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Cost-effective strategies to mitigate multiple pollutants in an agricultural catchment in North Central Victoria, Australia*

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Strategies to reduce phosphorus and sediment yields are identified for two Australian catchments using a nonlinear optimisation model. This provides novel insight into the cost-effective management of dual pollutants of water courses in Australia. A strong degree of complementarity between the two pollutants is highlighted, given the adsorption of phosphorus to sediment that augments the value of gully and streambank management for mitigation. However, the relationship between the two pollutants is asymmetric. A 30 per cent reduction in phosphorus yield achieves a 75 per cent reduction in sediment yield in one catchment, while a 30 per cent reduction in sediment yield achieves only a 12 per cent reduction in phosphorus yield. Sediment abatement costs are low given the efficiency of gully and streambank management. A 30 per cent phosphorus reduction lowers profit by 3–7 per cent, while a 30 per cent sediment reduction lowers profit by around 1 per cent. Land-use optimisation requires spatial heterogeneity in land-use and gully/streambank management responses. Overall, this research demonstrates the need to determine whether one pollutant is more important than another, while recognising the potential that mitigation practices possess for the reduction of multiple emissions during their evaluation.

Key words: multiple pollutants, nonlinear optimisation, water quality.

1. Introduction

Nonpoint source pollution (NSP) of water courses involves the generation of pollutants from diffuse sites. NSP is the primary pollutant of global waterways (UNEP 2008); for example, 75 per cent of nitrate leaching in the United Kingdom arises from these sources (OECD 2002). Agricultural production is a key cause of NSP, both throughout Australasia (Drewry *et al.* 2006) and throughout the world (UNEP 2008). The grazing of dairy cows increases N and P leaching (Drewry *et al.* 2006), while gully erosion increases phosphorus and sediment delivery to waterways (Vigiak *et al.* 2011).

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Significant increases in N and P yields (i.e. emissions into rivers) arising from agricultural management have led to extensive water quality decline throughout Australia, with these nutrients alone or in combination being implicated with the onset of eutrophication (Davis and Koop 2006). Moreover, most of this nation's agricultural areas are highly weathered and subject to erosion. This has led to high turbidity of Australian water courses due to high sediment loadings (Davis and Koop 2006).

A wealth of Australian studies focus on the management of single pollutants of water quality. Bathgate and Pannell (2002) explored the economics of lucerne pastures for dryland salinity reductions on the South Coast of Western Australia. The cost of phosphorus mitigation across diverse land uses has also been explored in the Peel-Harvey region of Western Australia (Neville 2006) and the Gippsland Lakes region of Victoria (Roberts *et al.* 2012). Additionally, a number of studies focus on the management of multiple pollutants. Rolfe *et al.* (2011) discussed the use of tender instruments to achieve reductions in nutrient, pesticide and sediment loads to the Great Barrier Reef. In contrast, Smajgl *et al.* (2009) discussed a modelling framework to provide insights into the management of sediment and nutrients from agriculture to reduce damage to the Great Barrier Reef. However, no studies appear to apply mathematical programming to investigate the cost-effective management of multiple, nonpoint pollutants. This is restrictive since mathematical programming is flexible, can incorporate information from multiple modelling frameworks, can represent complex systems consisting of thousands of equations and can efficiently identify optimal or near-optimal management plans associated with alternative environmental goals.

This study contributes to the analysis of multiple, nonpoint pollutants in Australia through the development and application of an economic model for their study within a nonlinear programming framework. This model is used to analyse the management of multiple, water-borne pollutants (phosphorus and sediment) in two Australian catchments dominated by dryland agriculture. Given the difficulties surrounding the estimation of explicit benefits accruing to water quality improvement, this study follows typical practice and identifies how pollutant goals may be satisfied at least cost (Balana *et al.* 2011).

2. Methods

2.1. Study region

The analysis is applied to the Avon Richardson and Avoca catchments in North Central Victoria (Figure 1). The Avon Richardson catchment (36.5°S, 143°E) is a predominantly flat catchment of 2885 km^2 without an exit stream. The Avoca catchment is adjacent to the east of the Avon Richardson catchment and has a larger surface area of 4550 km^2. Rainfall is winter dominant and highly variable, ranging from <300 mm/year in the northern plains to 600 mm/year in the southern ranges.

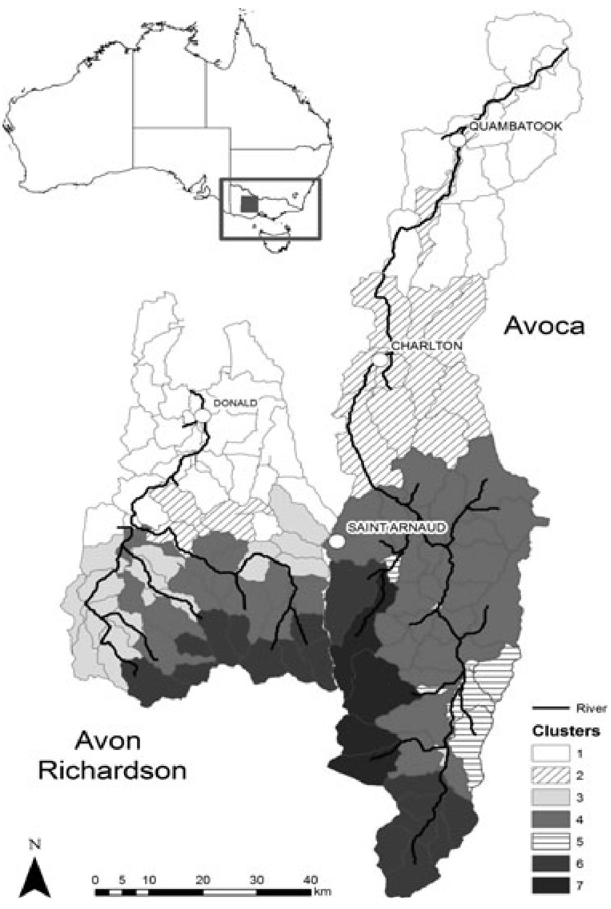

Figure 1 Cluster location and the position of main towns and rivers in the two study areas, the Avon Richardson and the Avoca catchments, in North Victoria (Australia).

Each catchment is divided into 70 river reaches and associated subcatchments (average size of 20–40 km^2). These units are used in the biophysical model (Section 2.2). Subcatchments are grouped into clusters (denoted CL hereafter) on the basis of agro-climatic characteristics, erosion processes and current land use (Table 1). The geographical location of each cluster in each catchment is shown in Figure 1. Current farming systems range from grazed, annual pastures (APs) in the southern hills (CL6–7 in Figure 1) to broadacre cropping systems (CL1–2 in Figure 1) in the northern plains (wheat, barley and legume crop rotations). The central parts of both catchments are dominated by mixed grazing and cropping systems (CL3–5 in Figure 1).

2.2. Biophysical model

The biophysical model used to estimate P and sediment yields in the catchments is a coupled point-to-catchment-scale model described by Vigiak

Table 1 Characteristics of each cluster in the Avon Richardson and Avoca catchments

Cluster (CL)	Agro-climatic Zone	Gully erosion	Stream bank erosion	Annual rainfall (mm/year)	Slope	Current land use†
CL1	Cropping	—	—	<420	Flat	CRz
CL2	Cropping	Yes‡	Yes‡	<420	Flat	CRz
CL3	Mixed	—	—	420–500	Gently sloping	AP/CRz
CL4	Mixed	Yes	—	420–500	Gently sloping	AP/CRz
CL5	Mixed	Yes§	Yes§	420–500	Gently sloping	AP/CRz
CL6	Upland	Yes	–	>500	Steep to very steep	AP
CL7	Upland	Yes‡	Yes‡	>500	Steep to very steep	AP

†Land-use key: CRz, canola–wheat–barley–legume rotation (zero tillage); AP, annual pasture.
‡Subcatchments possess gully and/or streambank erosion in this cluster.
§Subcatchments possess gully and streambank erosion in these clusters.

et al. (2011). Field water surplus, sediment losses and phosphorus losses are assessed for hydrologic response units – unique combinations of climate, soil and land use – with the point-scale model, *HowLeaky2008* (Melland *et al.* 2010). *HowLeaky2008* is a soil-column model that simulates daily water balance, soil erosion and nutrient exports from fields as a function of environmental factors (climate and soil) and farm management (e.g. vegetation cover, tillage operations).

Hydrologic response units losses are linked to a conceptual catchment-scale model based on CatchMODS (Vigiak *et al.* 2011). The model conceptually divides a catchment into river reaches and associated subcatchment areas (average size of 20–40 km^2) linked to a node-link system. Suspended sediment arises from hillslope, gully and streambank erosion. (Hillslope erosion refers to erosion that occurs on general agricultural land not subject to gully erosion.) Dissolved and particulate phosphorus field losses are estimated using *HowLeaky2008*. Particulate P yields from hillslope erosion are estimated as the weighted annual average particulate P export, corrected for subcatchment topography, sediment delivery and P enrichment. Particulate P yields due to gully or streambank erosion are assumed proportional to suspended sediment yields and average total P content of the gully or streambank wall.

Attenuation in these catchments is negligible – accounting for only 1–2 per cent of P yields – and differs little with the simulation of different sets of land uses throughout the catchment. These results reflect the poor health of the river reaches in these catchments and manifest in low biotic and abiotic uptake mechanisms. Accordingly, it is assumed that attenuation in each subcatchment is not a function of land-use decisions in others.

2.3. Economic information

Consultation with agronomists and producers in the study region highlighted that seven general land-use types should be considered:

1 A canola (*Brassica napus*)–wheat (*Triticum aestivum*)–barley (*Hordeum vulgare*)–legume rotation using zero tillage.
2 A canola–wheat–barley–legume rotation using minimum tillage.
3 A wheat–barley–fallow rotation involving full cultivation.
4 Annual pasture based on subterranean clover (*Trifolium subterraneum*) and annual ryegrass (*Lolium rigidum*).
5 Perennial pasture based on phalaris (*Phalaris aquatica*).
6 Perennial pasture based on lucerne (*Medicago sativa*).
7 Assorted native tree species, such as red ironbark (*Eucalyptus sideroxylon*).

The legumes present in the canola–wheat–barley–legume rotation are lentils (*Lens culinaris*) and faba beans (*Vicia faba*), depending on the soil type. All pasture is assumed to be grazed in accordance with standard practice.

All dollar amounts specified in this paper are defined in Australian dollars. Gross margin analysis is used to estimate the value of each land use on each soil type. Table 2 presents the range of gross margins used within the optimisation model. Variation in the profitability of a given land use within a given zone is due to differences in production and management on different soil types within that zone. For example, wheat yield and fertiliser application are higher on more productive soils.

A number of key points are apparent from Table 2:

1 Cropping is much more profitable than grazing, given high prices for crops and broad adoption of zero-tillage technology.
2 Cropping activities are more profitable in the mixed zone, relative to the cropping zone, given higher rainfall.
3 Zero tillage is more profitable than minimum tillage, due to its low cost and the higher crop yields that can be attained through water conservation.
4 Annual pasture is generally more profitable than perennial pasture options, as perennial pastures incur significant establishment costs.

Table 2 Land-use activities and the associated range of gross margins ($ per ha) across the different zones of the Avon Richardson and Avoca catchments

Land-use	Abbreviation	Gross margin range ($)		
		Cropping zone	Mixed zone	Upland zone
Canola–wheat–barley–legume rotation (minimum tillage)	CRm	141–224	198–312	—
Canola–wheat–barley–legume rotation (zero tillage)	CRz	171–246	214–312	—
Wheat–barley–fallow rotation	WBF	184–219	204–242	—
Annual pasture	AP	84	81	109
Perennial pasture	PP	—	42–65	90
Lucerne	LU	43–78	38–73	64–98
Trees	TR	−18	−18	0

The generation of economic information for both catchments requires the computation of 420 gross margins. These are formulated based on extensive consultation with farm consultants and agronomists from the Department of Primary Industries with experience in the study region. The costs of gully and streambank management are drawn from discussions with the North Central CMA.

2.4. Optimisation model

The river networks in each catchment are hydrologically independent (Figure 1). Thus, each catchment model is solved individually. This section presents the key equations of the optimisation model. Only gully erosion occurs in the Avon Richardson, while both gully and streambank erosion occur in the Avoca. Capital letters that are not superscripts denote decision variables in the model.

The model maximises total net benefits – expressed as the difference between producer profit and regulatory costs – for a given nutrient target.

There are a subcatchments in each catchment, labelled $sc = [1, 2, \ldots, a]$. The total land area in each subcatchment is allocated among b land-use combinations, labelled $lu = [1, 2, \ldots, b]$. These land-use combinations contain different permutations of the seven land uses defined in Section 2.3.

Three main decision variables describe the management options. First, the area (km^2) allocated to each land use in each subcatchment is denoted $A_{sc,lu}$. Second, the intensity with which gully erosion is managed in each subcatchment sc is denoted G_{sc}, where G_{sc} is a continuous decision variable in the interval [0, 100]. Last, the intensity with which streambank erosion is managed in subcatchment sc in the Avoca catchment is denoted M_{sc}, where M_{sc} is a continuous decision variable in the interval [0, 100]. The intensity of gully and streambank management is the percentage of the gully system or streambank length that is fenced and revegetated.

The profit (\$ per km^2) earned when land is allocated to a certain land-use combination in a given subcatchment is denoted $\pi_{sc,lu}$. The cost of gully management is described by the increasing, convex function $c_{sc}^{G} = \alpha_0 + \alpha_1 G_{sc} + \alpha_2 G_{sc}^2$, where α_i for $i = [0, 1, 2]$ are parameters. The cost of stream bank management in subcatchment sc is described by the increasing, convex function $c_{sc}^{M} = \beta_0 + \beta_1 M_{sc} + \beta_2 M_{sc}^2$, where β_i for $i = [0, 1, 2]$ are parameters. These increasing, convex cost functions represent decreasing cost-effectiveness of gully and streambank management as the intensity of management increases. This reflects the inefficiency of focussing on areas with smaller sediment yields as management intensity increases.

Total net benefit in a catchment (π) is computed:

$$\pi = \sum_{sc=1}^{a} \sum_{\mathrm{lu}=1}^{b} \pi_{sc,lu} A_{sc,lu} - \sum_{sc=1}^{a} \left[\alpha_0 + \alpha_1 G_{sc} + \alpha_2 G_{sc}^2 \right] - \sum_{sc=1}^{a} \left[\beta_0 + \beta_1 M_{sc} + \beta_2 M_{sc}^2 \right] \tag{1}$$

Phosphorus emissions (kg P/km^2) at the terminal node that occur when land is allocated to a certain land-use combination in a given subcatchment are denoted $p_{sc,lu}^A$. Phosphorus emissions (kg P) at the terminal node that occur with gully management in subcatchment sc are described by the decreasing, convex function $p_{sc}^G = \chi_0 - \chi_1 G_{sc} + \chi_2 G_{sc}^2$, where χ_i for i = [0, 1, 2] are parameters. Phosphorus emissions (kg P) at the terminal node that occur with streambank management in subcatchment sc are described by the decreasing, convex function $p_{sc}^M = \delta_0 - \delta_1 M_{sc} + \delta_2 M_{sc}^2$, where δ_i for i = [0, 1, 2] are parameters. These convex P yield functions represent decreasing marginal benefit of gully and streambank management for mitigation, as the intensity of management increases. This reflects the inefficiency of focussing on areas with smaller sediment yields as management intensity increases.

The total phosphorus yield (kg P) in a catchment (TP) is defined:

$$\begin{aligned} \mathrm{TP} = &\sum_{sc=1}^{a} \sum_{lu=1}^{b} p_{sc,lu}^A A_{sc,lu} + \sum_{sc=1}^{a} \left[\chi_0 - \chi_1 G_{sc} + \chi_2 G_{sc}^2 \right] \\ &+ \sum_{sc=1}^{a} \left[\delta_0 - \delta_1 M_{sc} + \delta_2 M_{sc}^2 \right] \end{aligned} \tag{2}$$

Sediment emissions are measured in units of tonnes of total suspended sediment yield (t TSS). Sediment yields (t TSS/km^2) at the terminal node that occur when land is allocated to a certain land use in a given subcatchment are denoted $s_{sc,lu}^A$. Sediment emissions (t TSS) at the terminal node that occur with gully management in subcatchment sc are described by the decreasing, convex function $s_{sc}^G = \phi_0 - \phi_1 G_{sc} + \phi_2 G_{sc}^2$, where ϕ_i for i = [0, 1, 2] are parameters. Sediment emissions (t TSS) at the terminal node that occur with streambank management in subcatchment sc are described by the decreasing, convex function $s_{sc}^M = \gamma_0 - \gamma_1 M_{sc} + \gamma_2 M_{sc}^2$, where γ_i for i = [0, 1, 2] are parameters. These decreasing, convex sediment yield functions represent that the marginal benefit of gully and streambank management for mitigation decreases, as the intensity of management increases.

The total sediment yield (t TSS) in a catchment (TS) is defined:

$$\begin{aligned} \mathrm{TS} = &\sum_{sc=1}^{a} \sum_{lu=1}^{b} s_{sc,lu}^A A_{sc,lu} + \sum_{sc=1}^{a} \left[\phi_0 - \phi_1 G_{sc} + \phi_2 G_{sc}^2 \right] \\ &+ \sum_{sc=1}^{a} \left[\gamma_0 - \gamma_1 M_{sc} + \gamma_2 M_{sc}^2 \right] \end{aligned} \tag{3}$$

The total area (km^2) of land that can be used in each subcatchment is defined h_{sc}. The total area allocated to each land-use combination is restricted through:

$$h_{sc} = \sum_{lu=1}^{b} A_{sc,lu} \forall sc \tag{4}$$

Baseline phosphorus emissions (kg P) in a catchment are denoted d. Baseline sediment emissions (t TSS) in a catchment are denoted f. The proportional decrease in phosphorus emissions, defined over [0,1], required by regulators is denoted g^P. The proportional decrease in sediment emissions, defined over [0,1], required by regulators is denoted g^S.

Target emissions levels are defined using the level constraints:

$$d \cdot (1 - g^P) \geq \mathrm{TP}, \text{and} \tag{5}$$

$$f \cdot (1 - g^S) \geq \mathrm{TS}. \tag{6}$$

The left-hand sides of Equations 5 and 6 each define the exogenous target for phosphorus and sediment, respectively.

Optimisation of the baseline model involves maximisation of Equation 1, subject to Equations 2–4. These models are used to identify baseline emissions (d and g). Optimisation with consideration of emissions targets involves maximisation of Equation 1, subject to Equations 2–6.

There are 70 subcatchments in each of the Avon Richardson and Avoca catchments (a = 70). There are 266 land-use combinations that can be applied in each of the subcatchments (b = 266). Each model is solved using nonlinear programming with the CONOPT solver in the General Algebraic Modelling System (Brooke *et al.* 2008).

2.5. Application of biophysical model to the study region

The biophysical model (Section 2.2) is used to generate input data for the optimisation model. 266 combinations of the seven alternative land uses (Section 2.3) are then generated for all subcatchments based on discussions with agronomists and producers, soil types, climate, relative emissions and relative profit. An example of a land-use combination is allocating 75 per cent to AP and 25 per cent to lucerne pasture in the uplands zone. The biophysical model is run for all land-use combinations in each subcatchment to identify $\pi_{sc,lu}$, $p^A_{sc,lu}$, and $s^A_{sc,lu}$.

The biophysical model is run for broadly different levels of gully and streambank management intensity in each subcatchment. These levels incorporate no and full management intensity. The output data from the biophysical model are used to estimate the parameters for the nonlinear functions representing cost (α_i and β_i for i = [0, 1, 2]), phosphorus emissions (χ_i and δ_i for i = [1, 2, 3]) and sediment emissions (ϕ_i and γ_i for i = [0, 1, 2]). This estimation is performed using nonlinear least squares in MATLAB (Miranda and Fackler 2002).

3. Results and discussion

3.1 Baseline phosphorus and sediment results

Total phosphorus yields are similar in the Avon Richardson and Avoca catchments (Table 3). However, the Avoca is much larger in area (4550 km^2 vs. 2885 km^2 in the Avon Richardson catchment). Thus, the TP-specific yield (kg TP/km^2) is 0.76 kg TP/km^2 (35 per cent) higher in the Avon Richardson. There are a number of reasons for this. First, soil types and slopes of cropping land in the Avon Richardson lead to higher losses of P. Second, cropping occurs on a higher proportion of land in the Avon Richardson, observable by the amount of land in clusters 1–5 in the Avon Richardson catchment, relative to the Avoca catchment (Figure 1). This increases P yield, but as cropping is more profitable than livestock enterprises (Table 2), it also increases base case profit ($ 229 per ha) above that for the Avoca region ($ 176 per ha; Table 3).

Total suspended sediment (TSS) yields are much higher (40 per cent) in the Avoca catchment (Table 3). This is due to the greater incidence of gully and streambank erosion in that catchment, with 70 per cent of TSS arising from gullies in the Avoca, compared with 43 per cent from gullies in the Avon Richardson. Nevertheless, the total specific yield of TSS per unit area is very similar given the larger size of the Avoca catchment.

Table 3 Baseline model output for the Avon Richardson and Avoca catchments

Variable	Avon Richardson			Avoca		
	Yield	Specific yield	% of total	Yield	Specific yield	% of total
	kg	kg TP/km^2		kg	kg TP/km^2	
Total phosphorus						
TP from land use	5772	2	91	5012	1.10	77
TP from gullies and streambanks	558	0.19	9	1498	0.33	23
Total	6330	2.19	100	6510	1.43	100
	t TSS	t TSS/km^2		t TSS	t TSS/km^2	
Total suspended sediment						
TSS from land use	1550	0.54	57	1359	0.3	30
TSS from gullies and streambanks	1162	0.4	43	3109	0.68	70
TSS	2712	0.94	100	4468	0.98	100
	$ m	$ per km^2		$ m	$ per km^2	
Profit						
Profit	66	22,877	—	80	17,582	—

TP, phosphorus; TSS, total suspended sediment.

TP-specific yield is higher in each cluster in the Avon Richardson catchment than in the equivalent cluster in the Avoca catchment, sometimes substantially so (Table 4). For example, CL6 in the Avon Richardson has a TP-specific yield that is nearly three times greater than that of CL6 in the Avoca (Table 4). This again reflects the soil types and slopes of cultivated land in the Avon Richardson and the higher proportion of land allocated to cropping in this catchment.

Total suspended sediment-specific yield in CL2 and CL4 is higher in the Avoca, compared with the Avon Richardson (Table 4). This is due to the impact of streambank erosion in these clusters in the Avoca region. TSS-specific yield in CL6 in the Avon Richardson is enormous (4 t/km^2), compared with the other clusters, due to the high sediment yields arising from active gullies.

Optimisation of the base case model yields land use that is allocated solely between the canola–wheat–barley–legume rotation (zero tillage; CRz) and AP land uses (Table 4). More diversity in land use is observed in these catchments than reported in Table 4. Nevertheless, the overall proportions of crop and pasture that are observed in reality are well represented in the model. Moreover, representing greater disparity is nontrivial, due to the lack of data regarding current land use and the potential bias associated with the calibration of optimisation models (Doole *et al.* 2011).

3.2. Optimisation to achieve pollutant reduction

Two model runs are performed for each region: optimisation to achieve a 30 per cent reduction in TP yield and optimisation to achieve a 30 per cent

Table 4 Baseline pollutant yields and management for each cluster in the baseline solution for the Avon Richardson and Avoca catchments. No gully management is performed under baseline management

	Cluster	Yield		Specific yields		Land use
		TP (kg)	TSS (t)	TP (kg/km^2)	TSS (t/km^2)	
Avon Richardson	CL1	1463	131	1.325	0.12	100% CRz
	CL2	234	72	1.375	0.42	100% CRz
	CL3	986	88	2.2	0.2	50% AP, 50% CRz
	CL4	1917	853	2.83	1.26	50% AP, 50% CRz
	CL6	1730	1568	4.41	4	100% AP
	CL1	935	102	0.92	0.1	100% CRz
Avoca	CL2	1147	820	1.14	0.82	100% CRz
	CL3	9	2	1.01	0.25	50% AP, 50% CRz
	CL4	3048	2457	2.06	1.66	50% AP, 50% CRz
	CL5	329	221	1.49	1	50% AP, 50% CRz
	CL6	685	324	1.53	0.72	100% AP
	CL7	358	541	0.95	1.43	100% AP

AP, annual pasture; CRz, canola–wheat–barley–legume rotation (zero tillage); TSS, total suspended sediment.

reduction in TSS yield. These levels of reduction are defined following a discussion of goal setting with the NCCMA. Other reductions can also be investigated using the model, but the focus of this application is the 30 per cent goal recommended by the NCCMA.

The 30 per cent TP reduction target in the Avon Richardson is achieved at least cost by targeting actions in CL6 and, to a lesser extent, CL2 and CL4 (Table 5). The substantial contribution of CL6 to both TP and TSS mitigation under the TP target is reinforced in Figure 2. This is indicated by noticing that the darkest-coloured subcatchments in Figure 2 are in the area covered by CL6 in Figure 1. In comparison with the Avon Richardson catchment, management actions are spread over a greater spatial scale – in specific subcatchments in each of the upper, middle and lower catchment – in the Avoca catchment to achieve the 30 per cent TP target (Figure 2). Figure 2b indicates the substantial amount of TSS abatement that is obtained with a 30 per cent TP reduction. This indicates the significant magnitude of the positive spillover that phosphorus management has upon sediment loads in this catchment.

Abatement occurs in the same clusters with the 30 per cent TSS reduction target (Table 5). However, the magnitude of abatement experienced for both TP and TSS is the same or lower in each cluster in the 30 per cent TSS reduction scenario, relative to the 30 per cent TP reduction scenario (Table 5). For example, TP yield decreases by 81 per cent in CL6 in the Avon Richardson for the 30 per cent TP reduction scenario, but by only 37 per cent in the TSS reduction scenario (Table 5). This is reinforced in Figure 3, which indicates the minor amount of abatement of TP (Figure 3a) and TSS (Figure 3b) obtained with a 30 per cent TSS reduction, particularly

Table 5 Abatement of phosphorus and sediment yield in each cluster in the Avon Richardson and Avoca catchments for two yield targets: (1) a 30 per cent reduction in TP and (2) a 30 per cent reduction in TSS

	Cluster	30 per cent TP reduction		30 per cent TSS reduction	
		Change in TP yield (%)	Change in TSS yield (%)	Change in TP yield (%)	Change in TSS yield (%)
Avon Richardson	CL1	0	0	0	0
	CL2	−10	−51	−10	−51
	CL3	0	0	0	0
	CL4	−24	−51	−5	−16
	CL6	−81	−83	−37	−41
Avoca	CL1	0	0	0	0
	CL2	−30	−49	−10	−21
	CL3	0	0	0	0
	CL4	−29	−45	−18	−39
	CL5	−4	−9	−2	−3
	CL6	−78	−55	−30	−36
	CL7	−50	−35	−15	−15

TP, total phosphorus; TSS, total suspended sediment.

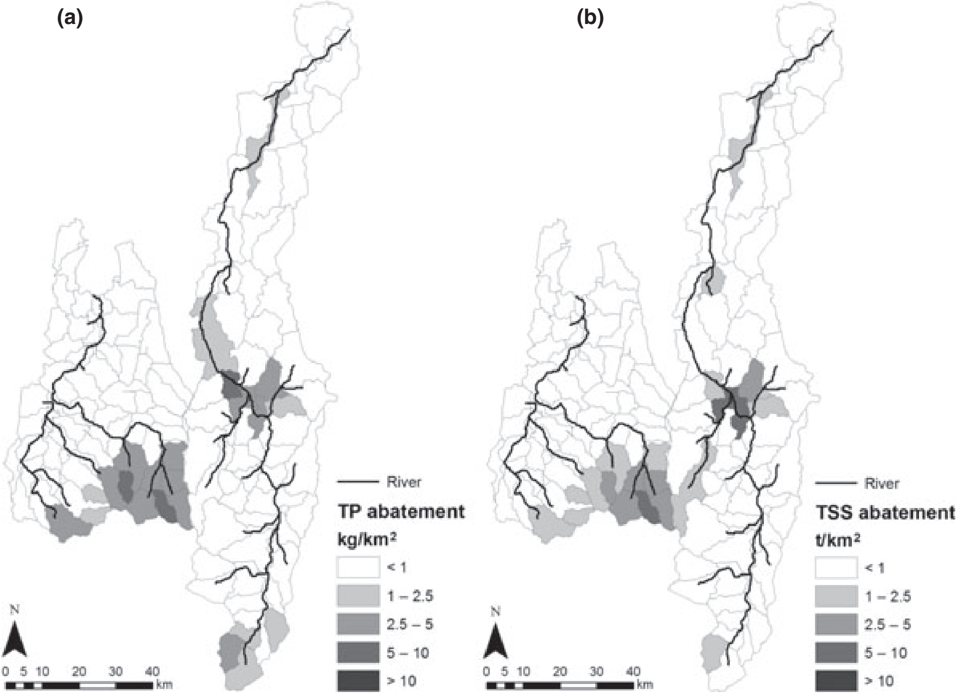

Figure 2 Absolute level of (a) total phosphorus (TP) abatement (kg/km^2) and (b) total sediment abatement (t/km^2) in each subcatchment in the Avon Richardson and Avoca catchments when each of these catchments is optimised individually to attain a 30 per cent reduction in TP yield at the outlet.

when compared with the level of TP (Figure 2a) and TSS (Figure 2b) achieved with a 30 per cent TP reduction.

Total phosphorus and TSS abatement are related since there is strong complementarity between mitigation practices for both pollutants. A primary driver of the complementarity is that P is mainly lost in particulate form (i.e. adsorbed by suspended sediment) from these catchments. However, the relationship between TP and TSS is not symmetric (i.e. one-to-one). The degree of correlation varies by cluster, but overall it is evident that TSS must decrease by a much larger amount in percentage terms to achieve a given level of TP reduction (Table 5). For example, TP yield falls by 10 per cent and TSS yield falls by 51 per cent in CL2 in the Avon Richardson catchment under both policies (Table 5). Accordingly, a 30 per cent reduction in TP yield leads to a 75 per cent and 45 per cent reduction in TSS yield in the Avon Richardson and Avoca catchments, respectively. In contrast, a 30 per cent reduction in TSS yield achieves TP reductions of only 12 per cent and 14 per cent in the Avon Richardson and Avoca catchments, respectively. An implication of this correlation is that the solution reported for the 30 per cent TP reduction scenario is the same as that obtained if the model is optimised to achieve 30 per cent reductions in both pollutants.

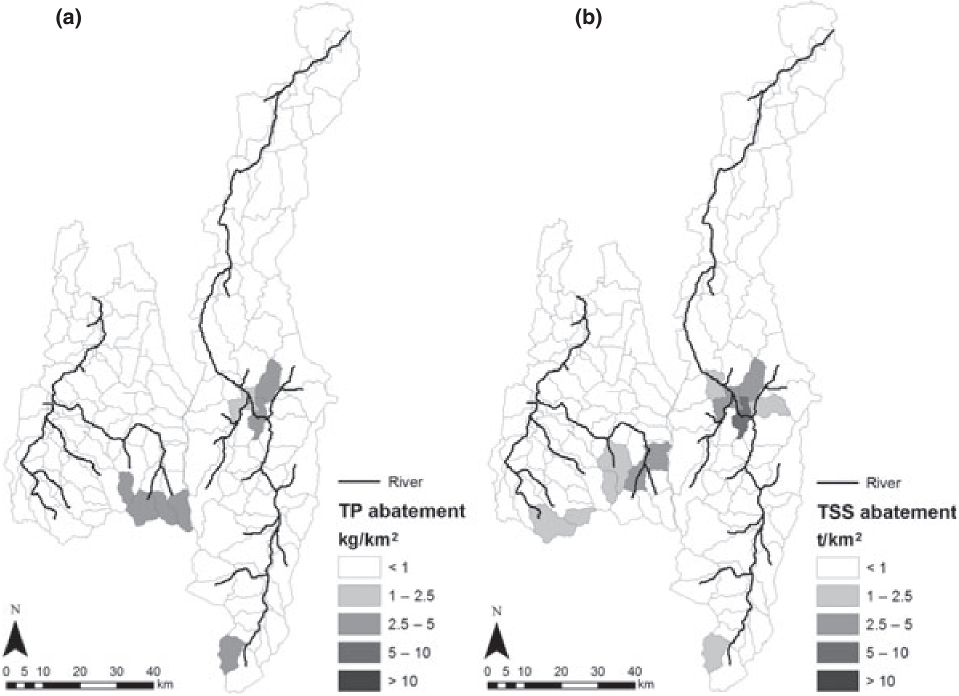

Figure 3 Absolute level of (a) total phosphorus abatement (kg/km^2) and (b) total sediment abatement (t/km^2) in each subcatchment in the Avon Richardson and Avoca catchments when each of these catchments is optimised individually to attain a 30 per cent reduction in total suspended sediment (TSS) yield at the outlet.

The degree of mitigation performed in each cluster differs broadly as a result of optimisation to reduce pollutant yields (Table 5). Indeed, clusters are present in Table 5 where no (e.g. CL1), moderate (e.g. CL2) or high levels of abatement (e.g. CL6) are performed. This highlights the importance of spatial optimisation to reduce pollution from agriculture in the study region. Mitigation of both pollutants in the Avon Richardson is achieved largely through targeting abatement in the grazed upland region (CL6) (Table 5). A similar situation exists in the Avoca catchment, where a significant amount of abatement occurs in CL6 and CL7. However, the mitigation of streambank erosion is also important in CL2 and CL4 in the Avoca (Table 5). In contrast, no abatement occurs in CL1 or CL3 in either catchment in any simulation reported in Table 5. These are the only clusters in which no gully or streambank erosion occurs (Table 1). This result highlights that gully and streambank managements are key practices for TP and TSS abatement.

3.3. Management change with pollutant reduction

Achieving a 30 per cent TP reduction requires changes to management in the Avon Richardson (Table 6). The main management action is to manage gully erosion at 100 per cent intensity in CL2 and CL6, which achieves a 96 per cent decrease in TP from gullies across the entire catchment. Also, land-use changes from 100 per cent AP to 77 per cent lucerne and 23 per cent trees in CL6, which achieves a 24 per cent decrease in TP from land use. The combination of land-use change and gully management in the grazed uplands (CL6) enables more-profitable land uses to remain in other parts of the catchment. This result reinforces the importance of spatial optimisation.

A target to achieve a 30 per cent TSS reduction requires less management changes to be made, relative to the 30 per cent TP reduction scenario, in the Avon Richardson (Table 6). This arises from the greater ease with which TSS yields are reduced, relative to TP yields. The only land-use change that occurs is in CL6, where lucerne replaces 37 per cent of AP. This achieves a 25 per cent reduction in TSS yield from land use. Gully management is applied at significant levels across CL2, CL4 and CL6 (Table 6), achieving a 37 per cent reduction in TSS from gullies.

A target to achieve a 30 per cent TP reduction also requires changes to management in the Avoca (Table 7). Low-to-moderate levels of gully management are applied in CL2, CL4, CL5 and CL7. Accordingly, TP from gullies and streambanks decreases by 68 per cent. Land use in CL2 changes from 100 per cent cropping to 90 per cent cropping and 10 per cent pasture. Also, lucerne is used on 94 per cent of CL6 and all of CL7 under optimal management. Accordingly, TP yield from land use declines by 19 per cent, relative to baseline levels. Land-use change is a key component of P mitigation in the Avoca, as 77 per cent of TP in this catchment arises from land-use decisions, while 70 per cent of sediment arises from gullies.

A target to achieve a 30 per cent TSS reduction results in much less drastic management change compared with the 30 per cent TP target (Table 7), as observed also in the Avon Richardson (Table 6). Gully management occurs at low levels of intensity (mean of 8 per cent) over CL2 and CL4–7. These low levels of gully management have a large impact though, reducing TSS from gullies by 40 per cent. The contribution of gully management is significant, as 70 per cent of TSS comes from gullies in the Avoca catchment (Table 1). In

Table 6 Optimal management within the Avon Richardson catchment for two yield targets: (1) a 30 per cent reduction in TP and (2) a 30 per cent reduction in TSS

Cluster	Baseline	30 per cent P reduction		30 per cent S reduction	
	Land use†	Land use	Gully‡	Land use	Gully
CL1	100% CRz	100% CRz	0	100% CRz	0
CL2	100% CRz	100% CRz	100	100% CRz	100
CL3	50% AP, 50% CRz	50% AP, 50% CRz	0	50% AP, 50% CRz	0
CL4	50% AP, 50% CRz	50% AP, 50% CRz	58	50% AP, 50% CRz	28
CL6	100% AP	77% LU, 23% TR	100	63% AP, 37% LU	40

†Land-use key: CRz, canola–wheat–barley–legume (zero tillage), AP, annual pasture, LU, lucerne, TR, trees.
‡Gully management is described through the average percentage intensity of management. For example, gully management performed at an intensity of 0 and 100 per cent corresponds to no and full effort across the cluster, respectively.

Table 7 Optimal management within the Avoca catchment for two nutrient yield targets: (1) a 30 per cent reduction in TP and (2) a 30 per cent reduction in TSS

Cluster	Baseline	30 per cent TP reduction			30 per cent TSS reduction		
	Land use†	Land use	Gully‡	Stream‡	Land use	Gully	Stream
CL1	100% CRz	100% CRz	—	—	100% CRz	—	—
CL2	100% CRz	8% AP, 90% CRz, 2% LU	33	9	100% CRz	11	1
CL3	50% AP, 50% CRz	50% AP, 50% CRz	—	—	40% AP, 54% CRz, 6% LU	—	—
CL4	50% AP, 50% CRz	49% AP, 49% CRz, 2% LU	20	—	52% AP, 48% CRz	14	—
CL5	50% AP, 50% CRz	50% AP, 50% CRz	10	—	47% AP, 50% CRz, 3% LU	3	
CL6	100% AP	6% AP, 94% LU	0	–	90% AP, 10% LU	4	—
CL7	100% AP	100% LU	15	—	100% AP	7	—

TP, total phosphorus; TSS, total suspended sediment.
†Land-use key: CRz, canola–wheat–barley–legume (zero tillage), AP, annual pasture, LU, lucerne.
‡Gully and streambank management is described through the average percentage intensity of management. For example, gully management performed at an intensity of 0 and 100 per cent corresponds to no and full effort across the cluster, respectively.

contrast, TSS from land use declines by only 6 per cent, arising mainly from lucerne replacing some AP in CL3, CL5 and CL6. Accordingly, TP reductions from land-use change are small (2 per cent), especially compared with those from gullies (55 per cent).

3.4. Cost of pollutant reduction

The cost of the 30 per cent TP reduction is $ 4.4 m (7 per cent of profit) and $ 2.26 m (3 per cent of profit) in the Avon Richardson and Avoca, respectively. In comparison, the cost of the 30 per cent TSS reduction is $ 0.47 m (0.7 per cent of profit) and $ 0.76 m (1 per cent of profit) in the Avon Richardson and Avoca, respectively. The cost of the 30 per cent TP reduction in the Avoca is nearly half of that in the Avon Richardson, but their abatement levels are similar, with 1.9 t TP and 1.95 t TP mitigated in the Avon Richardson and Avoca regions, respectively.

Reduction in TP yields of up to 20 per cent can be achieved at relatively low cost in the Avon Richardson (Figure 4a). For example, a 20 per cent TP reduction costs around $ 840,000 or 1 per cent of profit. However, cost rises quickly at levels of abatement above this, as extreme land-use change is required in CL6 to achieve more stringent goals in the Avon Richardson (Figure 4a). Cost-effective reductions in TP yield of up to 20 per cent have also been previously reported in southern Victoria for the Gippsland Lakes catchment (Roberts *et al.* 2012). In comparison, the cost of TP reductions is lower in the Avoca catchment (Figure 4b) because of the greater scope to use gully and streambank management to reduce pollution, rather than expensive land-use change. Moreover, Figure 4 shows that it is more expensive to mitigate TP, relative to TSS. Overall, these results highlight that significant reductions in pollutant yield can be attained at a low-to-moderate cost.

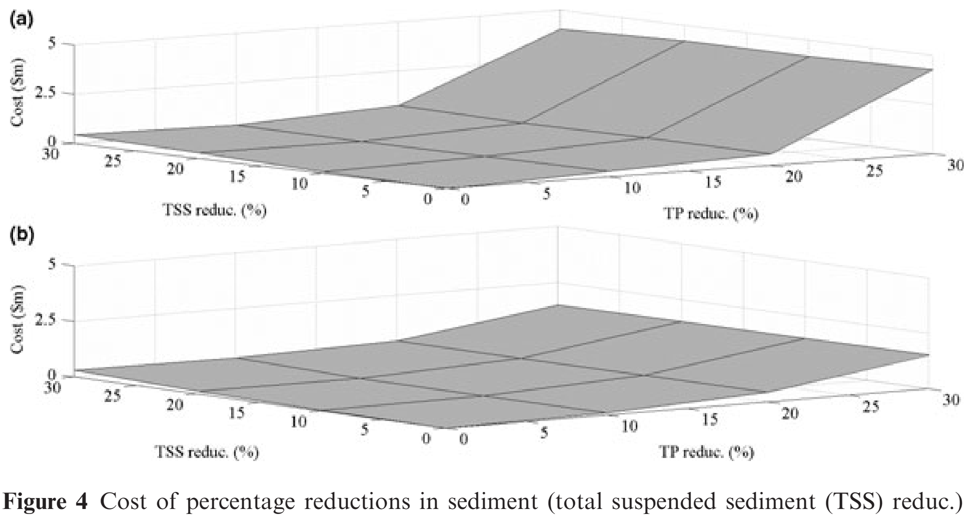

Figure 4 Cost of percentage reductions in sediment (total suspended sediment (TSS) reduc.) and phosphorus (total phosphorus (TP) reduc.) in the (a) Avon Richardson catchment and (b) Avoca catchment.

The cost incurred across representative clusters in the cropping (CL2), mixed (CL4) and upland (CL6) zones for TP and TSS reductions is shown in Figure 5 for both catchments. The diversity of these relationships (Figure 5) emphasises the importance of spatial optimisation in the determination of the cost-effective abatement of multiple pollutants.

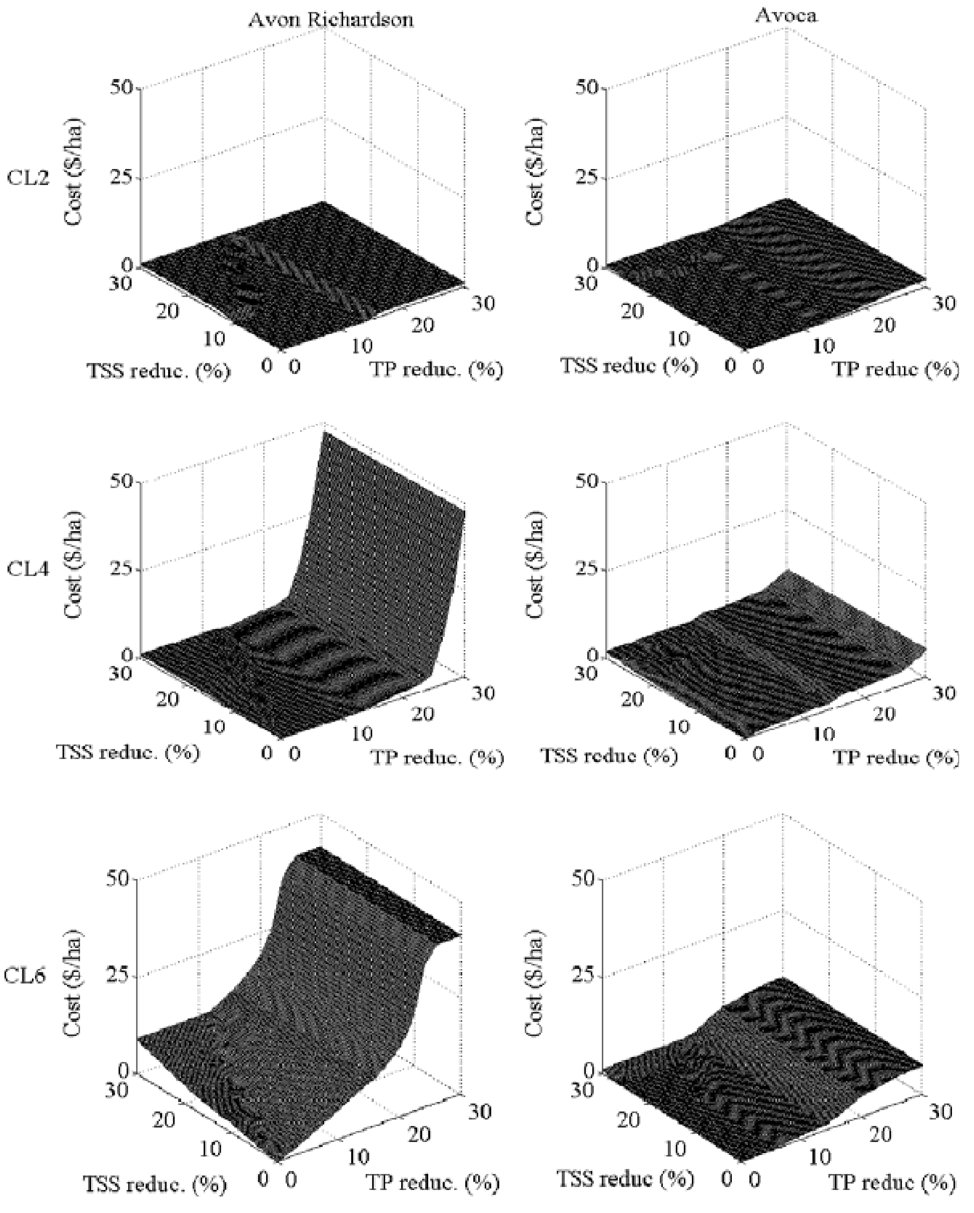

Figure 5 Cost incurred in the different clusters of the Avon Richardson and Avoca catchments with different reductions in total suspended sediment (TSS) and total phosphorus (TP) imposed at the catchment scale. Clusters are located in the cropping (CL2), mixed (CL4) and uplands (CL6) zones of each catchment.

The cost of abatement is minimal in the cropping zone (CL2), as most abatement is done in the uplands zone in both catchments in both simulated scenarios. Accordingly, land use is seldom altered from 100 per cent CRz. For example, land use in CL2 in the Avoca does not change for a 30 per cent TSS reduction, but incorporates 10 per cent pasture and 90 per cent CRz for a 30 per cent TP reduction (Table 7).

The cost of TSS abatement in CL4 is low in both catchments (Figure 5). However, the cost of TP abatement is large in CL4 in the Avon Richardson when significant TP reductions are required, as gully management must be used at high intensity (Table 6). The cost of gully management is greater in CL4, compared with CL2, given the greater size of this cluster (Figure 1) and because gullies are more expensive to manage in this region given their greater size.

The cost of TP and TSS abatement in CL6 is high in the Avon Richardson, particularly relative to the other clusters in this catchment (Figure 5). This reinforces how optimal management under TP and TSS yield reduction scenarios involve significant abatement efforts in the uplands region to maintain high-value land uses in the cropping and mixed zones. This involves intensive gully management, and land-use change away from AP towards lucerne and tree enterprises as goals to reduce TP and TSS are made more restrictive (Table 6). Land-use change is particularly expensive, as trees earn no annual income. In contrast, the cost of TSS abatement in CL6 in the Avoca catchment is much lower, as this cluster plays a minor role in reducing TSS. TP abatement in CL6 incurs some cost in CL6 in the Avoca, but this is moderate. Land use switches from AP to lucerne under optimal management (Table 7), but these enterprises are of similar profitability. For example, the annual gross margin for AP and lucerne is \$ 109 and \$ 98, respectively, on a grey vertisol soil.

4. Conclusions

This analysis investigates the management of phosphorus and sediment emissions from two Victorian agricultural catchments using a nonlinear optimisation model. Model output shows that there is a strong degree of complementarity in managing phosphorus and sediment in both catchments, as P is adsorbed by suspended sediment. The net benefits of gully and streambank management for mitigation are thus promoted, as a positive spillover for the management of another pollutant is experienced.

The cost of the 30 per cent phosphorus reduction is \$ 4.4 m (7 per cent of profit) and \$ 2.26 m (3 per cent of profit) in the Avon Richardson and Avoca, respectively. In comparison, the cost of the 30 per cent sediment reduction is \$ 0.47 m (0.7 per cent of profit) and \$ 0.76 m (1 per cent of profit) in the Avon Richardson and Avoca, respectively. Cost-effective management involves land-use and gully/streambank management responses that differ spatially. No one practice is responsible for cost-effective mitigation, though gully/streambank management is most advantageous. Rather, the use of different sets of strategies over a high number of dissimilar spatial units allows location-specific strategies to be used to reduce the overall cost of abatement. This emphasises the importance of spatial heterogeneity in management response when seeking to mitigate dual pollutants.

A number of policy responses are pertinent based on model output. First, through focussing agri-environmental policy on phosphorus reduction, regulators can achieve substantial reductions in sediment at no extra cost. Second, a coordinated focus on land-use change and gully/streambank management is required if least-cost pollutant reductions are to be obtained. However, a second-best solution could focus on gully and streambank management only, given their cost-effectiveness. Third, policies aimed at alleviating phosphorus and sediment yields should be spatially targeted, with most focus placed on the grazed upland zones. Last, there is little benefit accruing to targeting sediment reductions in one catchment, relative to another.

Overall, this research highlights the significance of being clear about whether one pollutant is more important than another in terms of environmental protection because the cost implications can be very different. Nevertheless, the design of appropriate policy instruments to deliver these outcomes has not been addressed and thus should be a key focus for future work.

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