

Cost-effective abatement of pollution from agricultural sources classified in risk classes[†]

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Abstract

Water pollution from agricultural sources is plagued with uncertainty of various proveniences. In the face of this uncertainty, catchment management authorities in Australia and elsewhere have been recently attempting to classify agricultural areas in the catchment in so called ‘risk classes’ according to their potential to contribute to ambient water pollution. This classification is intended to be used to aid decision making in allocating financial assistance to supporting abatement. This paper looks more closely at this classification and provides a theoretical representation of this approach. In addition, it compares its cost-efficiency to an alternative mechanism for allocating funds to abatement in a catchment based on economic optimisation. It is found that theoretically, the classification in risk classes is simply expressing the uncertainty about pollution loading parameter from a given agricultural area in discrete groups of expected realisations. While this classification gives priority for funding to abatement efforts in areas classified as ‘high-risk’, it is found that this does not provide a cost-effective outcome. The paper shows that abatement should be prioritised towards those farmers who can achieve greatest expected reduction of ambient water pollution at least-cost.

Key words: abatement, cost-effectiveness, water pollution.

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1. Introduction

Measuring environmental outcomes from various activities designed to curb water pollution from diffuse agricultural sources is difficult because of the complexity of the underlying bio-physical processes. This creates a serious impediment to environmental decision making in relation to reducing water pollution from agriculture. One particular problem related to this uncertainty is how to allocate financial assistance to landholders to achieve reduction of pollution from agricultural sources.

These issues are faced by of catchment managers in Australia who are responsible for large catchments that provide essential water supply to large urban conglomerates. A prominent example of this is the Sydney Catchment Authority (SCA), which manages several catchments of total size of about 16,000 km² and caters water to distributors that service a population of nearly 5 million people. One of the key concerns for SCA and other catchment management authorities is water quality. The focus is predominantly on the diffuse agricultural sources in the catchments, which contribute substantially to nutrient loads in the water bodies as a result of agricultural practices. In many catchments, including the catchments under management of SCA, phosphorus loading from agricultural sources is a key water quality issue.

In light of this, catchment management authorities (CMA) spend significant funds in supporting abatement activities from diffuse agricultural sources. In allocating those funds, the managers need to know the effectiveness of the abatement activities. This amounts to assessing the magnitude of the reduction of pollution achieved as a result of an abatement activity being undertaken by a landholder, which is financially supported by the catchment management authority. Since there is widespread scientific uncertainty about the pollution fluxes in agriculture and the effects that various abatement activities have on those fluxes, one recent trend has been to classify agricultural areas in risk classes according to the estimated potential of those areas to emit nutrients, and to allocate abatement funding accordingly. Whether or not this is a cost-effective strategy is one of the questions that this paper addresses.

As catchment managers are fiscally constrained, their objective should be to achieve cost-effective improvements in water quality. This implies attaining the greatest reduction in ambient pollution concentration per dollar, or euro, spent on abatement activities. The use of a risk classification system for identifying and prioritising agricultural areas where abatement activities should be undertaken presents catchment managers with a relatively straightforward way of improving environmental decision making under uncertainty. However, despite its appeal, the cost-effectiveness of allocating limited abatement budget through the prioritisation of funds to “high risk” areas is largely unknown. The research reported here focuses on developing key components of a framework that can be used to answer this question.

Consequently, the aim of the paper is to test the cost-effectiveness of a system where a given budget devoted to abatement is allocated based on the prioritisation of agricultural areas classified as being ‘high risk’. The specific objectives are to: a). establish a link between the risk classification and the underlying uncertainty posed by the diffuse nature of agricultural pollution; b.) develop a conceptual framework for representing the problem from an economic perspective; c). conduct an empirical analysis of the cost-effectiveness of the allocation rule for funding abatement based on risk

classification, and compare it to the cost-effectiveness of alternative allocation rule based on economic optimality.

2. Literature review

The economic literature on the treatment of risk and uncertainty in terms of water pollution from agricultural sources has been prolific. An early seminal contribution in this research area was made by Seggerson (1988), where the probabilistic nature of the agricultural pollution problem was specified and optimality conditions were derived with an explicit consideration of the uncertainty about pollution from agricultural sources. Another strain of literature that appeared early on dealt with risk and uncertainty in terms of probability of achieving a given environmental target and the health risks associated with pollution from agricultural sources. This approach was prominently showcased by Lichtenberg et al. (1989) and Shortle (1990), who built on an earlier work by Beavis and Walker (1983). The findings of these early contributions, together with other issues related to the economics of diffuse pollution and its control were summarised by Shortle et al. (1998).

Recently, there has been a revival of the literature that deals with the uncertainty related to agricultural water pollution. The uncertainty about the change in observed water quality as a result of various abatement actions has been framed using the concept of option price by Bergstrom et al. (2001). Khana and Fansworth (2006) and Isik and Khana (2002 and 2003) incorporate uncertainty into a farmer's decision of whether to adopt an environmentally friendly technology by applying the real options approach to decision making. In another strain of literature, Horan (2001) has examined the effect of the probability of a particular magnitude of water pollution from nonpoint sources on the environmental policy goals. Gren et al. (2002) offer comparison of cost-effective allocation of abatement efforts under alternative distributional assumptions (normal vs. log-normal distribution) for pollution emission from agricultural sources under alternative abatement options.

Most recently, a body of literature was started by Kaplan and Howit (2002) and Kaplan et al. (2003), followed by Farzin and Kaplan (2004). This literature explicitly treats the acquisition of information as means of reducing the inherent uncertainty present in the water pollution problems related to agriculture. The key point is that sufficiently intensive collection of information may in effect transform the non-point sources of pollution into point sources of pollution. Acquiring more information about the processes that govern pollution fluxes from agriculture will reduce the uncertainty and will subsequently result in an optimal allocation of resources to abatement. Typically, this literature has used the metric of information entropy to measure the uncertainty related to water pollution problems. This metric enables explicit valuation of the effects of information acquisition on the level of uncertainty.

The current paper builds on these literature sources, but contributes specifically by focusing on the economics of risk classification approach to funding abatement of agricultural pollution in a catchment.

3. Analytical framework

Model of classification according to risk

To put forward a way of thinking about the research problems that were outlined above, consider a catchment made up of a number of streams which converge at the mouth of a dam. These streams receive and carry phosphorus load coming from numerous agricultural areas located throughout the catchment. The catchment manager focuses their attention towards mitigating this phosphorus load. The manager has a fixed budget at their disposal every year, which they can use to fund abatement at agricultural areas in the catchment. This is typically done by contributing funds to certain abatement activities applied at the individual farm level. However, due to the large degree of uncertainty relating to the flux of pollutants (phosphorus) from agricultural areas, the benefits from assigning funding to abatement at individual farms are not clear. In particular, it is typically not possible to measure how much the application of an abatement activity at a particular farm reduces the phosphorus load originating from that farm. One way in which the catchment manager can try to overcome the difficulties posed by this uncertainty is by considering the riskiness of each agricultural area in terms of its potential to contribute towards the pollution of the head dam.

To conceptualise this uncertainty, we follow the work of Kaplan et al. (2003) and define a pollution loading parameter for each agricultural site within the catchment (indexed by i). The pollution loading parameter θ_i describes the contribution of each agricultural site to the concentration of phosphorus measured in the head dam. The value of this parameter is determined by scientists based on bio-physical and management characteristics of a given agricultural area. The realisation of the pollution loading parameter remains uncertain due to the diffuse nature of agricultural pollution. This can be described by a probability density function which characterises the distribution of the pollution loading parameter.

Using the expected value, the first moment of the distribution of the pollution loading parameter $E(\theta_i)$, agricultural areas can be classified into risk classes. This expected value is formed from the perspective of the catchment manager. Areas with a high expected value are classified as ‘high risk’ and those with lower expected values are classified into a lower risk class (e.g. ‘medium’, ‘low’, etc). This can be represented as follows:

If $k \leq E(\theta_i) \leq l$ then site i is classified as high risk,

if $l \leq E(\theta_i) \leq m$ then site i is classified as medium risk,

if $m \leq E(\theta_i) \leq n$ then site i is classified as low risk,

Currently, the number of risk classes and the size of the interval bounds (k, l, m, n) are determined purely by scientific judgment without an input from economists. This may be less than optimal, since both the number of risk classes as well as the magnitude of the interval bounds will have a significant impact on the cost-effectiveness of a risk based abatement funding mechanism, and economists could help interpreting the

importance of these parameters for cost-effectiveness. While this is beyond the scope of the present paper, it is of imminent interest for future research.

Once agricultural areas have been grouped into risk classes, the catchment manager is able to allocate abatement funding based on this classification. This can be done by weighting the allocation of the budget towards higher risk classes, which in effect represents prioritisation of funding towards agricultural areas that are perceived to be “high-risk”. For example, if there are three risk classes, the catchment manager may allocate the budget in a 60:30:10 proportion between high, medium and low risk classes respectively. The budget for individual risk class would then be allocated evenly between agricultural areas within the same risk class. A version of this allocation mechanism was simulated in the empirical study reported below to estimate the cost-effectiveness of the abatement funding allocation rules based on risk classification.

Model based on economic optimisation

From an economics standpoint, the objective of the catchment manager in dealing with diffuse source water pollution should be to allocate the budget to the activities that will bring most reduction of water pollution in a cost-effective manner. If it is assumed that the catchment manager has decided to commit its entire annual budget earmarked for abatement, the following problem needs to be solved every year to assure cost efficiency:

$$\begin{aligned} \max_{a_i} \sum_i E(\theta_i) - E(\theta_i|a_i) \\ \text{s.t.} \\ \sum_i C_i(a_i) \leq \bar{C} \end{aligned} \quad (1)$$

where $C_i(a_i)$ represents the abatement cost function when abatement activity a is implemented in agricultural area i , the notation $(\theta_i|a_i)$ refers to the value of the pollution loading parameter for the area i given the abatement activity undertaken in that area, and \bar{C} is the budget that the catchment manager has devoted to pollution abatement.

Analytically, this problem can be solved by setting up the Lagrangian:

$$\max_{a_i} L(a_i) = \sum_i (E(\theta_i) - E(\theta_i|a_i)) + \lambda (C_i(a_i) - \bar{C}), \quad (2)$$

and by deriving the first order condition:

$$-\frac{\Delta E(\theta_i|a_i)}{\Delta a_i} + \lambda \frac{\Delta C_i(a_i)}{\Delta a_i} = 0. \quad (3)$$

This can be further manipulated to get

$$\frac{\Delta E(\theta_i|a_i)}{\Delta a_i} = \lambda \frac{\Delta C_i(a_i)}{\Delta a_i}, \quad (4)$$

and subsequently can be used to represent the Lagrange multiplier, λ as:

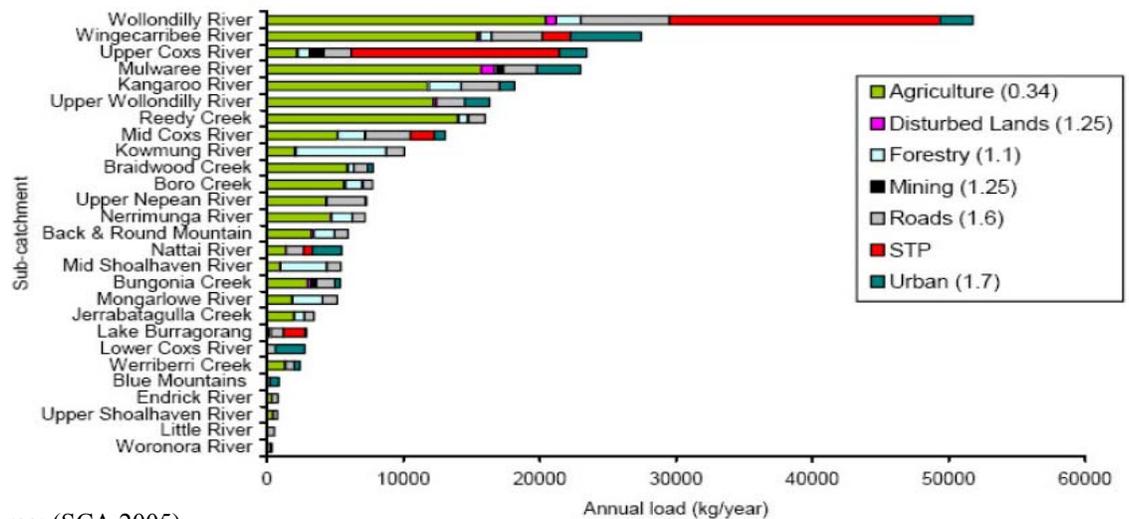
$$\lambda = \frac{\Delta E(\theta_i|a_i)}{\Delta C_i(a_i)}, \quad (5)$$

which states that the Lagrange multiplier may be interpreted as a change in the expected value of the pollution loading parameter given the abatement activity undertaken in agricultural area i , per unit of cost expended on that abatement activity. This representation offers an adequate criterion, which can be used to allocate abatement activities to agricultural areas. The abatement options and agricultural areas that have high value for λ should be given priority in allocating abatement. A version of the problem presented in equations 1-5 was solved using a dynamic chance constraint programming model (Charnes and Cooper, 1959) in the ensuing empirical analysis.

4. Method and data

To test the cost-effectiveness of the two alternative approaches to allocating funds for supporting abatement activities in agricultural areas—one based on prioritising according to the risk classification, and another based on economic optimisation — an empirical analysis was conducted using existing data provided by the Sydney Catchment Authority (SCA), (Davis 1996). Studies conducted by SCA reported that agriculture is the largest source of phosphorous load in their catchment (Figure 1).

Figure 1. Composition of phosphorus loads in SCA sub-catchments (export potential)



Source: (SCA 2005)

The data provided were specific to the Warragamba Dam catchment (containing 13 sub-catchments), which is located 65 kilometres west of Sydney and is the city’s main raw water supply. Data from 57 agricultural areas located across 13 sub-catchments consisted of phosphorus load emissions estimates, and of abatement quantities and cost data for eight commonly used abatement options. The data indicated the suitability of each abatement option for a particular land use practice in a particular location.

Using the available phosphorus load estimates, agricultural areas were grouped into risk classes based on the estimated potential to emit phosphorus into adjacent waterways. This was done in order to assess the cost-effectiveness of the risk-classification approach of allocating funds to abatement activities. Three risk classes were defined as follows:

If	$E(\theta_i) < 100$	Low Risk
if	$100 \leq E(\theta_i) < 1000$	Medium Risk
if	$E(\theta_i) \geq 1000$	High Risk,

where all values are given in terms of total expected phosphorus load from an agricultural area in kilograms per year.

Following the classification, an annual budget was allocated between risk classes in proportion of 60:30:10 to high, medium and low risk classes respectively. This was done to simulate the effect of using allocation rules that prioritise abatement funding to areas classified in the “higher-risk” classes. Abatement funds were then evenly distributed to farms within each risk class. Since sufficient abatement can not be undertaken in a single year due to budgetary constraint, this process was repeated for consecutive years, until the specified target phosphorus concentration in the dam was achieved, or until the devoted budget was not exhausted. At the end of the simulation, the values of the expected phosphorus concentration in the head dam, and the cost of the expended funds for abatement in agricultural areas were recorded.

As an alternative to the allocation of abatement funds according to the risk classification, several optimisation scenarios were simulated using a dynamic chance constraint program set up in Microsoft Excel. As with the risk classification scenarios, abatement funds were reallocated each year over the planning horizon. Three different optimisation scenarios were simulated for comparison with two risk classification scenarios and for conducting comparative statics. The full set of simulated scenarios is presented below in Table 1.

Table 1. Description of analysed scenarios by method of allocating funds for abatement.

Scenario	Method of allocation	Budget (\$)	Minimum expenditure in an area (\$)
1	Optimisation	Unconstrained	0
2	Optimisation	Unconstrained	1000
3	Optimisation	2 million	1000
4	Risk classification	2 million	1000
5	Risk classification	3 million	1000

5. Results

The results from the empirical analysis lend support to the expectations based on the theoretical analysis. In short, the results indicate that allocating a fixed budget by prioritising funding towards ‘higher-risk’ classes is less likely to meet the set pollution standard, and in the same time it is more costly in terms of discounted streams of expenditure on abatement measured as a net present value (NPV) over the planning horizon, in comparison to the optimisation scenarios. These results are summarised below in Table 2.

Table 2. Performance of the risk classification and optimisation scenarios against a phosphorus concentration standard for the head dam of 0.01 mg/L.

Scenarios	P concentration (mg/L)	Standard met (yes/no)	Cost expended (NPV \$)	Cost/kg P removed (NPV \$)	Planning horizon (years)
Optimisation scenarios					
1	0.010	Yes	3,477,722	4,860	9
2	0.010	Yes	3,762,674	5,235	7
3	0.007	Yes	3,864,468	5,183	3
Risk classification scenarios					
4	0.015	No	7,248,632	11,012	5
15	0.011	No	10,872,948	14,347	5

It can be seen that all three optimisation scenarios performed very well in relation to meeting the set pollution standard. In contrast, the two risk classification scenarios were both found to fall short of meeting the set pollution standard. For scenario 4, the phosphorus concentration in the head dam was 36 per cent above the allowable standard, and for scenario 5 the phosphorus concentration in the head dam was 10 per cent above the standard.

Further, as funding allocation is guided by rules which treat all areas within a risk class as equally risky, funding can not be directed toward areas at which abatement would be most cost-effective. Additional inefficiency is introduced by the inability of the risk classification system to account for the importance of site location in the transportation of phosphorus load to the head dam.

In addition to the failure to meet the set concentration standard, both scenarios in which abatement funding was prioritised toward 'higher-risk' areas were more costly than the corresponding optimisation scenarios. Total costs for each of the three optimisation scenarios were estimated to be less than \$4 million in terms of net present value (NPV), as opposed to the two risk classification approaches for which the total cost were estimated at \$7 million (NPV) and \$10 million (NPV) respectively. Further, the use of a funding rule based on risk classes leads to much higher average costs than what can be achieved under an economic optimisation approach. Average costs per unit of phosphorus removed at the dam wall for the two risk class scenarios were estimated at \$11 000 and \$14 000, which in both cases was more than double the estimated average cost figures under the optimisation scenarios.

6. Summary and conclusion

Diffuse nutrient pollution from agricultural areas, in particular phosphorus, remains a key concern for water managers worldwide. As a result, catchment management authorities are spending significant sums of public funding to address the issue through the support of various abatement options on farms. However, the allocation

of this funding is problematic, due to the inherent uncertainty related to pollution of diffuse nature. One way in which this uncertainty has been addressed is by grouping agricultural areas into groups based on their potential to contribute to ambient pollution levels. This is done through classification of agricultural area in 'risk-classes' in relation to the pollutant in question, in this case phosphorus. The designation of agricultural areas into risk classes presents catchment management authorities with the opportunity to create relatively simple rules for allocating a fixed budget based upon this risk classification. Typically, this is done by assigning priority towards 'high risk' class areas.

Although these budget allocation rules may seem intuitive, their economic performance, in terms of cost-effectiveness has yet to be fully understood. The lack of research in this area was a key motive for the work reported in this paper, which was undertaken to set up a framework for analysing the problem of cost-effectively allocating limited funding to reduce diffuse pollutants from agricultural areas classified in risk classes.

An analytical framework was presented establishing a way of thinking about the issues surrounding the problem of allocating a fixed budget to agricultural areas classified by risk. A risk classification system was explained, and its use in determining a simple allocation rule which prioritises funding towards high-risk areas was demonstrated. As an alternative, an economic optimisation model for allocating funds for abatement to agricultural areas was presented. Using data provided by the Sydney Catchment Authority, an empirical simulation was undertaken to compare the cost-effectiveness of the two alternative budget allocation systems: risk classification and economic optimisation. It was found that following a budget allocation rule which prioritises funding towards 'higher risk' areas does not result in a cost-effective outcome. The results indicate that when allocating a budget based on risk classification, a catchment manager is unable to satisfy an exogenously set pollution standard, despite spending more than they would in any of the comparable optimisation scenarios.

The findings of this paper show that basic cost-effectiveness analysis is still relevant in the cases when the uncertainty about water pollution from agricultural sources is 'packaged' in a form of classifying those areas in risk classes. The key economic message, that allocating resources to abatement activities so that the expected reduction of pollution per monetary unit spent is greatest, stands firmly in this case too.

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