Effectiveness of Mitigation Measures on Phosphorus Delivery

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INTRODUCTION

Diffuse pollution from agricultural land has become the dominant factor controlling freshwater quality in many catchments. Phosphorus (P), as one of the main macronutrients, plays a key controlling role in the eutrophication of surface waters. To meet our environmental management responsibilities there is a need to estimate the likely effect of current and future soil and land management policies on water quality and choose the most effective strategies given catchment characteristics, climate and economic drivers.

Mitigation methods employed to meet standards set to protect ecological function include measures to reduce P inputs to catchment systems (e.g. reduced fertiliser application rates), those to reduce the mobilisation and transport of P from agricultural land to water (e.g. improved soil management) and others to reduce the fluxes of P delivered to waterbodies (e.g. buffer zones and constructed wetlands (CWs) (Cuttle et al., 2006; Daverede et al., 2004; Johnes et al., 2007; Kay et al., 2009)). Where measures to reduce P delivery are used, some farm infrastructures have been proven to be useful such as riparian buffer zones (RBZs) and CWs (Abu-Zreig, 2003; Braskerud, 2005; Kay, 2009; Uusi-Kämppä, 2000).

Determining which land management option (or combination of options) is the most effective mitigation strategy for a given catchment or catchment type and what is the likely magnitude of their effect in isolation and in combination is difficult and depends upon factors such as catchment characteristics, climatic conditions and agronomic structure.

A number of phosphorus transport and delivery models have been developed in recent years (Heathwaite et al., 2003; Dougherty et al., 2004; Haygarth et al., 2005; Schärer et al., 2006; Haygarth et al., 2009). However, those of a dynamic, process-based nature can often be over-parameterised. In addition, there are significant uncertainties in representing the effects of any mitigation. The mitigation process is much more complicated at the catchment scale than it at the plot scale as there are many factors affecting the effectiveness of mitigation options, such as the localization of preferential surface and subsurface flows in a catchment and the distributed patterns of different soil types (Beven, 2010). The spatial locations of where mitigation measures being installed also affect their effectiveness of reducing P delivery. Without consideration of the uncertainty in our current ability to estimate the behaviour of diffuse pollutants, estimation of the effectiveness of mitigation measures, and hence cost-effectiveness, might be misleading.

In this paper we illustrated how we have incorporated the uncertainties associated with limited information at appropriate scales in the development of fuzzy rules describing the likely effectiveness of CWs within headwater catchments. We used information from literature reviews and expert opinion as a basis for the rules. The expert opinion was derived from the project team and a focused workshop of invited experts. The Critical Source Areas (CSAs) was delimitated as the most important area for P delivery by using Digital Elevation Model (DEM) data and the Sensitive Catchment Integrated Modelling Platform (SCIMAP) protocol. The influence of spatial distributions of installed or to be installed mitigation measures was investigated on P delivery. These rules were applied to modify the P delivery coefficient estimates with installed or to be installed mitigation measures depending on catchment characteristics.

MATERIALS

This work used data from five data-rich catchments and seven data-poor catchments. The data-rich catchments refer to catchments with an existing set of time series measurements of high resolution (daily or sub-daily) hydrometric and water quality monitoring data and wide coverage of the Aquatic Landscape classes (Defra, 2003), while the data-poor catchments are those with one year of monitoring data of approximately 10 storms plus occasional base flow samples. All of these catchments are headwater catchments generally less than 6 km^2. The 10m resolution DEM data, the land cover map and 30 years annual rainfall data were used to delineate the CSAs.

As we would like to model the likely effect of the mitigation methods on reducing P delivery coefficients, it is ideal if we have monitoring data before any mitigation measure being installed. But in fact, all of our experimental catchments have been installed with several mitigation measures and the monitoring data were collected after their applications. Therefore, P delivery coefficients of current status based on hydrologic and geographic factors are the necessary foundation. Tabulated raw data is available on http://www.lancs.ac.uk/staff/zhangt/Table_Catchment features and phosphorus.htm. It lists the estimated P delivery coefficients without mitigation measure effectiveness (revised results from the PEDAL project, unpublished data), the observed P delivery coefficients and key catchment characteristics (see Defra, 2006).

METHODOLOGY

Model structure

In this paper, the estimated P delivery coefficients without mitigation measure effectiveness in the above link are used as the input. The P delivery coefficient is defined in Equation 1 (Beven et al., 2005; Brazier et al., 2006). DESPRAL is an index of P mobilisation and expressed as a concentration (Withers et al., 2007). The delivery coefficients without mitigation measure effectiveness are also given in the above raw data table link.

$$\text{Phosphorus delivery} = \frac{\text{Annual flow weighted mean (mg l}^{-1}\text{)}}{\text{DESPRAL index value (mg}^{-1}\text{)}}$$

Equation 1

A set of fuzzy rules were built to modify the P delivery coefficients without mitigation measures effectiveness, as there might be installed or to be applied mitigation measures affecting the P delivery results. We constructed a fuzzy-rule base to implement a modification of the fuzzy delivery coefficients. Figure 1 (see in full version of the paper) shows the model structure schematically and demonstrates how the likely effects of CWs are implemented in the model. The model took the P delivery coefficients without mitigation measure effects as inputs, established a set of fuzzy rules for P reduction rate of each mitigation method, the control areas effects, the effect of catchment properties and installed mitigation measures, and exported the revised P delivery coefficients as outputs. The model also has the facility to incorporate information on existing mitigation measures (e.g. by visual assessment of fields where possible) that may have a significant impact on effectiveness (e.g. in the extreme the effectiveness of additional measures may be zero where optimal mitigation exists).

Critical Source Areas

To ensure the most efficient deployment of mitigation effort, it is important to focus upon those parts of a catchment where restoration is likely to give the greatest added value. Certain areas are diffuse pollution hotspots, where high nutrient inputs and/or inappropriate land use generate a significant nutrient source that is also connected with a hydrological flow path to the drainage network. Evidence suggests that this delivery process may be conditioned by local, often sub-field scale hydrology (e.g., Blackwell *et al.*, 1999; Burt *et al.*, 1999; Quinn, 2004) and nutrient transformation processes (Harris and Heathwaite, 2005). These patterns of runoff generation and hydrological connection occur at spatial scales of the order of ≤10 m (Western *et al.*, 1999, 2001; Lane *et al.*, 2004; Heathwaite *et al.*, 2005), often related to quite subtle topographic attributes.

A set of DEM data with 10m resolution, the land cover map and annual rainfall data were used to generate a risk based critical source areas, which gave the most risk parts of the catchment for P delivery. Topographic wetness index was calculated from DEM data and land cover erosion risk was derived from the land cover map and rainfall data. Both the risk indices were used to give the risk map of P delivery at given catchment. The critical source areas was delineated based the risk map and field visits at wet conditions. Mitigation measures, such as wetlands, installed within CSAs will be given high weight when calculating its effectiveness of reducing P delivery.

Mitigation measure effectiveness rule

Stevens and Quinton (2009a, 2009b) reported that observations of the reduction efficiency of diffuse pollution mitigation measures show highly variable results for TP. This variability is highlighted in Figure 2, which shows the broad distribution of the reduction efficiency of CWs (1% to 91%) on TP flux from published sources. Using the information presented in Figure 2, a fuzzy rule was constructed for mitigation measure effectiveness applied to the a priori estimated delivery coefficient distribution. The fuzzy rule is of the type:

Rule 1:

If the estimated P delivery coefficient is A and mitigation option reduction efficiency is B, then the final P delivery coefficient is A× (1-B).

1- reduction efficiency (B) refers to the delivered P passing through CWs. Fuzzy multiplication of two fuzzy membership functions refers to the fuzzy union of every point from the multiplicand membership function multiplied by the multiplier membership function (Beven, 2009). Fuzzy membership function refers to a curve or function that specifies the degree to which a given input belongs to a set or is related to a concept.

Fuzzy membership function for wetlands was built and is presented in Figure 3.

Control area rule

Every mitigation measure has an upslope control area. When mitigation measures are installed in a catchment, parts of the area in the catchment will be covered and protected. If the whole catchment has already been controlled and protected by the installed mitigation measures, there will be the minimum need for a new mitigation measure.

The catchment control area is estimated based on Visual Assessment (VA) (Kovacic et al., 2000) information reported in Defra (2006). Table 1 shows the installed mitigation measures and the estimated catchment control areas in experimental catchments.

A fuzzy range is been given based on Table 1 and a fuzzy trapezoidal shaped membership function is adopted to represent the fuzzy control areas of experimental catchments (Figure 5).

Apart from catchment control areas, the control area of each mitigation measure affects how much delivered P it can reduce and eventually affects the delivered P at the outlet. Due to the limited information, an expert opinion is applied here. We assume every installed mitigation measure works at its maximum effectiveness. A trapezoidal shaped fuzzy membership function is built as below (Figure 6), in which, n means the number of mitigation measures within the catchment control area. As n varies in different catchments, the fuzzy membership function in Figure 6 will change accordingly.

Spatial pattern rule

When multiple mitigation options are combined in the same catchment, there will be an interacting effect between them. The spatial distributions of mitigation measures will lead to different effectiveness on P delivery.

We assume that all the mitigation measures work equally well on diffuse P pollution. The interacting effect could be an additive or multiplication relationship that depends on the spatial locations of the mitigation options. Figure 7 is an example of how spatial location affects the mitigation measure effectiveness. When two mitigation measures are implemented in the same sub-catchment, they may work as a multiplicative relationship if implemented in series; otherwise an additive relationship if in parallel. When they are in different sub-catchments, an additive relationship occurs. The combination effect is also closely related to whether or not the critical source areas (CSAs) (Maas et al., 1985; Gburek & Sharpley, 1998; Pionke et al., 2000) have been mostly covered by installed mitigation measures. If the CSAs have been fully covered by installed mitigation measures, the combination effect between a new mitigation measure and installed ones will be minimal. That is to say, a new mitigation in the catchment would not be expected to have a significant impact.

In this situation, information about the installed mitigation measures is required. This will normally be assessed by making a VA of the catchment of interest (Defra, 2006). There may be several levels of VA information that could be collected. First of all, a partial level of VA information as to whether or not there is any mitigation measure currently installed; then a full level of VA information extending to the catchment characteristics and mitigation measure properties (like the buffer strip length and its location). An example is shown below how partial level VA information will be incorporated into the fuzzy rule model.

Due to the limited VA information, we could only give a range of possibilities covering the minimum and maximum situations. The fuzzy rule is of the type:

Rule 2:

If two mitigation measures are in the same sub-catchment, they work as a multiplication or additive relationship depending on whether they work as in series or parallel.

If they are in different sub-catchments, an additive relationship occurs.

Combination effect depends on the spatial locations of mitigation options and whether or not the CSAs have been fully covered by installed mitigation options.

Final fuzzy rules

Final fuzzy rules for mitigation methods are the combination of fuzzy rule 1, rule 2, rule 3, control area rule and the up-scaling rule:

If there are CWs in the catchment, the estimated P delivery coefficient is A, wetlands' P loss reduction proportion is B, the catchment control area is CA, the mitigation measure control area is CC and the combination effect is C, then the final P delivery coefficient is $A \times CC \times (1-B) \times CA \times C$.

RESULTS AND DISCUSSIONS

The results of applying the proposed fuzzy rules are presented in Figure 9. Figure 9a and 9b and 9c demonstrate P delivery coefficients where without mitigation measures effectiveness, taking installed mitigation measures effects into account and applying a new CW at the catchments respectively. It is clearly shown from the comparison of these three figures that P delivery has been much improved at these catchments after the mitigation measures being installed. As it is shown, where there is installed RBZs or much more RBZs than wetlands installed, applying a new CW is more effective than applying in those catchments with several CWs installed. We assume every mitigation measure work effectively and we don't take time lag effect into account in the model. Besides, as we do not have enough information of the installed mitigation measures, we do not know which kind of combination relationship the installed mitigation measures have. Therefore, a full range of possibilities is given in the model covering both the multiplicative and additive relationships. In this case, detailed information about the spatial locations of installed mitigation measures is required in the future.

As we have limited VA information about the installed mitigation measures, a full range of possibilities instead of accurate estimations of the combination effect is given in the paper. The combination effect of multiple mitigation measures is not only related to the spatial location but also related with CSA and mitigation measures properties (like the area ratio of wetlands to the catchment). For example, if the CSAs have been fully covered by the wetlands, then there is no need for a new wetland to be installed; but if there is a large proportion of CSA not being protected, then extra mitigation measures will be needed.

Other than CSAs, the wetland surface-area/watershed-area ratio plays an important role in wetlands' retention ability (Uusi-Kämppä et al., 2000). The timing issue is also important for the combination effect. The time when installed mitigation measures are implemented and VA information and samples are collected should be recorded appropriately.

Besides this, pollution swapping can occur when one mitigation option applied to reduce one pollutant leads to an increase in a different pollutant (Stevens and Quinton, 2009a). We have little evidence on the full range of impacts these mitigation measures have on different diffuse agricultural pollutants. Further research will be needed in the future.

Some of the variation associated with factors mentioned above has been included in the range of the effectiveness data we have used. However if supplementary field visits and experimental campaigns are targeting on these factors in future then more accurate simulations of mitigation strategies effectiveness will be achieved. The combination effect rules could be used to evaluate not only installed but also to be installed mitigation methods' efficiency when considering land management strategies.

CONCLUSIONS

This study has provided a first approximation of how CWs (i.e. delivery mitigation features) affect P delivery coefficients by coupling expert knowledge with data from twelve catchments studied. A set of fuzzy rules of P trapping efficiency, control area rule and the combination effect for CWs were built. These fuzzy rules were incorporated into a fuzzy model of P delivery coefficient from the previous PEDAL project (Defra, 2006). The results demonstrated how effective each mitigation method could be for reducing the P delivery coefficient and that mitigation options should be selected according to catchment properties. These fuzzy rules can be applied for the evaluation of the effect of installed and to be installed mitigation measures on P delivery coefficient and give support for land management strategies. As the fuzzy rule model is a learning process, its accuracy is based on the raw data. Optimized results will be provided to land management policy makers when more detailed VA data become available.

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