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INCREMENTAL AND AVERAGE CONTROL COSTS
IN A MODEL OF WATER QUALITY TRADING
WITH DISCRETE ABATEMENT UNITS

by

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Arthur J. Caplan

ABSTRACT

This paper answers three questions related to the discrete nature of pollution abatement: (i) does a source's incremental control cost necessarily exceed its average control cost, (ii) is incremental control cost a better approximation of a source's willingness to pay for abatement credits than average control cost, and (iii) exactly how do discrete and continuous abatement markets differ from one another? We find that the answer to the first two questions are both "no," suggesting that the U.S. Environmental Protection Agency needs to refine its reliance on incremental control cost as the sole measure upon which to assess the financial feasibility of water quality trading. In answer to the third question, the equilibrium outcome for a discrete abatement market can be solved through a process of implicit sequential consistency. For the general case where the sources' average control cost curves "cross," the equilibrium is inherently sensitive to the initial allocation of abatement responsibilities.

Key words: discrete abatement; incremental control cost; average control cost; willingness to pay.

INCREMENTAL AND AVERAGE CONTROL COSTS IN A MODEL OF WATER QUALITY TRADING WITH DISCRETE ABATEMENT UNITS¹

1. Introduction

According to the United States Environmental Protection Agency (EPA), the first step in assessing the financial attractiveness of water quality trading (WQT) in any given watershed is to calculate dischargers' incremental costs of control (IC) [EPA, 2004]. This is because IC, defined as the average cost of control *of the incremental reduction required for a discharger to achieve its target load*, represents a better approximation of a discharger's, or source's, upper-bound willingness to pay (WTP) for pollutant reduction credits.² The logic behind this statement is that each control "step," once implemented, is a sunk cost. If a source had previously installed a control technology, its expense should not influence the next step decision for pollutant control. As the EPA puts it, "if a source implements step 1 control technology and is now looking toward a step 2 option, the IC considers only the cost of the second step of control technology; the previous step cost is sunk and is no longer part of the decision making analysis" [EPA, 2004, page 34].

This paper takes a close look at IC in the context of discrete or discontinuous abatement. In particular, the relationships between IC and both the traditional measure of average cost of control (AC) and WTP is examined. Three questions about these relationships are answered. First, is IC necessarily larger than AC, i.e., is it necessarily a better approximation than AC of

¹The author acknowledges the generous financial support provided by the U.S. Environmental Protection Agency through its Watershed Initiative Grant Program.

²Subtracting the source's target load from its current load results in the source's total reduction needed to comply with its Total Maximum Daily Load (TMDL) abatement allocation.

upper-bound WTP? Second, is IC a better approximation than AC of WTP itself? Third, how does the process of equilibrium determination in a discrete abatement market compare with equilibrium determination in a continuous abatement market? These questions are important because little is presently known about IC and how it compares with AC and WTP. Indeed, if the financial attractiveness of WQT is to be based on IC, rather than AC, it seems imperative to understand exactly how IC and AC differ. Further, while the pollution trading literature has addressed a wide variety of issues that relate to the feasibility of market establishment, the issue of discreteness in abatement units has yet to be considered in any theoretical way.³

In answer to the first question, we find circumstances under which IC may not exceed AC. In particular, when the initial technology step (step1) is *capable* of meeting or exceeding the source's target load, IC is at least as large as its corresponding AC. However, when technology step 1 is *incapable* of achieving the source's target load, and the source has not previously implemented its step 1 technology, IC exceeds its corresponding AC only when the efficiency of its step 1 technology is large enough relative to its subsequent technology steps. This result is explained in Section 4.

In answer to the second question, AC is indeed a better approximation than IC of a source's WTP. This is because in the presence of discrete abatement units, AC is identically equal to traditionally defined marginal control cost (MC). Since in general any source is capable of being a buyer or a seller of pollution reduction credits depending upon its choice of how much

³Prominent issues addressed in the pollution trading literature include the identification of optimal trading ratios for non-point sources [Shortle, 1987 and 1990; Malik et al., 1993; Horan and Shortle, 2005; Farrow et al., 2005; Hung and Shaw, 2005], empirical/numerical estimates of cost savings with pollution trading [Fullerton et al., 1997; Bernstein et al., 1994; Hahn and May, 1994; Coggins and Smith, 1993; Bohi and Burtraw, 1992; Atkinson and Tietenberg, 1991; Hahn and Hester, 1989a and 1989b; Hahn, 1989], the roles of transaction costs [Winebrake et al., 1995; Stavins, 1995; Lund, 1993; GAO, 1994; Montero, 1997], market concentration/failure [Cason et al., 2003; Atkinson and Tietenberg, 2001; Misiolek and Elder, 1989; Hahn, 1984; O'Neil, 1983], market size [Atkinson and Morton, 2004], banking [Wen et al., 2005; Germain et al., 2004; Cronshaw and Kruse, 1996], noncompliance [Konishi, 2005; Keeler, 1991], moral hazard [Joskow and Schmalensee, 1986], and price uncertainty [Baldursson and von der Fehr, 2004; Rubin, 2001; Chao and Wilson, 1993].

to abate relative to its target load, its WTP is ultimately its MC. Thus, by a simple application of transitivity, a source's WTP equals its AC. Moreover, given that IC will not necessarily exceed AC, IC is also not necessarily the appropriate upper-bound WTP.

In answer to the third question, the process of equilibrium determination in a discrete abatement market is markedly different than the corresponding process in a continuous abatement market. The solution process for a discrete market requires "implicit sequential consistency" in any "move" away from the initial allocation of abatement responsibilities. As demonstrated graphically in Section 5, corner solutions (where one source is paid by the other to abate the entire aggregate amount to meet the sources' target loads) are likely even when the sources respective AC curves "cross."

Only two previous studies have addressed the issue of discrete abatement, both strictly in the context of numerical analysis and thus as a kind of epilogue to the main thrust of their analyses. Fullerton et al. [1997] find numerical evidence that in the presence of discrete abatement an electric utility's compliance choices (e.g., across options such as fuel switching, investment in abatement technology, and pollution trading) are highly sensitive to slight deviations in the Public Utility Commission's (PUC's) "symmetric regulatory treatment" of shareholder vs. ratepayer portions of the cost of sulfur dioxide permit purchases, the gain on permit sales, the extra cost of fuel, and the cost of abatement technology. For example, a 1% increase in the portion of permit costs shared by shareholders is enough to induce the shareholders to completely eschew the purchase of permits resulting in substantial increases in ratepayer expenditures on electricity. Thus, changes in PUC rules such as can apparently sensitize the equilibrium allocation of abatement to the initial allocation of abatement responsibility.

Montero [1997] similarly finds numerical evidence that in the presence of discrete abatement, transaction costs, and regulatory uncertainty, the equilibrium allocation of abatement across sources (and thus aggregate control costs and equilibrium credit price) is sensitive to the initial allocation of abatement requirements, even when marginal transaction and uncertainty costs are constant. As we show in Section 5, the equilibrium outcome with discrete abatement is sensitive to the initial allocation of abatement responsibilities even without accounting for the types of inefficiencies examined in Fullerton et al. [1997] and Montero [1997].

To establish a benchmark for our subsequent analysis, the next section presents the textbook example of pollution trading when abatement units are continuous. Section 3 examines the relationship between IC and AC in the context of a simple numerical example of a watershed. The purpose of this section is to demonstrate exactly how these cost measures are calculated. Section 4 provides a formal comparison of IC and AC, resulting in our first main finding—IC does not necessarily exceed AC and thus is not a universally better measure of upper-bound WTP. Section 5 recasts in discrete units the continuous-unit pollution-trading example depicted in Section 2. This section demonstrates how the process of implicit sequential consistency is used to determine an equilibrium trading outcome when the discontinuous AC curves cross, and explains our second main finding—the conditions under which the equilibrium allocation of abatement is sensitive to the initial allocation of abatement responsibilities. Section 6 concludes.

2. Water Quality Trading with Continuous Abatement Units

It is well-known that in the presence of continuous abatement units a competitive WQT market induces pollution sources to voluntarily choose the least-cost abatement allocation. This

result is perhaps most easily understood in a graphical framework, as depicted in Figure 1.⁴

[INSERT FIGURE 1 HERE]

Figure 1 shows the MCs for two sources (1 & 2), where the level of abatement for Source 1 (2) increases from 0 to 25 units going left to right (right to left). In this example, a total of 25 units of abatement across both sources are required by the regulatory authority; thus the horizontal axis depicts all possible allocations of the 25 required abatement units between the two sources. As depicted in the figure, Source 2 faces relatively higher control costs than Source 1 per unit reduction. Source 2 therefore has incentive to purchase abatement units from Source 1 whenever a quota established by the regulatory authority allocates anything greater than (less than) 10 (15) units of abatement to Source 2(1).

To see why a trade in Figure 1 is mutually beneficial, assume the regulatory agency determines that the two sources must clean up 12.5 units each, i.e., each source's initial abatement allocation is 12.5 units. At this allocation, total variable cost of control for Source 1 equals area A, while for Source 2 it equals area B + C + D. Therefore, for this allocation total variable cost across both sources equals A + B + C + D. An incentive to trade exists for the two sources at this allocation because the marginal cost of control for Source 2 (point *a*) is substantially higher than that for Source 1 (point *c*). Source 2 could therefore lower its control cost by paying Source 1 something less than *a* but greater than *c* to incrementally increase its abatement from 12.5 so that Source 2 can incrementally reduce its abatement from 12.5. In other words, point *a* represents Source 1's WTP for the first unit of reduction obtained from Source 2, and point *c* represents Source 2's minimum willingness to accept (WTA) payment from Source 1 for that unit.

⁴See Tietenberg (2006) and Kolstad (2000) for further details about this framework.

Continuing in this manner, until all gains from trade are exhausted, the least-cost solution is ultimately obtained where the marginal control costs for each source is equal. In Figure 1, this occurs at point *b*, where Source 1 cleans up 15 units and Source 2 ten units, leading to (minimized) total control costs of area $A + B + C$. In other words, unrestricted pollution trading naturally leads to the least-cost allocation of abatement across the two sources, and this solution is independent on the initial allocation of abatement responsibilities. What helps drive this result is the continuity of abatement, and thus the smoothly increasing MC curves, as well as the absence of inefficiencies such as transaction costs, regulatory uncertainty, and asymmetric regulatory treatment.

3. An Example of Incremental and Average Control Costs

As mentioned in Section 1, EPA (2004) argues that in the presence of discrete abatement (which typifies reality), IC is an appropriate estimate of MC when assessing the financial attractiveness of WQT, and therefore an approximation of a potential buyer's WTP for abatement credits (EPA, 2004). To see how IC is calculated, we present hypothetical cost-of-control and control-effectiveness data for total phosphorus (TP) in Table 1.

[INSERT TABLE 1 HERE]

To begin, note that the current loads, target loads, and total reductions needed for each respective source to comply with the watershed's TMDL for TP are provided in columns 2-4, which, as explained in EPA [2004], are (ideally) obtainable from the TMDL itself.⁵ Next, note that consecutive technology steps are assumed to exist for each source (except for Stinky's and Smelly's Cheese Factories, which have single technology steps). For point sources (PSs) such as WWTFs #1 and #2 and the two cheese factories, these steps are typically referred to as "tiers"

⁵These and all subsequent physical measurements are in lbs. per day.

[EPA, 2003]. For NPSs, such as Bob's Farm, these steps are different BMPs, e.g., conservation tillage, grass buffer strips, etc.

Each step is associated with incremental and cumulative reductions achieved (columns 5 and 6 in Table 1) and the incremental reduction needed for compliance with the TMDL (column 7), which is calculated as the difference between the TP reduction needed and the incremental reduction achieved. Surplus TP reductions, or credits, are then calculated in column 8 as the difference between cumulative reductions achieved and reductions needed (which is zero if the difference is negative). Total control cost in column 9 (which we henceforth denote as TC_j for $j = 1, \dots, m$ different possible technology steps) is next, reflecting the annualized fixed, operations, maintenance, and associated opportunity costs of implementing technology step j .⁶

Thus, considering Bob's Farm in Table 1, technology step 1 results in a reduction of 91 lbs. of TP per day at a TC_1 of \$49,823. This leaves 255 lbs. of TP (364 lbs.-91 lbs.) still needing to be reduced. Adding Step 2 technology at a TC_2 of \$464,444, results in an additional reduction of 623 lbs. of TP, or a cumulative reduction of 714 lbs. Therefore, with technology steps 1 and 2, Bob's Farm obtains 368 credits (714 lbs.-364 lbs.) for possible sale in a water quality trading market.

IC in column 10 is then calculated as TC_{j^*} divided by the incremental reductions needed for compliance, divided again by 365 (to normalize to a daily basis), where j^* represents the technology step at which the source comes into compliance with its TMDL abatement allocation. For example, Bob's Farm's IC of \$4.99 /lb./day is calculated as $(\$464,444/255 \text{ lbs.})/365 \text{ days}$. As defined in EPA (2004), IC therefore represents the cost per unit reduction that Bob's Farm must incur to ultimately (or incrementally) bring itself into compliance.

⁶In particular, TC_j equals the sum of (1) fixed cost of installing technology step j /useful life of technology step j , (2) annual operating and maintenance costs of technology step j , and (3) Opportunity Cost (which equals the sum of (1) and (2) times the market interest rate).

IC is unlikely to be a good estimate of a potential purchasing source's WTP. This is because a forward-looking source will always base its WTP on MC, even in the case of discrete abatement.⁷ As we show below, given the discrete nature of abatement, MCs are themselves discretely constant (i.e., step-like) over successive technology steps (e.g., we can think of there being successive levels of marginal control costs (MC_j) defined over corresponding ranges of abatement). Further, each MC_j effectively coincides with its corresponding Average Control Cost (AC_j).⁸ As we also show in Section 4, IC generally exceeds AC_j , $\forall j$. Thus, a purchasing source's IC exceeds its WTP.

AC_j in column 11 of Table 1 equals TC_j divided by technology step j 's corresponding incremental reduction achieved (normalized by 365 days per year). For example, the AC_1 of \$1.50/lb./day associated with Bob's Farm's Step 1 technology equals \$49,823/91 lbs./365 days. Similarly, the AC_2 of \$2.04 associated with Bob's Step 2 technology is equal to (\$464,444/623 lbs.)/365 days. Weighted AC in column 12 is a single measure of average control costs, measured simply as the sum of the AC_j 's (i.e., $\sum_j AC_j$) divided by the total amount of reductions achieved. Continuing with Bob's Farm, its Weighted AC of \$1.97 equals $((\$464,444 + \$49,823)/(91 \text{ lbs.} + 623 \text{ lbs.}))/365 \text{ days}$, or $(91 \text{ lbs.} / (91 \text{ lbs.} + 623 \text{ lbs.})) * \$1.50 + (623 \text{ lbs.} / (91 \text{ lbs.} + 623 \text{ lbs.})) * \2.04 .

⁷By "forward-looking" we mean that the potential purchasing source understands that if it instead chooses to abate more than its TMDL abatement allocation it will have credits to sell.

⁸For goods that can be produced in continuous units at constant marginal cost, this coincidence occurs asymptotically. In the case of discrete goods (such as abatement), the coincidence is exact when MC is measured on a per-unit basis. Note that if we do not measure MC on a per-unit basis, MC of the first abatement unit of the first technology step equals TC_1 and MC of all subsequent abatement units attributable to the first technology step equal zero. In similar fashion, the marginal cost of the first abatement unit of the second technology step equals TC_2 and MC of all subsequent abatement units attributable to the second technology step equal zero, and so on with each subsequent technology step.

4. A Formal Comparison of Incremental and Average Control Costs

To compare IC with both AC_j and Weighted AC more formally, let $\bar{A}$ represent total reduction needed, A_1 and A_2 represent reductions achieved for technology steps 1 and 2, respectively, and $A = A_1 + A_2$. Assume $A \geq \bar{A}$, i.e., the source is capable of abating beyond its TMDL abatement allocation. Further, let TC_1 and TC_2 represent the annualized control costs associated with achieving A_1 and A_2 , respectively, and $TC = TC_1 + TC_2$. There are two scenarios of particular interest.

Scenario 1

In the first scenario, we assume $A_1 \geq \bar{A}$, i.e., the source's step 1 technology is capable of generating a reduction level that exceeds its total reduction level required by the TMDL. In this case,

$$IC = \frac{TC_1}{\bar{A}} \geq AC_1 = \frac{TC_1}{A_1} \quad (1)$$

i.e., IC is at least as large as AC_1 . Note from the information provided in Table 1, the three sources meeting the assumption for this scenario—WWTF #1, Stinky's Cheese, and Smelly's Cheese—all satisfy condition (1). In each case, $IC > AC_1$.

Scenario 2

In the second scenario, $A_1 < \bar{A}$ (but, as assumed earlier, $A \geq \bar{A}$), i.e., although the source's step 1 technology is incapable of generating a reduction level that exceeds its total reduction level required by the TMDL, steps 1 and 2 together are capable of generating such a reduction level. In this case, $IC = TC_2 / (\bar{A} - A_1)$, $AC_1 = TC_1 / A_1$, $AC_2 = TC_2 / A_2$, and Weighted AC = TC/A .

To begin, note that,

$$\frac{TC_2}{\bar{A} - A_1} \geq \frac{TC}{A} \Rightarrow \frac{TC_2}{TC} \geq \frac{\bar{A} - A_1}{A} \Rightarrow IC \geq \text{Weighted AC} \quad (2)$$

i.e., IC is no less than Weighted AC when the reduction needed from the step 2 technology to ensure TMDL compliance as a percentage of the total reduction possible from technology steps 1 and 2 is less than the proportion of total control costs attributable to technology step 2. The comparison in (2) would be relevant for a source that has not yet implemented any control steps and is considering whether to implement both steps 1 and 2 to ensure TMDL compliance. Note that the inequality is more likely to hold the more efficient is the source's step 1 technology relative to its step 2 technology. From the information provided in Table 1, Bob's Farm satisfies condition (2). However, WWTF #2 does not, i.e., its Weighted AC exceeds its corresponding IC. A relatively high value of TC_2 / TC drives Bob's Farm's result, while a relatively high value of $(\bar{A} - A_1) / A$ (due to a relatively low value for A_1) drives WWTF #2's.

Next, note that

$$IC \geq AC_2 \quad (3)$$

since $(TC_2 / (\bar{A} - A_1)) \geq (TC_2 / A_2)$. As envisioned in EPA (2004), this comparison is relevant for a source that had previously implemented step 1 technology and is now considering whether to implement step 2. In Table 1, both Bob's Farm and WWTF #2 satisfy condition (3). In the case of Bob's Farm, $IC > AC_2$ because $A > \bar{A}$, whereas in the case of WWTF #2, $IC = AC_2$ because $A = \bar{A}$. Lastly,

$$\frac{TC_2}{\bar{A} - A_1} \geq \frac{TC_1}{A_1} \Rightarrow \frac{TC_2}{TC_1} \geq \frac{\bar{A} - A_1}{A_1} \Rightarrow IC \geq AC_1 \quad (4)$$

i.e., IC is no less than AC_1 when the reduction needed from the step 2 technology to ensure TMDL compliance as a percentage of the total reduction possible from technology step 1 is less than the ratio of technology step 2's annualized control cost to step 1's. The comparison in (4) would be relevant for a source that has not yet implemented any control steps and is considering whether to implement solely step 1 technology to move toward TMDL compliance. Similar to the relationship between IC and Weighted AC, this inequality is more likely to hold the more efficient is the source's step 1 technology relative to its step 2 technology. From the information provided in Table 1, both Bob's Farm and WWTF #2 satisfy condition (4). Thus, while WWTF #2's step 1 technology is efficient enough to ensure $IC > AC_1$, it is not efficient enough to ensure $IC > AC_2$ or $IC > \text{Weighted AC}$.⁹

Conditions (1) – (4) may therefore be summarized in the following two propositions.

Proposition 1: In the case where technology step 1 is capable of meeting or exceeding the total reduction needed to comply with the source's TMDL abatement allocation (Scenario 1), IC exceeds its corresponding AC.

Proposition 2: In the case where technology step 1 is incapable of meeting the TMDL allocation (Scenario 2), IC may not exceed its corresponding AC. IC is more likely to exceed AC the more efficient is the source's step 1 technology relative to its subsequent technology steps.

Propositions 1 and 2 are important because given the discrete nature of abatement units, and thus the coincidence of AC and MC, AC represents a given source's WTP for abatement credits. In cases where IC exceeds (is exceed by) its corresponding AC, IC is thus perform an over- (under-) estimation of WTP. As indicated by some of the costs calculated in Table 1, this over- (under-) estimation could potentially be quite large.

⁹WWTF #2's AC_3 exceeds IC by a relatively large amount due to the relative inefficiency of WWTF #2's step 3 technology relative to its steps 1 and 2 technologies.

5. Water Quality Trading with Discrete Abatement Units

Figure 2 depicts a stylized version of Scenario 2, as well as a discrete version of Figure 1 where the MC (cum “un-weighted” AC) curves similarly “cross” (explained in detail below). In this figure, a total of $\bar{A} = \bar{A}^1 + \bar{A}^2$ units of abatement across both sources is required by the regulatory authority (superscripts henceforth denote sources 1 and 2). Without loss of generality, we assume that $\bar{A} = (A_1^1 + A_2^1) = (A_1^2 + A_2^2)$. Initial abatement allocations from the regulatory authority are assumed to be A_0^1 and A_0^2 .

[INSERT FIGURE 2 HERE]

To begin, note that $\text{Weighted AC}^1 > \text{Weighted AC}^2$. Thus, if the WTPs for sources 1 and 2 are reflected in their respective Weighted ACs rather than their respective AC_js (discussed below), equilibrium in the abatement market results in a “move” from the initial allocation of (A_0^1, A_0^2) to the “corner” allocation of $(0, \bar{A})$, where source 1 abates nothing and source 2 abates the full amount. The equilibrium price will therefore lie somewhere between Weighted AC^1 and Weighted AC^2 . With respect to the un-weighted average control cost measures (i.e., AC_1^1, AC_2^1, AC_1^2 , and AC_2^2), note that although source 2’s successive average control costs for technology steps 1 and 2 (represented by AC_1^2 up to abatement level A_1^2 and AC_2^2 up to $\bar{A}$, respectively) are exceeded by source 1’s corresponding average control costs (represented by AC_1^1 up to abatement level A_2^1 and AC_2^1 up to $\bar{A}$, respectively), AC_2^2 nevertheless exceeds AC_1^1 . This is what is meant by the two source’s un-weighted AC curves crossing.

To characterize the likely trading equilibrium between sources 1 and 2 using the un-weighted average control cost measures, we refer to Figure 3, which is a redrawing of Figure 2

with pertinent rectangular areas demarcated.¹⁰ For example, areas $F + G$ and $A + B + D$ represent source 1's total costs of control for technology steps 1 and 2, respectively, while areas B and $C + D + E + F + G$ similarly represent source 2's respective total costs of control.¹¹

[INSERT FIGURE 3 HERE]

To determine the equilibrium outcome for sources 1 and 2, we look for implicit sequential consistency in any “move” away from initial allocation (A_0^1, A_0^2) . By “implicit sequential consistency” we mean that although the equilibrium outcome is determined as a one-shot trade between sources (i.e., the sources do not reach an equilibrium through an explicit sequence of trading events), we can nevertheless treat the equilibrium as if a sequence of moves takes place, as long as the moves are consistent with each other along the path to the equilibrium.

To see this, we begin by asking whether sources 1 and 2 have incentive to trade away from the initial allocation (A_0^1, A_0^2) to the allocation represented by (A_1^1, A_1^2) in Figure 3. The answer is yes. Due to the discrete nature of abatement units, source 2 must incur a total control cost of area $F + G$ to be able to reach abatement level A_0^2 with its step 1 technology. If source 2 were then able to sell the extra abatement units that it obtains from implementing this technology (distance $A_1^2 - A_0^2$), the minimum payment from source 1 that it would willingly accept for the move to A_1^2 would be area F . This is essentially the portion of its total cost attributable to the extra abatement units.

¹⁰Given that abatement is achieved in discrete units according to successive technology steps, it seems most likely that trading decisions will be based on the un-weighted rather than weighted average control costs. We restrict the market to two sources in order to be directly comparable with the equilibrium established in Section 2 for the case of continuous abatement units.

¹¹If Figures 2 and 3 had instead been drawn such that $A_1^2 < A_j^1$, $j = 1, \dots, m$, then similar to the result for the Weighted ACs discussed above, the corner allocation of $(0, \bar{A})$ would naturally obtain through trading.

Source 1, on the other hand, would have to incur *an added* total control cost of area $C + D + E + F + G$ *plus* area $\theta_1 r_1 (E + F + G)$ to reach the allocation indicated by A_1^1 (which reflects the added cost to source 1 of moving beyond the allocation represented by abatement level A_2^1), where $0 < r_1 < 1$ is source 1's discount rate (e.g., the market interest rate) and $0 < \theta_1 < 1$ is the probability associated with source 1 *not* being able to trade credits valued at area $E + F + G$ to a third party.¹² In other words, in the absence of trading with source 2, source 1 would need to incur the added full cost its step 2 technology, which consists of the added total control cost plus the expected opportunity cost associated with the unused portion of its total amount of abatement from implementing the technology. Obviously $C + D + E + F + G + \theta_1 r_1 (E + F + G) > F$, i.e.,

$$C + D + E + G + \theta_1 r_1 (E + F + G) > 0 \quad (5)$$

implying that the two sources will indeed choose to move from (A_0^1, A_0^2) to the allocation represented by (A_1^1, A_1^2) .

Next, will sources 1 and 2 have incentive to trade away from the allocation represented by (A_1^1, A_1^2) to the allocation represented by (A_2^1, A_2^2) ? If not, then by remaining at allocation (A_1^1, A_1^2) source 1 again incurs the added full cost represented by area $C + D + E + F + G + \theta_1 r_1 (E + F + G)$. If yes, and we assume for now that the two sources do not consider trading beyond allocation (A_2^1, A_2^2) to allocation $(0, \bar{A})$, then source 1 incurs no added cost (i.e., by not moving from allocation (A_1^1, A_1^2) to allocation (A_2^1, A_2^2) , source 1 does not implement its step 2 technology). In this case, source 2 incurs the added full cost of its step 2 technology represented by area $A + B + D + \theta_2 r_2 (A + B)$, where $0 < r_2 < 1$ is source 2's discount rate and $0 < \theta_2 < 1$ is the

¹²It is likely that θ_1 is a function itself of the number of market participants (i.e., available third parties) as well as expected transaction costs and regulatory uncertainty [Montero, 1997]. Since the determination of θ_1 is beyond the scope of our analysis, we assume without loss of generality that it is a constant term.

probability of source 2 not finding a third party to whom to sell its abatement credits.¹³ Thus, without accounting for the possibility of moving all the way to allocation $(0, \bar{A})$, the two sources will agree to move from (A_1^1, A_1^2) to (A_2^1, A_2^2) if

$$[C + E + F + G + \theta_1 r_1 (E + F + G)] > [(A + B) + \theta_2 r_2 (A + B)]. \quad (6)$$

To check whether the two sources indeed have the incentive to move all the way from allocation (A_1^1, A_1^2) to allocation $(0, \bar{A})$, we first note that inequality (6) is actually a *necessary* condition for stopping at allocation (A_2^1, A_2^2) (i.e., if the inequality does not hold, then the two sources will instead remain at allocation (A_1^1, A_1^2)). The *sufficient* condition for stopping at (A_2^1, A_2^2) is that the two sources' net gain of moving from (A_1^1, A_1^2) to (A_2^1, A_2^2) , i.e., area $[C + E + F + G + \theta_1 r_1 (E + F + G)] - [(A + B) + \theta_2 r_2 (A + B)] > 0$, be greater than their net gain associated with the move from allocation (A_1^1, A_1^2) all the way to allocation $(0, \bar{A})$, i.e., area $[C + E + F + G + \theta_1 r_1 (E + F + G)] - A$, in other words¹⁴

$$B + \theta_2 r_2 (A + B) < 0 \quad (7)$$

Condition (7) obviously does not hold, thus as long as condition (6) is met the two sources will trade away from their initial allocation (A_0^1, A_0^2) to the corner allocation $(0, \bar{A})$. In other words, condition (6) can be thought of as both *necessary* and *sufficient* for the equilibrium

¹³Similar to source 1's added costs associated with the move from (A_0^1, A_0^2) to (A_1^1, A_1^2) , area $\theta_2 r_2 (A + B)$ represents source 2's expected opportunity cost associated with the unused portion of its total amount of abatement from implementing the technology.

¹⁴The net gain of moving from (A_1^1, A_1^2) to (A_2^1, A_2^2) is simply a rewriting of condition (6). The net gain of moving from (A_1^1, A_1^2) to $(0, \bar{A})$ is the difference between area $[B + C + D + E + F + G + \theta_1 r_1 (E + F + G)]$, which is the value of what source 1 saves by not having to abate up to allocation (A_1^1, A_1^2) , and area $A + B + D$, which is the added cost that source 2 incurs by implementing its step 2 technology. Therefore, the net gain of moving from (A_1^1, A_1^2) to $(0, \bar{A})$ is equal to area $[C + E + F + G + \theta_1 r_1 (E + F + G)] - A$.

outcome $(0, \bar{A})$, rather than the outcome associated with allocation (A_1^1, A_1^2) , when the two sources base their abatement decisions on their respective un-weighted average control costs.

It is important to note, however, that condition (6) does not apply to potential initial allocations located to the *left* of (and including) allocation (A_2^1, A_2^2) in Figure 3. In other words, if the initial allocation (A_0^1, A_0^2) had been located to the left of (A_2^1, A_2^2) , rather than at its present location to the right of allocation (A_1^1, A_1^2) , the equilibrium allocation after trading would unconditionally occur at the corner allocation $(0, \bar{A})$. To see this, note that if the initial allocation is (A_2^1, A_2^2) , source 2 will have already implemented its step 2 technology. Thus, it will be in source 1's interest to avoid implementing its step 1 technology to obtain abatement level A_2^1 if it can pay source 2 anything less than area B. Since it would be in source 2's interest to accept any payment from source 1 for its abatement beyond level A_2^2 , a trade will occur and the corner allocation $(0, \bar{A})$ will obtain in equilibrium. For equivalent reasons, corner allocation $(0, \bar{A})$ obtains for any initial allocation to the left of (A_2^1, A_2^2) .¹⁵ Thus, the equilibrium outcome in this case—for any initial allocation to the left of (and including) allocation (A_2^1, A_2^2) —is unrestricted by condition (6), implying that the equilibrium outcome in Figure 3 is indeed sensitive to the initial allocation of abatement responsibilities.

¹⁵For the same reasons that corner allocation $(0, \bar{A})$ obtains when the initial allocation in Figure 3 is at (or to the right of) (A_0^1, A_0^2) , sources 1 and 2 have no incentive to trade to the right of allocation (A_2^1, A_2^2) should that be the initial allocation.

6. Conclusions

This paper has answered three questions related to the discrete nature of pollution abatement. The first question is, does incremental control cost necessarily exceed its corresponding average control cost, as presented in EPA (2004)? The answer is no. When its first technology step is incapable of achieving the source's target load, and the source has not previously implemented its first technology step, incremental control cost exceeds its corresponding average control cost only when the efficiency of its step 1 technology is large enough relative to its subsequent technology steps.

The second question—is a source's incremental control cost a better approximation of its willingness to pay for abatement credits than its average control cost?—again elicits the answer no. In the presence of discrete abatement units, average control cost is identically equal to marginal control cost. Since in general any source is capable of being a buyer or a seller of pollution reduction credits, the source's willingness to pay is ultimately equal to its marginal (and thus its average) control cost.

Lastly, how exactly does the determination of an equilibrium outcome in a market with discrete abatement differ from the equilibrium determined in continuous-abatement market? To this question we offer two answers. First, the equilibrium in a discrete-abatement market is determined through an application of implicit sequential consistency. Second, unlike with a continuous-abatement market, the equilibrium for a discrete-abatement market is generally dependent upon the initial allocation of abatement responsibilities. This, in turn, suggests that the numerical evidence provided in Montero [1997] relating the sensitivity of a pollution-trading equilibrium to the constancy of transaction costs and regulatory uncertainty in the presence of discrete abatement, is in fact more general than previously thought. Indeed, in the case where

sources' average control cost curves "cross," the equilibrium outcome in a discrete-abatement market is inherently sensitive to the initial allocation of abatement responsibilities.

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Figure 1. Water Quality Trading in the Presence of Continuous Abatement Units.

Figure 2. Water Quality Trading in the Presence of Discrete Abatement Units.

Figure 3. Likely Trading Equilibrium in the Presence of Discrete Abatement Units.

Table 1. Hypothetical Cost of Control and Control Effectiveness Data.*

Source	Current Load	Target Load	Reduction Needed	Incremental Reduction Achieved	Cumulative Reduction Achieved	Reduction Needed for Compliance	Credits	TC	IC	AC	Weight. AC
Bob's Farm	873	527	346								
<i>Step 1</i>				91	91	255	0	49,823	---	1.50	---
<i>Step 2</i>				623	714	0	368	464,444	4.99	2.04	1.97
WWTF #1	917	633	284								
<i>Step 1</i>				662	662	0	378	2,074,237	20.01	8.58	---
<i>Step 2</i>				107	769	0	485	5,222,364	---	133.72	26.00
Stinky's Cheese	698	410	288	506	506	0	218	6,308,251	60.01	34.16	34.16
WWTF #2	72	25	47								
<i>Step 1</i>				10	10	37	0	56,032	---	15.35	---
<i>Step 2</i>				37	47	0	0	219,022	16.22	16.22	---
<i>Step 3</i>				20	67	0	20	339,450	---	46.50	25.13
Smelly's Cheese	274	166	108	163	163	0	55	590,906	14.99	9.93	9.93

*The actual Excel spreadsheet in electronic form for this figure is available upon request from the author.