchments is required, it represents a promising screening tool for evaluating diffuse source P transfers, particularly in data poor catchments.

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