Bringing Biophysical Models into the Economic Laboratory: An Experimental Analysis of Sediment Trading in Australia

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BRINGING BIOPHYSICAL MODELS INTO THE ECONOMIC LABORATORY: AN EXPERIMENTAL ANALYSIS OF SEDIMENT TRADING IN AUSTRALIA[1]

Abstract

Experimental economics has emerged and matured as a formal method for questioning and stress testing economic theory and assumptions concerning individual behavior. More recently, experimental methods have been used successfully in an economic laboratory to test alternative environmental policy options. The data underpinning these experiments is often stylized or hypothetical in nature. Ecologists and experimental economics have much to gain by exploring ways to underpin economic experiments with data generated from biophysical models in terms of external validity and salient features of the issue at hand.

The study makes a contribution by demonstrating how underpinning experiments with regionally modeled biophysical data may give insights which would not necessarily arise from stylized data. In this study sediment data generated from an Environmental Management Support System (EMSS), a software model of sediment runoff in catchments was used to populate the player decision space. The study investigated the relative performance of four different instruments (closed first and second price call tenders, cap and trade and command and control regulation) as mechanisms for promoting riparian management and reducing total suspended solids exiting a catchment and, as traditional auction structures, logical choices for exploring the consequences of incorporating modeled biophysical data.

The study found unexpected insights into player behavior which may not have been foreseen from stylized data, suggesting that further exploration of integrated biophysical economic experiments is warranted.

Keywords: sediment trading, EMSS, natural resource markets, experimentation.

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Introduction

An important dimension of ecological economics is to develop logical linkages between and/or integration of ecological or biophysical models and economic models. Using biophysical data generated from industry standard models to determine the parameters of an experiment adds a level of external validity which in turn promotes adoption by key stakeholders of the research findings. It can also provide at times insights which may not arise from stylized data.

There are a number of policy instruments available to achieve environmental targets. This paper explores the relative performance of closed call tenders, cap and trade and regulation, in the form of command and control, as mechanisms for achieving reductions in total suspended solids exiting the Somerset Stanley Catchment of Queensland Australia. The method used to evaluate the options integrates an Environmental Management Support System (EMSS), developed for modeling sediment runoff in catchments with an experimental economic environment designed to explore resource economic issues and policy options under laboratory conditions.

The paper is organized as follows. The paper begins by outlining the basic notions underpinning the management of non-point pollutants such as sediment. Advances in monitoring and modeling are opening opportunities to use more point source policy instruments. Given these advances, the paper outlines how a first and second price closed call tender, a cap and trade market and a regulatory system could be used to achieve aggregate sediment reduction targets. This is followed by an outline of the biophysical model used and the experimental procedures. The paper concludes with the results and findings arising from the experiments.

Issues in sediment reduction management

The stochasticity and unobservability of non-point pollution, such as sediment in catchments, combined with spatial and temporal heterogeneity among emitters makes the management of such pollution difficult (Baumol and Oates, 1993; Bouzaher and Shogren, 1997). Baumol and Oates (1975) argue that where the contributions of individual pollutants can be measured, emissions-based instruments, such as cap and trade, tendering and regulation among others, could be effective. Limited information on the processes of natural variation and problems associated with monitoring and measurement has led to adverse selection and moral hazard problems (Braden and Segerson 1993; Shortle and Dunn 1986; Segerson 1988). As the science and monitoring underpinning biophysical models improve, traditionally considered non-point pollutants will increasing be able to be managed as point sources. In the meantime, in many catchments, such as the Minnesota River Basin, sub-catchment groups have been established with the authority to trade on behalf of those in their region (Fang and Easter, 2003).

Following a review of point-nonpoint source pollution trading projects in Minnesota, Fang and Easter (2003, p.29) concluded that:

> "[s]cientific uncertainties in credit evaluation procedures have the potential to compromise the environmental benefits expected from point-nonpoint source trading projects. However, with the help of advanced scientific tools, properly defined trading ratios can take these scientific uncertainties into account and provide assurance for the environmental accountability of point non-point source trading."

Given the limitations of current biophysical modeling but with the expectation of farm levels models in the future, this study, in accordance with Fang and Easter (2003), implemented sediment trading at a sub-catchment level as a point source in order to demonstrate proof of concept. At a sub-catchment level it is assumed that there are regional groups which coordinate activities and which have the authority to trade sediment credits and make reduction decisions on behalf of the farmers in their sub-catchment. Such groups are not uncommon. In Australia, for example, regional natural resource management groups, such as Landcare and catchment management authorities, have a long history of cooperative and group representative action on behalf of landholders (Williams, 2004; Roberts 1995; Connell, 1994). More recently, regional groups have been established as part of a national action plan for salinity and water quality to coordinate land management actions on a regional scale (see www.napswq.gov.au). These groups consist of key stakeholders and regional government agents in each region (Natural Resource Management Ministerial Council, (NRMMC) 2004). As mentioned, in many catchments, such as the Minnesota River Basin, sub-catchment groups have been established with the authority to trade on behalf of those in their region (Fang and Easter, 2003). It is conceivable that such groups in Australia may also act as representative traders in the future.

Policy options for controlling sediment runoff

In this study four policy instruments were explored: a first and second price tender system, a cap and trade market, and command and control regulation as instruments often used in natural resource management to control pollution levels.

In the tender experiments players acting as farmers made offers to a central authority to construct riparian buffer zones to reduce sediment loads entering a river system. A sealed offer procedure was used in the first and second price tender experiments. The central authority accepted the lowest price offer upwards until the reduction target or the budgetary constraint was met. In the first price tender experiments the successful sellers were all paid the price of the highest successful offer. In the second price tender successful sellers were paid the price of the first unsuccessful offer,[2] consistent with the notions of a second price sealed bid proposed by Vickey (1961).

The cap and trade system, as the name suggests, involved a regulating authority imposing an upper limit on the level of total suspended solid loads exiting the system and allowing farmers to trade in sediment credits to achieve the cap. The notion of cap and trade implies that each player can potentially be a buyer or seller. In this experiment players

2 In an English auction, by contrast, the successful trader only has to pay the price of the next highest offer.

produce credits by constructing riparian buffer zones which capture more sediment than required. When the market price of credits is below the players' marginal cost of constructing buffer zones, they are expected to enter the market and buy units rather than construct buffer zones. When the market price is above the marginal cost of constructing buffer zones, players are expected to exceed their target production level, produce credits and sell the additional units.

The most recent and significant applications of the cap and trade approach is in the implementation of the Clean Air Act by the U.S. Environmental Protection Agency to achieve its Clear Sky objective[3]and the European Union greenhouse gas emissions-trade scheme, which expected to start in 2005 (see European Union, 2001). The Clear Air Act 1990 introduced a cap and trade policy instrument on the electric utility industry in the US in order to reduce emissions (Schmalensee, *et al*. 1998; Fullerton and Metcalf, 2002; Groenenberg and Blok, 2002; Tietenberg, *et al*., 1999).

A number of authors have explored the relative merits of a cap and trade instrument. It is difficult to determine the optimal policy objective using a cap and trade approach as it can achieve a variety of results and impose different transaction costs. A policy of cap and trade at a regional level might be the most appropriate direction forward. Schwarze and Zapfel (2000, p.1) and others have found that "provisions to assure political acceptance, functional interdependencies and overlapping regulation are the most important influences on the design of applied cap-and-trade permit programs". Colby (2000) noted that cap and trade policy instruments have been applied to a number of environmental problems with varying success and that such mechanisms require a political or legal mandate to cap resource use or in this case emission of total suspended solids. The experimental work reported in this paper tends to confirm these theories.

Australia is accustomed to the use of cap mechanism, such as that imposed on water extraction from the Murray Darling Basin, but the use of markets to effectively manage the cap is relatively new, but not without precedent. Where this study differs from

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3 For a discussion of the relative benefits of the Clean Sky scheme see Winters (2002).

traditional cap and trade mechanism is that instead of setting a cap on emission levels, a reduction cap is set and the players have to produce the reduction rather than reduce production to meet a specific target.

A standard closed call auction structure was used in the cap and trade experiments. There is a large body of divided literature comparing and debating the relative merits of call and double auction structures (see, for example, Davis and Holt 1993; Smith *et al.*, 1982). A closed call auction structure was chosen because it is the most commonly used in natural resource markets in Australia. The Northern Victoria Water Exchange, for example, use closed call auctions to operate temporary water markets. It is assumed that when the participants are inexperienced, a closed call pool price auction structure minimizes the likelihood that ill considered offers will determine the pool price and as such adversely impact on the players' income during a period when they are learning how the market operates. Poor outcomes may result in low market participation in latter years.

An alternative to either a closed call tender or cap and trade is a command and control regulation, such as standards prescribing riparian land management or levels of pollution emission. While market based instruments are gaining political standing, command and control instruments are still used more commonly by state and federal agencies to control pollution emissions as a result of gaps between normative theory and positive reality (Keohane et al., 1998). To minimize the risk of adverse selection and moral hazard associated with non-point pollution emission regulation, regulation has tended to be on production rather than emission levels per se (see for example Helfand, 1995).

Under the regulatory instrument explored in this study each landholder was required to construct riparian buffer zones, as emission proxies for defuse sources of pollution on portions of each type of riparian land which in aggregate would achieve equivalent emission reductions to the tender or cap and trade instruments. The requirement imposed on each landholder is determined by proportioning. The cost of meeting the regulation imposed on each landholder would therefore also be proportional to their cost of supply. For example, if the requirement was a reduction by 20% then each landholder would be required to construct riparian buffers on 20% on each type of riparian land type on their property.

The model

To demonstrate the integration of ecological model data with experimental economic techniques, a simplified version of the sediment load problem was used in which the relative size of the revenue returned to the farmers from a first price auction compared to the cost of achieving a regulative instrument. In this study it was assumed that the government wished to reduce the tonnage of total suspended solids exiting a catchment by examining policy options that would promote the construction of riparian buffer zones. The property right in this study is sediment loads measured in tonnage/day. Credits are created by constructing riparian buffer zones on farms in a catchment. These buffer zones reduce the total load of suspended solids exiting a catchment. In some cases biophysical models may allow for conversion of distance of riparian buffer into total suspended solid loads, at least at a sub-catchment level.

In Figure 1, supply (S) reflects the combined marginal cost of sediment reduction of each of the sub-catchments. It is assumed that it is possible, through regional farming associations, to coordinate land use within a sub-catchment. Setting a reduction target Q* opens a number of possible policy incentives. First, the authority could establish a first price tendering system, resulting in a market price P*. Alternatively, the government could impose a regulatory requirement that each farmer establish buffer zones to capture Total Suspended Solids (TSS) proportional to current aggregate loads, resulting in S^1. Finally, the government could establish a cap on end of pipe emissions and allow trade.

The cost to the authority of purchasing loads through a first price auction is the area {O, P*, B, Q*}. Assuming A = {O,P*,E} and X = (E,S^1,B), the merits of a regulatory approach over a uniform tender system depends on the relative size of A and X. If A > X then the payment to farmers through the first price tender is greater than the cost of meeting regulatory requirements. Under cap and trade the demand (Dc) images aggregate supply but constrained by the cap (Q*). Supply (Sc) reflects the capacity of the players to produce above their cap target. A cap and trade policy and uniform tender are expected to be equally efficient. A second price tender, according to Vickrey (1961), will limit strategic behavior and produce an unbiased report of suppliers' marginal cost of supply resulting in a competitive equilibrium price.

To explore the relative merits of the policy instruments further, a case study of a catchment in South East Queensland was selected. Modeling the consequences of introducing riparian buffer zones was done using an Environmental Management Support System (EMSS) developed by research staff in the Cooperative Research Centre for Catchment Hydrology.

The Environmental Management Support System (EMSS)

The Environmental Management Support System (EMSS) estimates the storage and transport of daily runoff and daily pollutant loads to the receiving waters from 175 catchments in an area of approximately 23,000 km^2 and encompasses a diversity of land types, land uses and climates across southeast Queensland. The model estimates are sensitive to changes in climate, storage operations, land-use and land management practices in estimating runoff and pollutant export loads. For each sub-catchment, the EMSS predicts a daily runoff volume and a daily load of suspended sediment, total phosphorous and total nitrogen. The flows and pollutant loads from each sub-catchment are routed through over 2000 km of stream network, down to the tidal limits in the estuaries. The EMSS contains a simple representation of storages and their effect on sediment and nutrient trapping, and water losses and diffuse management treatments and riparian management options are ascribed particular pollutant stripping potential that will reduce the original pollutant load prediction, the efficacy of which is assumed to vary spatially and temporally (Chew et al. 2002; Cooperative Research Center for Catchment Hydrology, 2002)[5].

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5 While the model has become the industry standard and adopted by many State and Federal agencies, judging the accuracy and efficacy of the model is beyond the scope of this study.

In this case study the focus was on the sediment released from the Somerset Stanley Catchment (see Map 1). The Somerset Stanley Catchment is the main catchment for Wivenhoe dam, which is the main storage for Brisbane's water supply. Water from the dam is released and extracted 70 km downstream at the Mt Crosby Treatment Plant where it is treated to a potable standard and piped to Brisbane households and industry.

Data Generation

This catchment consists of eleven sub-catchments and in each there are opportunities to establish riparian buffer zones along the banks of the rivers and streams that flow through them. EMSS has up to five types of streams in each sub-catchment, from major rivers to ephemeral streams. For each there is a length of riparian land. Within EMSS it is possible to set a Sediment Loading Threshold Rate (SLTR) expressed as tons/km/day for each of the stream types in each of the sub-catchments. In this study the SLTR for the five stream types was set at 1, 0.8, 0.6, 0.4 and 0.2 respectively. The notion is that level 1 streams (large rivers) will have a higher load rate than smaller streams.

Simulations in EMSS were run and data captured for each stream type in each sub-catchment to end of catchment loads[6]. EMSS has two riparian treatments levels, superior and standard. The modeling used superior riparian buffer management which results in a one-ton per km per day sediment loading rate at sill (compared to a 0.1 loading for standard riparian buffer management). The catchment, consisting of 11 sub-catchments is in the upper northern section of the Brisbane Valley. The Stanley River sub-catchment was seen as a major player in the system due to its size. In order to avoid confounding the results due to market concentration[7], the catchment was split in two and Upper Lake Somerset sub-catchment was combined with the Lake Somerset and surrounds sub-catchment. Simulations were run for each type of stream in each of the 11 sub-

6 As discussed previously, EMSS treats riparian total suspended solid loads at a block conceptual sub-catchment level. Development of the model to site-specific contributions is underway and expected to overcome many of the problems associated with the management of non-point pollution of this nature.

7 In order to avoid complications arising from market thinness and power in CO2 markets highlighted by Liski (2001), larger sub-catchments were split and given to two players.

catchments. The cost of riparian buffer per kilometer was assumed constant throughout the catchment at $A475[8]. The simulated load reductions were used to estimate unique cost functions per unit of sediment reduction for each stream.

Experimental design

Three experimental sessions of ten-repeated trade rounds were conducted under first price and second price closed call auction structures and cap and trade. Each session used eleven students (player 1 to player 11), each representing one trading units for each sub-catchment in the Somerset Stanley Catchment.

The EMSS modeled estimate of the amount of total suspended solids (TSS) exiting the catchment is 73,000 tons per day. The experiment assumed a target reduction of 10,000 tons per day. Appendix A.1 gives a summary of the length of streams in each sub-catchment (for stream orders 1 to 5), sediment loads given riparian zones and linear models based on percentage and absolute reductions of TSS in the system for each of the players. A relative cap and trade policy was explored in which each player had a specific emission target. In this experiment each player was given a target production level to represent riparian buffer management and a cost structure for up to five different types of units representing the five different types of streams in each sub-catchment. Figure 2 shows Player 1’s production and income table screens populated with EMSS generated data for sub-catchment 1 (Kilcoy Creek 1).

Each session took approximately 2 hours to complete the instructions, quiz and ten-repeated trade periods. Software and information trials were conducted during early 2003. The six sessions were conducted during mid 2003 at the Griffith University Experimental Laboratory, Brisbane. The experiments used students recruited from across the University. The laboratory advertises across the University for students to participate. Advertising available sessions and student recruitment occurs through designated

8 Argent and Mitchell (1998) and McGuckian (1996) as reported in Cason et al. (2002) estimate the cost of installing filter/buffer zones at between $15 and $65 ha/yr. The median translates to an average estimate of $475 km/yr.

websites[9]. Students registered expressions of interest and the system selected them on the basis of producing unique sets for each session.

On arrival, students signed-in and were allocated a player number at random. Once all the students arrived they were directed to a set of PowerPoint instructions, which was followed by a quiz consisting of a set of multiple-choice questions. Successfully completing all the questions gave the participants their password to enter the session and a hotlink to the session where they logon and acquire their production characteristics[10]. Students were paid $A10 turn-up fee and additional payments according to their ability to tender successfully to produce units. The environment captured the biophysical characteristics and in accordance with standard experiments practice stylized the situation into "production" and "units". The experiments were conducted using the experimental software system (TESS), an experimental economics software package developed at the Cooperative Research Center during the last five years. As mentioned earlier, the experimental computer package determined the first and second price and cap and trade outcomes and updated players' computer screens.

Potential buyers and sellers lodged bids and asks during a prescribed time frame of 90 seconds and after which the bids and asks were ordered and the pool price determined. The sell asks were ordered from the lowest to highest price and the buy bids were ordered from the highest to lowest price. Buy bids were filled, highest bid price downwards from the lowest sell ask price upwards until the market cleared. In the case of the tender only the government entered a buy bid. In the cap and trade the players could chose to enter a bid or ask according to their circumstances. In the cap and trade treatment, the package clears the market and determines individual production levels to ensure that individual targets (and associated units sold) are met. During the experiments there was no opportunity for the participants to communicate.

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9 http://www.economicexperiments.com

10 Copies of the instructions and quiz are available from the author.

Results

Bringing the data into the laboratory provides an opportunity to compare the performance of the cap and trade market and first and second price tender systems under controlled conditions. Calibration of the model using the Somerset Stanley Catchment EMSS run data produced the supply and demand curves shown in Figure 3, given a reduction target of 10,000 tons per day. The following sections will discuss and compare the efficiency of the tenders in terms of minimizing the cost of pollution reduction, market clearing prices and production levels.

First and second price tenders

Tables 2 and 3 present the modeled cost and the round and aggregate costs arising from the first and second price tender sessions. The modeled cost of reducing TSS by was estimated to be $49.92 per ton to achieve a reduction of 10,000 tons.

In the first price closed call tender sessions less quantity was offered than modeled, resulting is a decrease in supply and higher realized prices. Figure 4 shows the supply curve for session 1 and round 1 that typifies the situation. Supply has shifted to the left of modeled supply resulting in an increase in price from $49.92 to $80 per ton. As a result, in all sessions and on average the aggregate costs were greater than the expected modeled cost (session 1, $t = 6.979$; session 2, $t = 9.362$; session 3, $t = 9.514$; average, $t = 15.169$; $p < 0.01$ in all cases), and at times up to twice the EMSS data generated cost. The modeled cost of $449,260 was exceeded by more than $500,000 in 17 out of the 30 rounds across the three sessions, as shown in Table 2. Figure 5 shows graphically the first price closed call tender prices through time. With the exception of session 3, there was little sign of convergence to competitive equilibrium. Even in session 3 convergence only began to appear in the latter rounds 7-10, suggesting that the strategy of restricted supply was sustainable through time.

One possible explanation is that players took on a tactically concerted action to restrict supply in the hope of realizing higher prices in the inelastic section of the supply function. Recent studies using experiments have shown that uniform pricing rules contrary to theoretical predictions, might not lead to superior market outcomes particularly in the case of environmental auctions (see for example Latacz-Lohmann and Van der Hamsvoost 1997; Cason *et al.*, 2002 and Stoneham *et al*., 2003). This actions of players observed in this study, however, was not in all the players' best interests and neither side payments nor communication were possible. Yet, supply was restricted in almost all rounds and experimental sessions of the first price treatment. A likely cause could lie in the thinness of these types of markets, leading to questions for further research. In a stylized setting the inelastic characteristics of the supply curve, restriction of supply and resulting increased government cost of the tender would not have been realized.

In a second price cost call tender there is no incentive to increase offer price above the cost of production, based on the writings of Vickrey (1961). In contrast to the first price closed call tender results, beyond the fifth round there was no statistical differences between the modeled price and that observed in the second price experimental sessions ($t = 0.368$, $p > 0.05$) as shown in Figure 6. Nevertheless, the associated aggregate costs in session 1 and averages presented in Table 3 were still higher than modeled ($t = - 2.33$, $p < 0.05$).

Cap and Trade

The third experimental treatment involved the implementation of a cap and trade regime. The players were able to make buy or sell offers to a closed call auction. Figure 7 shows the estimated supply and demand curves resulting from the first experimental cap and trade session, with a competitive equilibrium of $49. Figure 8 shows the bids and asks lodged in the three cap and trade sessions. The bids and asks the three sessions showed signs of converge around rounds 5 and 6 with increasing variance of bids following. All three sessions showed signs of outlying bid strategies. In contrast, the ask prices showed clear convergence in the first session, which was not replicated as strongly in the second or third sessions.

Figure 9 shows the levels of price convergence in each of the cap and trade sessions. Sessions 2 and 3 showed strong price convergence to that modeled throughout the ten repeated trade periods. Session 1, while beginning with a low market price converged quickly towards the competitive equilibrium. Optimal and realized production levels are shown in Table 4. Players 2, 4,7 and 8 established riparian buffer zones and players 1, 5, 9, 10 and 11 purchased credits to achieve the least cost production of the sediment reduction target. Through the repeated market experiments production in each session moved to those players with the lower marginal costs of production as those with higher marginal cost purchased credits rather than installing buffer zones. In comparison the average cost of reduction under the second price tender was significantly lower than the cost under the uniform tender system ($t = -14.474$, $p < 0.01$).

Regulation

Figure 10 shows the regulatory supply function for each participant meeting a proportion reduction target. Based on the modeled data the difference between the regulatory and tender instruments (A-X), where A = {O,P*,E} and X = (E,S^1,B), is positive. The modeled cost of purchasing 10,000 tons of total suspended solids through a tender process {O, P*, B, Q} is A$499,260. The modeled cost to landholders, the area {S^1, O, Qd}, is A$359,360. The difference between a regulatory and tender system (A-X), where A = {O,P*,E} and X = (E,S^1,B), is therefore A$129,900. In other words, in this example, based on EMSS run data, the estimated cost to landholders of meeting the regulatory requirements is less than the cost to the authority of purchasing through either of the tendering processes. The difference between the cost of regulation and the tender options is even greater when compared on the basis of the experimental results, suggesting that regulation in this instance will meet the target at least cost. The choice of policy instrument is often not based on cost alone. It is also based on other factors, such as equity and the burden on responsibility to account for past land use decisions.

Conclusion

This paper evaluated policy instruments and trading market structures for sediment runoff in the Brisbane catchment of Australia using an integrated experimental/biophysical model. The method of analysis integrated an environmental management support system (EMSS), developed for modeling sediment runoff in catchments with an experimental economic environment designed to explore resource economic issues and policy options under laboratory conditions. To demonstrate application, the model and experimental methods were applied to a case study involving the management of total suspended solids exiting a catchment.

As a proof of concept, the integration of biophysical modeling and experimental economic methods is shown to produce insights beyond those achievable using more conventional economic analysis. It opens new doors for analyzing policy options where there are important behavioral, biophysical and economic linkages. In the case study it was found that being able to observe behavior, rather than assuming economic optimizing agents, allowed for more detailed analysis of the differences between cap and trade and uniform tendering, which in theory should be equally efficient policy instruments. Cap and trade was found to be superior to the uniform tendering system.

The modeling found that (a) the cost of meeting the regulatory requirement is less than either a first or second price auction, (b) in a first price closed call tender sessions there was evidence of strategic behavior to restrict supply and produce above competitive prices and relatively low rates of convergence, (c) in the second price closed call tender sessions, while the aggregate cost was greater than modeled, prices converged to the equilibrium after 5 periods and (d) the cap and trade produced high levels of convergence and production, which moved towards minimizing the cost of achieving the cap reduction level. Based on EMSS run data, the estimated cost to landholders of meeting the regulatory requirements is less than the cost to the authority of purchasing through either of the tendering processes.

The policy implications of these findings are dependent on the integrated use of ecological and economic modeling under laboratory conditions, the results of which may not have been as transparent using stylized data. The results suggest that further applied work of this nature is important.

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Map 1. Somerset Stanley Catchment in EMSS

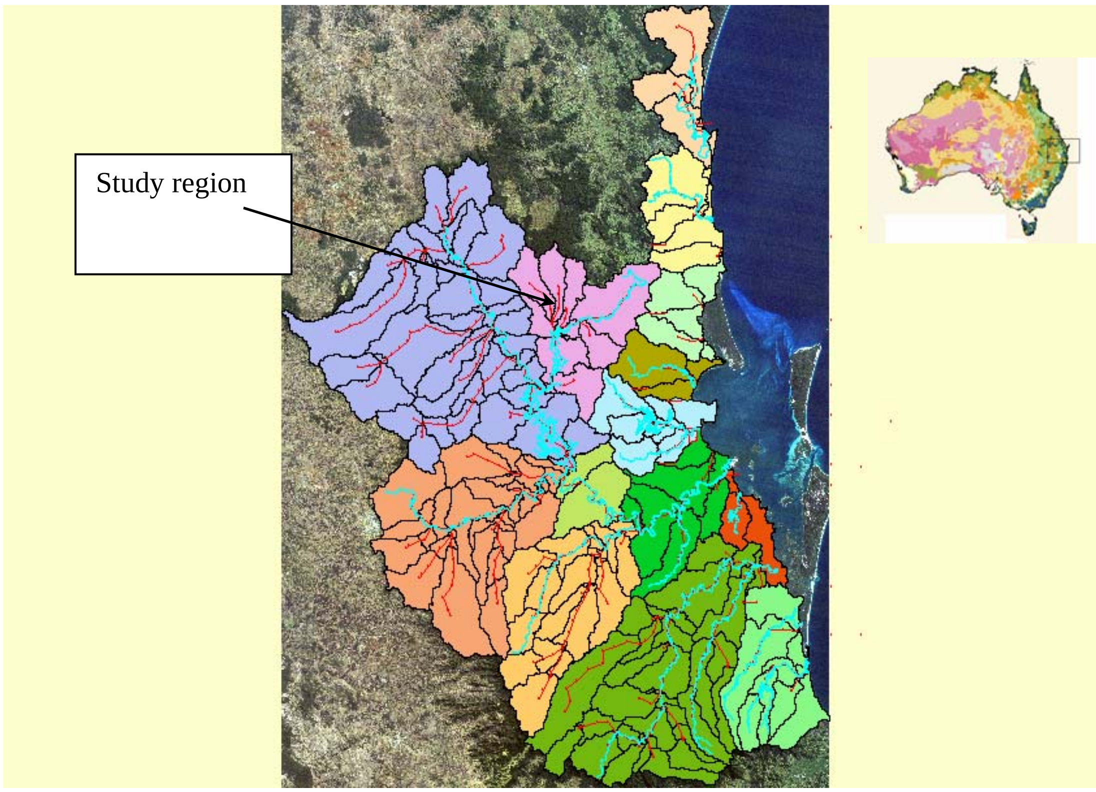

Figure 1. Hypothesized comparison of command and control and first price tendering.

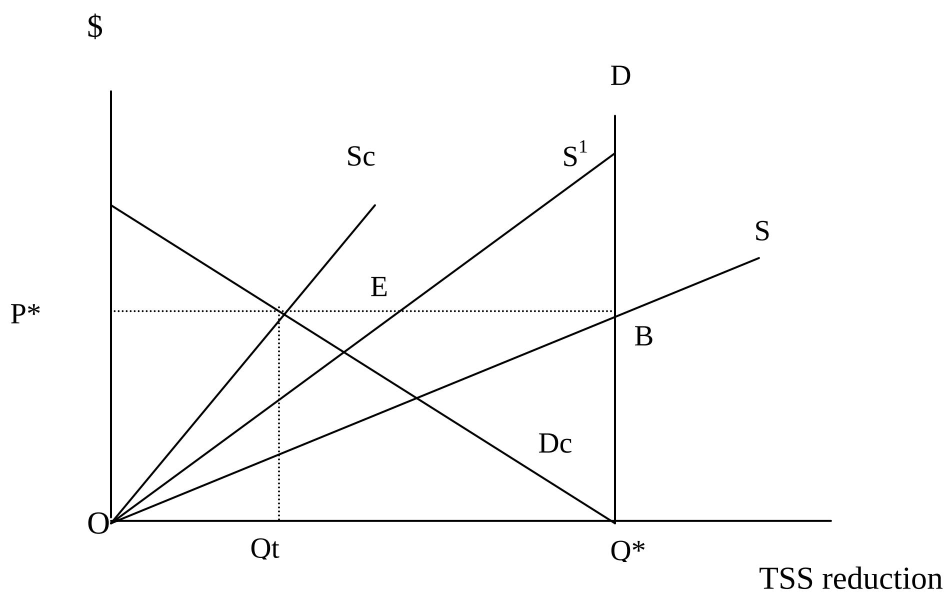

Figure 2. Cap and Trade experiment: Player 1 Screen

Production Table Session: 25 User: 1

Production target 594 units

Total traders income $10

Cost of production unit #1 $49.93	Max number of units #1 373
Cost of production unit #2 $53.29	Max number of units #2 211
Cost of production unit #3 $57.14	Max number of units #3 237
Cost of production unit #4 $0	Max number of units #4 0
Cost of production unit #5 $0	Max number of units #5 0

Trade period	Unit #1	Unit #2	Unit #3	Unit #4	Unit #5	Total production	Qty Sold	Qty bought
1	0	0	0	0	0	0	0	0

Cost of Production Table

Trade Period	Total Production	Total Cost of Production	Market Price	Cost of Units bought	Revenue from Sale	Total Cost	Traders Income

Figure 3. Calibration of the model to the Somerset Stanley Catchment

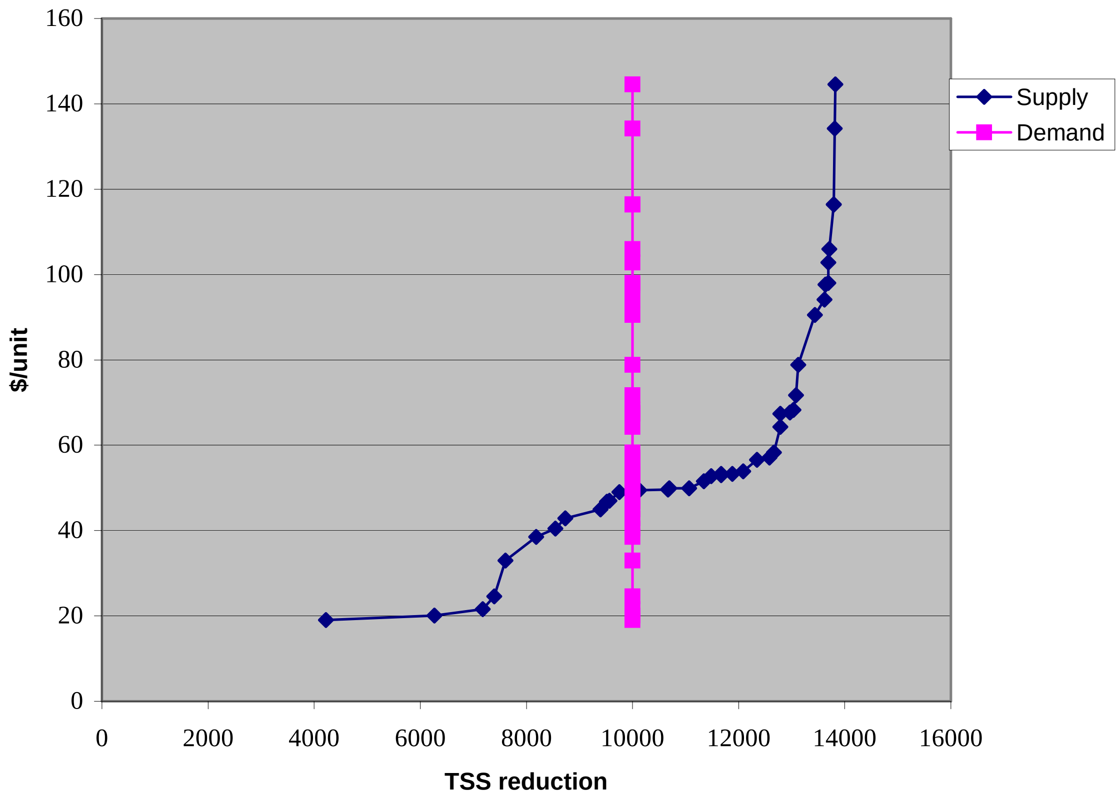

Figure 4. First price tender: session 1 round 1 supply

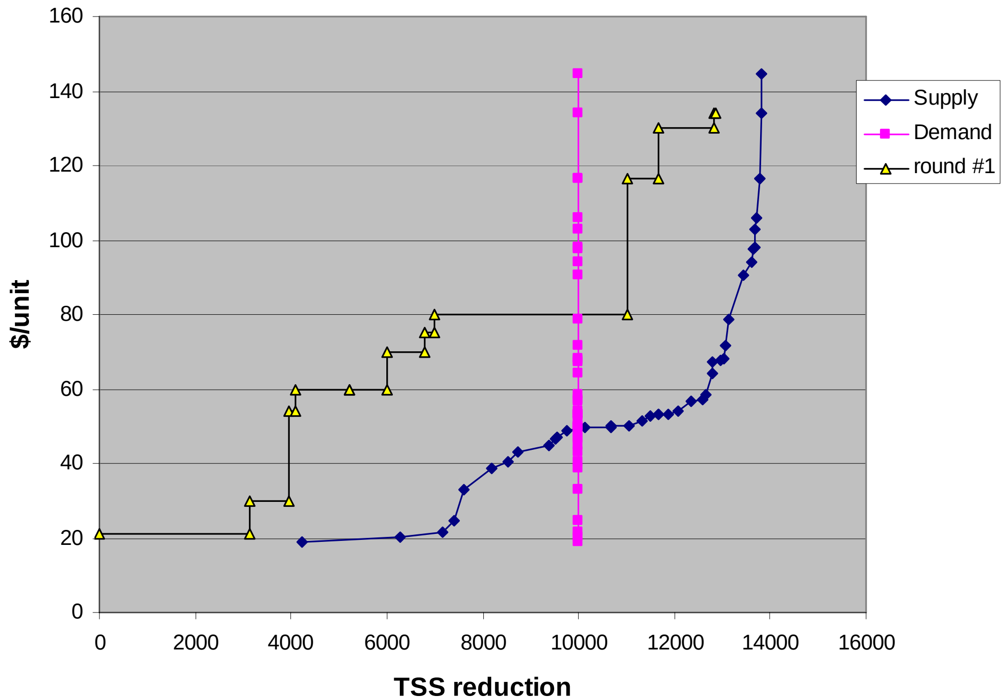

Figure 5. First price closed call tender prices through time

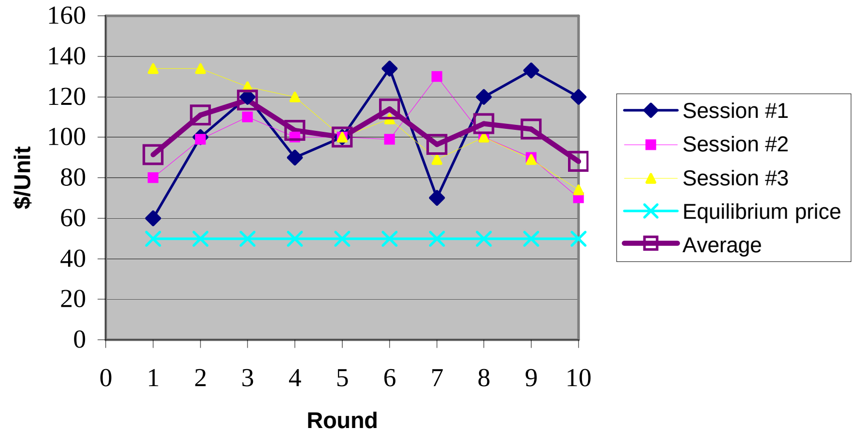

Figure 6. Second price closed call tender prices through time

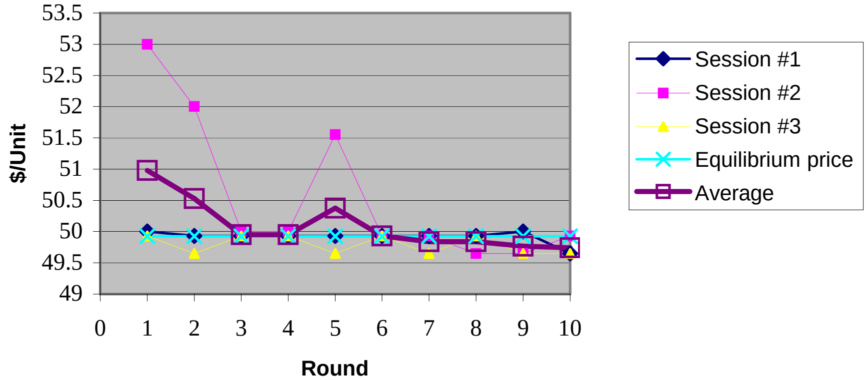

Figure 7. Cap and trade market

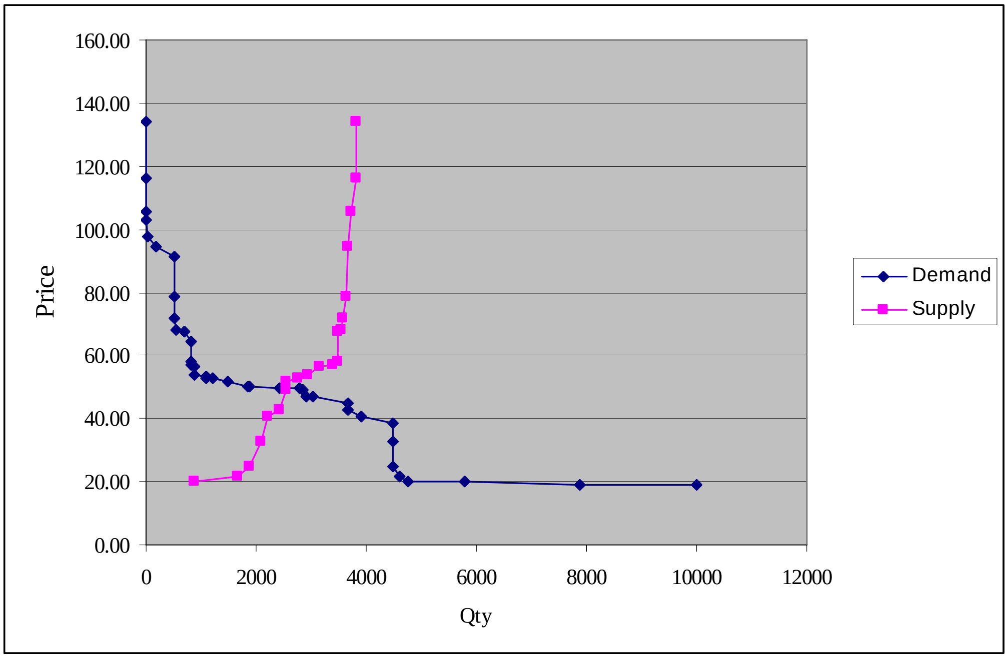

Figure 8. Bids and asks in cap and trade experiment

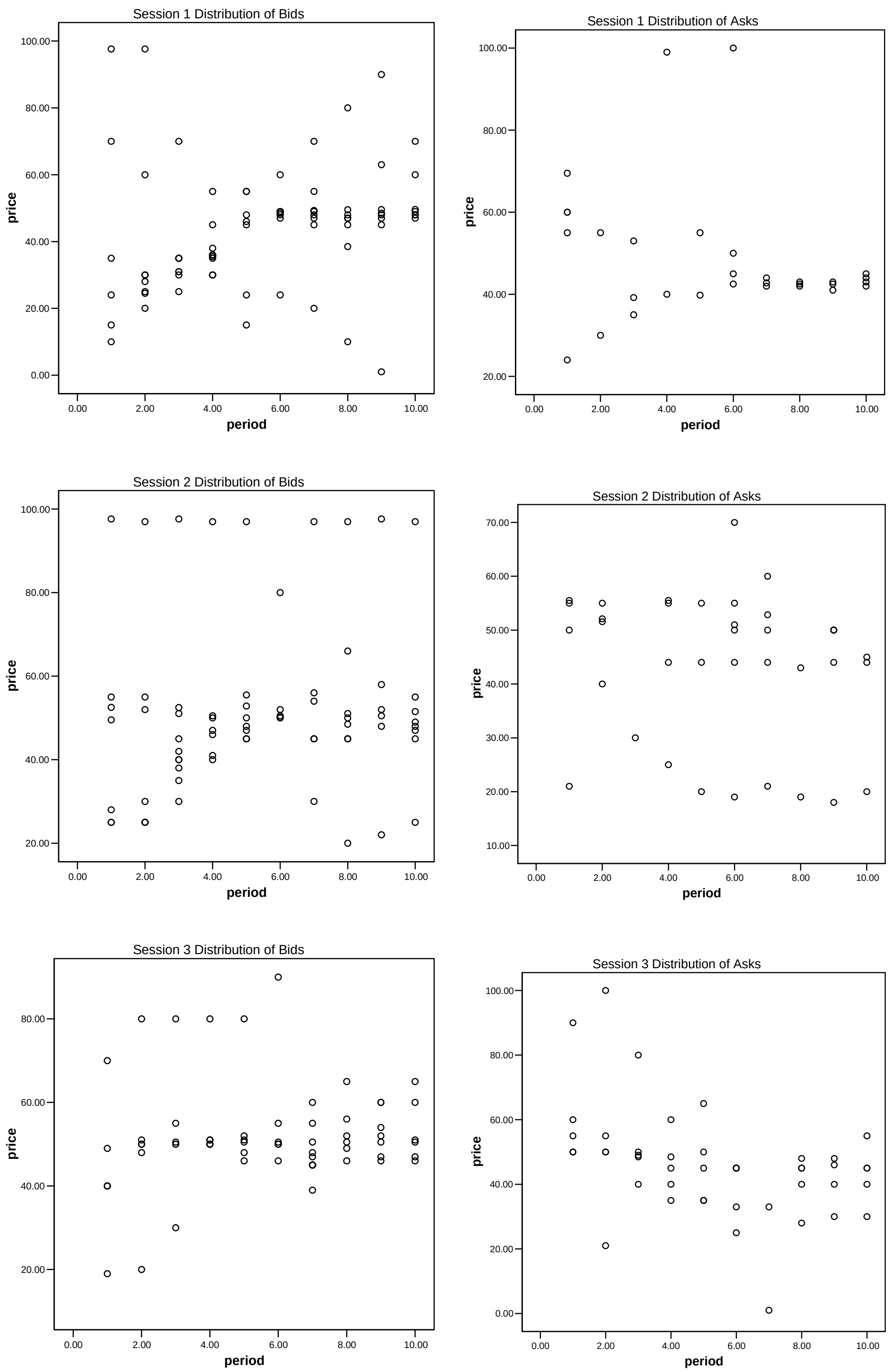

Figure 9. Convergence of cap and trade market prices

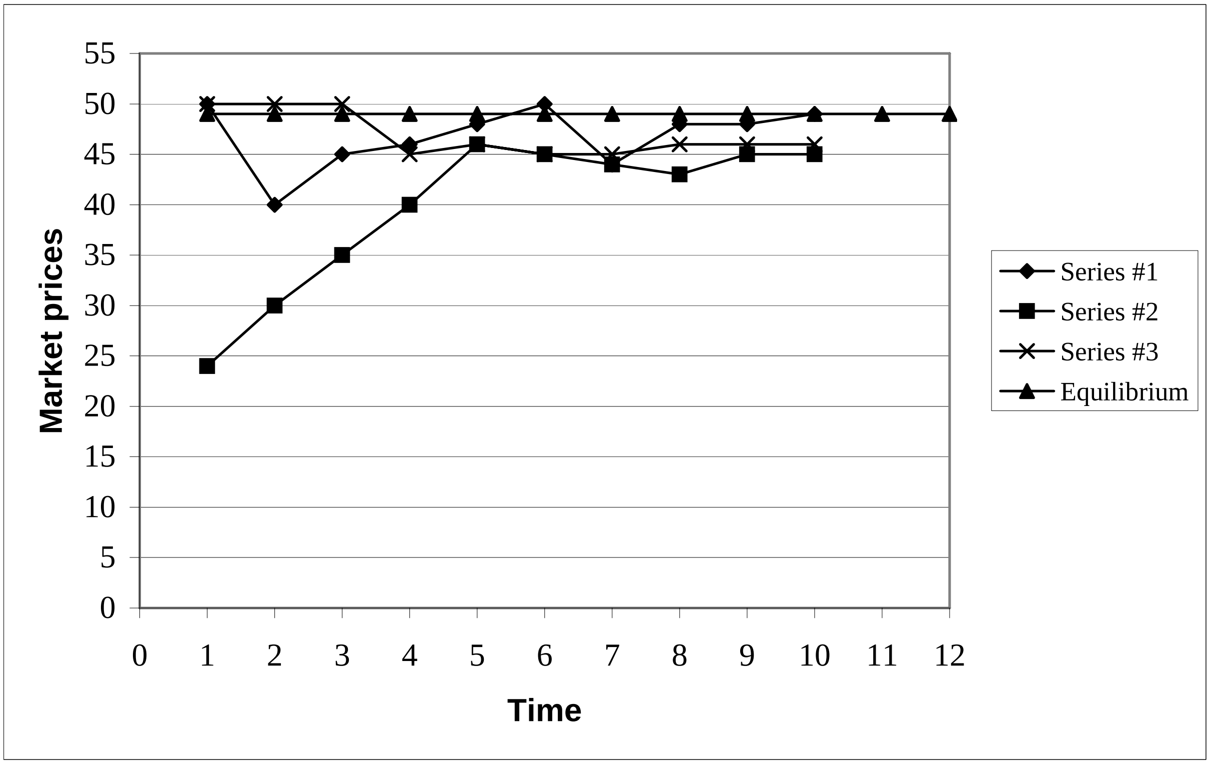

Figure 10. Cost of TSS reduction in the Somerset Stanley Catchment

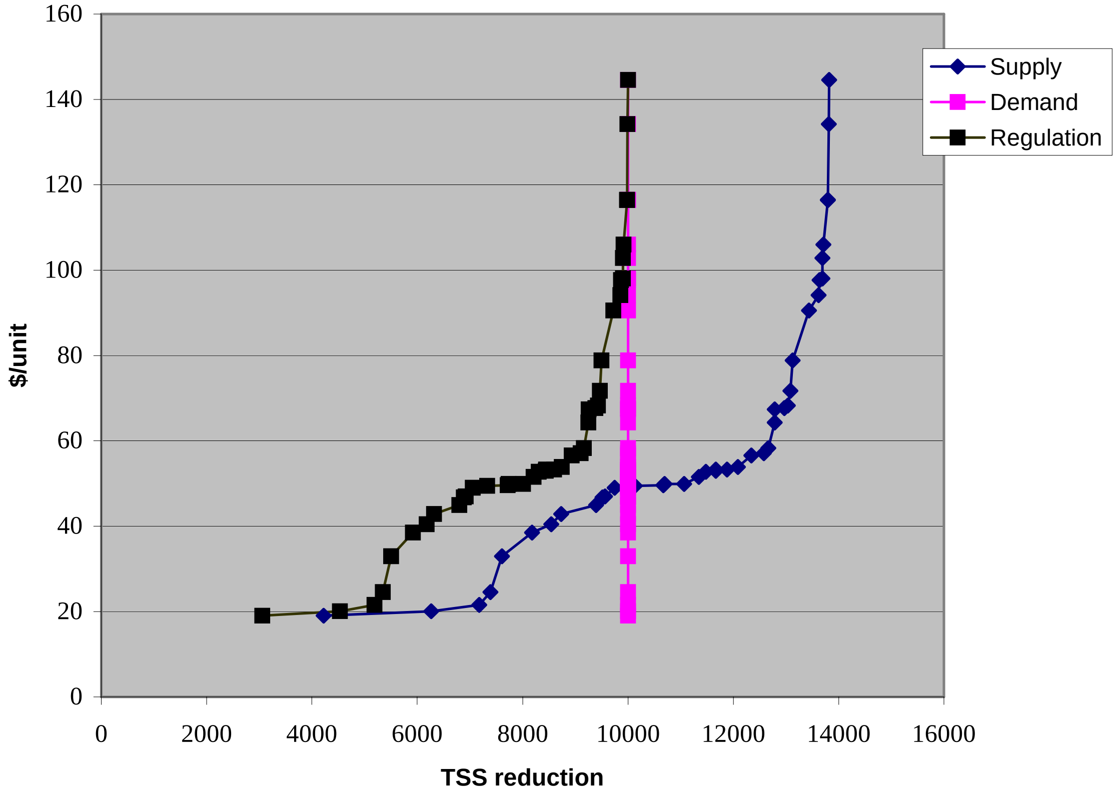

Table 1. Player Characteristics

		Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Total	Target
Player 1	Cost	49.93	53.29	57.14	0.00	0.00		
	Units	373.00	211.00	237.00	0.00	0.00	821	594
Player 2	Cost	44.98	46.75	49.00	53.01	0.00		
	Units	662.00	119.00	184.00	187.00	0.00	1152	834
Player 3	Cost	49.48	52.78	56.55	0.00	0.00		
	Units	378.00	138.00	255.00	0.00	0.00	771	558
Player 4	Cost	19.01	20.11	21.57	24.58	32.97		
	Units	2111.00	1021.00	911.00	216.00	216.00	4475	3238
Player 5	Cost	64.27	67.66	71.75	78.87	0.00		
	Units	120.00	181.00	46.00	45.00	0.00	392	284
Player 6	Cost	46.96	49.92	53.28	68.30	0.00		
	Units	51.00	24.00	1.00	67.00	0.00	143	103
Player 7	Cost	38.49	40.45	42.87	0.00	0.00		
	Units	575.00	364.00	188.00	0.00	0.00	1127	815
Player 8	Cost	19.01	20.11	0.00	0.00	0.00		
	Units	2111.00	1021.00	0.00	0.00	0.00	3132	2266
Player 9	Cost	91.31	94.27	105.81	102.82	116.35		
	Units	328.00	184.00	66.00	0.00	87.00	665	481
Player 10	Cost	97.65	134.19	0.00	0.00	0.00		
	Units	16.00	14.00	0.00	0.00	0.00	30	22
Player 11	Cost	49.65	51.55	53.89	58.31	67.38		
	Units	541.00	277.00	207.00	87.00	1.00	1113	805
						Totals	13821	10000

Table 2. Cost of sediment reduction: First price closed call tender

Round	Modeled cost	Session #1	Session #2	Session #3	Average cost of reduction
1	499260	600000	800000	882122*	800000^
2	499260	1000000	990000	1231594*	995000^
3	499260	1200000	1100000	1250000	1183333
4	499260	900000	1000000	1200000	1033333
5	499260	1000000	1000000	1000000	1000000
6	499260	997496*	990000	1090000	1040000^
7	499260	700000	1300000	890000	963333
8	499260	1200000	1000000	1000000	1066667
9	499260	1330000	900000	890000	1040000
10	499260	1200000	700000	740000	880000

*less than 10000 units offered for sale.^ averaged only of those where 10000 units traded.

Table 3. Cost of sediment reduction: Second price closed call tender

Round	Modeled cost	Session #1	Session #2	Session #3	Average cost of reduction
1	499260	496050	564344	507338	522577
2	499260	504043	553384	483988	513805
3	499260	520220	498000	505141	507787
4	499260	512132	505450	508237	508606
5	499260	520719	526170	494911	513933
6	499260	520719	506340	519921	515660
7	499260	520719	516326	490442	509162
8	499260	520719	487463	473885	494022
9	499260	489050	493421	490442	490971
10	499260	490045	502445	490095	494195

Table 4. Production levels in cap and trade experiments

Optimal:

p1	p2	p3	p4	p5	p6	p7	p8	p9	P10	p11	sum
0	1152	65	4475	0	51	1126	3131	0	0	0	10000

Experimental results:

Session #1

	P1	p2	p3	p4	p5	p6	p7	p8	p9	p10	p11	sum
1	594	0	558	4475	203	103	815	2266	181	0	805	10000
2	194	560	378	4475	284	103	815	2266	120	0	805	10000
3	194	834	558	4475	284	103	400	2266	81	0	805	10000
4	594	834	558	3444	284	103	815	2266	297	0	805	10000
5	285	834	558	3238	0	103	1015	3131	31	0	805	10000
6	94	834	378	4259	0	3	815	3131	481	0	5	10000
7	94	834	378	4298	0	3	1126	3131	131	0	5	10000
8	0	834	158	4475	0	3	1126	2918	481	0	5	10000
9	266	834	0	4475	0	3	1126	3131	160	0	5	10000
10	0	1079	0	4475	0	3	1126	3131	181	0	5	10000

Session #2

	p1	p2	p3	p4	p5	p6	p7	p8	p9	p10	p11	sum
1	594	834	0	4438	84	103	815	2646	481	0	5	10000
2	594	834	558	4025	0	103	815	2266	0	0	805	10000
3	594	834	0	4438	284	103	815	2266	0	0	666	10000
4	563	834	0	4438	34	103	1126	2266	481	0	155	10000
5	424	834	0	4438	4	103	1126	2266	0	0	805	10000
6	0	834	0	4438	4	103	1126	2690	0	0	805	10000
7	594	834	558	4438	0	0	1105	2266	0	0	205	10000
8	594	834	0	4475	4	103	1126	2266	0	0	598	10000
9	404	834	0	4438	24	103	1126	2266	0	0	805	10000
10	594	834	0	4475	384	103	1126	2266	0	0	218	10000

Session #3

	p1	p2	p3	p4	p5	p6	p7	p8	p9	p10	p11	sum
1	594	834	558	3408	284	103	1126	2266	0	22	805	10000
2	0	1152	434	3238	0	103	815	3131	0	22	1105	10000
3	553	1152	0	3238	284	142	815	3131	0	30	655	10000
4	0	834	58	4475	0	103	1094	3131	0	0	305	10000
5	119	1152	0	4475	0	103	815	3131	0	0	205	10000
6	0	971	0	4475	0	103	815	3131	0	0	505	10000
7	446	834	0	4475	0	103	815	3122	0	0	205	10000
8	187	834	0	4475	0	142	1126	3131	0	0	105	10000
9	422	1152	0	4475	0	0	815	3131	0	0	5	10000
10	116	1152	0	4475	0	0	1126	3131	0	0	0	10000

Appendix A.1 Load levels for the sub-catchments of the Somerset Stanley Catchment

Stream order (lengths in km)														
	Load	1	2	3	4	5	Sum	A	B (x = %)	B (x=ha)	$/unit	Max units	Target	Target cost
p1	72,564.67	39.245	23.661	28.476			91.382	73385.66	-8.21	-8.98	-5.29	-820.99	-399.398	2111.662
	73,012.30	39.245					39.245	73385.66	-3.73	-9.51	-4.99	-373.35	-181.631	906.8764
	73,174.76		23.661				23.661	73385.66	-2.11	-8.91	-5.33	-210.90	-102.6	546.7602
	73,148.93			28.476			28.476	73385.66	-2.37	-8.31	-5.71	-236.73	-115.167	658.0256
p2	72234.42	62.679	11.695	18.962	20.837		114.173	73385.66	-11.51	-10.08	-4.71	-1,151.24	-560.06	2638.318
	72723.77	62.679					62.679	73385.66	-6.62	-10.56	-4.50	-661.89	-321.999	1448.391
	73266.84		11.695				11.695	73385.66	-1.19	-10.16	-4.68	-118.82	-57.8042	270.249
	73201.85			18.962			18.962	73385.66	-1.84	-9.69	-4.90	-183.80	-89.4176	438.1753
	73198.93				20.837		20.837	73385.66	-1.87	-8.96	-5.30	-186.72	-90.8381	481.503
p3	72614.21	39.393	15.387	30.341			85.121	73385.66	-7.71	-9.06	-5.24	-771.45	-375.299	1966.983
	73007.52	39.393					39.393	73385.66	-3.78	-9.60	-4.95	-378.14	-183.959	910.2964
	73247.19		15.387				15.387	73385.66	-1.38	-9.00	-5.28	-138.47	-67.3637	355.564
	73130.82			30.341			30.341	73385.66	-2.55	-8.40	-5.66	-254.84	-123.976	701.1221
p4	65778.72	168.947	86.472	41.351	11.178	14.958	322.906	73385.66	-76.07	-23.56	-2.02	-7,606.93	-3700.66	7461.736
	69163.56	168.947					168.947	73385.66	-42.22	-24.99	-1.90	-4,222.10	-2053.99	3904.04
	71343.02		86.472				86.472	73385.66	-20.43	-23.62	-2.01	-2,042.64	-993.713	1998.202
	72474.95			41.351			41.351	73385.66	-9.11	-22.02	-2.16	-910.71	-443.046	955.5421
	73169.67				11.178		11.178	73385.66	-2.16	-19.32	-2.46	-215.98	-105.073	258.3021
	73170.15					14.958	14.958	73385.66	-2.16	-14.41	-3.30	-215.51	-104.842	345.6506
p5	72969.07	16.217	25.776	6.908	7.467		56.368	73385.66	-4.17	-7.39	-6.43	-416.59	-202.663	1302.556
	73265.8	16.217					16.217	73385.66	-1.20	-7.39	-6.43	-119.86	-58.3078	374.7437
	73204.71		25.776				25.776	73385.66	-1.81	-7.02	-6.77	-180.95	-88.0286	595.6338
	73339.93			6.908			6.908	73385.66	-0.46	-6.62	-7.18	-45.73	-22.2475	159.6306
	73340.69				7.467		7.467	73385.66	-0.45	-6.02	-7.89	-44.97	-21.8773	172.548
p6	73242.37	5.058	2.551	0.141		9.574	17.324	73385.66	-1.43	-8.27	-5.74	-143.28	-69.7056	400.3243
	73334.49	5.058					5.058	73385.66	-0.51	-10.12	-4.70	-51.17	-24.8915	116.8806
	73361.38		2.551				2.551	73385.66	-0.24	-9.52	-4.99	-24.28	-11.8094	58.9487
	73384.4			0.141			0.141	73385.66	-0.01	-8.91	-5.33	-1.26	-0.61151	3.258239
	73319.07					9.574	9.574	73385.66	-0.67	-6.95	-6.83	-66.59	-32.3927	221.2367

p7	72259.14	46.551	30.965	17.005			94.521	73385.66	-11.27	-11.92	-3.99	-1,126.51	-548.033	2184.198
	72811.13	46.551					46.551	73385.66	-5.75	-12.34	-3.85	-574.53	-279.499	1075.704
	73022.07		30.965				30.965	73385.66	-3.64	-11.74	-4.05	-363.59	-176.879	715.5416
	73197.26			17.005			17.005	73385.66	-1.88	-11.08	-4.29	-188.40	-91.6544	392.9528
p8	73357.72	3.573		0.23		3.344	7.147	73385.66	-0.28	-3.91	-12.15	-27.94	-13.5924	165.1534
	73369.64	3.573					3.573	73385.66	-0.16	-4.48	-10.60	-16.01	-7.79058	82.56516
	73384.72			0.23			0.23	73385.66	-0.01	-4.08	-11.65	-0.94	-0.45632	5.314858
	73374.67					3.344	3.344	73385.66	-0.11	-3.29	-14.46	-10.99	-5.34502	77.27341
p9	72748.42	59.498	36.238	11.312	0.071	21.357	128.476	73385.66	-6.37	-4.96	-9.58	-637.24	-310.007	2968.833
	73073.58	59.498					59.498	73385.66	-3.12	-5.25	-9.06	-312.08	-151.822	1374.884
	73202.83		36.238				36.238	73385.66	-1.83	-5.05	-9.41	-182.83	-88.9427	837.3905
	73330.85			11.312			11.312	73385.66	-0.55	-4.85	-9.80	-54.81	-26.6633	261.3986
	73385.33				0.071		0.071	73385.66	0.00	-4.62	-10.28	-0.33	-0.15957	1.640673
	73298.47					21.357	21.357	73385.66	-0.87	-4.08	-11.63	-87.19	-42.4177	493.5192
p10	73355.89	3.273				3.911	7.184	73385.66	-0.30	-4.14	-11.46	-29.77	-14.4807	166.0084
	73369.74	3.273					3.273	73385.66	-0.16	-4.86	-9.76	-15.92	-7.74534	75.63273
	73371.81					3.911	3.911	73385.66	-0.14	-3.54	-13.42	-13.84	-6.73491	90.37569
p11	72270.12	56.535	30.083	23.513	10.703	0.141	120.975	73385.66	-11.16	-9.22	-5.15	-1,115.54	-542.695	2795.5
	72844.75	56.535					56.535	73385.66	-5.41	-9.57	-4.96	-540.91	-263.143	1306.415
	73108.48		30.083				30.083	73385.66	-2.77	-9.21	-5.16	-277.18	-134.844	695.1603
	73178.42			23.513			23.513	73385.66	-2.07	-8.81	-5.39	-207.24	-100.819	543.3402
	73298.47				10.703		10.703	73385.66	-0.87	-8.15	-5.83	-87.19	-42.4177	247.3257
	73384.66					0.141	0.141	73385.66	-0.01	-7.05	-6.74	-0.99	-0.48357	3.258239