A proposed smart market for sediment discharge

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Abstract

Society faces high costs due to environmental degradation from sediment discharge. Development can increase stream peak flows and sediment discharge. Excess sediment discharges threaten natural habitat, recreational places, rural areas, and commercial ports. In New Zealand, the 2004 North Island floods were estimated to cost about NZ$300 million. Annual soil erosion and sedimentation in NZ cost about NZ$127 million. As a potential solution to minimizing environmental impacts and social costs, we developed a smart market for sediment discharge. This approach would encourage individuals to internalize the environmental and social cost of sediment. The smart market system uses a hydrological simulator and a linear program that would allow an auctioneer to manage the third-party effects of trades, which are not possible with an ordinary auction. The system would give better price signals related to the sensitivity of key environmental features by location. Importantly, the proposed system would reduce transaction costs, because users do not need to search for trading partners, bargaining is simpler, price history information can be made available, and the auction manager ensures market discipline.

Key words: Smart markets, sediment discharge, management, erosion control, trading.

1 Introduction

Excess sedimentation and contaminated sediments have been identified as significant causes of ecological impacts in catchments, waterways, and estuaries (E.P.A. 1993; Eigenraam et al. 2005; Hill et al. 2007; Pappas et al. 2008; Strappazzon et al. 2003; Tang et al. 2005; Walls and McConnell 2004; Westra et al. 2005). Environmental impacts may include the loss of fish, wildlife populations and habitat, which in turn may have a negative impact on the value of surrounding property. Furthermore, sedimentation and sediment laden contaminants threaten the viability of many recreational and commercial ports because of restrictions on dredging of navigational channels due to the high costs of disposal of the dredged sediments. Although many studies have focused on the problem of contamination costs, quite little has been developed to control sediment problems through market–based instruments and no one by smart markets.

A smart market is an auction which is assisted by a computer model. The use of a computer model allows the auction to manage complexities and third-party effects of trades that are not possible with an ordinary auction (McCabe et al. 1991). The smart market design of sediment discharge has the advantages of using all available hydrological information and accepting community input on the desired environmental standards. This approach explicitly avoids "the tragedy of the commons" (Hardin 1968) where the public eventually has higher costs due to environmental degradation and sedimentation, but these costs are not usually paid for by those who create the problems. The method is computationally efficient and calculates the prices of sediment discharge based on auction bids and the environmental standards. The auction is cleared by an optimisation model, which is developed from an environmental model. The environmental model calculates users environmental impacts (sediment loads) based on their land use. The users would buy and sell rights to those environmental impacts. Prices depend on both the environmental impact (to the extent that these impacts are modelled as sediment loads), and the users' willingness to pay. The system would create incentives to improve management of sediment discharge, especially near environmentally sensitive areas. The long-term goal of implementing such a market system would be to enable society to satisfy a range of desired environmental outcomes at minimum cost.

Raffensperger and Cochrane (2008) developed a smart market model for controlling runoff and problems near environmentally sensitive areas. They used the SCS curve number method (SCS, 1985) to predict excess runoff at the outlet of the catchment and users trade for changing impervious cover. They found interesting implications for runoff management as well as for solving these problems easily at lower cost to society. They noted that property owners would be encouraged to reduce impervious cover and that governments would be able to improve the environment standards. In the same way, Raffensperger and Milke (2008) worked with a deterministic linear program to operate a smart market for ground water in New Zealand. They found that the market could be easily set up using a MODFLOW model. They noted that the smart market would eliminate transaction costs, would reduce risk of users, and would improve the reliability of environmental flows.

The market requires a clear specification of what is being traded. We define transferable discharge credits (TDCs), where one or more aggregate sediment discharge caps must not be exceeded. Market participation is compulsory, in the sense that the auction is the only legal means of obtaining the credits, and the penalties for non-compliance are significant. In theory, transferable credits should achieve the same cost-minimizing allocations as controls imposed by environmental taxes (Stavins 1998, 2004). However, the tradable system avoids problems with the income distributional consequences of taxes.

To define a TDC, the market system needs a physical model of sediment movement. The ARC Contaminant Load Model (ARC CLM) (ARC 2006) is used to predict sediment discharge from urban sites and allows for the simulation of implementing erosion control measures. For large scale predictions GLEAMS is used and the catchment area can be divided into a matrix of grid cells and erosion is predicted for each zone or each grid cell area. The erosion modelling translates to a prediction of the sediment yield from the outlet of the catchment. Currently, the GLEAMS and ARC CLM are used widely to evaluate impacts of development and control in rural and urban places in New Zealand. Most of these applications have been focused on a variety of water quality issues. Parshotam and Wadhwa (2007) applied GLEAMS and ARC CLM within the Central Waitemata Harbour to predict contaminant sources and sediment loss for different scenarios.

In this way, the present study improves existing market-based approaches for sediment control, through development of a smart market for transferable discharge credits.

2 Methods

2.1 Defining transferable sediment discharge credits

A TDC is a right to discharge a fixed numbers of kilograms from a specific location into a catchment. But how many credits does the user require? A user may need more or fewer credits, depending on their land use. Sellers could choose between different technologies for controlling sediment discharge according to their opportunity costs and to obtain credits for controlling sediment discharge. Buyers would enter the market to purchase credits, if they were planning to exceed their current sediment discharge rate due to development or other change in landuse.

The difference between a user's initial right and their desired right will be resolved through the smart market auction. To determine new requirements for TDCs the erosion model is run with initial land use/conservation practice conditions and erosion predictions for each individual zone or grid cell area are obtained. Then, the model is run again with the proposed changes in land use and conservation practices within the catchment. If a user proposes a change that increases erosion, and therefore sediment discharges from his/her property over the year, this user would have to buy a discharge credit from another user that had credits available to sell. At the beginning of the auction, each user has some known initial credits. The regulator should choose the maximum allowable discharge at each control point, and thereby also determine the total maximum quantity of TDCs allowed to all firms. If the catchment is over-allocated, i.e. the current total sediment discharge in the catchment is higher than some environmental or social threshold; the regulator should reduce the quantity of credit allowed initially for discharging at the control points. This could be done proportionally. Under this market-based program, a player can be a buyer or seller and he/she trades credit within an overall limit of sediment control. The price of buying or selling would be set by the market.

The market would be monitored by the auction manager, who would minimize environmental impact by setting limitations on how much sediment leaves the catchment. Thereby, our smart market would utilize this erosion model together with imposed limitations on sediment yield from the catchment to run an auction where bids would be placed to buy and sell credit to discharge sediment.

The regulator in charge of overseeing the auction must check and validate the trade between buyers and sellers, through the smart market system. Sellers and buyers firms are informed in advance about the auction rules. Then, to decrease transaction costs, auction participants could bid over the internet. The auction starts when all buyers and sellers are ready to trade at a given point in time. This auction could operate at intervals, such as once a month, every four months or once a year. The auctioneer or regulator would then run and clear the auction, and prices and quantities for TDCs would be determined.

2.2 Smart market model

The proposed smart market for tradable discharge credits “SmartTDC” would act like an auction that considers sets of sell offers and buy bids, to buy or sell consent to discharge into the control point. The control point could be the outlet of a microcatchment, a catchment, a rivermouth, etc. “SmartTDC” assumes that sellers and buyers have fixed areas of land with a sediment discharge related to the activity developed over it.

The model requires a set of impact coefficients, which are the effects of each user’s discharge on each control point. These coefficients could be obtained with a sediment routing model, or we would assume that all sediment simulated by the ARC CLM or GLEAMS for a particular site ends up in the stream. The operation of the smart market requires a linear programming model that clears the market. A linear programming model was developed to reallocate credits, measured in kilograms of sediment discharged within a catchment, based on users’ willingness to pay. We propose some auction rules and procedures. The auction assumes that buyers and sellers express their willingness to trade through their bids. The model assumes a uniform price auction. Thereby, based on the impact coefficients and the bids, we can obtain quantities and prices traded between different participants. In addition, marginal utilities of sellers and buyers are obtained. Interestingly, the economic theorem of Coase says that the total quantity they want to own does not depend on their initial condition. Rather, the total quantities they want to own depend only on the market price and their willingness to pay.

How, then, does the auction balance seller and buyer demand, and the discharge cap? This is done though an optimization model, which is described next.

Indices

i = firm, $i = 1,\dots,n$.

k = control points, $k = 1,\dots,K$.

b = bid step, $b = 1,...,B$.

Parameters

A_i = Total current discharge rights for firm i. (kg)

C_i = Initial allocation in kg for firm i. (kg)

D_{ib} = Total kg demanded (offered) to discharge right for firm i in the bid step b. (kg)

F_{ik} = Impact coefficient, which is the marginal change in sediment discharged associated with firm i and control point k. (kg in control point vs. kg discharged). Often, this coefficient may be 1, but could be between 0 and 1.

P_{ib} = Bid price for discharging sediment per kg from firm i and bid step b. This is the maximum (minimum) willingness to pay (receive) per kg of sediment discharged. ($/kg)

S_k = Maximum allowable discharge at the control point k. (kg).

α = Fitting factor $0 \leq \alpha \leq 1$. If catchment is over-allocated, α should be lower than 1.

Decision variables

P_i = Price to discharge for firm *i*.

P_k = Price to discharge at the control point *k*.

Q_{ib} = Amount in kg discharged by firm *i* and bid steps $b = 1,...,B$. (kg)

$Qsell_i$ ($Qbuy_i$) = Amount in kg sold (bought) by firm *i*. (kg)

Model SmartTDC

1) Maximize $\sum_i^n \sum_b^B Q_{ib} P_{ib}$ subject to

2) $Q_{ib} \leq D_{ib}$ for all firms *i*, and steps $b = 1,...,B$.

3) $A_i = \sum_b^B Q_{ib}$, for all firms i each control point $k = 1,...,K$. (dual price P_i)

4) $A_i = Qbuy - Qsell + C_i \alpha$, for each firm *i*.

5) $\sum_i^n F_{ik} A_i \leq S_k$, for each control point $k = 1,...,K$. (dual price P_k)

6) $Q_{ib} \geq 0$.

Explanation

1. Maximize total economic surplus.

2. Firm *i* cannot sell (buy) more than their maximum own capacity in kg to discharge rights or initial condition of credit right.

3. Total discharged from firm *i* is equal to the right sum to discharge (control) in the different bid steps. The shadow price on this constraint is the price P_i.

4. Net purchase.

5. Total discharge at control point *k*. The shadow price on this constraint is the price P_k.

Operation of the auction requires that all buyers and sellers are ready to trade at a given point in time. The auction could be a web site on the internet. Thereby, the transaction costs are reduced. The regulator could operate a series of tentative rounds to discover the prices during the auction (Raffensperger 2007). After several tentative rounds, the regulator then operates a final auction, in which bid prices and quantities would be final.

After the auction, the manager would obtain the price to charge each user from the linear programming model. The dual price P_i by firm is found on the constraint 4 and this indicates the improvement in total social welfare if we give firm i another unit of credit. This price reflects the marginal value to society of each user's sediment discharge. Thus, following economic theory, the market manager should charge each user with this price. Next, following the solution given by the model, each user i should be charged (or paid, if the value is negative) by $P_i(Qbuy_i - Qsell_i)$.

If the catchment is over allocated, the regulator could alter the initial discharge rights for all users to fit the desired maximum discharge in the catchment. In this case, a parameter α is incorporated in the model. The parameter α is the largest fraction of initial rights that can be allocated to all users, without overloading any control point.

For example, suppose two firms want to trade and there is one control point. Each firm has an initial right to 10 kg and they would buy all the credit for \$1 per kg or would sell all 10 kg for \$2 per kg. Each firm's discharge has a different marginal effect in sediment F_i at the control point, of 0.1 and 1 respectively. The recommended limit on sediment at the river mouth is 9 kg. One optimal solution is: firm A buys 80 kg and pays 1 * 80 = \$80; firm B sells 10 kg and receives 10*10 = $100. Although this is an efficient solution, it is obtained by over-allocated sediment discharge in the catchment (10 kg * 0.1 + 10 kg * 1 = 11 kg compared to the 9kg limit). Because the catchment was over-allocated in this example, the regulator would be required to pay a net $20 to cover the over-allocation. Alternatively, if the regulator does not want to be a net payer, it should fix proportionally the initial allocation of credit prior to the auction. In this case α could be set to 0.8181 and that would satisfy the control point constraint.

The auction rules would require that all users abide by the results of the ARC CLM or GLEAMS. However, those who are not happy with it could have the option of monitoring their site for sediment discharge at their own expense. If the monitored sediment discharge proves to be less than the ARC CLM or GLEAMS model predictions, the user would gain a discharge credit for the next auction which they could either use or sell.

The regulator could evaluate the social impact in the catchment through analysis of the model. The shadow price on constraint 5 indicates the improvement in the total welfare if the regulator allows another kg of sediment at the control point k. This price information would be useful to the regulator in choosing least-cost policies.

The regulator will need to encourage user participation. Raffensperger and Cochrane (2008) noted that the implementation of a renewal system would incentive participation: the regulator could annul all rights at regular intervals, and require land owners to re-purchase the credits. The rights could be time-based, where sellers or buyers could enter the auction at any change of land use, technology change or major development. Alternatively, the right must be renewed periodically.

Following the auction, the regulator could distribute information on the prices Pi and quantities that were traded. This strategy would encourage participation of future participants in the auction. Publication could be done by web page, in an official news report, or serial journals, and published monthly or annually.

3 Conceptual example: Auckland, New Zealand

A small hypothetical catchment was used to illustrate the application of the SmartTDC model using the GLEAMS and ARC CLM. The relevant local government regulator could be the Auckland Regional Council (ARC). We considered the BIR and LIN stormwater manager units (SMU) within the Swanson catchment in Auckland (Parshotam and Wadhwa 2007). The number and size of specific properties within the SMU were assumed for this application, as well as all sediments are discharged to a stream with one control point; every property is assumed to have one point of discharge. Table 1 summarizes the land use and the estimated sediment discharged from the BIR and LIN subcatchments. The sediment discharged from urban areas was calculated assuming 50% of impervious cover, and their outcomes were obtained from ARC CLM.

To control their discharge, the firms can choose a best management practise (BMP) or erosion control technologies. Within these SMUs, a few developers wish to discharge an amount of 330.130 kg/year. If a discharge limit for the SMU (catchment) were not set, developers would not be pressured to control sediment discharge. However, if an upper limit of sediment discharge is set for a specific control point, the firms would be forced to control discharges in the catchment. The developers (firms) can choose different erosion control technologies or management practise for controlling discharge, and the quantity that they do not control must be purchased in the auction.

Table 1. Different land use, number of firms and sediment discharged from the BIR and LIN stormwater management units in Auckland. Sediments discharged are calculated by ARC CLM for urban areas and GLEAMS for change in land from rural use. We assumed twenty firms.

Land use	Area, ha	Discharge rights, kg/year	Number of firms
BIR			
Bush	4.7	1,206	2
Pine mature trees	16.1	3,331	1
Native forest	22.3	3,063	1
Pasture/grassland	129.6	144,458	10
Bush	1.45	372	1
Urban	28.2	13,376	1
Total BIR	**202.35**	**165,806**	**16**
LIN			
Native forest	0.67	34	1
Pasture/grassland	16.8	5,853	1
Native forest	0.06	2.7	1
Urban	168.6	80,004	1
Total LIN	**186.13**	**85,894**	**4**
Total	**388.48**	**251.700**	**20**

Nobody in the catchment can control all the discharges from their own properties. Participates in the auction want to buy or sell discharge rights. A BMP is used in function to feasibility of implementation, opportunity cost, etc. The catchment was defined as fully allocated; nobody can discharge more sediment than the initial allocation. The developers want to participate in the auction to buy discharge rights. For this reason, they evaluate available technologies to control sediment discharge according to their opportunity cost, thus, the minimum (maximum) willingness' to accept (pay) are determined. The technologies for controlling sediment discharge will be used consecutively as a treatment train and every firm has three technological options to evaluate. For this example application we assumed costs for each technology and that the cost of technologies to control sediment discharge was different for each firm. Each of the firms has different characteristics and requirements.

We developed bids for 20 notional firms, 16 in the BIR subcatchment (firms 1-16), and 4 in the LIN subcatchment (firms 17-20). Some firms plan construction, and therefore could use the ARC CLM model to plan their bids, such as Firm 1, described below. Other firms plan land use changes, and could use the GLEAMS model to plan their bids, such as Firm 15, described below. In addition, we assumed costs for each technology and BMP to control sediment discharge for each property. We also give an example of urban land owned by the regulator, as Firm 20. Table 2 summarises the requirement from different firms in the catchment as well as their options. We assume that every firm's discharge of has a one-to-one effect on the control point, so $F_i = 1$ for all firms i=1,…,20.

Table 2. Firms' initial credit allocated in kg, quantity controlled and requirement in kg and maximum (minimum) willingness to pay (accept) in $/kg.

Firm	Initial discharge, kg	Required discharge, kg	Option 1 Control		Option 2 Control		Option 3 Control	
			Kg	$/kg	Kg	$/kg	Kg	$/kg
1	603	0	108	9.29	36	27.67	36	30.44
2	603	0	85	12,00	24	38,00	12	66.00
3	3,331	265,412	265,442	0.57	124,980	2.54	54,764	14.00
4	3,063	0	536	3.73	153	9.79	77	19.59
5	14,445	0	4,886	1.02	3,309	1.54	882	3.40
6	14,445	0	12,654	3.16				
7	14,445	0	1,612	2.39	4,533	4.41	1,813	11.03
8	14,445	0	4,533	6.62	4,533	6.62	2,684	11.18
9	14,445	0	4,533	8.82	4,533	8.82	2,684	14.91
10	14,445	0	2,341	8.54	4,533	11.03	870	22.98
11	14,445	0	3,632	5.52	3,632	8.27	3,632	11.03
12	14,445	0	4,533	4.41	4,533	6.62	907	11.03
13	14,445	0	4,533	3.31	4,533	4.41	2,674	7.48
14	14,445	0	11,469	3.49				
15	372	63,772	63,771	0.63	31,886	4.70	19,132	15,00
16	13,376	0	8,427	15,00	1,484	20,00	1,039	25,00
17	34	0	10	19.74				
18	5,853	0	3,476	5.75	1,392	14.37	981	15.29
19	2.7	946	946	5.59	567	17.63	340	39.17
20	80,004	0	60,003	8.83	8,000	18.75	3,600	27.78
Total	251,692	330,130						

4 Conclusion

The auction manager would collect the data on the catchment, and invite the firms to bid. To estimate what the firms might bid and their resulting discharges, we can use the GLEAMS and ARC CLM.

A case of an over-allocated catchment is presented. The use of a smart market to allocated sediment rights is likely to reduce transaction costs for the regulator and firms, as the decision may be made much more quickly and transparently. Further, the smart market will allow society to reduce its impact on the catchment at much lower cost, by enabling trade. We solved the SmartTDC model using AMPL (Fourer et al. 2003).

For the over-allocated catchment, the regulator sets a discharge limit of 150,000 kg/year. This limit is much less than the existing discharge rights. The auction manager runs the model and observes that the initial allocation is above the upper limit of the catchment. Consequently, before the auction, the auction manager informs participants that the catchment condition is over-allocated, and that the auction manager will reduce initial credits of all firms proportionally.

To obtain an allocation that satisfies the control point constraint, the auction manager can adjust every firm's initial credit by applying the α factor. In this case, α = 59%. All firms are losing some rights to discharge, without compensation. We note that this may be politically difficult. Government could choose to set a higher α, in which case the auction manager would be a net buyer of discharge rights. Then, the auction manager runs the model again, determines prices and quantities, and pays or charges each firm. Table 3 summarises the outcomes. Quantities traded were 70,507 kg from sellers and 72,002 kg to buyers. The auction manager would receive a net of $20,935. Note that because the auction manager had a net gain, the auction manager could choose to increase α slightly, and re-run the model. This would result in a lower net payment from the firms to the auction manager. All firms traded in this example. Of particular interest are the urban firms 16 in BIR and 20 in LIN. To move back up to its original allocation, firm 16 must buy back an amount equivalent to the quantity adjusted downwards by the auction manager. On the other hand, firm 20 would sell discharge rights, and this money could pay for installing technologies to control discharge. On the other hand, if firm 3 still wants to harvest forest, they would be required to pay $636,190 to buy sediment. However, if they replanted forest the following year and sold sediment credits, they could gain back some or all of these expenses.

Table 3 Transaction between sellers and buyers for α =0.59.

Firm	Initial credit right, kg	Credit sold, kg	Credit bought, kg	Final discharge, kg	Net payment, $
1	603	139	0	495	$1,952
2	603	162	0	518	$2,274
3	3,331	45,442	0	47,408	$636,190
4	3,063	567	0	2,375	$7,940
5	14,445	0	3,154	5,369	-$44,159
6	14,445	0	6,731	1,792	-$94,237
7	14,445	0	2,035	6,488	-$28,493
8	14,445	0	5,827	2,696	-$81,581
9	14,445	0	3,143	5,380	-$44,005
10	14,445	0	951	7,572	-$13,317
11	14,445	0	4,973	3,550	-$69,625
12	14,445	0	4,050	4,473	-$56,703
13	14,445	0	5,817	2,706	-$81,441
14	14,445	0	5,546	2,977	-$77,647
15	372	19,285	0	19,504	$269,985
16	13,376	5,484	0	13,377	$76,783
17	34	14	0	34	$194
18	5,853	0	1,076	2,377	-$15,071
19	2.7	908	0	910	$12,713
20	80,004	0	27,201	20,002	-$380,815
Total	251,691.7	72,001	70,504	150,003	20,937

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