Estimating the Cost of Agricultural Pollution Abatement: Establishing Beneficial Management Practices in the Bras d'Henri Watershed

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Introduction

The intensification of agriculture has raised the necessity of finding new solutions to the growing problem of non-point source pollution from agriculture. Despite a consensus that policies are necessary to protect the quality of water, the type of policy that must be implemented is subject of debate. This paper employs an integrated model that combines a hydrologic and an economic model to estimate the cost of implementing beneficial management practices (BMPs) to reduce non-point source pollution. With this integrated model, it is possible to estimate pollution abatement cost curves from reducing non-point source pollution from agricultural activity. The abatement cost is determined as the variation in profit between the new regulation and the baseline situation, i.e. before the additional regulation was introduced. It is possible to build an abatement cost curve by calculating this variation for various pollution emission targets. The behaviour of the resulting pollution abatement cost is one measure available to evaluate the economic efficiency of an environmental policy. It can also better provide information about the application of these policies in the context of monitoring non-point source pollution. To provide a realistic scenario, a menu of BMPs is presented to the farm producers in the model to allow them to attain a desired pollution target that optimizes their production (commodity) choice based on profit-maximizing criteria taking into account the agricultural reality of their farming situation.

The method used for this evaluation is a simulation of decisions for profit maximizing farmers facing production and environmental regulatory constraints that are based on on-farm surveys completed in the study area; the Bras d'Henri Watershed in the Province of Quebec, Canada. This simulation-optimization model maximizes net farm income subject to production and environmental constraints. The simulation model uses real farm information about the farms of the Bras d'Henri Watershed, a region near Quebec City where agricultural activity is intensive. The information used by the model includes not only realistic economic constraints but also the agricultural reality of the region. The resulting model can thus generate the optimal managerial decision for individual farms while taking into account their unique agrologic and environmental characteristics. This simulation allows the researcher to estimate the cost of abating pollution at both the farm and the watershed level. It also illustrates the behaviour of farmers when facing different methods of regulation. With the same model, a variation in the objective function can be used to generate results for different environmental regulations. Comparing BMP adoption and other managerial behaviour of individuals when facing different environmental regulations provides information about the potential outcome of different policy implementation. Indeed, the integrated model can show the level and type of BMP adoption when farms face various levels of environmental constraints.

The evaluation of the interaction between agricultural economic activity and their environmental impact help to evaluate how the environmental regulations are affecting economic activity. The results from various scenarios permits one to assess what are the best policies to employ to attain the desired environmental quality while minimizing the cost of the measure.

Objective

The main objective of the study is to evaluate the impact of adopting BMPs as a means of reducing non-point source pollution. An integrated simulation-optimization model was designed for this assessment. This model merges hydrological information with on-farm economic information to create a model where the farmers incorporate environmental information into their economic decision framework. The integration of hydrological information with economic decision making was made possible by surveying the farms in the watershed and locating their fields within a geographical information system (GIS). Such a model better reflects the reality of where farmers are managing their farms at the field level and the reality that every field is different, both in terms of size of surface area and characteristics such as soil type and slope. The unit of measurement to calculate the resulting change is net farm income, the adoption of BMPs, the livestock unit and the crop mix. For example, the variation of pollution target in the objective function creates a variation of net farm income. Plotting the change of net farm income at various level of pollution target creates abatement cost curves. The aim is to evaluate the potential benefit of shifting the scale of environmental policy from individual farms (similar to a standard) to the watershed level (market based instrument).

Current situation

Legislative effort has been expended to improve water quality in the province of Quebec. The enacted legislation, the Quebec Regulation Respecting Agricultural Operations, limits the quantity of organic and chemical fertilizers that can be applied to agricultural land based on the richness of the soil (MDDEP, 2012). It also set rules concerning the access of livestock to waterways. Where agricultural land is adjacent to waterways a 3-meter buffer strip must be inserted between the land and the waterway and it is mandatory that a low ramp is used for manure spreading. Such command-and-control regulations can be efficient in term of pollution abatement but are recognized as not necessarily optimal with respect to the social outcome. More specifically, the distribution of pollution abatement among emitters is not distributed based on the marginal cost of abatement and thus does not provide the best allocation of resources for society. Thus, potential gains from trade between emitters can provide a potential improvement from the status quo. The literature and experience provide various instruments that might improve the marginal cost allocation among emitters. For instance, tradable permits of sulphur oxide proved itself to be an efficient instrument for the regulation of sulphur dioxide emissions (Horan and Shortle, 2011).

The success of decreasing abatement cost with other pollutants has encouraged some legislative bodies to design similar regulatory schemes for water pollution from agricultural nutrients. The non-point source nature of these pollutants requires a good assessment of the abatement cost incurred by the farm to implement a successful regulation. In fact, Horan and Shortle (2011) warn that theoretical abatement cost curves in the context of water quality trading differ from practical ones. Three factors were identified as creating a divergence: properly identifying the commodity to be traded, defining rules governing commodity exchange, and setting the target. This study will help to improve the information about the pollution abatement cost and the relationship between the level of abatement and the cost of abating non-point source pollution.

Type of BMPs

Beneficial Management Practices (BMPs) in agriculture refer to actions that farmers are taking to reduce their environmental footprint . In the context of this modelling exercise, the menu of BMPs presented to the producers was established with the collaboration of the agronomists that are in contact with the producers located in the watershed. The BMPs considered are described in Table 1. They all provide some environmental improvement from the status quo. However, they all generate various environmental and economic outcomes. The economic cost included in the model is limited to the operating cost of adopting the particular BMP and does not include the investment cost or the cost of capital.

Table 1 : BMPs included in the integrated model

	Outcome	
BMPs	Environmental	Economic
No till	• Reduces Erosion	• Increases pesticide cost • Reduces plowing cost • Increases Seeding cost • Potentially reduces yield
Buffer Strip	• Reduces Erosion • Captures pollutants	• Reduces cultivated area • If the buffer strip is large enough, an alternative crop can be harvested from it
Low Ramp	• Reduces leaking • Increases capture of fertilizer	• Reduces fertilizer cost as it increases fertilizer efficiency • Increases application cost
Reduced pesticide	• Reduces potential leaking	• Increases cost of pesticide application

Method

The model developed for this study can be categorized as a sector model with large representative farms (McCarl, 1982). This type of model has the strength of providing a good representation of microeconomic farming constraints. As explained by McCarl, the best approach is to include representative farm-level crop budgets generated with farm plans for all possible crop mixes. With this information, activities can be generated using linear programming and appropriate crop and livestock mixes can be attained. Linear Programming is an interesting tool for the evaluation of responses of firms for various situations given a set of budget and operational constraints.

A large body of literature exists where this method is used in various situations such as farm responses from opening trade barriers (Adams et al., 1999) or supply responses to changing biofuel policy (Chen, Önal; 2012). The method as used in past studies can generate insightful results for policy design and the resulting implications. Therefore, linear programming has been shown to be a good analytical tool and its application to non-point source pollution is an application that becomes even more valuable when linked with new GIS technologies.

Hydrologic model

The challenge of measuring water non-point source pollution resides in the difficulty of calculating the emission as it varies over time and over each precipitation episode. For this purpose, a large modelling effort has been devoted to this task in the study area. GIBSI (Gestion Intégré par Bassin Versant à l'Aide d'un Système Informatisé) is a model that includes simulation models (hydrological, soil erosion, agricultural-chemical transport, and water quality), a management module (land use, point source, agricultural production systems, and reservoir management modules), a relational database management system and a geographic information system (GIS) (Salvano et al., 2006; Mailhot et al., 1997; Villeneuve et al., 1998; Rousseau et al. 2000, 2005). GIBSI uses HYDROTEL (Fortin et al., 2001), a physically and GIS-based model to calculate rainfall-runoff processes and integrates this information in RUSLE (Renard et al., 1997; Wishmeier and Smith, 1978), the sediment transport equation. Finally, the pollution coefficients used in the economic model are from the SWAT transport algorithms (Arnold and Williams, 1995) and EPIC (Sharpley and Williams, 1990). This model provides information based on real climatological trends combined with realistic runoff information to generate potential information about pollutions from hydrological units.

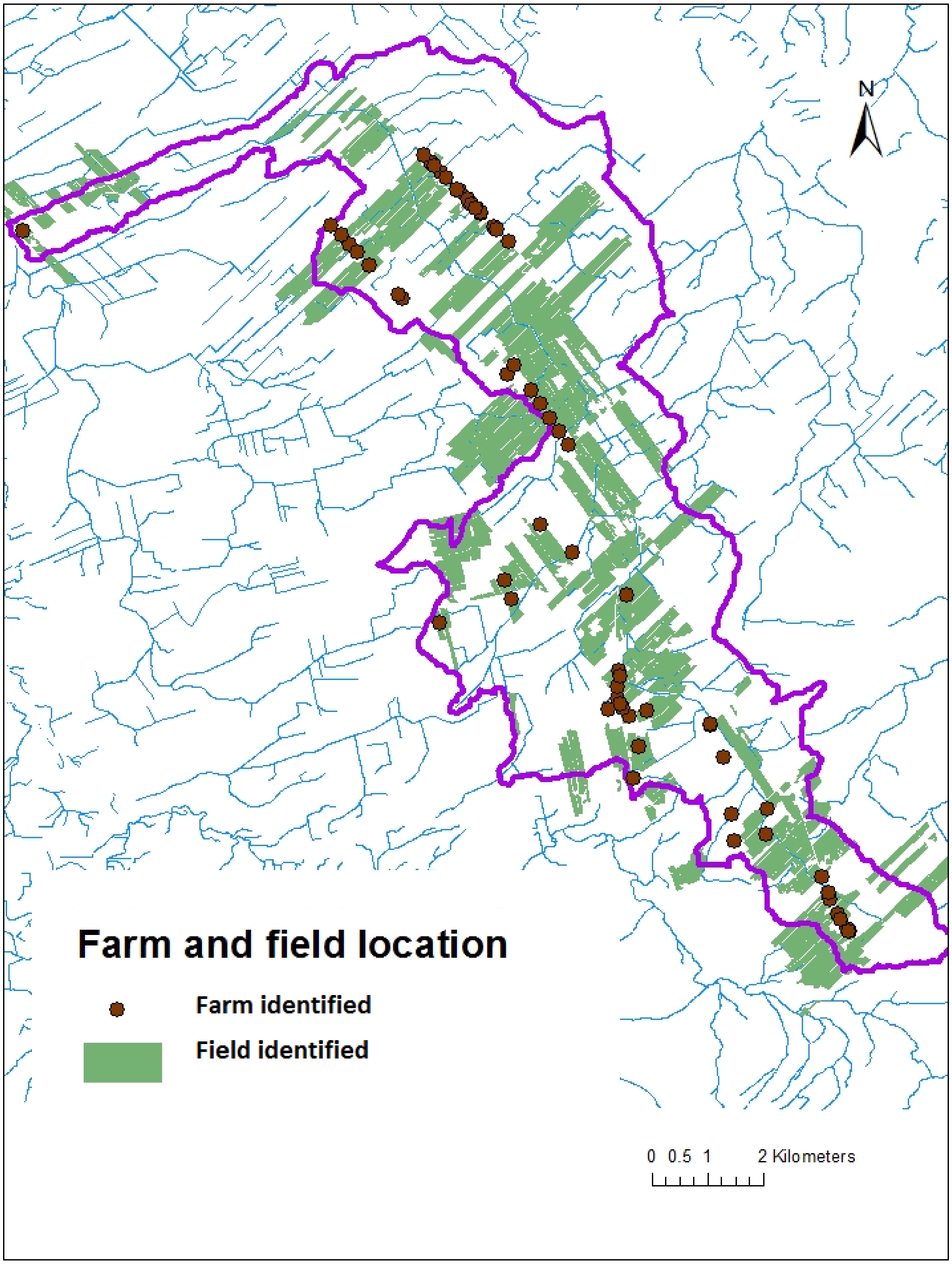
The hydrological units that are constructed by HYDROTEL respect the topography but are not related to the field boundaries that are used for the daily management of the agricultural producers; therefore each field is assigned their own hydrological unit and if more than one unit is found in the field a weighted average is used to evaluate the contribution of the studied pollutant from this field. The release of pollutant is calculated for every crop and agricultural practice included in the economic model.

Economic model

The agricultural economic model is based on the 69 farms surveyed in the watershed. Each farm was surveyed in the spring of 2010 to provide detailed information about their crop mix, livestock inventory, BMPs used (if any), and the location of their field. Figure 1 provides an overview of the location of the various farms and fields. This information was included in the agricultural economic model linked with economic information. The economic information related to agricultural practices and farm practices were generated using relevant economic literature (CRAAQ, 2008, 2009, and 2011) and regionalized to account for the weather of the watershed. The agronomic requirements such as nutrient requirements for animals and effluent releases from animal production were taken from the National Research Councils (various editions: 1994; 1998; 2000; 2001), Dissart (1998), and Cheeke (1999).

There are 84 farms identified in Figure 1 and yet only 69 of these were included in the modelling effort. The difference in these numbers is due to 84 farms being approached for their information but completed surveys were only received from 69 farms.

Figure 1 : Farm and field location in the Bras d'Henri Watershed



The objective function is based on the work of Rivest (2009):

$$Max \sum_{i=1}^{73}\sum_{j=1}^{J}\sum_{f=1}^{P}\sum_{b=1}^{T}\sum_{p=1}^{W}\sum_{b=1}^{B}\left[\alpha_b Y_{ib}+\delta_p\left(SE_{ip}-BU_{ip}\right)-x_p A_{ijpt}-\eta_w O_{jpw}-\lambda_p P_{ijp} - \pi_{ij}R_{ij}-\phi IM_i-\phi EX_i\right]$$

Where:

Subscript	Parameters	Variables
i: farm index number	x_p: Cost of production	A_{ijpt}: Area in crop production
j: Field index number	η_w: Cost of buffer strip per length	O_{jpw}:Length of buffer strip
p: Crop index number	λ_p: Cost of pesticide use	P_{ijp}: Area produced with reduced pesticide use.
t: Tillage practice index number	π_{ij}: Additional cost of spraying manure using dribble bar	R_{ij}:Area sprayed with dribble bar
w: Width of buffer strip index number	α_b: Net return from animal unit	Y_{ib}: Number of animals
b: livestock index number	ϕ: Price of transporting manure	EX_i: Volume of manure exported
		IM_i: Volume of manure imported
	δ_p: Price of crop	SE_{ip}: Weight of grain sold
		BU_{ip}: Weight of grain bought

The objective function is constrained by 17 equations that can be classified in five groups:

1. Farm characteristics constraints
2. BMP constraints
3. Animal Nutrient requirement constraints
4. Environmental constraints
5. Crop constraints

The farm characteristics constraints are related to the size of the farm and the restricted resources in term of land and animals for each farm operation. For the animal production, the productions that are under supply management, such as dairy and poultry, are assumed to be held constant because the flexibility of acquiring and liquidating the right of production (quota) is virtually absent in the short term.

The BMP constraints were accounted for in terms of their impact on total crop produced, level of abatement implemented, and operating cost for their implementation. The animal requirement constraint ensures that the nutritional requirements of the livestock would be fulfilled by either the crop produced on the farm or by the purchase of sufficient quantity of the required crop. The nutritional requirements included in the model are dry matter, crude protein, total energy, total digestible nutrient, calcium, phosphorus, and magnesium. The requirements are individualized for every animal type. Some flexibility was allowed to account for the preparation of animal feeds.

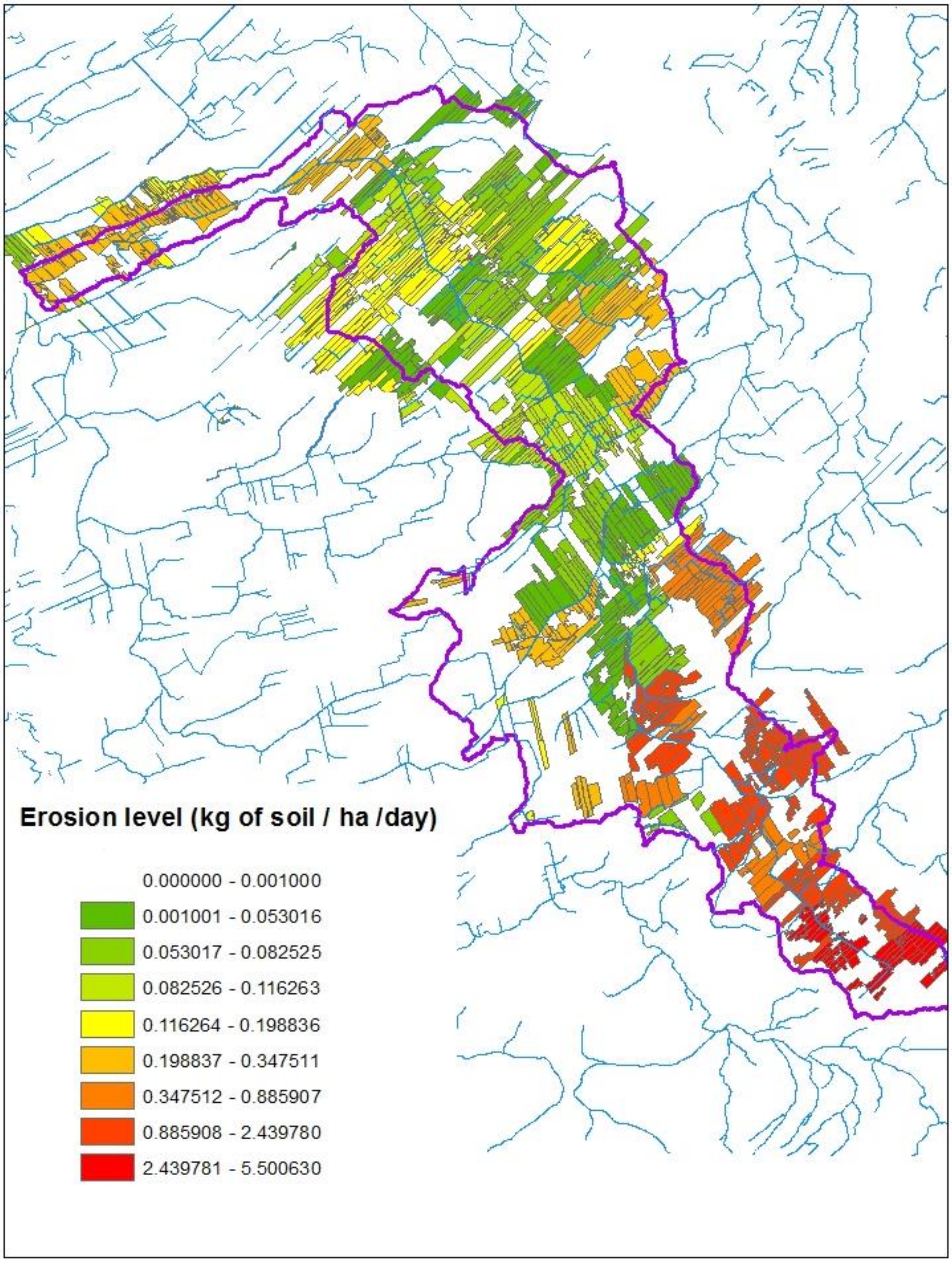
The environmental constraints were at both the farm and the watershed level. At the farm level, the main restriction relates to manure application. Quebec legislation set limits for the quantity of fertilizers that can be applied by unit of land area. It is presented in the model as the maximum number of animals by farm, by animal type (cow, hog, or chicken) that cannot be exceeded. Thus, it implies that the number of animals per farm cannot be increased without exporting manure outside the watershed. At the watershed level, the summation of the contribution of nutrients from every field was limited to the status quo level. Therefore, the model did not permit a reduction of pollutant at the expense of an increase of another pollutant above the status quo level.

The crop inventory constraint controls the amount of crop for each farm through sale of the crop produced or feeding the crop to animals on the farm. The crop yields used in the model were the average yields reported by La Financière Agricole du Québec which is the main crop insurer in the province (FADQ, 2010). The yield reported is for a small region in the watershed and increases the accuracy of the yield data of the model. The quantity of grain produced varies with the BMPs implemented. Indeed, it is recognized that no-till can reduce yield (Morand, 2004) and a buffer strip reduces harvested area.

Integrated model

Geographic information system (GIS) is used as a platform to link the economic and the hydrologic models. The spatial location of the two models is used to merge the information from the hydrologic and the economic models. In this respect, each individual field bears its own unique set of information regarding the pollution coefficient for various crop scenarios and the animal mix of the owner. The cost asymmetry of adopting BMPs originates from the heterogeneity of farm composition and pollution coefficients. Figure 2 illustrates the magnitude of the sediment emission heterogeneity: the most fragile soil is releasing 500 times more weight of sediments than the least fragile in the watershed. Thus, the cost asymmetry related to the BMPs necessary for reducing sediment emission provides a fertile ground for some economy from trade as recognized by the theory. The interesting contribution is the empirical calculation of the level of saving available when an economic mechanism is used. As presented by the objective function in the economic model section of this paper, the model is design to allow for a flexibility in various aspects of the decision making process of a farm. Examples are livestock and crop mix, crop location, on- or off-farm acquisition of animal feed, or BMPs adoption. For the results presented in this study, it is assumed that producers are not modifying the number of animals that they own but will adopt appropriate BMPs to reduce their emissions. In addition, the producers have to keep the manure in the watershed and not exported to another watershed. However, it is possible for a producer to send some quantity of manure to another producer in the watershed. The producers will base their choice of BMPs on the best allocation of resources available.

Figure 2 : Level of sediment emission level of each field in the Bras d'Henri watershed



The type of crop grown is allowed to vary not only based on the need for feed but also on the necessity of reducing pollution emissions if the policy requires it. For example, a producer can acquire corn for feeding their animals and sell barley if the environmental target requires an important reduction of emissions.

Results

The linear programming model generates abatement cost curves for the various pollutants identified in the study[4]. To generate the curves, the model was calibrated to generate the pollution emission given the number of animal units and crop declared by the producer at the time the survey was administered. Results generated given this set of information provided the status quo against which other results can be compared. It is then possible to vary some constraints and assess what is the impact on the environmental and economic components.

The first set of tests performed was to vary the pollution constraint and observe how the aggregate benefit varied. For this task, the model recorded the variation of profit over various level of pollution emission restriction and generated curves for every pollutant studied. Figure 3 shows the impact on net farm income as each of the emissions are reduced individually and the constraint is set at the farm level. Satisfying the constraint for e-coli provides the greatest and fastest reduction in net farm income of all of the pollutant constraints. Net farm income would decrease by 10 percent for an 80 percent decrease in sediment and phosphorus when the constraint was set at the individual farmer level. This reduction was only 8 percent for an 80 percent decrease in nitrogen, but approximately 20 percent for e-coli reductions.

[4] The pollutants included in this study are; sediment, nitrogen, phosphorus, e-coli and pesticide (atrazine).

Figure 4 provides the results when the emission reduction is set at the watershed level. With this approach it is the watershed as a whole that must fulfill the constraint and thus allows for environmental targeting of BMP implementation. The efficiency in setting the constraint at the watershed level can be seen in the amount of net farm income that is forgone to satisfy any of the constraints is less than the amount required when the constraint is set at the individual farm level. In this situation, the loss in net farm income from the baseline is 5 percent for sediment and nitrogen, 6 percent for phosphorus and 14 percent for e-coli.

In both cases, the highest reduction in net farm income from the baseline is found when the e-coli constraint is trying to be satisfied. In addition, there is a slight change in the ordering of the cost of satisfying the other emissions. When the constraint at the individual farm level the least costly constraint is nitrogen followed by sediment and phosphorus, while when set at the watershed level both sediment and nitrogen are the least costly constraints to fulfill. As expected, the reduction in net farm income is always lower when the environmental constraint is set at the watershed level and not the individual farm level.

Figure 3. Reduction in Net Farm Income from Emission Reductions when the Constraints were set at the Individual Producer Level.

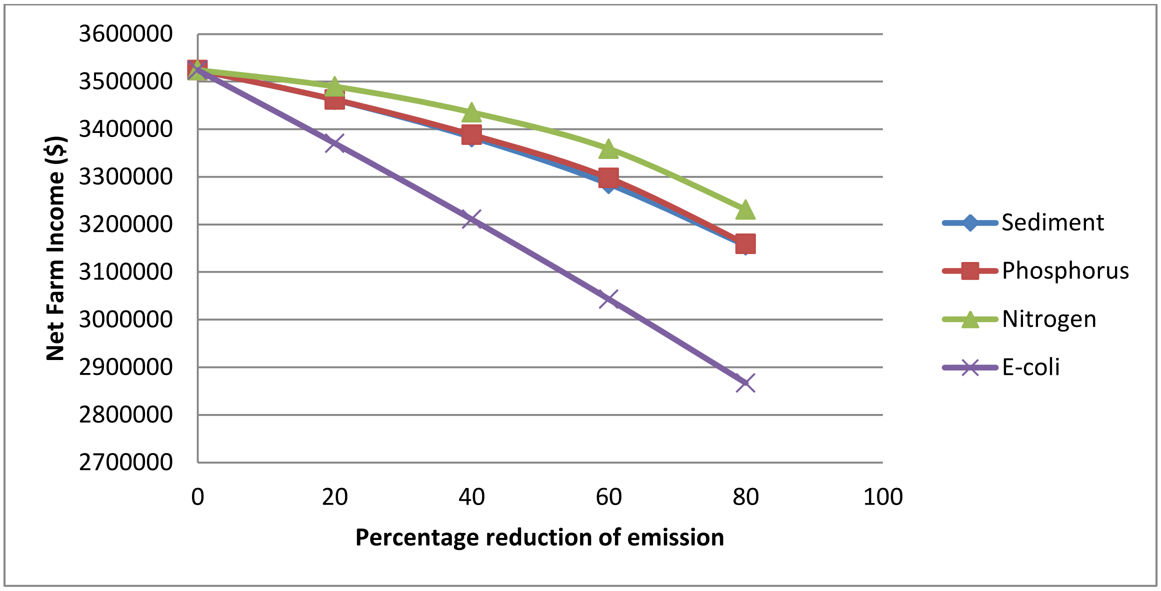
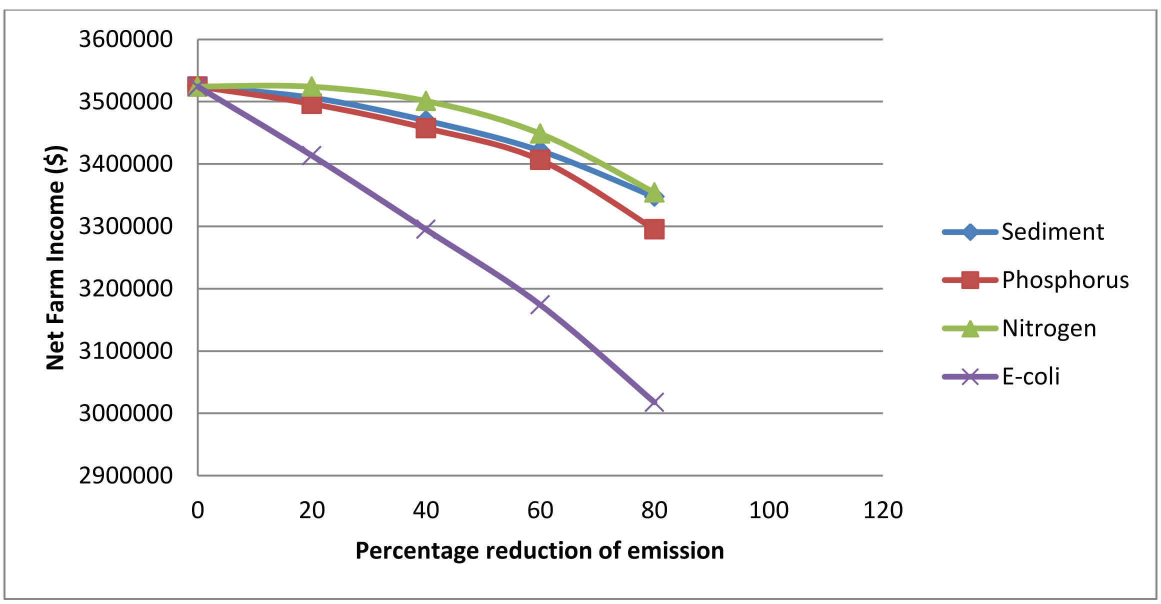


Figure 4. Reduction in Net Farm Income from Emission Reductions when the Constraints were set at the Watershed Level.



Figures 5 through 8 provide the average and marginal costs of individual emission reductions when the constraint is set at the individual farm level. The shape of the average and marginal cost curves are as expected from economic theory. The highest marginal cost at the 80 percent reduction level is for e-coli at a cost of $8,800.00 with an average cost of $8,200.00 per percentage reduction. The lowest marginal costs for emission reductions is for nitrogen at $6,300.00 at the 80 percent level while the average cost of emission reduction was $3,660.00. The marginal costs for reducing sediment and phosphorus were very similar at $6,470.00 and $6,900.00 respectively. The average costs for sediment and phosphorus reductions were $4,600.00 and $5,560.00 respectively.

Figure 5. Average and Marginal Cost of Sediment Reductions when Set at the Individual Farm Level.

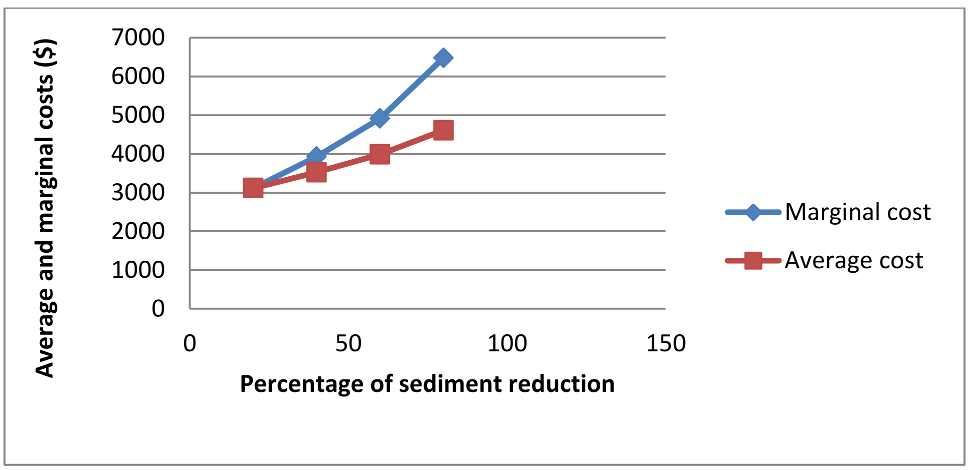


Figure 6. Average and Marginal Cost of Phosphorus Reductions when Set at the Individual Farm Level.

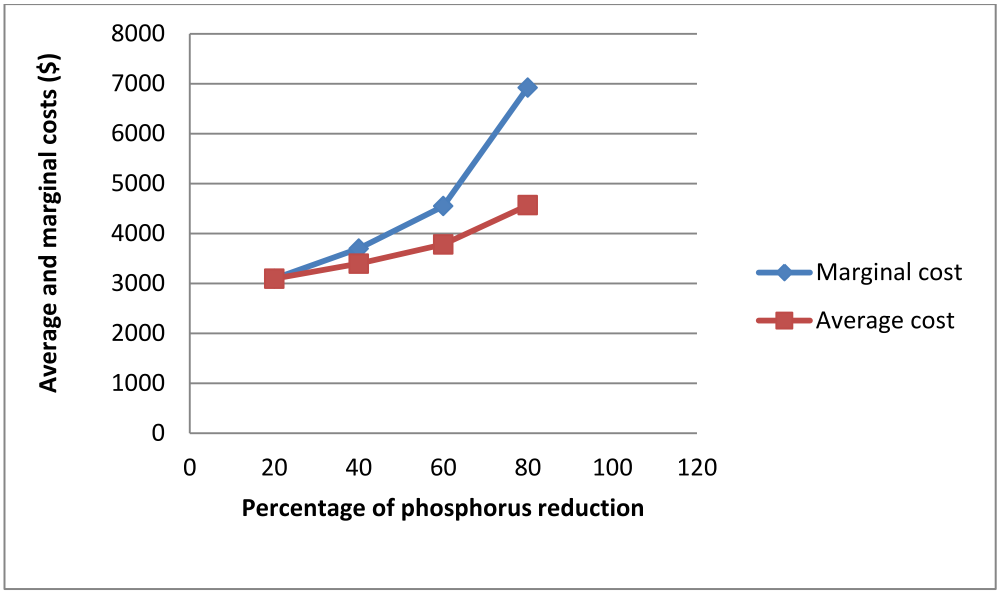


Figure 7. Average and Marginal Cost of Nitrogen Reductions when Set at the Individual Farm Level.

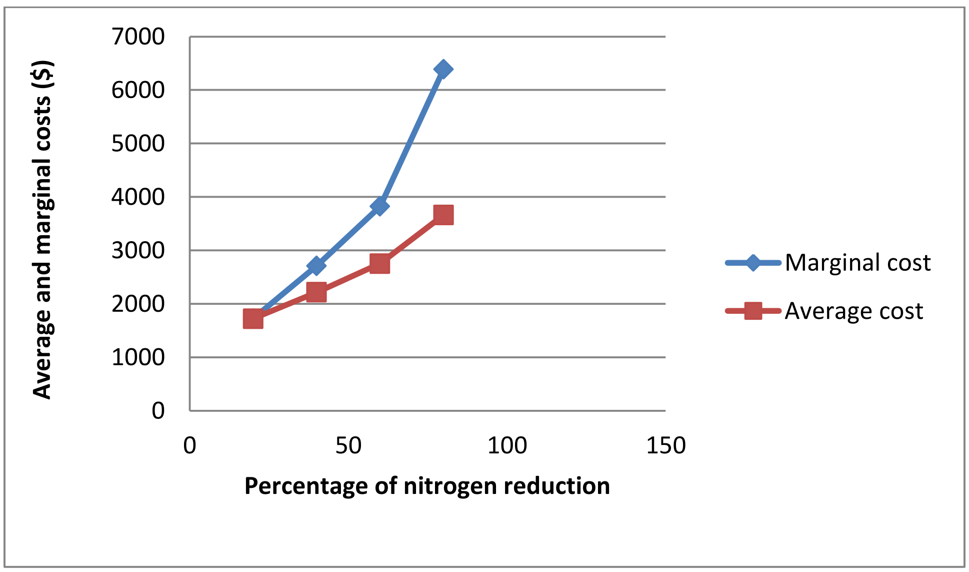
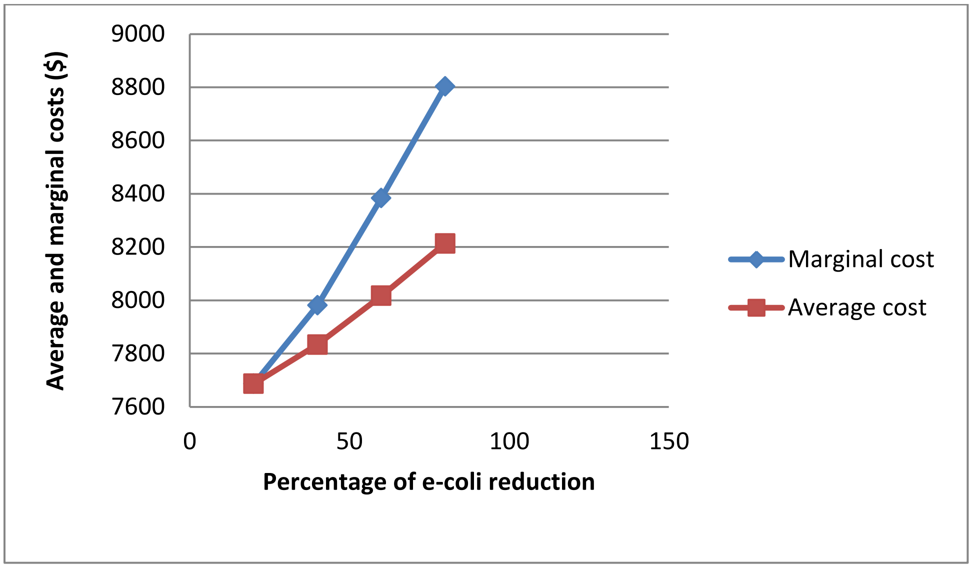


Figure 8. Average and Marginal Cost of E-Coli Reductions when Set at the Individual Farm Level.



The marginal and average cost curves when the constraint is set at the watershed level are given in Figures 9 through 11. As with the individual farm constraint information, the largest marginal costs for emission reductions is for e-coli. In this case, the marginal cost of emission reductions was $7,800.00 at the 80 percent reduction level. The average cost for e-coli reductions when set at the watershed level was $6,300.00. The lowest marginal cost for emission reduction was for sediment, at a cost of $3,690.00 at the 80 percent level. The average cost of sediment reduction when the constraint was set at the watershed level was $2,200.00. The marginal cost of reducing nitrogen was the next lowest cost at $4,700.00 at the 80 percent level, while the average cost was $2,100.00. The marginal cost for phosphorus reduction was $5,500.00 at the 80 percent level and the average cost was $2,800.00.

Figure 9. Average and Marginal Cost of Sediment Reductions when Set at the Watershed Level.

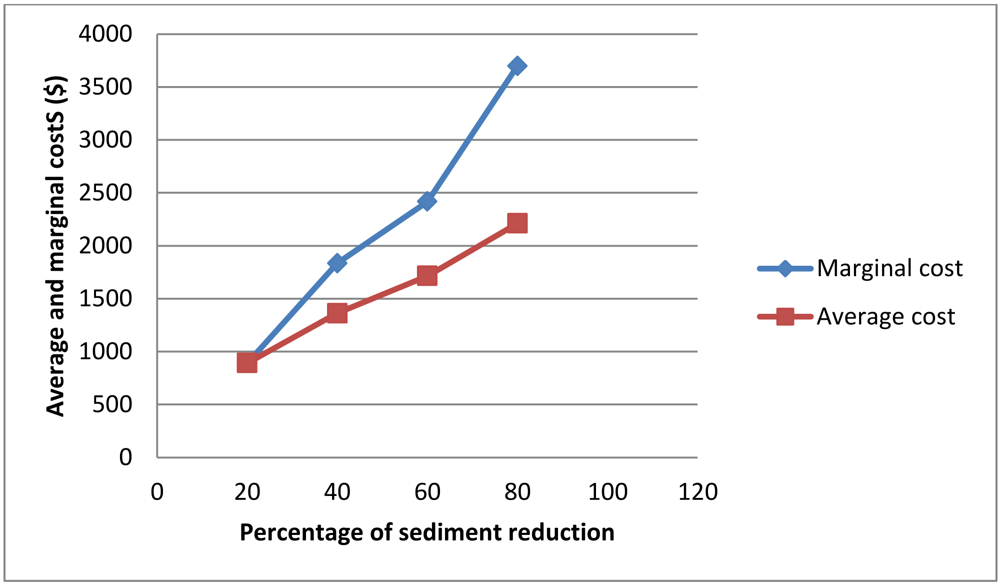


Figure 10. Average and Marginal Cost of Phosphorus when Set at the Watershed Level.

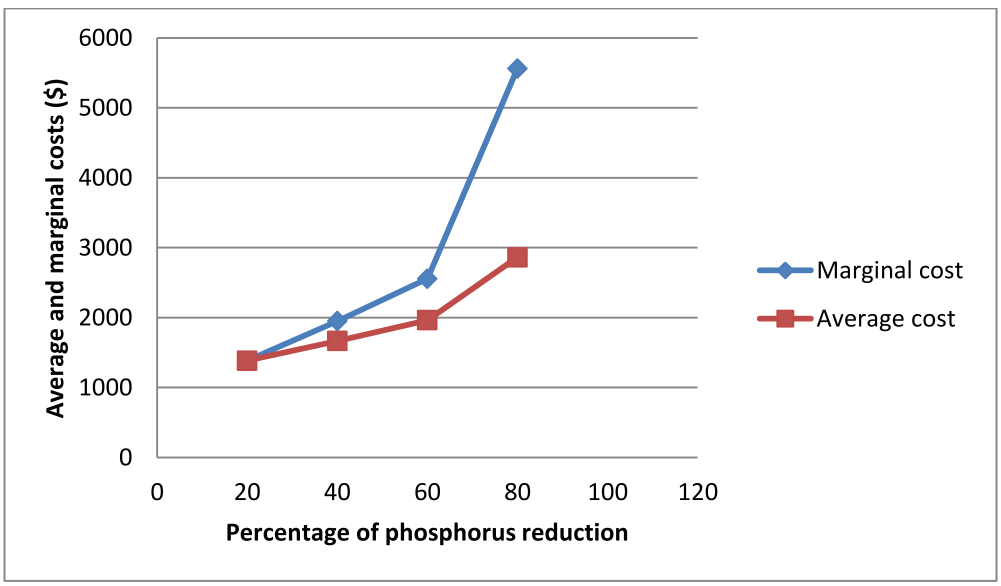


Figure 11. Average and Marginal Cost of Nitrogen when Set at the Watershed Level.

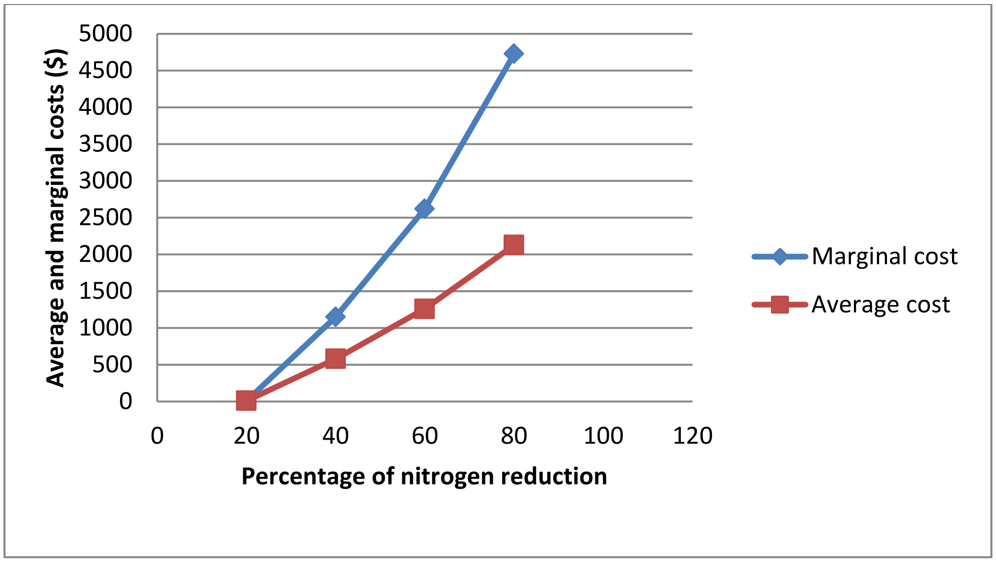
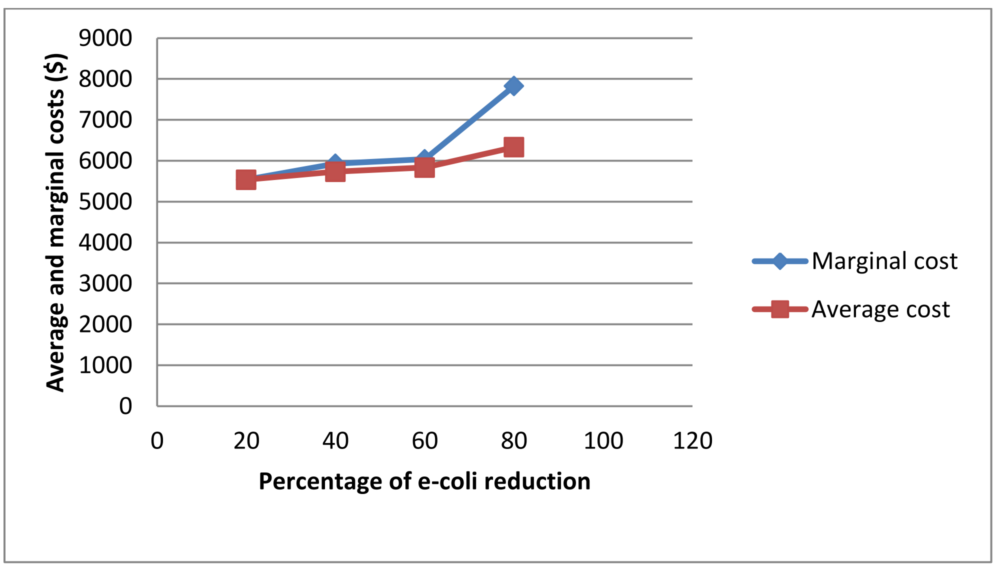


Figure 12. Average and Marginal Cost of E-Coli when Set at the Watershed Level.



As expected, the marginal and average cost of reducing emissions was greater when the constraint was set at the individual farm level as compared to the watershed level. In all cases both the marginal and average costs are lower when the constraint is set at the watershed level. The greatest different in the average cost of emission reduction can be found for sediment. In this case, the difference in the average cost for sediment reduction was $2,400.00 for a reduction of 80 percent. The next highest average cost difference was for e-coli ($1,880.00), followed by phosphorus ($1,700.00), and then nitrogen ($1,500.00). The reduction in costs associated with setting the constraint at the watershed level was expected because when the environment constraint is set at this level is allows for greater flexibility within the watershed and the ability to target the adoption of BMPs.

Impact of policy on individual farms

Since the model simulates decisions at the farm level, it is possible to refine the level of analysis at the farm level to see if the size and composition of the farm has an impact on the net farm income (NFI) of the individual farm. Indeed, a look at the distribution of net farm income for each farm facing the two policy scenarios shows that: 1) the smallest farms have the highest relative variation of NFI, and 2) the farms that have a large number of animals but a small quantity of land are more negatively impacted. Pertaining to the first assertion, the analysis of the percentage of variation between a standard set at the watershed level versus one at the farm level, provided a variation of 40% in net farm income for the 20 smallest producers and a 5% variation for the 20 largest producers. Therefore, the size of the farm has an important impact on the reduction of pollution against an environmental standard. If setting the pollution standard at the level of the watershed is advantageous for the larger farms, the design of the policy has to take into consideration such information if reducing the number of small farms is an effect that the policy wishes to avoid. Concerning the second assertion, a part of the impact can be explained by the assumption of not allowing a reduction of animal units. Relaxing this assumption would reduce the impact on net farm income, but would in all likelihood be the most efficient way to reduce pollution associated with animal production activities.

Conclusion

The study uses an integrated economic-hydrologic model to investigate the reduction in net farm income that would result by setting an environmental policy that constrains the amount of emissions from farms. Using a GIS system, individual farm and field hydrological data can be integrated into an economic optimization model to investigate the impact of setting environmental policy at the farm level versus the watershed level. The results indicate that the marginal and average costs of emissions reductions are lower when the environmental constraint is set at the watershed level. This occurs because of the greater flexibility in applying BMPs, the ability to target environmentally sensitive areas, and to identify those BMPs and areas that have the lowest costs per unit of emission.

The ability to include farm ownership boundaries into the model allows an analysis of the distributional impacts of environmental policy choice. The impact of setting the constraint at the individual farm or watershed level has a different impact on producers of different size farms. The smallest farms in the watershed have the greatest variability.

The research can be extended by designing environmental policies and market mechanisms that can used at the watershed. Such work could include the design of auction systems that incorporate the cost and benefit information from the integrated economic-hydrologic model.

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