SMART MARKETS AND IMPROVED MANAGEMENT OF SEDIMENT DISCHARGE

8 May 2008

Final Report

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This report presents a proposed smart market for transferable discharge credits model, for managing and improving sediment discharge from catchments in the Auckland Region.

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, Pugh, and Mullen 2007; Pappas et al. 2008; Strappazzon et al. 2003; Tang et al. 2005; Walls and McConnell 2004; Westra, Zimmerman, and Vondracek 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 and recreational areas. 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.

Market-based instruments are regulations that encourage behaviour through market signals rather than through explicit directives to control environmental degradation. These market-based instruments, such as licences, credits, or degradation charges (taxes), are often depicted as "harnessing market forces" (Stavins 1998, 2004). If they are well designed and implemented, they oblige firms to bear some of the social costs of environmental degradation. Efficient market instruments do not have to restrict how and where land should be allocated among urban uses, agricultural uses, and forestry and other open spaces. On the contrary, these policies promote the best use of the land, associated with the full social costs of their actions on the place (catchment).

This study extends and improves on existing market-based approaches for sediment control, through development of a smart market for transferable discharge credits. A smart market is an auction in which complex trades are coordinated through use of a computer model. Compared to existing market approaches, a smart market usually has lower transaction costs and can manage shared resources, such as the sediment in a channel. We call the smart market model “SmartTDC.” The smart market is designed to improve management of sediment discharge from Auckland catchments, with the goal of reducing sedimentation in channels and/or estuaries. The development of this system is explained in the following sections. Section 2 describes the smart market and gives an economic support for it. Section 3 defines what is traded: tradable discharge credits. Section 4 shows an overview of the smart market for tradable discharge credits, and the proposed model SmartTDC. Section 5 presents example applications of the SmartTDC. Section 6 is a summary of cases. The section 7 is recommendations for the implementation of the SmartTDC model. Finally, section 8 is the bibliography cited.

2. Smart Markets

An auction is a trading institution where buyer and seller can discover prices and select quantities to maximize their gains. McAfee and McMillan (1987) define an auction as a "market institution with an explicit set of rules determining resource allocation and prices based on bids from market participants". The literature distinguishes different auction types, such as the English, Dutch, and first-price sealed bid and second-price sealed bid, as well as variations of each of them (e.g. Chu and Shen 2007; Eigenraam et al. 2005; Latacz-Lohmann and Hamsvoort 1997; e.g. McAfee and McMillan 1987; Montero 2006; Raffensperger and Cochrane 2007; Strappazzon et al. 2003). Auctions usually have low transaction costs, transparency and fairness, and increase competition and efficiency. They can be vulnerable to collusion, and may not work efficiently when participants are risk averse; such cases can lead to lower prices and higher social costs (Guasch and Glaessner 1993; Latacz-Lohmann and Hamsvoort 1997; Latacz-Lohmann and Schilizzi 2005; Montero 2006). Most importantly, however, these simple auction types cannot manage interactions between bids or coordinate among bids.

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, Rassenti, and Smith 1991). In this study, the auction is cleared by an optimisation model, which is developed from an environmental model. The environmental model calculates users (landowners) 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.

A smart market design for this problem 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 system creates incentives to improve management of sediment discharge, especially near environmentally sensitive areas. Most importantly, the proposed system would reduce the transaction costs which are commonly associated with other market-based systems such as tradable development rights, as users need not search for trading partners, bargaining is simpler, price history information can be made available, and the auction manager ensures market discipline. 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.

The market requires a clear specification of what is being traded. This study defines 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, this market-based instrument 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.

Figure 1 portrays an agency, whether a public or private entity, whose main purpose is to reduce the sediment discharge in the catchment. The entity predicts sediment discharge, evaluates sediment control practices, and allocates credit for the associated reduction in sediment discharge at some point in the catchment, which it can then sell in the smart market. In addition, the agency records the history of prices and traded quantities, and registers owners of credits, while controlling and monitoring the sediment along the catchment.

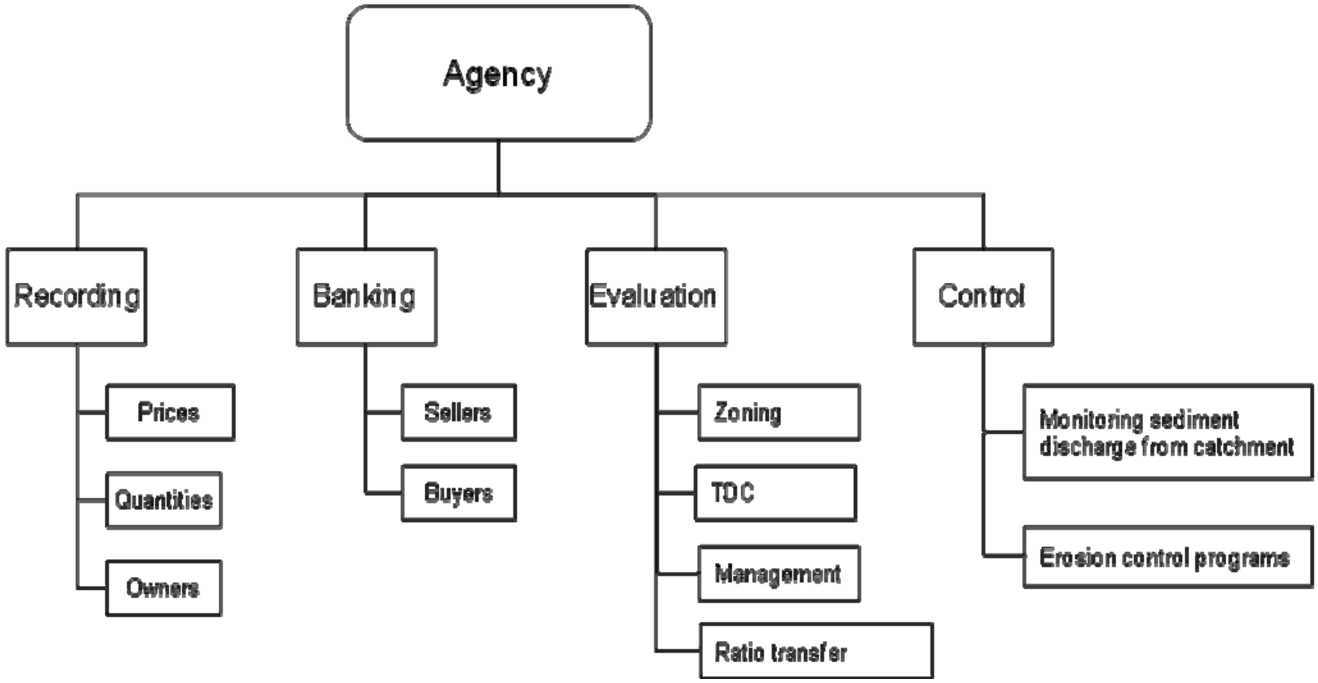


Figure 1 Tradable Discharge Credits' Agency structure.

The auctioneer (i.e., the agency 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 agency would then run and clear the auction, and prices and quantities for TDCs would be determined.

3. What is a Tradable Discharge Credit (TDC)?

To define a TDC, the market system requires a physical model of sediment movement. Two models (ARC Contaminant Load Model or GLEAMS) are used to predict erosion from small urban areas and larger rural/urban areas within a catchment respectively. The ARC Contaminant Load Model (ARC CLM) is used to predict sediment discharge from urban sites and allows for the simulation of implementing erosion control measures. For large scale predictions (GLEAMS), the catchment area can be divided into a matrix of grid cells and erosion is predicted for each zone or each grid cell area. This prediction is a function of land use, soils, climate, conservation practices and topography. The erosion modelling translates to a prediction of the sediment yield from the outlet of the catchment. The TDC model uses a cap, which is an upper limit on the level of total sediment discharge "SD_{max}" (inelastic supply). 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. Figure **2**1 shows how this would work.

A TDC, therefore, is a right to discharge a fixed numbers of kilograms from a specific location into a catchment. At the beginning of the auction, each user has some known initial credits. The agency 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 agency should reduce the quantity of credit allowed initially for discharging at the control points. This could be done proportionally. There is quite diverse economics literature about optimum allocations for initial rights (e.g. Coase 1960; Eigenraam et al. 2005; Strappazzon et al. 2003; Tinbergen 1956) .

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. The GLEAMS model or ARC Contaminant Load Model "ARC CLM" would then be used to calculate the credits that a user could sell if they have achieved a reduction in sediment discharge by implementing an erosion control measure. 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.

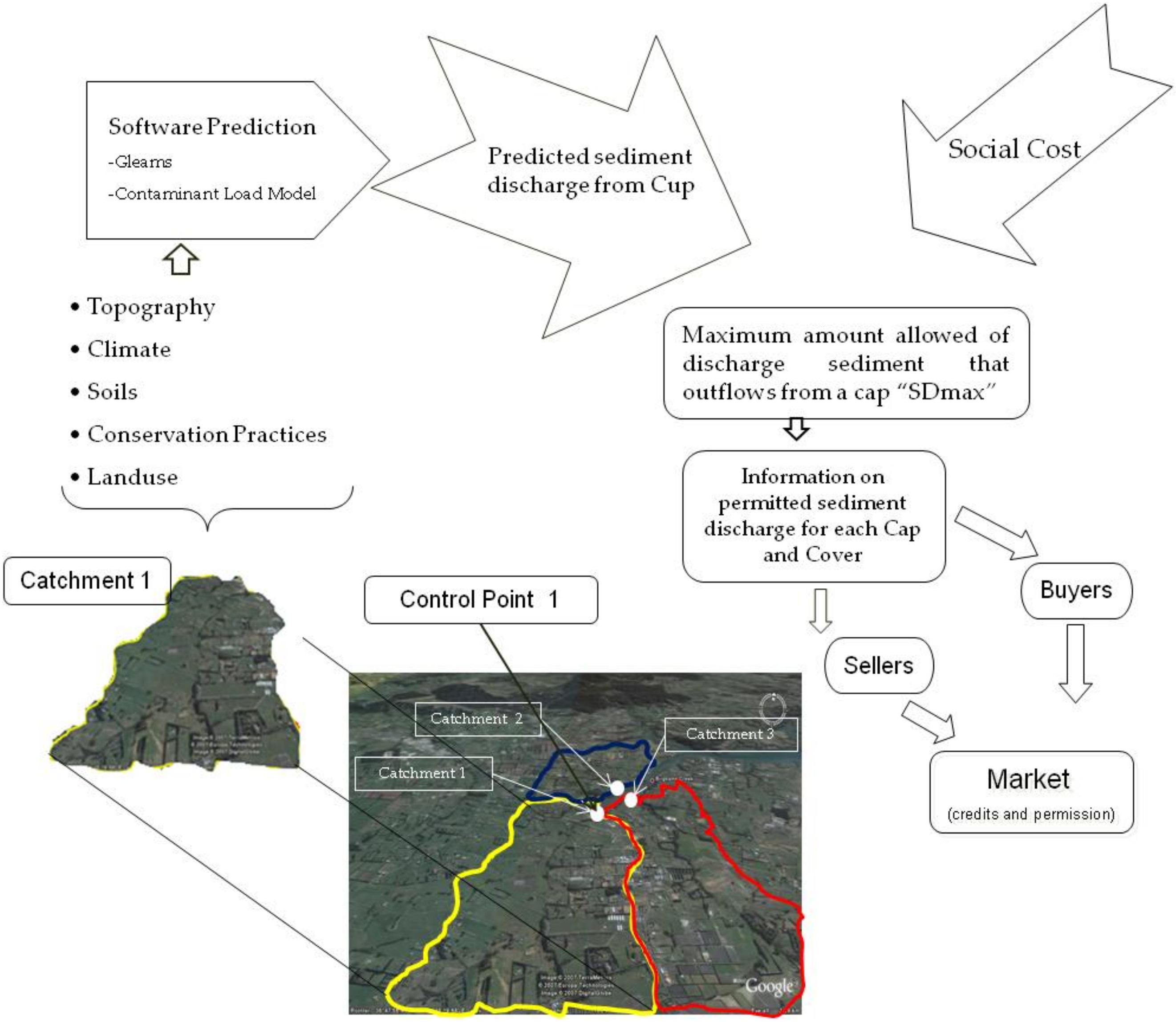


Figure 2 General schematic of tradable credits for sediment discharge.

As Figure 2 indicates, 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. 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.

4. Proposed Smart Market for Tradable Discharge Credits ”SmartTDC”

The operation of the smart market requires a linear programming model that clears the market. In this section, we present the linear programming model, and we propose some auction rules and procedures.

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.

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.

4.1. Development of the “SmartTDC” Model

A linear programming model was developed to reallocate credits, measured in kilograms of sediment discharged within a catchment, based on users’ willingness to pay. The auction assumes that buyers and sellers express their willingness to trade through their bids. For example, if a developer wishes to buy 10 kilos of sediment discharge, someone else has to sell an equivalent quantity of credit. A sell offer corresponds to a user offering to accept at least a price per kilo discharged, for consenting to give up a fixed quantity of credit from a given initial credit available (kg sediment discharged). A buy bid corresponds to a user offering to pay at most a price per kilo, for the right to discharge a fixed quantity of sediment.

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. A user could run ARC CLM or GLEAMS to determine the amount of discharge he or she needs to buy or can sell. For example, a user who just made an improvement in his property would run the ARC CLM or GLEAMS and determines he has reduced sediment discharge from his property, so he could sell that specific amount of sediment discharge.

Based on the impact coefficients and the bids, we can use the linear programming model to 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.

The model is as follows.

Indices

i = firm, $i = 1,\ldots,n$.
k = control points, $k = 1,\ldots,K$.
b = bid step, $b = 1,\ldots,B$.

Parameters

A_i = Total current discharge rights for firm i. (kg)
C_{ib} = Total kg demanded (offered) to discharge right for firm i in the bid step b. (kg)
D_{ib} = Maximum amount that firm i in the bid step b is willing to buy (sell) at price P_{ib} (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 $b = 1,\ldots,B$. (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) $Q_{ib} \leq C_{ib}$ for all firms i, and steps $b = 1,\ldots,B$.

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

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

5) $\sum_i^n F_{ik} * A_i \leq S_k$, for each control point $k = 1,\ldots,K$. (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 in the control point *k*. The shadow price on this constraint is the price P_k.

4.2. Auction operation

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 and Cochrane 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 correct 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 agency could alter the initial sediment discharge rights for all users to fit the desired maximum discharge in the catchment. In this case, a parameter alpha 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 agency would be required to pay a net $20 to cover the over-allocation. Alternatively, if the agency 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 simulations. 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 agency 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 agency or regulator allows another kg of sediment at the control point k. This price information would be useful to the agency in choosing least-cost policies.

The agency will need to encourage user participation. Raffensperger and Cochrane (2007) 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 agency could distribute information on the prices P_i 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.

5. Example applications of the "SmartTDC" model

This section presents two examples. Section 5.1 gives a small example using the ARC CLM to calculate sediment discharge. Section 5.2 uses the ARC CLM and GLEAMS both, also with an area within the Swanson catchment in Auckland.

5.1. Example applications using data from the ARC Contaminant Load Model

A small hypothetical urban catchment was used to illustrate the application of the SmartTDC model using the Auckland Regional Council Contaminant Load Model (ARC CLM). The relevant local government agency could be the Auckland Regional Council (ARC). The catchment is 10 ha in size and consists of 10 users with different land uses (approximately 1 ha each). For simplicity, we group the users based on their land use. Table 1 summarizes the quantity of the sediment discharged for each type of user as simulated with the ARC CLM.

For this example, all sediment discharged by each user is assumed to reach the stream control point. Every user has one point of discharge from their property. To control or reduce their discharge, the users can choose different technologies such as dry ponds, wet ponds, wet extended ponds, constructed wetlands, swales, wet ponds with flocculation, hay bales, vegetative filter strips, silt fences, etc. (as define in the ARC CLM). For this example, two users want to develop their properties (we will call them developers) and would discharge more sediment to the stream during the development than they do at present. The developers can choose different technologies for controlling discharge, and the quantity that they do not control must be purchased in the auction. We solved the SmartTDC model using AMPL (Fourer, Gay, and Kernighan 2003).

Table 1 Land use and predicted sediment discharge for a micro catchment application example.

Land use	Area Ha	Total Predicted Discharge using ARC CLM Bottom of Site out-fall Loads (kg/year)
Agriculture (Farmer pasture)	4	4,000
Stable Bush	2	100
Urban Lawns (Residential)	4	1,348
Total Discharged	10	5,448

Each firms current sediment discharge is as follows (based on ARC CLM predictions):

- Firms 1, 2, 3 and 4 are farms with pasture and slopes between 10 and 20%, and are discharging 1000 kg/ha/year each.
- Firms 5, 6, 7 and 8 are urbanized land; on average, these have 520 m^2 covered with roof and residential pave surfaced or roads. They are discharging 337 kg/ha/year each.
- Firms 9 and 10 are stable bush with slopes lower than 10%. Firms 9 and 10 are discharging 50 kg/ha/year each.

Nobody in the catchment can control a hundred percent of the discharges from their own properties. 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 (see Table 2). Each of the firms has different characteristics and requirements. These are described in detail in Appendix 2.A.

Table 2 Technology Costs assumed for each firm in $/ha to control sediment. Prices are only for illustrative purposes.

Technology	Firms 1-8 $/ha	Firms 9-10 $/ha
Dry pond	400	-
Wet pond	500	600
Wet extended pond	600	800
Wet pond with flocculation	700	1200
Constructed wetland	500	-
Storm-filter	400	800
Hay bales	150	400
Silt fence	200	600

Table 3 Firm's initial credit allocated in kg, quantity controlled and requirement in kg, maximum (minimum) willingness to pay (accept) in $/kg and relative impact to the control point (*Fi*).

	Initial Sediment Discharge (kg)	Required discharge (kg)	Option 1 Control		Option 2 Control		Option 3 Control		F_i	
			Kg	$/kg	kg	$/kg	kg	$/kg	Case 1	Case 2
Firm 1	1000		630	0.63	148	3.37	66.6	9	0.7	1
Firm 2	1000		770	0.65	92	5.43	41.4	14.5	0.3	1
Firm 3	1000		400	0.375	120	1.25	192	2.6	0.5	1
Firm 4	1000		400	0.375	180	1.11	126	3.17	0.2	1
Firm 5	337		169	1.18	50.5	3.95	30.3	13.18	0.8	1
Firm 6	337		212.3	1.88	49.8	10	22.4	24.8	0.1	1
Firm 7	337		259.5	1.92	31	16.12	14	43	0.3	1
Firm 8	337		168.5	1.18	55	3.95	35	11.3	0.5	1
Firm 9	50	1750	1312.5	0.61	132.5	4.6	92	8.7	0.7	1
Firm 10	50	1250	962.5	0.62	115	5.21	51.8	15.4	0.4	1
Total		3000								

We next present two different cases. In Case 1, the firms' impact coefficients F_i are all different, and each coefficient is less than 1. In Case 2, the firms' impact coefficients F_i are the same, and each coefficient equals 1.

5.1.1. Case 1: Application of the SmartTDC model using ARC CLM were sediment discharge impact coefficients are different.

A maximum of 2,615 kg/year has been selected as the sediment discharge limit at the control point. Every firm will participate in the auction offering prices and quantities. The marginal contribution or impact (F_i) of sediment discharge at the catchment control point is different for every firm (see Table 3). The catchment is not over allocated because the current discharge at the control point is 2,328 kg/year given the varying F_i values. However, if a value of $F_i = 1$ is used for every firm, the catchment would be over allocated. The agency then runs the model, determines prices, quantities and pays (charges) for every firm i, and the market clears. Table 4 summarizes this simulation.

The quantities traded were 920.3 kg from sellers and 725 kg from buyers. The agency would receive a net of $ 7.50. Not all bids were accepted, e.g., firms 1, 2 and 4. The developers obtain different quantities and were charged different prices. Firm 9 and 10 should use their first options to control sediment discharged (dry pond and storm-filter respectively). They would buy the difference of 437.5 kg and 287 kg and would pay $229 and $86 respectively.

Table 4 Transaction between sellers and buyers for Case 1.

	Initial Credit Right (kg)	Credit Sold		Credit Bought		Final Discharge (kg)	Net Pay ($)
		Quantity (kg)	Percentage	Quantity (kg)	Percentage		
Firms 1	1000	0	0%	0	0.0%	1000	0
Firms 2	1000	0	0.0%	0	0.0%	1000	0
Firms 3	1000	286	37.7%	0	0.0%	731	100
Firms 4	1000	0	0.0%	0	0.0%	1000	0
Firms 5	500	162	65.3%	0	0.0%	337	97
Firms 6	500	162	57.3%	0	0.0%	337	12
Firms 7	500	162	53.5%	0	0.0%	337	36
Firms 8	500	163	63.1%	0	0.0%	337	61
Firms 9	50	0	0.0%	437	100.0%	487	-229
Firms 10	50	0	0.0%	287	100.0%	337	-86

5.1.2. Case 2: Application of the SmartTDC model using ARC CLM were sediment discharge impact coefficients are all equal to 1.

The second case has the same assumptions with respect to firms and sediment discharge limit at the control point. However, a values of $F_i = 1$ is used for every firm, which represents the condition that all sediment produced on site reaches the control point (see Table 3). The agency then runs the model and observes that the catchment is over allocated. Hence, before the auction, the agency adjusts every firm's initial credit by applying an alpha α value to obtain an allocation that satisfies the control point constraint. In this case, alpha = 0.4287.

Next, participants are informed about the new conditions in the catchment and the necessity to reduce initial credits. All firms in the catchment have to control sediment discharge. But now, they have an additional incentive to participate in the auction because they could trade the excess controlled. The agency then runs the model, determines prices and quantities, and pays (charges) for every firm *i*. Table 5 summarizes this simulation.

In this case, the quantities traded were 781.6 kg from sellers and 782.14 kg to buyers. All the bids were accepted in some proportion, i.e. sellers could sell and buyers could buy. The agency would receive a net of $ 1.71. The developers obtain different quantities and are charged different prices. In fact, firm 9 could buy 466 kg, and it would pay $1477, with the difference controlled by a storm filter. Firm 10 would use the first option to control sediment discharge (wet pond) and would buy the difference of 316 kg and would pay $1001.

Table 5 Transaction between sellers and buyers for Case 2.

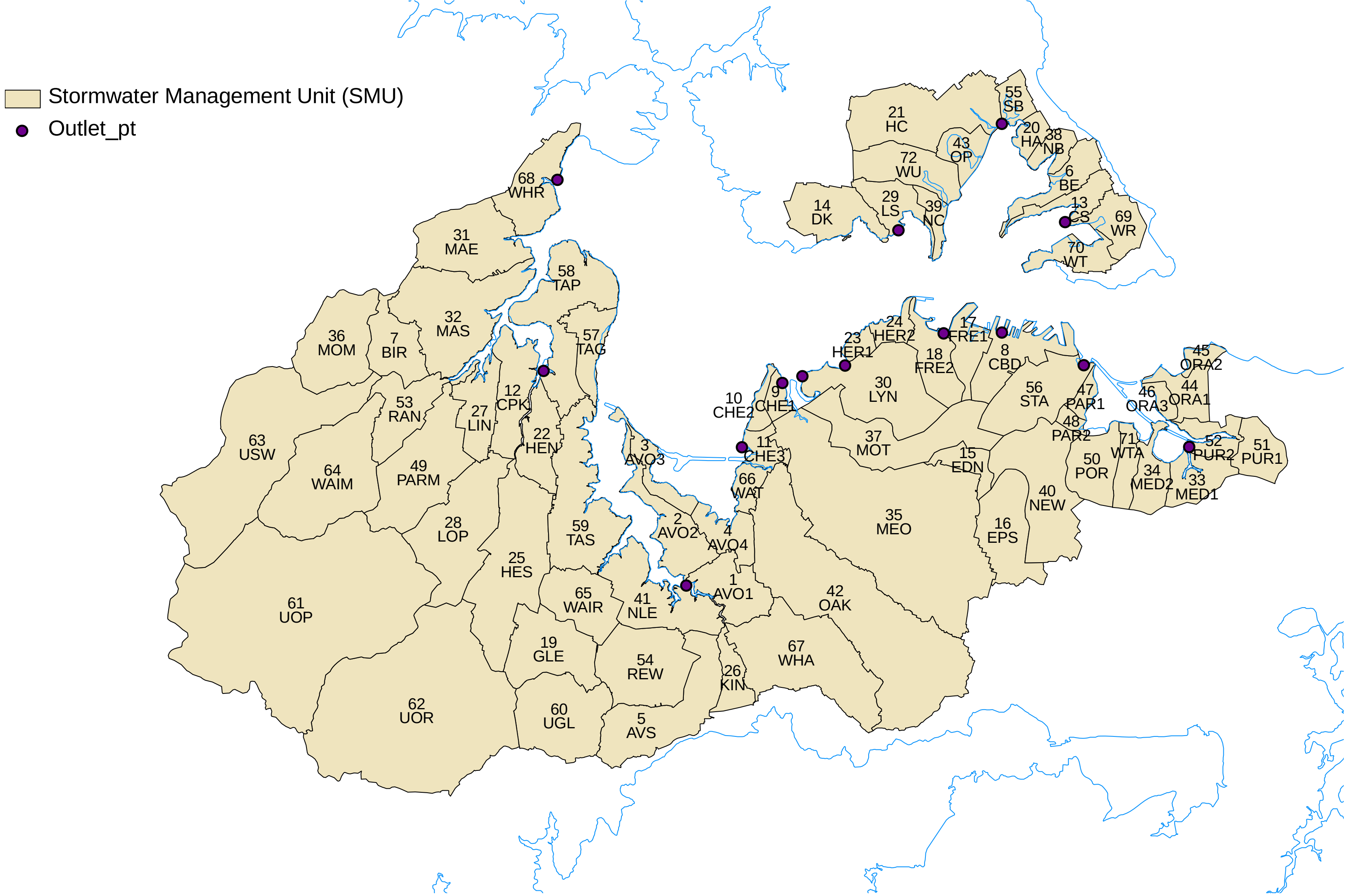
	Fitted Credit Right (kg)	Credit Sold Quantity (kg)	Credit Bought Quantity (kg)	Final Discharge (kg)	Net Pay ($)
Firms 1	428	58	0	370	185
Firms 2	428	198	0	229	629
Firms 3	428	140	0	288	445
Firms 4	428	65	0	363	207
Firms 5	214	46	0	168	146
Firms 6	214	89	0	124	284
Firms 7	214	136	0	77	3433
Firms 8	214	45	0	168	145
Firms 9	21	0	466	487	-1477
Firms 10	21	0	316	337	-1001

Both cases show that SmartTDC Model could serve to enable a rights-based market to control discharge and moreover that it could be an efficient instrument to control sediment discharge.

5.2. Example applications using data from the Gleams and ARC Contaminant Load Model

The BIR 7 stormwater manager unit (SMU) within the Swanson catchment in Auckland (from (Figure 3 from Parshotam and Wadhwa 2007) was used to illustrate a large scale application of the SmartTDC model using GLEAMS and the ARC CLM. The size and number of specific properties within the SMU were assumed for this application.

Figure 3 Map of stormwater management units (SMUs) in Auckland.



ERROR! NOT A VALID BOOKMARK SELF-REFERENCE. summarizes the land use and the estimated sediment discharged from the BIR 7 subcatchment. The sediment discharged from urban areas was calculated assuming 50% of impervious cover and its outcome was obtained from ARC CLM. Sediment discharge for other land uses was calculated with GLEAMS.

Table 6 Different land use, number of properties and sediment discharged from the BIR stormwater management unit in Auckland. Sediment discharge is calculated by ARC CLM for urban areas and GLEAMS for other land use. The number of properties is assumed.

Land use	Area Ha	Sediment Discharge kg/year	Number of properties
Bush	4.70	1,206.85	2
Native forest	22.25	3,063.74	1
Pine mature trees	16.1	3,351.38	1
Pasture/grassland	129.58	144,458.4	10
Bush (Earthworks*)	1.45	371.66	2
Urban	28.19	13,376.81	1
Total	202.27	165,829	17

* Current earthworks land uses discharge 63,771.82 kg/year.

All sediment is assumed to discharge to a stream with one control point. Every property has one point of discharge. To control their discharge, the users can choose a management practise "BMP" or erosion control technologies. Within this SMU, a few developers wish to discharge an amount of 214,770.97 kilos/year. The developers 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. If a discharge limit for the SMU (catchment) is 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. We solved the SmartTDC model using AMPL (Fourer, Gay, and Kernighan 2003).

Currently properties are used for different purposes. If we use the Gleams Model to estimate sediment discharge and assuming different property sizes the sediment discharged are as follow:

- Properties 1 and 2 are bushes and are discharging 603.4 kg/year each.
- Property 3 is native forest and is discharging 3,063.74 kg/year.
- Property 4 is pine mature plantation and is discharging 3,351.38 kg/year. The user wants to harvest 5 hectares and this project would discharge 150,999.15 kg/year.
- Properties 5 to 14 are pastures and grasslands and are discharging on average 14,445.84 kg/year each.

- Property 15 and 16 are currently under bush cover discharging 185.83 kg/year each. They plan to develop the properties (earthworks) and would discharge on average 31,885.91 kg/year each during the development.
- Property 17 is an urban place. Assuming a 50% of impervious cover and estimating by ARC CLM, the sediment discharged would be 13,376.81 kg/year.

We take similar assumption to anterior cases: e.g. nobody can control a hundred percent of the discharges; participates in the auction want to buy or sell discharge rights; the technologies for controlling sediment discharge in urbanized areas will be used consecutively as a treatment train and every firm has three technological options to evaluate; a BMP is used in function to feasibility of implementation, opportunity cost, etc. In addition, we assumed costs for each technology to control sediment discharge for each property (see Table 7). Each of the properties has different characteristics and requirements. These are described in detail in Appendix 2.B.

Table 7 Technology Costs assumed for each property $/ha to control sediment. Prices are only for illustrative purposes.

Technology	Technology cost $
Dry pond	4000
Wet pond	5000
Wet extended pond	6000
Wet pond with flocculation	7000
Constructed wetland	5000
Storm-filter	4000
Hay bales	1500
Silt fence	2000

Table 8 Properties' initial credit allocated in kg, quantity controlled and requirement in kg, maximum (minimum) willingness to pay (accept) in $/kg and impact in the catchment Fi.

	Initial Sediment Discharge (kg)	Required discharge (kg)	Option 1 Control		Option 2 Control		Option 3 Control		*Fi*
			Kg	$/kg	Kg	$/kg	Kg	$/kg	Case 3, 4 & 5
Property 1	603.42		60.34	2.1	36.21	4.5	12.07	20.1	1
Property 2	603.42		84.48	1.9	48.27	3.8	18.10	18	1

Property 3	3,063.74		153.19	3.5	61.27	4.35	30.64	11.65	1
Property 4	3,351.38	150,999.15	150,537.00	0.18	59,937.51	0.22	14,637.76	3.27	1
Property 5	14,445.84		2,889.17	1.3	2,734.61	2.3	2,050.95	2.9	1
Property 6	14,445.84		3,626.43	0.96	2,496.68	2.33	713.94	7.27	1
Property 7	14,445.84		12,662.03	0.35					1
Property 8	14,445.84		4,333.75	0.44	3,433.04	3.76	1,716.52	10.03	1
Property 9	14,445.84		3,178.09	0.75	3,306.78	1.8	3,306.78	2.7	1
Property 10	14,445.84		3,322.54	0.85	5,169.15	3.45	3,251.04	6.15	1
Property 11	14,445.84		3,033.63	1.25	1,345.01	1.779	1,008.76	4.19	1
Property 12	14,445.84		4,533.04	0.76	4,533.04	1.922	2,683.56	3.955	1
Property 13	14,445.84		11,748.21	0.43					1
Property 14	14,445.84		4,533.04	1.3	1,596.95	2.35	2,350.12	4.55	1
Property 15	185.83	31,885.91	25,508.00	0.203	3,188.60	1.704	956.70	4.54	1
Property 16	185.83	31,885.91	23,914.94	0.16	3,188.60	1.25	1,434.87	2.78	1
Property 17	13,376.81		8,427.40	0.47	1,484.80	2.69	1,039.38	5.77	1
Total	165,829	214,770.97							

5.2.1. Case 3 results of the SmartTDC market. The catchment is currently at an agreed upon sediment discharge limit.

The catchment for case 3 is assumed to be at its current sediment discharge limit of 165,828.8 kg/year. The catchment is not over allocated. The marginal change in sediment discharge at the catchment (F_i) is similar for every firm $F_i = 1$ (Table 8). Every property's user will participate in the auction offering prices and quantities. Then, the agency runs the model, determines prices, quantities and pays (charges) for every firm *i*, and the market clears. Table 9 summarizes this simulation.

The quantities traded were 28,524 kg from sellers and were 28,522 kg from buyers. The agency would receive a net of $ 0. Not all bids were accepted, e.g., properties 1, 2 and 17. The developers obtain different quantities and were charged different prices. In order to be able to harvest their pine plantation, user 4 would have to use their first, second and third options to control sediment discharge and would also have to buy 14,175 kg paying $6,237. Property users 15 & 16 should use their first options to control sediment discharged (wet extended pond and storm filter respectively). They would buy the difference of 6,377 kg and 7,949 kg and would pay $2,806 and $3,507 respectively. Property users 7, 8 & 13 would sell credits of 12,662kg, 4,114 kg and 11,748 kg of sediment discharge and would receive $5,571, $1,810 and $5,169 respectively. Final sediment discharge at the control point for all users combined would remain at 165,829 Kg.

Table 9 Transactions between sellers and buyers for Case 3

	Initial Credit Right (kg)	Credit Sold Quantity (kg)	Credit Bought Quantity (kg)	Final Discharge (kg)	Net Pay ($)
Property 1	603.42	0	0	603	0
Property 2	603.42	0	0	603	0
Property 3	3,063.74	0	0	3,063	0
Property 4	3,351.38	0	14,175	17,526	-6,237
Property 5	14,445.84	0	0	14,445	0
Property 6	14,445.84	0	0	14,445	0
Property 7	14,445.84	12,662	0	1,783	5,571
Property 8	14,445.84	4,114	0	10,331	1,810
Property 9	14,445.84	0	0	14,445	0
Property 10	14,445.84	0	0	14,445	0
Property 11	14,445.84	0	0	14,445	0
Property 12	14,445.84	0	0	14,445	0
Property 13	14,445.84	11,748	0	2,697	5,169
Property 14	14,445.84	0	0	14,445	0
Property 15	185.83	0	6,377	6,563	-2,806
Property 16	185.83	0	7,970	8,156	-3,507
Property 17	13,376.81	0	0	13,376	0
		28,524	28,522	165,816	0

5.2.2. Case 4 results of the "SmartTDC" market. The catchment is below an agreed upon sediment discharge limit.

The fourth case shows a simulation where the agency sets an upper limit for the catchment at 180,000 kg/year. This is 14,171.2 kg above the currently discharged allowed. Thereby, before the auction, the agency informs to participants of the catchment conditions. The agency then runs the model, determines prices and quantities, and pays (charges) for every property *i*. Table 11 summarizes this simulation.

In this case, the quantities traded were 14,353 kg from sellers and 28,522 kg to buyers. The agency would receive a net of $ 6,093 because the agency would participate as the seller of the excess sediment discharge available. The developers obtain different quantities and are charged different prices. Property's user 4 could buy 14,175 kg, and would pay $6,095 and the rest of the sediment it plans to discharge would be reduced by three erosion control options.

Property's user 15 & 16 would use their first options to control sediment discharge and would buy 6,377 kg and 7,970 kg of discharge at a price of $2,742 and $3,427 respectively.

Table 10 Transaction between sellers and buyers for Case 4

	Initial Credit Right (kg)	Credit Sold Quantity (kg)	Credit Bought Quantity (kg)	Final Discharge (kg)	Net Pay ($)
Property 1	603.42	0	0	603	0
Property 2	603.42	0	0	603	0
Property 3	3,063.74	0	0	3,063	0
Property 4	3,351.38	0	14,175	17,526	-6,095
Property 5	14,445.84	0	0	14,445	0
Property 6	14,445.84	0	0	14,445	0
Property 7	14,445.84	12,662	0	1,783	5,444
Property 8	14,445.84	0	0	14,445	0
Property 9	14,445.84	0	0	14,445	0
Property 10	14,445.84	0	0	14,445	0
Property 11	14,445.84	0	0	14,445	0
Property 12	14,445.84	0	0	14,445	0
Property 13	14,445.84	1,691	0	12,754	727
Property 14	14,445.84	0	0	14,445	0
Property 15	185.83	0	6377	6,563	-2,742
Property 16	185.83	0	7970	8,156	-3,427
Property 17	13,376.81	0	0	13,376	0
	165,829	14,353	28,522	179,987	6,093

5.2.3. Case 5 results of the "SmartTDC" market. The Catchment is above an agreed upon sediment discharge limit.

The catchment for case five is currently above the target sediment discharge limit of 140,000 kg/year. The agency runs the model and observes that the initial allocation is above the upper limit of the catchment. Thereby, before the auction, the agency informs participants that the catchment condition is over allocated. All users are therefore required to decrease their sediment discharge. Users should implement sediment control options and if someone wants to maintain the current level of sediment discharge, they must buy credits. The agency adjusts every firm's initial credit by applying an alpha α factor to obtain an allocation that satisfies the control point constraint. In this case, alpha = 0.844. The agency then runs the model with new data, determines prices and quantities, and pays (charges) for every property *i*. Table 11 summarizes this simulation.

In this case, the quantities traded were 34,234 kg from sellers and 34,274 kg to buyers. All users traded; nevertheless, of particularly interesting were the cases of properties 1, 2, 3 & 14, because they maintained the initial allocation by buying an amount equivalent to the quantity adjusted by the agency. The buying was because their opportunity costs of controlling sediment discharge were larger than buying these amounts in the smart market. For instance, property's user 1 could buy 94 kg, and it would pay $117. This payment is lower than the maximum willingness to accept to control and it could maintain its initial discharge.

The agency would receive a net of $ 49. The developers obtain different quantities and are charged different prices. User 4 could buy 14,698 kg for $18,373. This payment would be lower than the maximum willingness to pay to develop the project, thus it would harvest the 5 hectares of pine plantation and would use its options to control discharge. Users 15 & 16 would use their first options (wet extended pond and storm filter respectively) to control sediment discharge and would buy 6,406 kg and 7,999 kg of discharge respectively. The urban area would implement the first option to control discharge and could sell the difference to pay the cost for implementation.

Table 11 Transaction between sellers and buyers for Case 5

Firm	Fitted Credit Right (kg)	Credit Sold Quantity (kg)	Credit Bought Quantity (kg)	Final Discharge (kg)	Net Pay ($)
Property 1	509	0	94	603	-117
Property 2	509	0	94	603	-117
Property 3	2,585	0	477	3,063	-597
Property 4	2,828	0	14,698	17,526	-18,373
Property 5	12,192	0	2,253	14,445	-2,816
Property 6	12,192	1,372	0	10,819	1,716
Property 7	12,192	10,408	0	1,783	13,010
Property 8	12,192	2,080	0	10,112	2,600
Property 9	12,192	924	0	11,267	1,155
Property 10	12,192	1,069	0	11,123	1,336
Property 11	12,192	268	0	11,924	335
Property 12	12,192	2,279	0	9,912	2,849
Property 13	12,192	9,494	0	2,697	11,868
Property 14	12,192	0	2,253	14,445	-2,816

Property 15	156	0	6,406	6,563	-8,008
Property 16	156	0	7,999	8,156	-9,999
Property 17	11,290	6,340	0	4,949	7,925
	139,953	34,234	34,274	139,990	49

5.2.4. Case 6: Applying the "SmartTDC" market to multiple SMUs

For case 6, the "SmartTDC" model is applied to 7 of 18 stormwater management units in the Henderson Creek catchment. The units used were 7 (BIR), 12 (CPK), 27 (LIN), 32 (MAS), 49 (PARM), 53 (RAN) and 64 (WAIM) (Figure 3). We assumed 168 properties and within them would there be 7 urban areas (properties 17, 34, 48, 88, 111, 136 & 168) and 10 properties with earthworks (properties 15, 16, 33, 46, 47, 87, 110, 135, 166 & 167). Tables A1 and A2 in Appendix 3 summarise the current land uses and the number of properties in each storm unit. Earthwork properties need to control sediment discharge and therefore participate in the smart market. The capacity of the catchment is 1,497,593 kg/year, there is just one control point and the discharge capacity is at its limit.

The participants place their bids and then the agency runs the model, determines prices and quantities, and pays (charges) for every property. Table 12 summarizes this simulation. In this case, the quantities traded were 145,914.7 kg from sellers and 145,915.9 kg to buyers. Not all the bids were accepted and the agency would receive a net of $ 0.4. The developers obtain different quantities, would use different technologies to control discharge and would be charged different prices. For instance, property's user 15 could use the first and second technology to control discharge and would buy the remaining required sediment discharge credit in the smart market. On the other hand, user 135 would buy all required credits in the smart market (his opportunity cost of controlling is bigger than the clear price in the market).

Table 12 Transaction between sellers and buyers for Case 5

	Initial Discharge (Kg)	Requirement (Kg)	Quantity Sold (Kg)	Quantity Bought (Kg)	Final Discharge (Kg)	Net Pay ($)
Property 5	14,445.8		5,778.0	0.0	8,667.8	2,094.0
Property 7	14,445.8		7,222.9	0.0	7,222.9	2,617.7
Property 9	14,445.8		5,778.3	0.0	8,667.5	2,094.1
Property 11	14,445.8		5,778.0	0.0	8,667.8	2,094.0
Property 12	14,445.8		7,222.9	0.0	7,222.9	2,617.7
Property 14	14,445.8		6,665.5	0.0	7,780.3	2,415.7

Property 15	0.0	31,885	0.0	3,189.3	3,189.3	-1,155.8
Property 16	0.0	31,885	0.0	4,782.4	4,782.4	-1,733.2
Property 22	74.1		34.7	0.0	39.4	12.6
Property 33	0.0	2,798	0.0	615.0	615.0	-222.9
Property 34	66,789.2		26,954.6	0.0	39,834.6	9,768.7
Property 46	0.0	472	0.0	472.7	472.7	-171.3
Property 47	0.0	472	0.0	150.5	150.5	-54.5
Property 53	1,152.8		785.9	0.0	366.9	284.8
Property 56	1,152.8		639.5	0.0	513.4	231.8
Property 57	1,152.8		527.4	0.0	625.5	191.1
Property 62	1,152.8		661.4	0.0	491.5	239.7
Property 65	1,152.8		596.5	0.0	556.4	216.2
Property 81	1,152.8		576.6	0.0	576.3	209.0
Property 86	1,152.8		541.2	0.0	611.6	196.1
Property 87	0.0	16,363	0.0	16,363.7	16,363.7	-5,930.4
Property 91	5,943.8		3,417.7	0.0	2,526.1	1,238.6
Property 95	7,967.1		3,922.0	0.0	4,045.0	1,421.4
Property 100	7,967.1		5,550.5	0.0	2,416.6	2,011.6
Property 101	7,967.1		4,183.4	0.0	3,783.6	1,516.1
Property 103	7,967.1		3,784.4	0.0	4,182.7	1,371.5
Property 106	7,967.1		3,832.9	0.0	4,134.1	1,389.1
Property 109	7,967.1		4,612.2	0.0	3,354.9	1,671.5
Property 110	0.0	13,251	0.0	13,251.5	13,251.5	-4,802.5
Property 112	393.0		255.5	0.0	137.6	92.6
Property 131	1,103.2		627.2	0.0	476.0	227.3
Property 132	1,103.2		685.0	0.0	418.2	248.3
Property 135	0.0	48,789	0.0	48,789.7	48,789.7	-17,682.0
Property 138	6,314.3		3,456.7	0.0	2,857.6	1,252.8
Property 142	3,752.7		1,994.0	0.0	1,758.7	722.7
Property 149	21,315.9		13,916.9	0.0	7,399.0	5,043.7
Property 156	21,315.9		11,674.7	0.0	9,641.2	4,231.1
Property 164	21,315.9		14,238.0	0.0	7,077.9	5,160.0
Property 166	0.0	29,150	0.0	29,150.6	29,150.6	-10,564.6
Property 167	0.0	29,150	0.0	29,150.6	29,150.6	-10,564.6
Other Properties	1,205,625.1		0	0	1,205,625.1	0
TOTAL	1,497,593.0		145,914.7	145,915.9	1,497,593.0	

If the capacity of the catchment were 1,033,340 kg/year, the catchment would be over allocated and the agency would fix the initial allocation by using alpha=0.69. In this case, the quantities traded would be 266,419.9 kg from sellers and 266,420.3 kg to buyers. All bids would be accepted and the agency would receive a net of $ 0.26.

6. Summary of cases

The SmartTDC was tested with several urban and rural scenarios using the ARC CLM or GLEAMS simulators to predict discharges. Initially, a small hypothetical urban catchment was used to illustrate applications from the ARC CLM. Subsequently, simulations were carried out within the Swanson catchment, however assumptions were made with respect to the size and number of specific properties as well as environmental impacts such as firm' impact coefficients F_i. The BIR 7 stormwater manager unit (SMU) within the Swanson catchment in Auckland was used to illustrate a large scale application using GLEAMS and the ARC CLM. The "SmartTDC" model was then tested within 7 of 18 stormwater management units in the Henderson Creek catchment.

The SmartTDC had significant implications for controlling sediment discharge. For all simulated scenarios, whether the catchment was above, at, or below the sediment discharge limit, the SmartTDC showed efficient outcomes with at lower cost to society. In this way, if a city or catchment has problems with sediment discharge it is possible to develop an auction as we have proposed and problems with sediment discharge could be solved.

7. Recommendations for the implementation of the SmartTDC model

The SmartTDC model facilitates a market for tradable credits for sediment discharge. Thereby, participants could implement technologies or practices that reduce their sediment discharge to earn credits, or they could buy credits from someone else. Tradable discharge credits require the implementation of several steps to develop or to create a market: (1) specification of sediment caps in the catchment or control points, (2) entitlement definition, process and rules, (3) general auction information, and (4) monitoring.

(1) *Specification of sediment caps in the catchment or control points* refers to identifying a measurable threshold of sediment discharge from the catchments or control points. As specified above, the SmartTDC requires an agreed of the environmental standards, however variables could be added that allow improvement to the environment and these prices would correspond to social values to improve the environmental standards. Additionally, these prices would give incentives to incorporate BMPs and technologies for controlling sediment

discharge or for controlling specific element such as nitrites, copper, etc., overall in sensitive areas.

(2) *Entitlement definition, process and rules* are critical to the success of a market of sediment discharge. Users require a clear understanding of their rights prior to trade. The use and security of property-rights (credits) should be well defined, for instance credits would start and expire.

(3) *General auction information* should include the aims of the auction, registration forms for bidders and observers, procedures and bid forms, timetables, etc. The auction information should contain clear rules on the auction itself and the process that will be used for bidders or participants. Furthermore, information should be provided on the scheme of the auction (as the output from the optimization), and the place of trade or the online website; the process for bids done online and multiple-round auctions; monitoring procedures; fee processing and recording systems (banking); and procedures of noncompliance and disputes

(4) *Monitoring*. The actions involved in this stage aim to ensure the continued progress of market operation. These involve managing auction processes, keeping a register of entitlements held by participants; and especially monitoring erosion and sediment at control points. The model would be updated or improved as more information becomes available. Users can select to do their own monitoring at their own costs.

The success of a SmartTDC depends on modelling and the legislative protections. Similar models have been used to manage point sources such as pollution. However, recent research and projects have used this mechanism to non-point sources e.g. sediment discharge. Thus, the feasibility of approach would be determined by the ability to develop a reasonably accurate discharge models, and the willingness of society to allocate discharges through computer-based auctions.

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Appendix 1.

In this section, we develop the economic motivation for our model. First we describe the problem as faced by the regulator, then the problem as faced by each firm. These economics points of view must be addressed by any market system.

1. The problem faced by the regulator

The objective of the regulator, and therefore the optimisation model, is to maximize the social net benefits from allocating tradable discharge credits in the catchment or subcatchment (Figure **4**). The total sediment discharge is found by maximizing the social net benefit NB, but the regulatory authority can impose an upper limit on the level of sediment discharge SD_{max} (which will have inelastic supply) from the whole catchment. These constraints appear explicitly in the SmartTDC model; other types of auctions cannot manage such constraints. The SmartTDC model also considers that individual users trade credits *SC* with the objective of maximizing their own welfare.

In the auction, each user can, potentially, be a buyer or a seller. In this way, the objective of the regulator can be presented in the following simplified model.

A = sediment discharge in kg.
$B(A)$ = benefits from production or economic activities from discharge A in \$/kg total sediment discharged.
$DD(A)$ = social cost or damage due to discharge A *\$/kg* total sediment discharged.

Net benefits $NB = B(A) - DD(\mathrm{A})$ [1]

Indirectly, equation [1] reflects the demand function of sediment discharge $D(A)$, as well as, the inverse of the cost function for controlling the sediment discharge $Cost(A)$ (note that $B(A) \cong \mathrm{D}(A) \equiv -Cost(A)$. Also, [1] represents the total cost of achieving the sediment discharge level $Cost(A) = \int_{A_0}^{A_1} D(A)$. The optimal allocation of credit for sediment discharge is obtained when the marginal cost for controlling sediment discharge equals the marginal damage of sediment discharge in the catchment SD_{max} or subcatchment S_j.

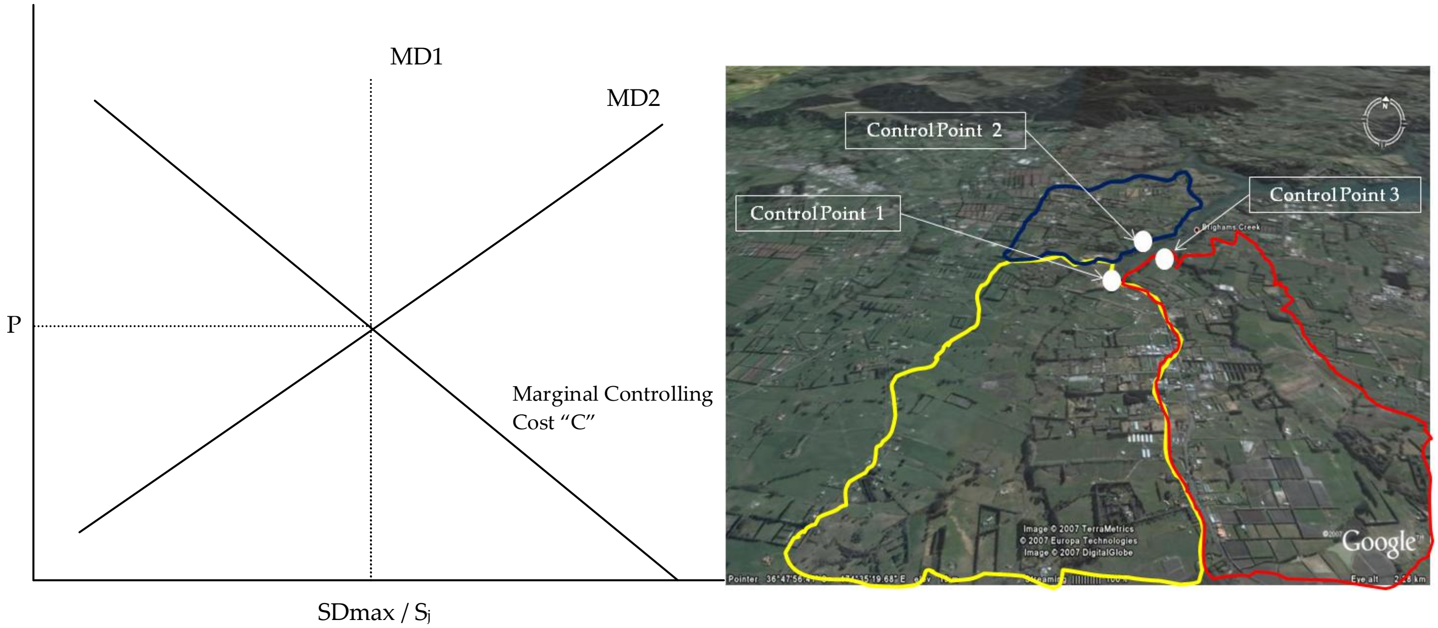

Figure 4 Allocation of maximum suspended solids by catchment or subcatchment.

2. The problem faced by the individual user, under regulation, without a market.

The objective of the user is to minimize the cost of production subject to level of production as well minimize cost subject to quantity allocated of sediment discharge. However, if is not allowed trade between users, the simple scenario of cost minimization of a single user, under regulation, without a market is given by:

Indices

i = user $i = 1..n$.

j = subcatchment or catchment $j = 1..m$.

k = condition $k = 0..K$. $K=0$ means initial condition where land user does not control sediment discharge, or control it only minimally. $K=1$ means new conditions of sediment right discharge by the time.

Parameters

A_{ijk} = the total sediment discharge from user i in subcatchment j and the condition k. If $A_{ij0} = A_{ij1}$ means initial sediment discharge is equal to total sediment discharge right allocated or it does not control sediment discharge. Furthermore, $A_{ij0} > A_{ij1}$ means the user is controlling sediment discharge ($A_{ij0} - A_{ij1} = SC_i$).

T_i = the technology used for controlling sediment discharge,

S_{ij} = the maximum sediment discharge (which will have inelastic supply) from the user *i* in the subcatchment *j*,

$C_i(A_{ijk}, SC_i, T_i)$ = the cost function of user *i*.

SD_{max} = the maximum sediment discharge from the catchment.

U_i = uncontrolled emissions of user *i*.

P = the market price determined by tradable rights,

Decision variables

SC_i = the reductions in sediment discharge or credits (abatement, BMPs, or control) by user *i*.

Model

1) $\mathit{Minimize} \quad C_i(A_{ij1}, SC_i, T_i)$ subject to [2]

2) $A_{ij1} \leq S_{ij}$, for all i, j

3) $SC_i \geq 0$

Explanation

1) Minimize cost of production. This function has implicitly a cost function of controlling sediment discharge.
2) User cannot use more than its quantity allowed of sediment discharge.

The results of the optimal condition for each source firm are:

$$\frac{\partial C_i(SC_i)}{\partial SC_i} \geq 0$$

Under this condition user would allocated its resources up to the marginal effect to control sediment discharge is equal to the price of the resource. In this case, the price would be zero, the user does not control and it would discharge the quantity A_{ij0} (Figure 5). However, the regulator could impose a limit to discharge from users A_{ij1} and firms could abate up to get this quantity. Certainly, this restriction would reduce the total quantity discharged; nevertheless, it could be inefficiency if the quantities allocated are different to the damage by firms and would cause social cost.

3. The problem faced by a firm in a market

Now the scenario is that users could trade between them and there are multiple users in the catchment. The following model with the option to trade sediment discharge controlled SC_i is given by:

Model

1) Minimize $\sum_{i=1}^{n}\left[C_i\left(A_{ij0}, SC_i, T_i\right) - P * \left(-A_{ij1} - U_i + SC_i\right)\right]$ subject to [3]

2) $\sum_{i=1}^{n} A_{ij1} \leq S_j$ for all user *i* in the subcatchment j.

3) $\sum_{j=1}^{m} S_j \leq SD_{max}$ for all subcatchment *j* in the catchment.

4) $A_{0ij} \geq A_{1ij}$, for all *i,j*

5) $SC_i \geq 0$

Explanation

1) Minimize cost of production. This function has implicitly a cost function of controlling sediment discharge.
2) Users cannot discharge more than the total sediment discharge in the subcatchment *j*.
3) The total sediment discharge from different subcatchment *j* must not be above the upper limit of the catchment.

Then, the new equilibrium conditions with different users in the catchment can be expressed as:

$$\frac{\partial C_i(SC_i)}{\partial SC_i} - P = \frac{\partial C_1(SC_1)}{\partial SC_1} - P = \frac{\partial C_2(SC_2)}{\partial SC_2} - P = K = \lambda_j$$

Where λ_j is the shadow price for having an extra permit (additional quantity of permits) in the subcatchment *j*. Likewise, λ_j is the social effect of each user in the subcatchment *j*. With this model, it is possible to allow trading between subcatchments.

Figure 5 shows supply and demand graphs for the market. Before the market, developers have different opportunity costs due to economic activity. The developers allocate their resources up to a point where the marginal cost for control equals the marginal damage or it could allocate A_{ij1} to each user. In this scenario, Agent 2 sells credit *SCi* to Agent 1 equal to $A_{2j1} - A_{2j1}^{*}$, because Agent 2 has incentives to abate or control at the market price; at the same time, the cost to Agent 1 of controlling damage is higher than buying a credit, so Agent 1 has an incentive for buying credit. Similarly, developers can incorporate new technologies to control sedimentation or incorporate new conservation lands to obtain additional sediment discharge credits for trading. That is the case of firm 2, where it can sell additionally $A_{2j1}^{**}-A_{2j1}^{*}$· . In this way, firms can keep their discharge below their allocated level and sell or rent their surplus credit.

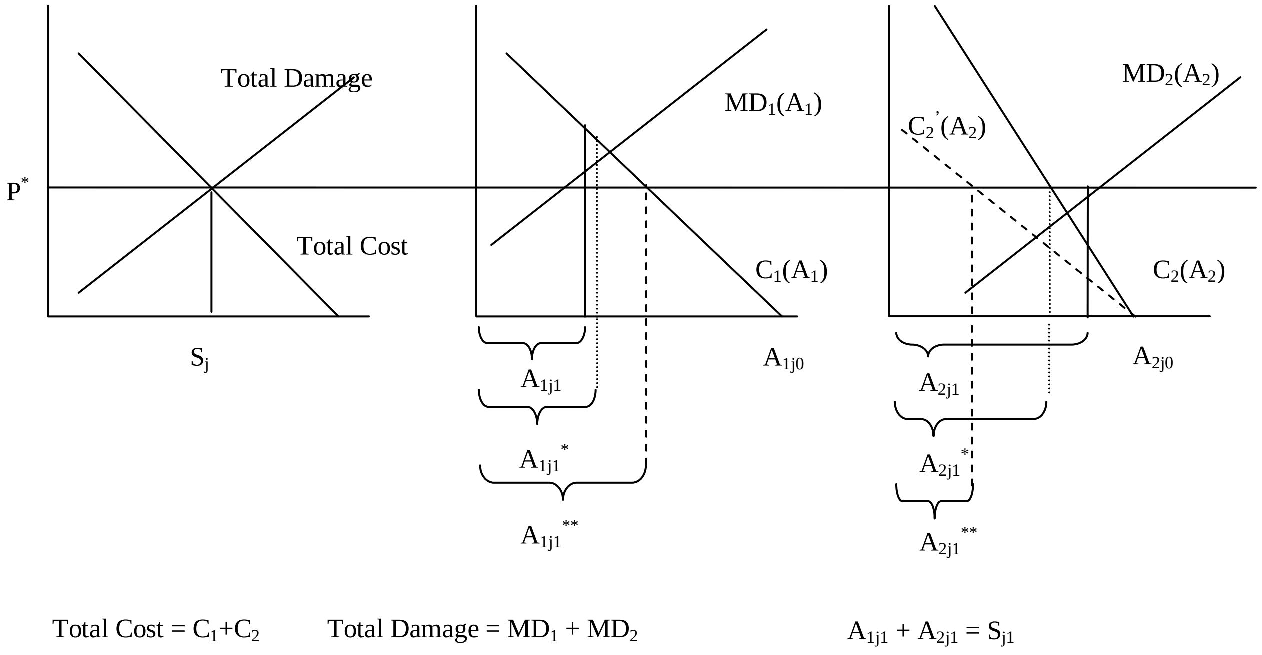

Figure 5 General conditions of tradable credits.

Appendix 2.A. Firms have the following options.

- Firm 1 could use a dry pond, wet pond and wet extended pond technology to reduce sediment discharge. With these technologies and its opportunity cost, it decides to use as a first and second option the dry pond and wet pond to reduce 630 kg and 148 kg of sediment respectively and as a third option to use a wet extended pond to reduce an additional 66.6 kg of sediment. The firm plans to sell the sediment in the market and the minimum willingness to accept to sell is $0.63, $3.37 and $9.0 per kg respectively.
- Firm 2 could use a wet pond, wet extended pond and wet pond with flocculation technology to reduce sediment discharge. With these technologies and its opportunity cost, it decides to use as a first and second option the wet ponds to reduce 770 kg and 92 kg of sediment respectively and as a third option a wet extended pond to reduce an additional 41.4 kg of sediment. The firm plans to sell the sediment in the market and the minimum willingness to accept to sell is $0.649, $5.53 and $14.49 per kg respectively.
- Firm 3 could use a constructed wetland, storm-filter and bay bales technology to reduce sediment discharge. With these technologies and its opportunity cost, it decides to use as a first and second option the bay bales to reduce 400 kg and 120 kg of sediment respectively and as a third option to use a constructed wetland to reduce an additional 192 kg of sediment. The firm plans to sell the sediment controlled in the market and the minimum willingness to accept to sell is $0.375, $1.25 and $2.6 per kg respectively.
- Firm 4 could use a storm-filter, bay bales and silt fence technology to reduce sediment discharge. With these technologies and its opportunity cost, it decides to use as a first option the bay bales to reduce 400 kg of sediment. In addition, it could use a second and third option the silt fences to reduce 180 kg and 126 kg of sediment respectively. The firm plans to sell the sediment controlled in the market and the minimum willingness to accept to sell is $0.375, $1.11 and $3.95 per kg respectively.
- Firm 5 could use a wet pond with flocculation, storm filter and silt fence technology to reduce sediment discharge. With these technologies and its opportunity cost, it decides to use as a first and second option the silt fences to reduce 168.5 kg and 50.55 kg of sediment respectively and as a third option to use a storm-filter to reduce an additional 35.38 kg of sediment. The firm plans to sell the sediment controlled in the market and the minimum willingness to accept to sell is $1.18, $3.95 and $11.3 per kg respectively.
- Firm 6 could use a dry pond, wet pond and wet extended pond technology to reduce sediment discharge. With these technologies and its opportunity cost, it decides to use as a first and second option the dry pond and wet pond to reduce 212.31 kg and 49.8 kg of sediment respectively and as a third option to use a wet extended pond to reduce an extra 22.4 kg of sediment. The firm plans to sell the sediment controlled in the market and the minimum willingness to accept to sell is $1.18, $10 and $24.8 per kg respectively.

- Firm 7 could use a wet pond, wet extended pond and wet pond with flocculation technology to reduce sediment discharge. With these technologies and its opportunity cost, it decides to use as a first and second option the wet ponds to reduce 259.5 kg and 31 kg of sediment respectively and as a third option to use a wet extended pond to reduce an additional 14 kg of sediment. The firm plans to sell the sediment controlled in the market and the minimum willingness to accept to sell is \$1.92, \$16.12 and \$43 per kg respectively.
- Firm 8 could use a dry pond, storm filter and silt fence technology to reduce sediment discharge. With these technologies and its opportunity cost, it decides to use as a first and second option the silt fences to reduce 168.5 kg and 55 kg of sediment respectively and as a third option a storm-filter to reduce an additional 35 kg of sediment. The firm plans to sell the sediment controlled in the market and the minimum willingness to accept to sell is \$1.18, \$3.95 and \$11.3 per kg respectively.
- Firm 9 wants to develop a project of 700 m^2 between constructions and roads. It would last a year. Firm could use a wet pond with flocculation, storm filter and silt fence technology to reduce sediment discharge. With this technologies and its opportunity cost, it decides that it would use as a first option the storm-filter to control 1,312.5 kg of sediment, then as a second option the silt fence to control an additional 132.5 kg of sediment and latterly a storm filter to control 92 kg of sediment more. The maximum willingness to pay is \$0.61, \$4.6 and \$8.7 per kg respectively.
- Firm 10 wants to develop a project of 500 m^2 between constructions and roads. It would last a year. Firm could use a wet pond, wet extended pond and hay bales technology to reduce sediment discharge. With this technologies and its opportunity cost, it decides that it would use as a first option the wet pond to control 962.5 kg of sediment, then as a second option the wet extended pond to control an additional 115 kg of sediment and as a third option a second wet extended ponds to control 51.8 kg of sediment. The maximum willingness to pay is \$0.62, \$5.21 and \$15.4 per kg respectively.

Appendix 2.B. Properties' users have the following options.

- Property's user 1 could implement BMPs in the property. The user has evaluated several practices and opportunity costs, and decides to implement different land proportions under BMPs. The user could implement a 60%, 80% and 100% of land under BMPs and reduce 60.34 kg, 36.12 kg and 12.07 kg of sediment respectively. The user plans to sell the sediment in the market and the minimum willingness to accept to sell is $2.1, $4.5 and $20.1 per kg respectively.
- Property's user 2 could implement BMPs in the property. The user has evaluated several practices and opportunity costs, and decides to implement different land proportions under BMPs. The user could implement a 70%, 90% and 100% of land under BMPs and reduce 84.48 kg, 48.27 kg and 18.10 kg of sediment respectively. The user plans to sell the sediment in the market and the minimum willingness to accept to sell is $1.9, $3.8 and $18 per kg respectively.
- Property's user 3 could implement BMPs in the property. The user has evaluated several practices and opportunity costs and decides to implement different proportions of land under BMPs. The user could implement a 40%, 70% and 100% of land under BMPs and reduce 153.19 kg, 61.27 kg and 30.64 kg of sediment respectively. The user plans to sell the sediment in the market and the minimum willingness to accept to sell is $3.5, $4.35 and $11.65 per kg respectively.
- Property's user 4 currently has 16.1 hectares of pine plantations and wants to harvest 5 hectares. According to GLEAMS the property would discharge 3,351.38 kg/years and harvesting would discharge 150,999.15 kg/year. The user has evaluated several practices and opportunity costs, and decides to implement BMPs to control discharge. In this way, as a first option could implement BMPs in the rest of the forest plantation to reduce 462.15 kg of discharge. Then, as a second option, could use conservation's practices in the harvest to control 90,599 kg of sediment (60% of the total discharged). Finally, as a third option, the user could use an additional practice to control an extra 45,299.75 of sediment (30% of the total discharged). The maximum willingness to pay is $0.18, $0.22 and $3.27 per kg respectively.
- Property's user 5 could implement management practices to control sediment discharge in the property. The user has evaluated several practices and opportunity costs, and decides to use as first option to implement BMPs to control discharge. With this practice would reduce up to 2,889.17 kg of sediment discharge from the property (20% would be reduced). Then, as second option, changes the landuse of 4 hectares and plants pines to reduce 2,734.61 kg of sediment discharge. As third option, the user changes the landuse of additional 3 hectares and plants pines to reduce an extra 2,050.95 kg of sediment discharge. The user plans to sell the sediment in the market and the minimum willingness to accept to sell is $1.86, $14.91 and $37.29 per kg respectively.
- Property's user 6 could implement management practices to control sediment discharge in the property. The user has evaluated several practices and opportunity costs, and decides to

use, as first option, to change the landuse of 4 hectares and plants pines to reduce 3,626.43 kg of sediment discharge. Then, as second option, could use BMPs in the other part of the property to reduce 2,496.68 kg of discharge (25% of sediment discharge) and, as third option, the user could plant another hectare with pines to reduce an extra 713.94 kg of discharge. The user plans to sell the sediment in the market and the minimum willingness to accept to sell is \$0.96, \$2.33 and \$7.27 per kg respectively.

- Property's user 7 currently has 12.95 hectares with pasture and wants to develop a private park with natural forest and to sell the credit for controlling sediment discharge. With this plantation would reduce up to 12,662.03 kg of sediment discharge. We assume the reduction's effect of sediment discharge is instantaneous, i.e. the change of landuse would work as an adult natural forest immediately. The user plans to sell the sediment in the market and the minimum willingness to accept to sell is \$0.35 per kg.
- Property's user 8 could implement management practices to control sediment discharge in the property. The user has evaluated several practices and opportunity costs, and decides to use, as first option, to implement BMPs to reduce up to 4,333.75 kg of sediment discharge from the property (30% would be reduced). Then, as second option, could plant 6 hectares with pines to reduce 3,433.04 kg of sediment discharge. As third option, the user changes the landuse of 3 hectares and plants pines to reduce an extra 1,716.52 kg of sediment discharge. The user plans to sell the sediment in the market and the minimum willingness to accept to sell is \$0.44, \$3.76 and \$10.03 per kg respectively.
- Property's user 9 could implement management practices to control sediment discharge in the property. The user has evaluated several practices and opportunity costs, and decides to use, as first option, to implement BMPs to reduce up to 3,178.09 kg of sediment discharge from the property (22% would be reduced). Then, as second option, changes the landuse of 5 hectares and plants pines to reduce 3,306.78 kg of discharge and, as third option, changes the landuse of additional 5 hectares and plants pines to reduce an extra 3306.78 kg of sediment discharge. The user plans to sell the sediment in the market and the minimum willingness to accept to sell is \$0.75, \$1.8 and \$2.7 per kg respectively.
- Property's user 10 could implement management practices to control sediment discharge in the property. The user has evaluated several practices and opportunity costs, and decides to use as first option to implement BMPs to reduce up to 3,322.54 kg of sediment discharge from the property (23% would be reduced). Then, as second option, changes the landuse of 7.95 hectares and plants pines to reduce 5169.78 kg of discharge and, as third option, changes the landuse of additional 5 hectares and plants pines to reduce an extra 3,251.04 kg of discharge. The user plans to sell the sediment in the market and the minimum willingness to accept to sell is \$0.85, \$3.45 and \$6.15 per kg respectively.
- Property's user 11 could implement management practices to control sediment discharge in the property. The user has evaluated several practices and opportunity costs, and decides to use, as first option, to implement BMPs to reduce sediment discharge. With this practice

would reduce up to 3,033.63 kg of sediment discharge from the property (21% would be reduced). Then, as second option, could change the landuse of 2 hectares and plants pines to reduce 1,345.01 kg of discharge and, as third option, could plant 1.5 hectares to reduce an extra 1,008.76 kg of discharge. The user plans to sell the sediment in the market and the minimum willingness to accept to sell is $1.25, $1.779 and $4.19 per kg respectively.

- Property's user 12 could implement management practices to control sediment discharge in the property. The user has evaluated several practices and opportunity costs, and decides to use, as first option, to change the landuse and plants 5 hectares with pines to reduce 4,533.04 kg of discharge. Then, as second option, changes the landuse and plants 5 hectares with pines to reduce 4,533.04 kg of discharge and, as third option, changes the landuse of additional 2.96 hectares and plants pines to reduce an extra 2,683.56 kg of discharge. The user plans to sell the sediment in the market and the minimum willingness to accept to sell is $0.76, $1.92 and $3.95 per kg respectively.
- Property's user 13 could implement management practices to control sediment discharge in the property. The user has evaluated several practices and opportunity costs, and decides to change the landuse of whole property and plants pines to reduce 11,748.21 kg of discharge. The user plans to sell the sediment in the market and the minimum willingness to accept to sell is $0.43 per kg.
- Property's user 14 could implement management practices to control sediment discharge in the property. The user has evaluated several practices and opportunity costs, and decides to use, as first option, to change the landuse of 5 hectares and plants pines to reduce 4,533.04 kg of discharge. Then, as second option, could use BMPs in the other part of the property to reduce 1,596.95 kg of discharge (18% of sediment discharge) and, as third option, could plant 3 hectares with pines to reduce an extra 2350.12 kg of discharge. The user plans to sell the sediment in the market and the minimum willingness to accept to sell is $1.3, $2.35 and $4.55 per kg respectively.
- Property's user 15 wants to develop a project that would discharge 31,885.91 kg/year. Property's user could use a wet extended pond and wet pond with flocculation to reduce sediment discharge. With these technologies and opportunity costs, the user decides that would use, as a first option, the wet extended pond to control 25,508 kg of sediment. Then, as a second option, the wet pond with flocculation to control an additional 3,166.6 kg of sediment and, latterly, the wet extended pond to control 956.7 kg of sediment more. The maximum willingness to pay is $0.23, $2.19 and $6.27 per kg respectively.
- Property's user 16 wants to develop a project that would discharge 31,885.91 kg/year. The user could use a wet pond, wet pond with flocculation and storm filter technology to reduce sediment discharge. With these technologies and opportunity cost, the user decides that would use as a first, second and third option the storm filters to control 23,914.44 kg, 3,188.59 kg and 1,434.86 kg of sediment respectively. The maximum willingness to pay is $0.16, $1.25 and $2.78 per kg respectively.

- Property's user 17 is an urban place, represented by the council. Assuming a 50% of impervious cover and estimating from ARC CLM, the sediment discharged would be 13,376.81 kg/year. In the urban place could be used different technologies to control sediment discharged. For instance, could be used a dry pond, wet extended pond and wet pond with flocculation to reduce sediment discharge. With these technologies, the council decides to use, as a first and second option, the dry ponds to reduce 8,427.39 kg and 1,484.8 kg of sediment respectively and, as a third option, to use the wet ponds with flocculation to reduce an additional 1,039.38 kg of sediment. The council plans to sell the sediment controlled in the market and the minimum willingness to accept to sell is $0.47, $2.69 and $5.77 per kg respectively.

Appendix 3

Table A1 Current land use and surface areas (ha) for specific SMU's in the Henderson Creek Catchment.

Catch_ID	Bush	Native forest	young pine trees	Pine mature trees	Pasture /grassland	Earth works	Motorway
7	4.71	22.26	0.00	16.10	129.58	1.45	0.00
12	14.47	1.47	0.00	0.00	69.13	0.18	6.17
19	6.66	11.05	0.00	4.32	29.91	3.78	0.00
22	4.05	0.00	0.00	1.01	26.33	0.65	0.00
25	10.75	15.08	0.00	15.65	97.70	2.19	0.00
27	0.00	0.67	0.00	0.00	16.82	0.06	0.00
28	12.17	43.88	0.00	7.14	72.48	12.80	0.00
31	18.89	12.35	0.00	5.35	89.30	1.16	5.35
32	0.00	39.74	0.00	7.04	51.06	0.46	7.00
36	127.54	22.26	0.00	19.98	191.83	1.78	0.00
49	68.19	8.74	0.00	25.30	115.01	0.41	0.00
53	2.88	7.71	0.00	1.83	39.23	2.38	0.00
58	0.00	6.57	0.00	0.00	72.46	1.45	4.76
60	67.67	94.37	0.00	0.00	14.86	4.73	0.00
61	410.65	973.03	1.20	52.67	619.95	0.00	0.00
62	458.72	668.41	0.00	32.05	389.78	0.37	0.00
63	220.25	428.33	1.14	8.70	287.79	1.80	0.00
64	100.83	44.04	6.27	36.82	325.22	1.20	0.00

Catch _ID	Urban	River	lakes and ponds	open water	coastal sands and gravel	mangrove	water vegetation	Total Surface
7	28.19	0.00	0.00	0.00	0.00	0.00	0.00	202.29
12	140.75	0.37	0.00	0.00	0.00	2.21	0.00	234.76
19	265.13	0.00	0.00	0.00	0.00	0.00	0.00	320.84
22	161.05	0.46	0.00	0.00	0.00	0.00	0.00	193.56
25	451.78	0.00	0.00	0.00	0.00	0.00	0.00	593.16
27	168.60	0.00	0.00	0.00	0.00	3.06	0.00	189.21
28	339.32	0.00	0.00	0.00	0.00	0.00	0.00	487.8
31	242.40	0.00	0.00	0.00	0.00	0.22	0.00	375.02
32	430.47	0.00	0.00	0.00	0.00	3.15	0.00	538.92
36	0.71	0.00	0.00	0.00	0.00	0.00	0.00	364.1
49	245.77	0.00	2.70	0.00	0.00	0.00	1.97	468.1
53	186.11	0.00	0.00	0.00	0.00	0.94	0.00	241.08
58	359.29	0.25	0.00	0.44	0.00	2.16	0.00	447.39
60	210.82	0.00	0.00	0.00	0.00	0.00	0.00	392.45
61	32.28	0.00	0.00	0.00	0.00	0.00	0.00	2089.78
62	61.65	0.00	0.00	0.00	0.00	0.00	0.00	1610.99
63	50.60	0.00	0.00	0.00	0.00	0.00	0.00	998.61
64	97.56	0.00	0.00	0.00	0.00	0.00	0.00	611.93

Source. NIWA

Table A2 Number of assumed properties and land use for specific SMUs in the Henderson Creek catchment.

Catch_ID	Bush	Native forest	young pine trees	Pine mature trees	Pasture /grassland	Earth works	Motorway	Urban	Total
7	2	1	0	1	10	2	0	1	17
12	4	1	0	0	10	1	0	1	17
19	1	1	0	1	3	1	0	1	8
22	1	0	0	1	3	3	0	1	9
25	2	1	0	1	10	1	0	1	16
27	0	1	0	0	10	2	0	1	14
28	2	3	0	1	20	10	0	1	37
31	3	2	0	1	10	1	0	1	18
32		2	0	1	35	1	0	1	40
36	4	1	0	1	10	1	0	1	18
49	3	1	0	2	15	1	0	1	23
53	1	1	0	1	20	1	0	1	25
58	0	1	0	0	50	1	0	1	53
60	9	1	0	0	10	1	0	1	22
61	20	20	1	2	20	0	0	1	64
62	20	10	0	1	10	1	0	1	43
63	10	10	1	1	9	2	0	1	34
64	5	2	1	1	20	2	0	1	32