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Water Quality Trading on the Minnesota River:

Lessons Learned from the Jordan Trading Program

A Thesis Submitted to the Faculty of the University of Minnesota by

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Abstract:

Water quality permit trading in an attractive option lower the costs of pollution cleanup in lakes and rivers, and while similar programs for air pollution have been successful, most attempts at Water Quality Trading have failed. The Jordan Trading Program, based on the Minnesota River, is one of the few exceptions. This paper examines the program to discover how the program succeeds where others have failed. The Jordan Trading has averaged 17 trades a year, and with some assumptions has resulted in cost savings. The river is modeled using a Farrow *et. al.* (2005) model to show that savings are theoretically possible, even if the program does not act in the same fashion. It was found that while cost savings occur, the facilities in the program are not profit maximizers due to their status as government wastewater treatment facilities, and thus the maximum potential cost savings are not achieve. The program has still been successful, and several suggestions are made for future water quality trading programs.

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Chapter 1: Introduction and Literature Review

Using permit trading programs to minimize the costs of pollution reduction programs has been used primarily to deal with air pollution and has been fairly successful. For this reason it is appealing to attempt to create similar programs to minimize the costs of water pollution reductions (Morgan and Wolverton 2005). Permit trading allows the permit holder to either emit a certain amount of pollution or sell the permit to another firm. Firms that do not hold enough permits to meet their pollution levels must either abate or buy permits from other firms. Thus the market will push the firms that have low costs of abatement to reduce their pollution and sell their permits to high cost firms, allowing for a reduction in pollution while minimizing the costs.

Water pollution, however, is much harder to deal with using these methods and attempts to this date have mostly been unsuccessful. Surveys of water permit trading programs in the United States have found that there have been few to no trades in programs that have been implemented (King and Kuch 2003). There are numerous problems that are created due to the nature of rivers, the sources of water pollution, and inefficient trading set ups. These can provide disincentives to trade within the programs, which cause them to fail. The Minnesota River, however, has a trading program that bucks these trends, averaging some 17 trades a year while meeting the water quality goals laid out in Total Maximum Daily Load (TMDL) document that dictates allowable pollution levels in the river at Jordan Minnesota. This program has been named the Jordan Trading Program and it has been one of the most successful water quality trading programs in the United States. Thus there is much we can learn from this program that will help us shape other future endeavors, allowing an increased chance of success.

My purpose, in part, is to explore the reasons behind the success of the Jordan Trading Program. To begin, in Chapter 1, I review the literature to examine current trading programs and their problems. I then move on to present an overview of several important economic models that were created in an attempt to address the differences between water quality trading and air quality trading in Chapter 2, before presenting the TMDL that created the Jordan Trading Program in Chapter 3. Chapter 4 of the paper will cover the estimation of costs of abatement for pollution sources along the Minnesota River, Chapter 5 will cover the estimation of damages as needed for our economic models, and Chapter 6 will lay out the results of a model estimation using a subset of the data. Chapter 7 contains concluding remarks, including what can be done to improve the implementation of water quality trading programs in the future.

Current Trading Programs and their Failures:

Water pollutions differs from air pollution in several ways, with a major issue being that many of the sources of water pollution are not traditional point sources. Point sources are still major sources of pollution and are primarily composed of waste water treatment facilities, although industrial sources do account for some of the pollution. These sources, however, have had restrictions placed on the amount they are able to pollute in the past, and thus many have already taken any low-cost steps available to reduce emissions. In fact much of the current pollution entering streams and lakes is coming from non-point sources such as farm runoff. Air pollution has its own share of nonpoint sources, such as automobiles, and as point sources for air pollution become cleaner these non-point sources will become more and more important in future pollution abatement policies. Nonpoint polluters are much harder to identify and it is difficult to accurately measure the amount of nutrient related pollution coming from them (King and Kuch 2003). Because point sources are easy to identify but have abated to the point where further abatement is quite expensive, future policies must focus on nonpoint sources. Water Quality Trading (WQT) programs are often designed to facilitate this. The majority of programs that have been attempted have involved trades between point and non-point sources, where point sources pay farmers or other non-point polluters to abate instead of doing so at the point source (Morgan and Wolverton 2005). The idea is that, since abatement will be cheaper at non-point sources, the point sources (which are easily identified and thus easy to place restrictions upon) will find and pay them to 'offset' some portion of the firm's pollution, allowing them to meet the requirements placed upon them.

Over the years a number of models have been suggested that would determine trading ratios for these polluters, as well as ways to organize systems that would result in the costs of abatement being minimized. Often this comes in the form of determining what prices pollutions sources should pay others to abate for them. In order to set these prices correctly we need the price of permits to reflect the marginal damages caused by each firm over the landscape that is impacted by its emissions (Konishi *et al.* 2013). Many of these models either set trade ratios to some fixed number or base them on simulation outcomes. More recent models have been suggested by Hung and Shaw (2005) and Farrow *et al.* (2005), which note that trading systems based on previous models miss potential gains from trades that might improve efficiency but that are not made. (Hung and Shaw 2005). Even these new models suffer from their own design flaws that might cause them to fail to achieve the optimal outcomes within typical river systems, as will be addressed in Chapter 4.

Transaction costs also represent a significant issue for trading programs due, once again, to the inclusion of non-point sources. In most trading programs that have been implemented point sources that trade with non-point sources are held liable for the pollution that the non-point source was paid to abate. In effect this means that if the non-point source fails to meet the abatement quota then the point source would face any consequences included in the program, which are often monetary fines. Coupled with this is how difficult it is to measure pollution from non-point sources and the fact that different abatement methods on non-point sources often have high levels of variability in their effects. Therefore point sources in many trading programs often are hesitant to trade with non-point sources before conducting lengthy and expensive studies to ensure the viability of the proposed abatement project. Point sources view these trades as risky, and thus the transaction costs associated with making a trade can be very high, often prohibitively so. Thus any trading program that includes non-point sources can immediately run into problems that prevent many trades from occurring (King and Kuch 2003).

Some programs have attempted to circumvent this issue by setting trading ratios that require non-point source involved in trades to take abatement steps in excess of the amount of pollution permits the point source is buying. This is essentially trying to eliminate the impact of the variability in the results and the necessity for point sources to engage in expensive studies to lower risk. These ratios can sometimes be 3 or 4 to 1 (King and Kuch 2003). Unfortunately this “solution” has the side effect of raising the cost of trades, and thus reducing efficiency, effectively leading to the same result of very few trades. It should be noted that high transaction costs can exist without the non-point source problem. For instance if a trading program is poorly designed so as to require an excessive amount of work to be done to finalize a trade some firms involved may opt to ignore the program, simply viewing it as too much work too bother with.

Morgan and Wolverton (2005) created a database listing all of the attempts at implementing water quality permit trading that have emerged after the successes of air pollution trading programs since the 1980s. Their paper sorted programs into types, such as those policies created by state or other local government, ongoing or finished trading programs, one time offset agreements, and non-trading programs aimed at general reduction. They explored in detail the various program's trading ratios, methods for making trades, and the various costs associated with these methods. While they observed very few trades, they were able to collect information to suggest why they did not happen. Their findings tend to agree with those of King and Kuch in that primary obstacles to trading tended to be high trading costs, difficulty in finding sellers, and regulatory obstacles. Morgan and Wolverton also found that there were some cases where limits on pollution were not strict enough or where previous initiatives already covered the required abatement. Overall, their paper was a useful survey of the water quality permit trading programs that have been implemented.

Morgan and Wolverton (2005) and King and Kuch (2003) both support the idea that high transaction costs discourage trading programs. In an attempt to address this Hung and Shaw (2005), here after HS developed the Trading Ratio System (TRS) for water pollution discharge permits. Whereas early models were so complicated that they led to high transaction costs, HS attempted to simplify their system so that, once it was set up, it would run quickly and cheaply, thus minimizing transaction costs. Their model used the fact that rivers flow in a unidirectional manner to allow them to create binding constraints for each polluter in the river. Permits are then assigned starting at the beginning of the river and moving down so that each zone (containing one polluter) meets the water quality standard that has been set and thus the standards will be met even if no trades occur. Each firm can then buy permits from those upstream of it, allowing low cost firms to abate while high cost firms purchase permits. Trading is done through a set of trading ratios that are calculated based on the amount of each source's pollution still the river at the other sources point on the river. These take into account the distance between polluters, the settling and uptake rates of pollutants, and the ratios of whatever pollutants are released by each firm (Sado *et al.* 2010). Hung and Shaw conclude that by determining these trading ratios prior to trading, all firms involved will be able to make quick, cost efficient trades (Hung and Shaw 2005).

Sado *et al.* (2010) estimated the potential savings from implementing Hung and Shaw's TRS to reduce phosphorus emissions from 22 wastewater treatment facilities in the Passaic River Basin. They set out to determine, using actual information from firms, what the cost savings could be from a TMDL rule requiring an 80% reduction in total prosperous emissions for the watershed if trading were to occur. Using Hung and Shaw's model, they first note that if there are no low cost firms upstream, no trades will occur. In order to ensure this occurred they set the base case for the simulations as one where most firms needed to upgrade their facilities to meet the new limit if no trading was allowed. They estimated the costs of abatement from data gathered after similar upgrades to wastewater plants occurred in the Chesapeake Bay area and thus they were able to estimate how much it would cost for the plants to upgrade.

Sado *et al.* (2010) estimated the costs of abatement to be approximately \$3.10 million, while with trading the costs fell to \$3.05 million. This is a savings of around 2%, but they found that by shifting capital cost assumptions slightly the savings could increase another \$38 thousand, resulting in about a 3% savings. These are meager gains and likely would not motivate the formulation of a WQT program. They found that by targeting specific firms, trading gains could increase to approximately 6%, and that by allowing upstream and downstream trading they could increase to approximately 4%. Long term contracts for trading also appear to be ideal. They note the savings of 2-3% appear consistent with the limited number of trials that actually had trades occur. They maintain that trading could yield significant trades but that the HS TRS is not the ideal system as it does not allow bidirectional trade and it covers all firms in a watershed instead of those that could benefit the most, as this increases the complexity and costs of the program. It should be noted that despite these results the total cost of the program that Sado et al. (2010) present is somewhat questionable. Their program assumes that all goals could be met using relatively low costing chemical treatment methods and they annualized capital costs over a long time frame. By comparison a recently completed upgrade to the Mankato Waste Water Treatment Facility cost $8 million to achieve a low effluent phosphorus concentration. Indeed Mankato estimates their operations and maintenance costs to be $1 million per year, which alone is significantly greater than the costs in Sado et al. (2010).

Farrow et al. (2005) proposed another trading scheme method. They designed their model to calculate damage ratios based on each polluter's zone of influence and the monetary damages caused by their pollution. They then allow firms to trade with any other firm in the watershed using the trading ratio for trades between the two firms. Their model assumes linear damages from pollution that decays as it spends time in the river (Farrow *et al.* 2005). The trading program initially allocates permits so that the overall monetary damages constraint is met. Trading is then allowed for all firms as long as original discharge limits are not exceeded (Farrow *et al.* 2005).

Both Farrow et al. (2005) and Hung and Shaw (2005) present useful models. They both, however, have problems that can lead them to solutions that do not actually minimize the costs of abatement. These will be explored further in Chapter 4 of this paper.

Chapter 2: Theoretical Trading Models:

Many attempts have been made to develop water-quality trading models that could be used to implement efficient pollution trading programs on rivers. Setting permit prices correctly for trading programs that reflect the changing marginal damages from emissions covering the entirety of the polluted landscape is necessary and quite possible for air emissions (Muller and Mendelsohn 2009). Water trading presents a problem, however, in that the transportation and absorption of emissions in rivers depends on landscape conditions. Thus each river is unique and requires careful study. Many water-quality trading systems have been developed in an attempt to solve these issues (Konishi *et al.* 2013). This sections presents an examination of two of the more recent models, Hung and Shaw's (2005) trading-ratio system (TRS) and Farrow *et al.*'s (2005) damage-denominated trading ratio system (DTRS), followed by an examination of the Jordan Trading Unit system (JTUS) currently being used to reduce phosphorus emissions into the Minnesota River.

Theoretical Model:

Before examining the various modeling systems a static model for water-quality management in a generic river basin must be explained. For this case we use the model presented in Konishi *et al.* (2013). Let $\mathbf{e} = (e_1, \ldots, e_i, \ldots e_n)$ be a vector of emissions for a pollutant, where e_i is the emissions from point source i. Variable i also indicates geographic location along the river. Assign $\bar{\boldsymbol{e}}$ to be a vector of uncontrolled emissions for each source with $e_i \leq \bar{e}_i$ for each source i. Let $\mathbf{x} = (x_1, \ldots, x_m, \ldots, x_M)$ be a vector of pollution levels, where x_m denotes that concentration at point *m*. We can then assume that there is a linear mapping $T : R^N \rightarrow R^M$ which describes the relationship between **e** and **x**. By letting *T* be given by $\boldsymbol{x = Te'}$, we now have *T* as a M x N matrix of nonnegative transfer coefficients representing the operator necessary to compare emissions levels between sources. Let $S : R^M \rightarrow R$ be a differentiable function represented by *S*(x) that describes the total economic damages as a function of the vector of pollution levels and assume that its derivative is positive for all *m.* Substituting for x we can show that the total economic damages are differentiable and can be represented by D(**e**) = S(T**e**'). We can then define a vector of abatement levels $\mathbf{a} = \boldsymbol{\bar{e} - e}$, where $\mathbf{a}_i \in [0,\ \boldsymbol{\bar{e}}_i]$ (Konishi *et al.* 2013).

With these definitions and assuming that each source has a twice differentiable abatement cost function $C_i(a_i)$, with both first and second derivatives greater than zero, we can create an equation representing an efficient program that minimizes the sum of abatement costs and damages of all facilities:

$$min_a \sum_{i=1}^{N} C_i(a_i) + D(\bar{e} - a) \qquad (1)$$

From this we can assume that there exists an optimum $\mathbf{a}^{eff}$ that solves equation (1) (Konishi *et al.* 2013). Basically the trading program will minimize the sum of abatement costs and damages across all facilities.

The Hung and Shaw model solves a slightly different version of this equation:

$$min_a \sum_{i=1}^{N} C_i(a_i) \;\; s.t.\, x_m \leq \overline{X}_m \forall\, m \wedge x = Te' \qquad (2)$$

where $\overline{X} = (\overline{X}_{1,} \ldots, \overline{X}_M)$ is a vector of environmental constraints on pollution levels with one value for each receptor. This equation represents a cost function that a social planner might solve in order to determine the cost-effectiveness of a program (Hung and Shaw 2005). This equation attempts to minimize the abatement costs subject to keeping the pollution levels at each receptor below the pollution restrictions. The primary difference between this and equation (1) is that damages are ignored in the Hung Shaw Model. Permits are set according to the imposed limits, which can be determined without considering damages if the social planner so chooses. We can assume there is some solution to this equation, which we will denote $\mathbf{a}^{HS}$ to indicate the Hung and Shaw (2005) solution. Konishi *et al.* show that the solution for equation (2) also solves for equation (1), and thus would be the optimal solution.

The Farrow *et al.* model solves yet another equation that approximates equation (1). DTRS is aimed at minimizing the sum of abatement costs subject to some constraint on the total damages, $\overline{TD}$. This model assumes damages are linear in nature such that (Farrow *et al.*, 2005):

$$min_a \sum_{i=1}^{N} C_i(a_i) \;\; s.t.\, D(\bar{e}-a) \le \overline{TD} \tag{3}$$

In order for a solution to equation (3) to equal the solution for equation (1) the social planner must set the constraint on total damages, $D(\boldsymbol{e})=\sum_i d_i e_i \;\; \overline{TD}$, at the efficient level (Muller and Mendelsohn, 2009). Once again we can assume a solution exists, which we will denote $\mathbf{a}^{FSCH}$. Konishi *et al.* go on to show that if a social planner implementing these schemes has perfect knowledge of T and D these two equations will yield identical results. These results do assume that the planner knows what $\mathbf{a}^{eff}$ is and thus they have complete information regarding the abatement cost functions. They also show that a social planner requires no more information to implement equation (2) than to implement equation (3). The actual trading programs of these two systems, however, are very different. Each requires different information and each has the potential for error once implemented in the field. Thus even with complete information they might yield different results due to issues with the trading program, not the theory (Konishi *et al.* 2013). The JTUS shares some similarities with Hung and Shaw's TRS but removes some constraints on trading.

Hung and Shaw's Trading-Ratio System:

While early models were overly complicated Hung and Shaw attempted to develop a system that minimized transaction costs and time involved in trades. Their model used that fact that rivers flow in a unidirectional manner to allow them to create binding constraints for each polluter in the river. The model divides the river into zones; for simplicity's sake one source is assigned per zone, although Hung and Shaw note that as long as there is at least one source per zone the system will operate. If there are multiple sources in a zone these sources will simply split the zonal tradable discharge permits (TDPs) assigned (Hung and Shaw 2005). These zones are indexed so that $m = 1$ indicates the first zone and so on downstream. Since these zones $\{m\}$ correspond to a set of polluting sources {i} we simply denote both zones and polluting sources with *i.*

Trading is done through a set of trading ratios that are calculated based on each source's relationship with one another in the river, including distance between polluters and the settling and uptake rates of pollutants. Each firm is allowed to purchase permits from any source upstream of it (firms cannot purchase permits from sources downstream as that would lead to a violation of the water quality standard in their zone as permits were assigned to meet it perfectly), allowing for low cost firms to abate while high cost firms purchase permits (Hung and Shaw 2005). Due to the upstream trading restriction the transfer matrix *T* includes a special characteristic: for any *m* and *n* with $m > n$, $\tau_{mn} = 0$, where τ_{mn} is the element of *T* that measures the water-quality impact from pollution from zone *m* on zone *n*. It is assumed in Hung and Shaw that each source affects its own zone so that $\tau_{ii} = 1$ for all *i*.

Permits were then assigned starting at the beginning of the river and moving down so that each zone meets the water quality standard, $\overline{X}$, even if no trades occur. Since the pollution decays slowly in the river sources in lower zones (further down the river) are only given permits if there exists a gap between pollutants entering their zone from upstream and the water quality standard. The regulator of the program uses the transfer coefficients from *T* to determine how much pollution from each source affects each zone, and thus how many permits are available for allocation in that zone. These are assigned as TDPs, denoted as the vector $\overline{Z}$. Indeed sources low on the river may be assigned very few permits, or even none, in the initial allocation (Hung and Shaw 2005).

Since we start allocating from the most upstream zone $\overline{Z}_1 = \overline{X}_1$ as there are no other sources affecting this zone, and thus the source there would be allocated permits equal to the zonal pollution standard. For $j > 1$ $\overline{Z}_j = \overline{X}_j \sum_{i=1}^{j-1} \tau_{ij} \overline{Z}_i$, which is the zonal pollution standard in the current zone minus the sum of the remaining emissions from all zones upstream of the source. If, however, for some *j* we find that $\tau_{(j-1)j}\overline{X}_{j-1}>\overline{X}_j$ this indicates that the level of pollution reaching a zone from upstream, where the upstream zone's standard is exactly met, exceeds the standard for zone *j* even when no pollution is emitted there. This zone is considered a critical zone. In order to correct for this issue Hung and Shaw set that zones allocation $\overline{Z}_j=0$ and reduces the next upstream zone's allocation until the standard is met (Hung and Shaw 2005). If necessary multiple zones will have their allocations reduced until zone *j* is no longer a critical zone. This can be expressed as $\overline{Z}_{j-1}=(\overline{X}_j/\tau_{(j-1)j})-\sum_{k=1}^{j-2}\tau_{kj-1}\overline{Z}_k$. Through the transfer coefficients the TRS allocations scheme ensures that the impacts of upstream zonal standards are accounted for in each area. Water quality standards $\overline{X}$, the transfer coefficients *T*, and the number of zones are all considered set values, while the price at which trades occur is variable.

Given trade restrictions and the model laid out each source *i* solves:

$$min_{r_{ki},r_{si},r_{sj}} C_i(a_i)-p_i r_{si}+\sum_j p_j r_{ji} \tag{4}$$

$$s.t.\ \overline{Z}_i \geq (\overline{e}_i - r_{ki})-\sum_{j=1}^{i-1}\tau_{ji} r_{ji} \tag{5}$$

$$a_i = r_{ki}+r_{si} \tag{6}$$

$$r_{si}=\sum_{j=i+1}^{n} r_{ij} \tag{7}$$

$$0 \leq r_{ki}, r_{si}, r_{sj} \tag{8}$$

where p_i and p_j are the market prices of permits from sources *i* and *j*, r_{ji} is the amount of pollution control purchased from source j by source i, r_{ki} is the amount of pollution control retained by source i to meet its zonal standards $\overline{Z}_i$, and r_{si} is the amount of pollution control sold by source i. This can be rewritten to express Hung and Shaw's trading constraint:

$$e_i \leq \overline{Z}_i + \sum_{j=1}^{i-1} \tau_{ji} r_{ji} - \sum_{j=1+1}^{n} r_{ij} \tag{9}$$

In this case r_{ij} is the net amount of zonal discharge permits sold by source i to source j, implying that each source may only purchase permits from upstream zones (as stated earlier) as the transfer coefficients allow for scaling that result in any allowable trade not violating any zone's pollution limit. Since trades must be at the exchange rates τ the equilibrium price of permits must satisfy:

$$\tau_{ij} p_j = p_i \tag{10}$$

One issue should be noted. In the case of a branching river trades between firms on different branches cannot occur, as purchases of permits from one source will not reduce the damages on the zone of the purchaser. Thus in the case of a branching river the firms might not be able to take advantage of beneficial trades *(Konishi et al.* 2013).

Konishi *et al.* (2013) explore potential issues with TRS. They explain that while Hung and Shaw's program attempts to solve equation (2), and thus solve equation (1) in the process, they actually fail to come to the correct solution in the case of a critical zone appearing at a confluence of a branching river. TRS does not account for this and thus fails to achieve the optimal solution. Thus another program might produce better results in the case of a river with multiple branches.

Farrow's Damage-denominated Trading-Ratio System:

Farrow *et al.* (2005) also developed a system to control water quality through permit trading, but the program is very different. Instead of being concerned with environmental constraints like TRS, DTRS cares about aggregate monetary damages, denoted $\overline{TD}$. Trading ratios are based on marginal damages rather than physical transfer coefficients of pollution in rivers. For each source *i* marginal damage, d_i, is calculated by integrating its contribution to monetary damages over that source's zone of influence. This zone of influence is similar to concepts in TRS, in that TRS's transfer coefficients were based on the amount of emissions remaining in river in each zone. Permits are distributed, denoted $\overline{L}_i$, in terms of emissions at the point of discharge so that aggregate damages meet the overall monetary constraint at the initial allocation: $\sum_i d_i \overline{L}_i = \overline{TD}$. Trade is allowed between any set of two sources according to the ratio of their marginal damages. As long as this is followed the aggregate limit of damages will be met for the trading program.

Farrow *et al.* (2005) assume that aggregate damages are linear such that

$D(\boldsymbol{e}) = \sum_{i=1}^{n} d_i e_i$, where **d** is the vector of marginal damages and **e** is the vector of emissions. As long as D(**e**) does not exceed TD the model shows that the goals of the trading program should be met. Assuming linearity implied that d_i's do not depend on emissions from other sources.

The cost minimization model for each source *i* is as follows:

$$min_{r_{ki}, r_{si}, r_{sj}} C_i(a_i) - p_i r_{si} + \sum_j p_j r_{si} \qquad (11)$$

$$s.t.(\bar{e}_i - r_{ki}) - \sum_j \frac{d_j}{d_i} r_{sj} \leq \bar{L}_i \qquad (12)$$

$$a_i = r_{ki} + r_{si} \qquad (13)$$

$$0 \leq r_{ki}, r_{si}, r_{sj} \qquad (14)$$

p_i and p_j are the market prices for a permit from source *i* and *j* respectively, while r_{sj} is the amount of pollution control purchased from source *j* by source *i*, r_{ki} is the amount of pollution control retained by source *i* to meet its own requirements L_i, and r_{si} is the amount of pollution control sold by *i*.

Similarly to the TRS equation (9) above we can write the trading constraint for Farrow *et al.* by substituting in $e_i = \bar{e}_i - a_i$ and $r_{ki} = a_i - r_{si}$:

$$e_i \leq \bar{L}_i + \sum_j \frac{d_j}{d_i} r_{sj} - r_{si} \qquad (15)$$

This amounts to saying that each source can trade with any other so long as the level of its discharge does not exceed the sum of the original discharge limits L_i and the net purchased damage-denominated permits $\sum_i (d_j / d_i) r_{sj} - r_{si}$. In order to trade at the exchange rates d_j / d_i the prices of permits in the equilibrium must satisfy:

$$\frac{d_j}{d_i} p_j = p_i \qquad (16)$$

Since only a source not participating in the program can have a $d_i = 0$ and marginal damages are used as trading ratios this implies that all sources can trade with one another regardless of their location on the river. Konishi *et al.* (2013) provide a proof that equation (16) holds for any equilibrium in the model. There are issues involving situations where the abatement level equals zero or $\bar{e}_i$ but Konishi *et al.* (2013) present solutions for dealing with these cases setting abatement decision given price equal to these levels.

While they show that equation 16 holds for any equilibrium Konishi *et al.* (2013) demonstrate that DTRS does not necessarily achieve the cost-effective solution in all situations. They show that if the aggregate damage function is nonlinear then DTRS does not minimize costs due to a breakdown in its allocation rule. Thus we can see that while both TRS and DTRS solve for equivalent equations, there are instances where their results will differ. Thus comparing the results of these theoretical models can provide evidence for the effectiveness of the models in real world situations.

Jordan Trading Unit System:

Unlike the others, JTUS is not a theoretical model but a program that is currently being implemented by the MPCA to control pollution on the Minnesota River (Minnesota Pollution Control Agency 2004). Thus this modeling is an examination of the current system and not a new theoretical model. The JTUS is similar in many ways to Hung and Shaw's TRS, but removes some constraints. It utilizes a transfer-ratio matrix for its trading system similar to TRS, but allows for trades between all sources. This is because the JTUS is only concerned with one area along the river. In this case that area is the Minnesota River at Jordan Minnesota, where certain water-quality requirements have failed to be met.

There are two ways we can think about this system. First, since there is only one area of concern, the JTUS could be viewed as treating the entire river as one zone. While this is not normally done in TRS it does allow for multiple sources in one zone (Hung and Shaw 2005). Each source's emissions are discounted by their transfer coefficients, which reflect the amount of emissions that are still in the river at Jordan Minnesota. The second way to view the system is mathematically easier and more accurate and will be used from here on to present the model. Instead of viewing it as one zone we can view the river as a TRS model with multiple zones with constraints on the transfer-coefficients instead of constraints on pollutants in each zone.

The JTUS makes use of special transfer coefficients, called the Jordan BOD (Biological Oxygen Demand) Factor. Each Jordan BOD factor δ_i represents the impact of the emissions from source *i* on the pollution level at Jordan. Thus $\delta_i = \tau_{iN}$ where N represents the zone at Jordan. All sources are allowed to trade with each other at trading ratios δ_j / δ_i, as will be explained below. Thus the JTUS is substantially different from the TRS in that sources do not use transfer coefficients τij for trades between zones *i* and *j*; they must use δ_j / δ_i instead. This allows all sources to trade with each other even when $\tau_{ij} = 0$ (e.g. across branches). The Jordan BOD Factors for sources in the Minnesota River basin are listed in Table 2.

TRS assigns permits to each zone until the zonal pollution standards $\overline{X}$ are met in each zone. In the case of JTUS the initial allocation of permits can be expressed so that the sum of allocated emissions from each firm, $\overline{L}_i$, weighted by their transfer coefficients is less than or equal to the environmental constraint $\overline{X}_N$ at Jordan. This can be expressed as:

$$\sum_i \delta_i \overline{L}_i \leq \overline{X}_N \tag{17}$$

The limit for allocation purposes is assigned as a total impact on Jordan. Thus if a source with a transfer coefficient of .5 was assigned 1 permit they would actually be able to emit 2 units at their plant, as only 50% of their emissions are still in the river at Jordan. Thus the social planner may allocate permits in any way so long as the total permits adjusted by each sources transfer coefficients is below the limit at the zone of concern is met. Similarly at the equilibrium after trading the model should have the following hold where the allocated permits $\overline{L}_i$ is replaced by actual emissions levels:

$$\sum_i \delta_i e_i \leq \overline{X}_N \tag{18}$$

Thus our ambient pollution standard is met so long as the sum of each sources transfer-coefficient-weighted emissions, e_i, does not exceed the pollution standard.

Once permits are distributed trading is allowed between all sources regardless of position on the river. Since all sources trade based on their respective transfer coefficients the pollution standard will be met regardless of which trades are made, resulting in any cost effective trade being allowable. Since JTUS requires that each source trade based on their transfer coefficients they must satisfy the following trading constraint:

$$(\bar{e}_i - r_{ki}) - \sum_j \frac{\delta_j}{\delta_i} r_{sj} \leq \overline{L}_i \tag{19}$$

$$a_i = r_{ki} + r_{si} \tag{20}$$

where $\bar{e}_i$ is the uncontrolled emissions for source i, r_{sj} is the number of permits purchased by source i from source j, r_{ki} is the permits retained by source i to cover its emissions, τ_{iN}

is the transfer coefficient for source *i,* and δ_j is the transfer coefficient for source *j*.

With this equality we can write the trading constraint by substituting in $e_i = \bar{e}_i - a_i$ and $r_{ki} = a_i - r_{si}$:

$$e_i = \overline{L}_i - r_{si} + \sum_j \frac{\delta_j}{\delta_i} r_{sj} \tag{21}$$

where r_{si} is the number of permits sold by source i. This basically states that a source's emissions must be equal to their initial permits minus any permits they sell, plus the sum of transfer coefficient adjusted permits they purchased from other sources. By substituting (21) into (18) we can obtain (17), thus showing that (19) and (20) satisfy the aggregate market clearing condition.

The price for permits sold is determined by each individual source and are not regulated. The one impediment to trading is that JTUS includes an environmental trading cost where for each permit a source purchases from another they must instead purchase 1.1, with the extra .1 permit being removed from the system (new sources are required to purchase 1.2 permits for each permit worth of emissions as a requirement of entering the system). This can be inserted into the above equations for trading. Each trade therefore serves to reduce total pollution in the river at Jordan. This constraint might prevent JTUS from coming to the most cost effective solution, but could also be eliminated in future programs.

The JTUS avoids the problems that TRS and DTRS suffer from by constraining transfer coefficients instead of pollution or damages in each zone. Like the DTRS, the JTUS does not act to control pollution levels at all points in a watershed and instead focuses on a single area of concern. Within this limitation the JTUS should solve equation (2) if you set *σ,* the environmental trading cost, equal to zero and thus JTUS will come to a cost-effective solution for the reduction of pollution at a specific point.

Model Summary:

Each of the examined trading programs can lead to the cost effective reduction of pollution in rivers when certain conditions are met. The models have been laid out theoretically so as to provide insight into how they operate, their trading requirements, and potential pitfalls. JTUS avoids the problems of TRS and DTRS, but only by limiting its area of concern and controlling transfer coefficients instead of pollution in all zones. Thus while TRS and DTRS will result in a certain environmental standard being met for an entire river system JTUS will only ensure that the goal is met at a specific point and thus will be most effective on watersheds where there is only one zone that fails water quality standards. TRS and DTRS would also function in these watersheds and thus the 3 models could be compared to determine their relative effectiveness in reaching the cost minimizing abatement solution. I will not examine the TRS in this paper.

Chapter 3: Minnesota Total Maximum Daily Load Summary

Basis for TMDL:

The Federal Clean Water Act, as well as the United States Environmental Protection Agency's Water Quality Planning and Management Regulations, require States to set a Total Maximum Daily Load (TMDL) for pollutants in bodies of water that fail to meet water quality standards. This is the case for the Minnesota River, which flows for approximately 335 miles from Big Stone Lake to the Mississippi River, shown in figure 1. Pollution issues are most pronounced for the lower 22 miles of the Minnesota River, which is impaired for dissolved oxygen, fecal coliform bacteria, turbidity, PCBs, and Mercury (Minnesota Pollution Control Agency 2004). Minnesotans are primarily concerned that rivers are drinkable, swimmable, available for industrial and agricultural use, and able to support aquatic life. To meet these goals Governor Arne Carlson made the Minnesota River a priority basin in 1992, with the goal of having the river be fishable and swimmable by 2002. This led to numerous recommendations for river cleanup, but by 2002 the river was still designated as impaired. At its current level of impairment, the Minnesota River is classified for use for industrial applications other than food processing, use for irrigation and livestock, and supporting some aquatic life, but not commercial fish. The Minnesota River is not suitable for domestic consumption (Minnesota Pollution Control Agency 2004). Thus a TMDL was created in 2002 to address the issue of dissolved oxygen impairment, with other TMDLs addressing other pollution issues to come later. The end result was the development of a point-point phosphorus trading systems designed to address the issues in a cost effective manner

(Minnesota Pollution Control Agency 2004).

Current Status of Point-Point Trading System:

Through processes outlined later in this paper a waste load allocation goal was determined. The TMDL program set a phosphorus emissions limit of 45,869 pounds over the 61-day low flow period from August 1st to September 30st, a reduction of approximately 30,500 pounds from existing discharge levels. 25,389 pounds of the limit was allocated to point sources, with 23,258 pounds for Wastewater Treatment Facilities (WWTFs). This amounts to approximately 416 pounds per day that can be discharged by WWTFs during the low flow period without violating water quality standards. A permit trading program was instituted along the river that limits the discharges by large WWTFs, those discharging over 1800 pounds of phosphorus per year, but allows them to trade the rights to discharge each pound of phosphorus between one another, allowing for the reduction to occur where it is most cost effective. Despite the TMDL stating limits for only the 61-day low flow period, the trading program is in effect from May1st through September 30th. Thus it used adjusted requirements for point sources' total allocations. There were 40 WWTFs involved in the permit, but as of 2009 seven new WWTF have been formed and 2 have closed leaving 45 that are currently involved in trading, with an average of 17 trades occurring each year. As of 2010, 61,512 pounds of phosphorus effluent are allowed during the 5-month period and distributed between firms as shown in Table 1 below (Minnesota Pollution Control Agency 2005). The current trading program ignores non-point sources as the program assumes that phosphorus discharged by them will remain relatively constant or be reduced through adoption of best management practices. According to MPCA officials the permit trading program is currently locked at 2010 levels awaiting final approval of the next phase of the permit program from the Minnesota government.

Figure 1: Minnesota River Basin Map

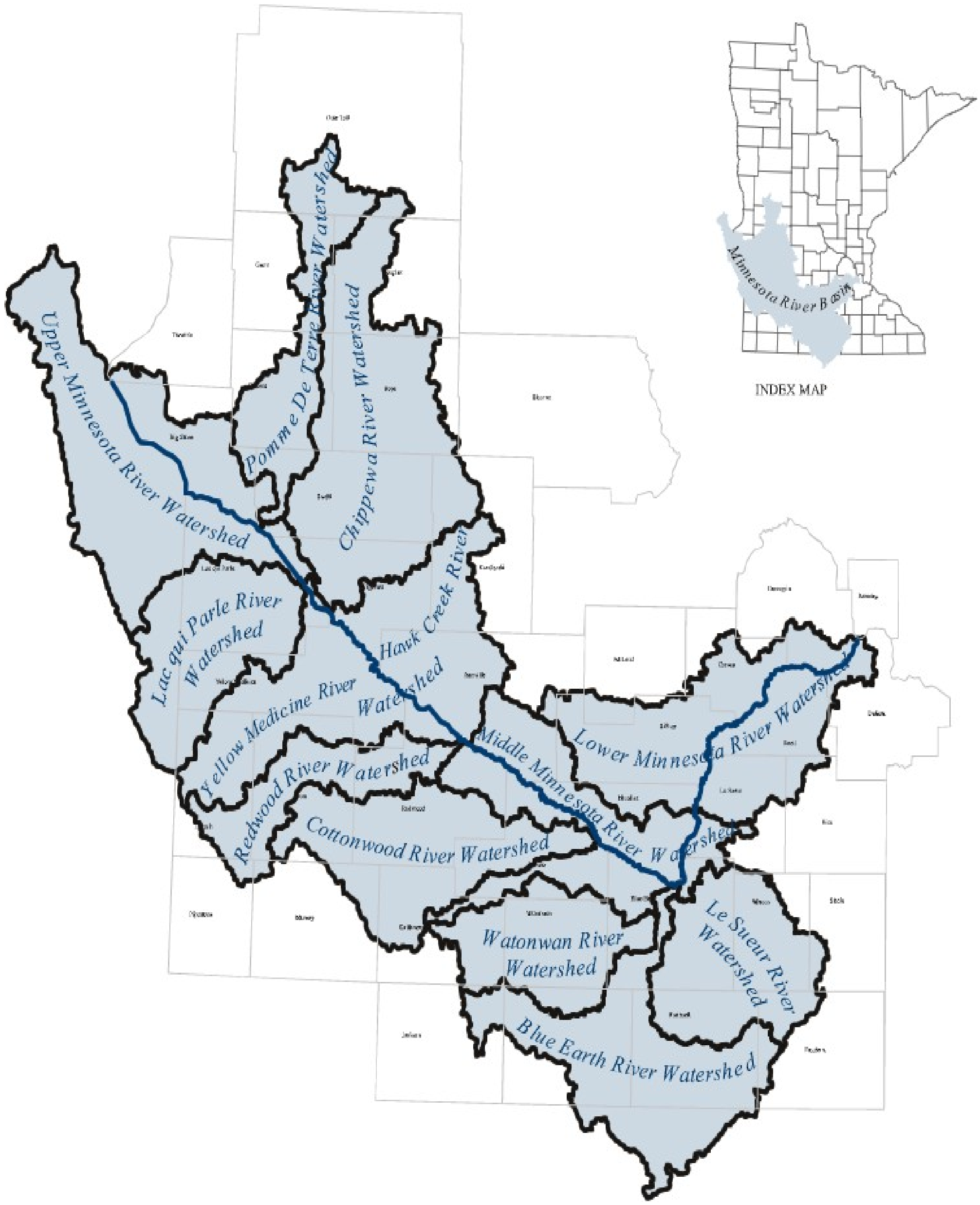


Table 1: Point Source Allocations on the Minnesota River

Permittee Name	Trading Baseline 2006-2007	Effluent Limit(EL) 2008	EL 2009	EL 2010	EL 2015
City of Amboy	111	111	111	111	1 mg/l or Final TMDL goal
ADM Co. - Marshall	5504	4512	3850	3189	1 mg/l or Final TMDL goal
City of Arlington	271	271	271	271	1 mg/l or Final TMDL goal
City of Belle Plaine	533	533	533	533	1 mg/l or Final TMDL goal
City of Benson	877	557	557	557	1 mg/l or Final TMDL goal
City of Blue Earth	1076	931	931	931	1 mg/l or Final TMDL goal
City of Clara City	292	281	274	266	1 mg/l or Final TMDL goal
Darling Int.	90	90	90	90	1 mg/l or Final TMDL goal
Del Monte Corporation	1726	1400	1183	967	1 mg/l or Final TMDL goal
City of Fairmont	2228	2057	2057	2057	1 mg/l or Final TMDL goal
City of Granite Falls	NA	NA	393	340	1 mg/l or Final TMDL goal
City of Lake Crystal	514	385	385	385	1 mg/l or Final TMDL goal
City of Le Center	417	348	348	348	1 mg/l or Final TMDL goal
City of Madelia	3484	1951	1951	1951	1 mg/l or Final TMDL goal
City of Mankato	12111	9603	9603	9603	1 mg/l or Final TMDL goal
City of Marshall	15234	12361	10446	8531	1 mg/l or Final TMDL goal
Milton Waldbaum Co.	1730	969	969	969	1 mg/l or Final TMDL goal
City of Montevideo	4934	4003	3383	2763	1 mg/l or Final TMDL goal
City of New Richland	243	243	243	243	1 mg/l or Final TMDL goal
City of New Ulm	7225	6036	5243	4450	1 mg/l or Final TMDL goal
City of Norwood Young America	3138	2546	2152	1757	1 mg/l or Final TMDL goal
City of Olivia	609	570	544	518	1 mg/l or Final TMDL goal
City of Redwood Falls	1277	1174	1105	1036	1 mg/l or Final TMDL goal
City of Renville	1681	1370	1163	956	1 mg/l or Final TMDL goal
City of Sacred Heart	142	127	117	107	1 mg/l or Final TMDL goal
City of Springfield	360	360	360	360	1 mg/l or Final TMDL goal
City of St. Clair	169	148	134	120	1 mg/l or Final TMDL goal
City of St. James	4743	3849	3252	2656	1 mg/l or Final TMDL goal
City of St. Peter	1531	1531	1531	1531	1 mg/l or Final TMDL goal
City of Starbuck	151	151	151	151	1 mg/l or Final TMDL goal
City of Trimont	NA	NA	154	154	1 mg/l or Final TMDL goal
City of Truman	319	319	319	319	1 mg/l or Final TMDL goal
City of Walnut Grove	137	126	117	110	1 mg/l or Final TMDL goal
City of Waseca	2600	2401	2268	2136	1 mg/l or Final TMDL goal
City of Welcome	104	104	104	104	1 mg/l or Final TMDL goal
City of Wilmar	12653	10372	8852	7332	1 mg/l or Final TMDL goal
City of Winnebago	687	687	687	687	1 mg/l or Final TMDL goal
MRVPUC	2923		2923	2923	1 mg/l or Final TMDL goal
NorthStar Ethanol	0	0	0	0	0
Granite Falls Energy LLC	0	0	0	0	0
Buffalo Lake Energy LLC	0	0	0	0	0
RBF Acquisition V	0	0	0	0	0
Highwater Ethanol LLC	0	0	0	0	0
Lower Sioux Indian Res.	0	0	0	0	0
Knollwood Mobile Home Park	0	0	0	0	0
Total:	91824	72477	68754	61512	
Removed Locations:					
City of Henderson	321	321	321	321	1 mg/l or Final TMDL goal
City of Le Sueur	2602	2602	2602	2602	1 mg/l or Final TMDL goal
Total:	94747	75400	71677	64435	

Note: For the years between 2010 and 2015, allocations remain fixed at their 2010 levels. The 1mg/l emission rate was determined to be a suitable goal for the final limits for discharges into the Minnesota River. Once this goal is set as the limit trades may still occur as necessary to make firms meet this discharge limit (Minnesota Pollution Control Agency 2005).

TMDL Goals:

The TMDLs Goal is to bring the Minnesota River into compliance with the dissolved oxygen standard. During summer low flow periods excessive Biochemical Oxygen Demand (BOD) depletes dissolved oxygen to dangerous levels that threaten fish species and macroinvertebrates. The problem mainly occurs in the lower 22 miles of the Minnesota River near Shakopee where the river is dredged to maintain a 9-foot navigation channel. Under low flow conditions, occurring during August and September, this channel becomes lake like with very slow-moving water. BOD largely comes from upstream sources in the form of direct discharges or algae blooms caused by excessive levels of phosphorus released into the river. The lake-like conditions of the channel allow these algae to decay, causing increased levels of BOD. Thus in order for the TMDL to achieve its goal BOD and phosphorus emissions must be reduced. To meet this end the TMDL process had 3 phases: (1) the 1985 Waste Load Allocation Study (WLA Study) which served as the basis for further study of the Minnesota River; (2) an analysis of nutrient impacts and the development of an implementation strategy; and (3) the development of a finer scale assessment system with information feedback loops to continually gather data on other impairment issues for the Minnesota River. This process ultimately resulted in the creation of a point-point trading program in the Minnesota River basin. Analysis suggested that this format could meet water quality goals while lowering costs. The permit program covered only select areas of the Minnesota River basin with areas upstream of Lake Laq Qui Parle included as one set value due to the lake slowing water flow into the river. Other areas were excluded either due to extreme distance reducing the effect of emissions or terrain that limited water flow into the River (Minnesota Pollution Control Agency 2004).

WLA Study and Modeling:

The 1985 WLA Study examined that water quality levels of the lower Minnesota River and concluded that unless the Blue Lake and Seneca WWTFs reduced their nutrient discharges the water quality of the Minnesota River would continue to decline. The study found that BOD from these sources would cause approximately 55% of the total shortage of dissolved oxygen at summer low flow periods. Reduction of discharges at these sources, however, would not be enough to correct the dissolved oxygen shortage. The WLA Study found that when these discharges combined with BOD already in the Minnesota River (from areas upstream of Shakopee) would cause BOD concentrations to average 6.1 mg/l during summer low flow periods at Shakopee where the resulting oxygen demand would overwhelm the river's ability to maintain water quality.

In order to meet the standard of an average of 5 mg/l dissolved oxygen per day (with compliance occurring if at least 50% of low flow days meet that goal) the WLA Study found that in, addition to reductions at the Blue Lake and Seneca facilities, BOD from upstream of Shakopee would need to be reduced by 40%. This set a BOD target of 3.7 mg/l at Shakopee, which requires a 0.131 mg/l phosphorus concentration. Discharge limits were created for the specific facilities and for the general upstream area of the river basin. Since BOD is primarily caused by excess levels of phosphorus spurring algae growth and death the WLA Study examined the primary sources of phosphorus in the river. While the largest source of nutrients in the Minnesota River is normally the agricultural sector, during low flow periods agriculture is not a major contributor due to decreased rates of run-off. Instead continuously discharging WWTFs become the primary source, contributing 65.1% of phosphorus despite contributing just 9% during other periods. Other sources include non-compliant sewage treatment systems, stormwater, and some agricultural discharges as even during low flow periods large storms can cause localized runoff. Phosphorus entering this way prior to low flow periods can also settle in the river before leading to BOD issues during the low flow period (Minnesota Pollution Control Agency 2004).

Following the WLA Study the Minnesota Pollution Control Agency (MPCA) began to identify upstream sources of BOD. Water quality was examined across the entire Minnesota River Basin and the information obtained linked BOD to algae and ultimately to phosphorus. Using this relationship, a basin scale computer modeling project was initiated using the Hydraulic Simulation Program – FORTRAN (HSPF). The model simulates water quality changes based on watershed hydrology, modifications of land use, and the amount of phosphorus and BOD discharged from point sources. An upstream boundary was set at Lac Qui Parle Lake as it has a dampening effect on the flow of the river, essentially counting all sources above there as one, while areas downstream divined into watershed segments. Data was provided for this project by the United States Geological Survey (USGS) and the Minnesota River Assessment Project (MRAP) monitoring stations along the river. Jordan Minnesota was used as the modeling endpoint (as opposed to Shakopee which was used in the WLA Study) as there is a monitoring station located there to provide superior data. The model covered 12,200 square miles of the 17,000 square mile Minnesota River Basin. Using data from 1986 to 1992 and updating for land use change and discharge data from 1999 or 2000 (depending on when data was available) the model defined low flow conditions as 272 cubic feet per second at Jordan Minnesota over a two-month period. It is noted that the HSPF model is more accurate for long-term water quality than for daily concentrations.

Sources of Biological Oxygen Demand:

There are a number of possible sources for oxygen demand. The TMDL document examines a list of common sources such as the nitrogen cycle, sediment oxygen demand such as the oxidation of iron, bacterial uptake of oxygen, direct discharges of organic material, and BOD from high levels of nutrients. Organic source and BOD are the primary concerns with the rest being relativity unimportant. Direct discharges of organic material are typically a large source of BOD, but the study found that it accounts for less than 30% of BOD at Jordan during low flow conditions. These discharges tend to mostly be absorbed by the river (either through uptake by plants or by settling on the riverbed) prior to reaching Jordan and thus they are more of a concern near the point source where they are discharged. Algal growth was responsible for 70% of BOD in the lower Minnesota River. On a daily basis, algae provides a net addition of dissolved oxygen to water, but during the night respiration can cause severe oxygen depressions.

MPCA Initial Scenarios:

In order to set emissions standards for the TMDL several scenarios were examined. The current loading of the Minnesota River was modeled as the first scenario for the river assuming no changes in land use or treatment of wastewater discharged. The model accounts for absorption and settling as sediment of phosphorus and finds that during low flow periods approximately 65.1% of phosphorus was generated by point sources under the current loading regime. While 75,000 pounds of phosphorus is discharged, only around 19,000 pounds is predicted to reach Jordan after losses within the watershed. The TMDL used this model as a baseline for comparison with other treatment scenarios that were generated to examine the effect of different pollution reduction initiatives.

Five scenarios, including the baseline model, were run to determine how sensitive the river was to various changes in discharges from different source categories. The various models evaluated the impact of high rates of non-point source abatement, point source controls, the load difference between actual discharge records and current permitted flows with larger facilities required to meet a phosphorus limit of 1 mg/l, and determined how much BOD loading was actually experienced at Jordan when compared to the nutrients released from various upstream locations. During the creation of these models the Minnesota Pollution Control Agency (MPCA) created guidelines to govern the scenario creation. These included considering the health of the entire basin as opposed to just the low flow event area, a requirement that each sector contribute something as each is part of the problem, concerns for timing, planning, and the cost of solutions, a baseline goal of reducing raw sewage released into the river by 90%, and a desire to include flexibility at the individual level rather than blanket requirements. By looking at comparisons of these models it appeared that the river was at a point of phosphorus saturation where other factors are limiting algae growth.

Another scenario (Scenario 6) was then created that aimed to balance the system. Using the previous scenarios and other data the MPCA created a few key assumptions for the model. First it set a limit of 1 mg/l phosphorus effluent year round for sites above 1,800 pounds of phosphorus discharged per year. It also assumes that agriculture would have 75% of row cropped land with 2% or greater slopes adopt 30% residue use or equivalent best management practices as well as some implementation of nutrient management systems. Standards were set for stormwater systems to reduce their phosphorus loading by 20-30 percent depending on category. Finally the scenario assumed that 90% of non-compliant independent sewage treatment systems (ISTS), which are generally privately owned septic systems, would come into compliance. Overall the scenario led to lower levels of phosphorus, higher water flows, and less algae growth.

After examining the response of the initial balance scenario, Scenario 7 was created. Scenario 7 was very similar to Scenario 6, but changed the requirements on WWTFs as well as added some goals for agriculture. WWTFs were allowed two different treatment plans. WWTFs could either use biological systems to reduce the amount of phosphorus or add chemicals to treat their emissions and raise flow levels during low flow periods in order to achieve the 1mg/l phosphorus limit. For agriculture the MPCA set goals of having 50% of surface tile intakes protected by row crops with 2 percent or less slope or buffer strips and having a 25% adoption of nutrient management for all row cropped acres. All other standards from Scenario 6 remained except the 90% compliance rule for ISTS, which was raised to 100% compliance. Overall Scenario 7 met the 3.7 mg/l BOD concentration goal at Jordan Minnesota with only 45,095 pounds of phosphorus discharged, a reduction of 30,500 pounds. These scenarios were then used as the baseline for determining target goals for phosphorus emissions that would result in the Minnesota River meeting the dissolved oxygen standard (Minnesota Pollution Control Agency 2004).

TMDL Allocations:

Minor adjustments were made and a loading capacity was selected for the river based on Scenario 7. As stated earlier the TMDL set the maximum pounds of phosphorus discharged over the 61-day low flow period at 45,869 pounds with 25,389 pounds allocated to point sources and 20,480 pounds allocated to non-point sources. Of the 25,389 pounds allocated to point sources 23,258 pounds are for WWTFs, 1,863 pounds are allocated to permitted stormwater sites, with the remaining 268.4 pound allocated to communities without proper sewage treatment systems. The non-point source phosphorus limit is split between agricultural land with 10,907 pounds, non-permitted stormwater cities with 8,999 pounds, natural sources that discharge 233 pounds, and non-compliant ISTS systems with 341 pounds. Overall the TMDL calls for a reduction in phosphorus discharged from 75,620 pounds during the 61 day low flow period to 45,869 pounds. The

TMDL differed from Scenario 7 in that WWTFs over the threshold of 1,800 pounds of phosphorus per year would participate in a watershed permit requiring seasonal effluent limits in 10 years as well as phosphorus management plans in the interim period, the ISTS goal was reduced to 90% compliance, and agricultural restrictions were removed. Phosphorus allocations were calculated for each major watershed in the Minnesota River Basin and permits were then distributed to individual point sources within each watershed.

Rather than set aside some amount of pollution to account for population growth or new facilities, also known as reserve capacity, and be forced to determine how to allocate extra permits, reserve capacity was instead accounted for in a number of different ways. For instance the plan reduces average concentrations of BOD to 3.68 mg/l, below the goal of 3.7 mg/l. Since much of the effluent from upstream sources is absorbed this small difference in projected outcome and the goal can allow some upstream sources a substantial amount of leeway. For sources closer to Jordan discharge limits for cities have 20 year projected growth capacity built into their allocations. Development of a permit trading program also can allow for some reserve capacity as trades could allow more efficient pollution abatement. For agricultural nutrient runoff the initial allocation was estimated for low flow conditions. When large storms come through they increase nutrient runoff, but the increased flow level more than offsets the increased amount of nutrients, and thus some reserve capacity is naturally built into the agricultural allocations as well.

A margin of safety was also calculated. For the most part this was included in the model assumptions and estimated to be 10% of the allocation, or 76 pounds of phosphorus per day. This was not used in the TMDL as a number of conservative factors included in the design built a margin of safety without it being expressly stated. These include the fact that the river has 17 additional miles to assimilate BOD between Jordan and Shakopee prior to the area of concern, that many of the permitted small inadequate WWTFs do not discharge anything to surface water but are part of the allocation anyways, the fact that agricultural goals were adopted that will hopefully reduce emissions that are not included in the TMDL, and finally many of the smaller facilities not included in the TMDL are still required to develop plans to reduce phosphorus by 30-50%. The model also shows that some of the best management practices for agriculture will increase the base flow of the river during low flow periods, lessening the frequency and duration of low flow periods, and thus help alleviate the problem. The TMDL estimates that these built in margins of safety will combine to reach the 76 pounds of phosphorus per day that was previously set (Minnesota Pollution Control Agency 2004).

Implementation:

The initial application plan laid out in the TMDL document has plans for each of the applicable sectors, although point sources are the primary focus. Starting in 2004 the TMDL would organize a watershed permit where WWTFs would develop phosphorus management plans that seek to reduce phosphorus discharges by 30-50%. During this same period the actual waste load allocation would apply to WWTFs that discharge over 1,800 pounds of phosphorus per year. To accomplish the reduction goal one of two strategies would be implemented for these facilities. The first would require them to meet a 1mg/l effluent limit to achieve a 51% reduction in phosphorus during the next 10 years. The second would be a point-point trading system to achieve a 35% reduction by the end of the first phase (2004-2009) followed by a second permit program requiring the 1mg/l effluent limit or equivalent pollutant trading offsets. If point-point trading were selected trading associations would be organized and incorporated into the permit to provide flexibility to achieve the interim goal of 35% reduction. Trade agreements would consider both geographic transport factors as well as actual discharged loadings. The TMDL program planned that whichever option was chosen new data would be consistently gathered and used to make adjustments. Ultimately a trading program was developed.

Agricultural reductions can be achieved with a number of implementation strategies. By implementing use of these best management practices phosphorus discharged should decrease. These practices include leaving crop residue on slopes with greater than a 3% incline to hold nutrients in place, reducing fertilizer use near waterways, shifting use of fertilizers to agronomic rates determined by the University of Minnesota, restoring native grasslands or wetlands, and increasing surface tile intake protection via pattern tiling, buffer strips, and other systems to hold nutrients in place or encourage ponding. ISTS systems have a much simpler approach whereby the TMDL simply suggests research to identify barriers to adoption of compliant systems and then development of strategies to resolve these issues. Urban stormwater systems will follow a similar path where they will evaluate their best management practices and develop plans for any new sites that will limit discharges (Minnesota Pollution Control Agency 2004).

Implemented Point-Point Trading Program:

The point-point permit trading program went into effect on December 1st 2005 and covered WWTFs that discharge more than 1,800 pounds per year. Guidelines and goals were the same as laid out in the TMDL document. WWTFs that fall under the permit must meet their assigned phosphorus effluent allocations or purchase permits from other facilities to offset the pollution. WWTFs that do not fall under the permit are still required to monitor phosphorus and develop phosphorus management plans. Unsewered or undersewered communities were included in the permit program and were required to apply for a permit, upgrade their system, and to purchase permits to offset any future increases in phosphorus discharged. Any new or expanding WWTFs in the Minnesota River basin will be required to purchase permits to offset their discharges above their initial allocation (which in the case of new facilities was 0). No reserve capacity for growth was built in so any expansion either had to result in no increase in phosphorus emissions or the firm was required to purchase the offsets. The permit program covered discharges between May 1st and September 31st with all firms being required to meet their 5 month allocations except in extreme cases. Trading was to be allowed at any time and constant flow monitoring ensures that WWTFs will have ample warning if they are nearing their limit. Permittees with a 1.0 mg/l phosphorus limit (the final goal of the TMDL) are not required to meet their 5-month mass phosphorus limits as long as they reached an agreement with the MPCA prior to April 2008. Firms that reach such an agreement are not participating in the permit trading program.

Trade associations are allowed in the permit, but according to the MPCA there have been no attempts to form them by permittees as of 2012. Trade associations would operate like an individual WWTF in that they were required to discharge phosphorus less than or equal to their allocation plus permits purchased and minus permits sold. Members inside a trade association would have some allocation of phosphorus that the association would assign to them. Trade associations add an extra layer of complexity, which is a possible reason they have not been formed.

Monitoring has occurred at each WWTF, which are required to report discharges every month. This allows the MPCA to keep track of how WWTFs are performing and thus warn them if they need to purchase more permits in order to meet their requirements. Each year prior to the start of trading each permittee will be required to create implementation plans to show how they intend to meet their 5 month goal. A number of other requirements are included such as estimations of permittee's anticipated phosphorus discharges.

Trading is performed using Jordan Trading Units (JTUs). JTUs take into account each WWTF's Jordan BOD factor, which is the percentage of their discharges that reaches Jordan as BOD, listed in Table 2, to make it so JTUs always represent the same impact at Jordan. Only large WWTF may participate in trading under this permit and all trades require trade forms to be filled out. Trading with non-point sources is not allowed, as non-point sources are not a major contributor to the problem during low flow periods. On top of this inclusion of non-point sources would add unnecessary complications to the trading system as determining the exact impact of various abatement options at non-point sources can be costly, as there are many variables to consider. Many other trading programs have failed due to trading being to expensive or time consuming and thus this program attempted to minimized transaction costs. When a WWTF enters into a trade they must compare their Jordan BOD factor with the other firm. First the WWTF decides on the kgs of phosphorous they want to buy. They then multiply the pollution they wish to purchase by their Jordan BOD factor, which gives the WWTF the number of JTUs they need to purchase. This number is then multiplied by a environmental trading (10% for current WWTFs and 20% for any new WWTFs) that ensures that with every trade total phosphorus permits are reduced. This tells the facility the total JTUs they must purchase. The seller then multiplies this number by the their own Jordan BOD factor to determine how much they must reduce their pollution by in kgs. In an effort to make this process easy and cheap, the MPCA made an online form for trades that is easily accessible and does all these calculations quickly showing exactly how many permits a firm would need to buy to raise its phosphorus limit to the desired amount. This form doubles as the paperwork to make a trade official after being signed off on by both parties. The simplicity of this form may have contributed to the lack of desire to form trade associations, as they eliminated most of the complexity from trading that they were designed to handle. While these are only the basics of the program it can be seen that trading is relatively simple and low cost. Since high costs and time delays have been a major problem for previous trading programs this system avoids a major pitfall (Minnesota Pollution Control Agency 2004).

Table 2: Jordan BOD Factor for source on the Minnesota River[1]

Permittee Name	ID	Jordan BOD Factor
City of Amboy	1	0.62
ADM Co. - Marshall	2	0.18
City of Arlington	3	0.67
City of Belle Plaine	4	1.00
City of Benson	5	0.11
City of Blue Earth	6	0.27
City of Clara City	7	0.13
Darling Int.	8	0.19
Del Monte Corporation	9	0.34
City of Fairmount	10	0.22
City of Granite Falls	11	0.10
City of Lake Crystal	12	0.72
City of Le Center	13	1.02
City of Madelia	14	0.29
City of Mankato	15	0.72
City of Marshall	16	0.18
Milton Waldbaum Co.	17	0.64
City of Montevideo	18	0.09
City of New Richland	19	0.36
City of New Ulm	20	0.47
City of Norwood Young America	21	1.00
City of Olivia	22	0.17
City of Redwood Falls	23	0.27
City of Renville	24	0.17
City of Sacred heart	25	0.17
City of Springfield	26	0.24
City of St. Clair	27	0.69
City of St. James	28	0.22
City of St. Peter	29	0.91
City of Starbuck	30	0.10
City of Trimont	31	0.15
City of Truman	32	0.19
City of Walnut Grove	33	0.20
City of Waseca	34	0.59
City of Welcome	35	0.15
City of Wilmar	36	0.13
City of Winnebago	37	0.30
MRVPUC	38	1.02
NorthStar Ethanol	39	0.72
Granite Falls Energy LLC	40	0.10
Buffalo Lake Energy LLC	41	0.22
RBF Acquisition V	42	0.69
Highwater Ethanol LLC	43	0.20
Lower Sioux Indian Res.	44	0.27
Knollwood Mobile Home Park	45	0.72
Total:		
Removed Locations:		
City of Henderson		1.03
City of Le Sueur		1.02
Total:		

1BOD Factors greater than 1 represent source whose emissions cause higher rates of BOD due to factors other than their emitted nutrients. Specifically heat from processed water can lead to BOD.

<u>Chapter 4: Cost Estimations</u>

In order to analyze the Jordan Trading Unit program currently in effect on the Minnesota River costs of pollution reduction at Waste Water Treatment Facilities (WWTFs) must be estimated. Each of the models presented in Chapter 3 seeks to minimize the cost of pollution abatement while meeting imposed emissions limitations. Therefore the actual cost of pollution abatement at each facility must be estimated. Estimates of these costs are available from an engineering study performed by Jiang *et al.* (2005) as well as from a paper on the Chesapeake Bay by Sado *et al.* (2010). This Chapter will examine the cost estimation strategies in each of these documents, a description of the data needed and its availability, followed by an example of the cost estimation strategy used in this paper.

Cost Estimation Strategy:

Jiang *et al.* (2005) is the second of a series of papers estimating the cost of phosphorus removal for WWTFs. The first paper, Jiang *et al.* (2004) is concerned with the cost of constructing new facilities and thus is not applicable to the process of minimizing cost of abatement for the current facilities in the Jordan Trading Unit Program. One exception to this is that the first paper does list the cost for the basic Activated Sludge system, which the second paper assumes is already installed prior to improvements in the WWTF. Jiang *et al.* (2005) estimate the cost for upgrading WWTFs of various sizes, ranging from 1 million gallons per day (MGD) to 100 MGD, to effluent standards of 2.0 mg/l phosphorus and several limits between 1.0 mg/l and .05mg/l. The paper assumes a general level of technology for the WWTF for phosphorus removal and assumes that plants start lower that a 4.0 mg/l phosphorus emissions level.

Jiang *et al.* (2005) analyze the cost of installing and operating several types of technology that are projected to achieve various levels of phosphorus emissions. The primary upgrades are installing biological tanks with remove phosphorus through Anoxic/Oxic reactions or through Anaerobic/Anoxic/Oxic reactions. They also include a design estimate for chemical additions to flows that remove phosphorus. They project these costs for applications of Alum (composed of aluminum and sulfate) that reacts to remove phosphorus. Other chemical methods such as applications of Feric Chloride are not estimated. Finally Jiang *et al.* (2005) estimates the costs for various other options such as sand filters, ultra-filters, and clarifiers. Jiang *et al.* (2005) is very careful to include costs for all aspects of installing and operating these systems including energy, chemicals, waste disposal, installation, operation, and maintenance (OM). While Jiang *et al.* (2005) calculated these costs as an example for what water quality treatment plants might face it is important to note that their study estimated the costs for a specific facility. Due to location, different inflows of pollution, and other factors, costs will vary from facility to facility.

The results of Jiang *et al.* (2005) list the costs of each method that is successful at meeting each phosphorus concentration target. The results break down where costs originate from and note which option is projected as the most cost effective. For instance between levels of 2.0 mg/l and 0.5mg/l phosphorus the activated sludge system with additions of alum was found to be the most cost-effective option, while at lower concentrations the size of the WWTF has a larger impact and influences design choices. Overall Jiang *et al.* (2005) contains a number of strong cost estimates for upgrades that result in various levels of phosphorus concentrations at WWTFs. These can be used to help estimate the costs of abatement for plants in a simulation of water quality permit trading using the various models stated above. Using the cost estimates regression analysis could be used to develop functions to estimate the cost of abatement for each WWTF in the model and thus provide the cost data necessary to complete my analysis.

Sado *et al.* (2010) estimated the costs for phosphorus abatement at 104 WWTFs in the Chesapeake Bay watershed using actual cost data and engineering methods. Using the data they gathered Sado *et al.* (2010) estimated cost functions for operation and maintenance (OM) as well as for capital costs (CC). They only estimated costs for two concentration levels (1mg/l and 0.1 mg/l) but the results are useful nevertheless. Using their data they estimated the following OM function:

$$\ln OM = \ln \alpha + \beta \ln \mathrm{C} + \gamma \ln \mathrm{F} + \delta \ln \mathrm{C} \ln \mathrm{F} + \ln \mathrm{u} \qquad (22)$$

where OM is the annualized operations and maintenance costs, C is the final phosphorus concentration in mg/l, and F is the daily flow of the facility in MGD. α, β, γ, and δ are the estimated parameters and *u* is the error term. From this equation they calculated the marginal cost of removing phosphorus to be the following equations:

$$\partial OM/\partial C = [\beta + \delta \ln F][OM/C] \qquad (23)$$

$$\partial OM/\partial F = [\gamma + \delta \ln C][OM/F] \qquad (24)$$

Their regression resulted in a high R^2 value of .879 as the estimates were based off of engineering relationships. They found their estimates to be statistically significant.

Similarly they estimated another equation for the capital costs for upgrading WWTFs to remove phosphorus. Their estimates were found to be statistically significant, but suffered from very little variation in capital costs estimated for each WWTF. The following equation represents their capital cost function:

$$\text{Ln CC} = \ln \eta + \kappa \ln C + \varsigma \ln F + \omega \ln C \ln F + \ln v \qquad (25)$$

where CC is the capital investment cost and *v* is the error turn while η, κ, ς, and ω are the variables. Using Sado *et al.* (2010)'s results for their regressions could allow for estimations of the OM and capital costs for the WWTFs involved in the Jordan Trading Unit program. Unfortunately these regressions assumed that WWTFs had no previous method available to them to treat water of phosphorus and thus the cost functions represent the costs of brand new technology and do not account for firms attempting to improve technology slightly. Therefore any data derived from using these functions would most likely be a poor estimate for costs of phosphorus abatement for WWTFs involved with the Jordan Trading Unit program as the majority already have some sort of phosphorus treatment system in operation. Sado *et al.* (2010) actually attempts to estimate the costs for abatement of only upgrading to use chemical inputs to reduce phosphorus, resulting in surprisingly low capital cost estimates due to their avoidance of installing more costly machines. This most likely would limit potential pollution abatement as there is only so much reduction that can be accomplished through chemical additions before the PH level of waste water becomes to acidic too be discharged from the WWTF.

Data Description and Background:

To estimate costs using either Jiang *et al.* (2005) or Sado *et al.* (2010) requires very similar data that is available from the same source. The MPCA has 5 years' worth of data available that list the average monthly phosphorus concentrations, water flow, total phosphorus, and more for each WWTF involved in the program. Other documents for the MPCA contain information on the design specifications for each WWTF including lists of all the pollution abatement technology present. This data should allow for the estimation of costs using either Jiang *et al.* (2005) or Sado *et al.* (2010).

The Sado *et al.* (2010) method would work quite easily as all it requires is data on the phosphorus concentration and daily flow rate. Both of these numbers are readily available and could result in quick estimations of cost for current OM for each plant as well as estimations for improving plants to better phosphorus concentration levels. As stated earlier Sado *et al.* (2010) will most likely result in poor estimates of the costs as the paper assumes that the WWTF do not currently have Phosphorus abatement systems in place. This would only play a factor in the estimation of capital costs, as will be shown later.

Estimating costs from Jiang *et al.* (2005)'s data can be accomplished in a similar manner to Sado *et al.* (2010), just with one more step added. By regressing the cost data in Jiang *et al*. (2005) on the size and phosphorus concentration listed we can estimate the equation used in Sado *et al.* (2010) but with the cost estimates from Jiang *et al*. (2005). While Jiang *et al*. (2005) assumes a lower level of technology than what is currently installed in most facilities this can be more easily adjusted for than Sado *et al.* (2010), where the base assumption is no phosphorus treatment technology at all. The regression results are similar to Sado *et al.* (2010) with the exception of the intercepts and the interaction terms. With this equation we can estimate the costs for all facilities in the trading program. The OM costs are easily managed by simply plugging in the size of the plant and the desired phosphorus concentration level. Capital costs are more difficult, as they assume upgrading from some basic level of technology to the end technology, with no steps in between. Because of this capital costs for a specific upgrade, say from 2 mg/l phosphorus to 1 mg/l phosphorus, can be adjusted by simply subtracting the capital cost estimate for the higher concentration level from the capital cost estimation for the goal phosphorus concentration level. The results from the regression are listed in Table 4.

Table 3: Cost Estimation using Jiang *et al.* (2009) Data

	Coefficient	Standard Error	t Stat	P Value
OM costs				
Intercept	6.27203	0.20681	9.878	1.49E-8***
ln C	-0.92282	0.12316	-7.493	2.32E-7***
ln F	0.81566	0.06489	12.570	3.08E-11***
ln C*ln F	-0.01134	0.03864	-0.294	0.772
R-squared	0.4123			
Adjusted R-squared	0.9535			
Observations	25			
Capital Costs				
Intercept	32.34955	0.48524	7.165	4.60E-7***
ln C	-0.82418	0.28898	-2.852	.00954**
ln F	0.34555	0.15225	2.270	.03389*
ln C*ln F	-0.1450	0.09067	-1.599	.12472
R-squared	0.9675			
Adjusted R-squared	0.7860			
Observations	25			

Illustration of Cost Estimation:

Costs will be estimated using the regression calculated with Jiang *et al.* (2005)'s data and Sado *et al.* (2010)'s equation. The issues inherent in Sado *et al.* (2010)'s assumptions make it more difficult to work with than Jiang *et al.* (2005) and thus will not be used to calculate costs for pollution abatement on the Minnesota River. A comparison of the results will be presented, however, so as to illustrate the impact of Sado *et al.* (2010)'s assumptions. Using the regression calculated from Jiang *et al.* (2005) we can easily calculate costs for each plant on the Minnesota River. As an example presented in Table 5 are the costs Jiang *et al.* (2005) would estimate for each Wastewater Treatment Facility at their current size and with their current emissions phosphorus concentration level. It should be noted that capital costs presented below are the costs associated with improving the plant to its current phosphorus concentration level from a level of 4 mg/l and in this case mean little. When used to estimate capital costs of improvement these capital costs will be subtracted from the costs estimated by the regression to determine the cost of the upgrade.

These cost estimates serve as an approximation of actual costs. For instance the wastewater treatment facility for the City of Mankato is estimated to have OM costs of $2.084 million per year. In actuality the City of Mankato estimated their OM costs for 2011 to be $1.009 million (Fralish 2012). While this estimate approximately doubles Mankato's reported OM costs this is most likely not very problematic assuming that OM costs are over estimated for other facilities as well. For Mankato's recent upgrade from a phosphorus concentration of approximately 3 mg/l to around .2 mg/l the equation estimates this costing $4.948 million, while in actuality the upgraded cost around $7 million. This reveals that regression for capital costs currently underestimates costs for firms reducing phosphorus to concentrations between 1 and .5 mg/l. At the same time it slightly overestimates the capital costs for smaller firms by a slight margin.

Table 4: Minnesota River Wastewater Facility Cost Estimates[2]

Permittee Name	Design flow (MGD)	Phos (mg/L) Avg	OM ($10^4)	Capital ($10^4)
City of Amboy	0.287	1.677	1.416	15.069
ADM Co. - Marshall	2.64	7.463	2.119	6.505
City of Arlington	0.67	0.837	5.326	32.276
City of Belle Plaine	0.84	0.598	8.740	45.952
City of Benson	0.985	0.810	7.522	38.255
City of Blue Earth	0.98	0.497	11.769	57.085
City of Clara City	0.46	1.826	1.920	16.113
Darling Int.	0.15	0.421	2.908	26.991
Del Monte Corporation	0.768	1.005	5.033	29.411
City of Fairmont	3.9	0.724	25.777	72.030
City of Granite Falls	0.8	1.841	2.981	18.470
City of Lake Crystal	0.59	0.272	13.474	71.437
City of Le Center	0.824	0.556	9.188	48.252
City of Madelia	1.31	0.872	8.874	39.969
City of Mankato	11.25	0.200	208.449	494.854
City of Marshall	4.5	6.440	3.715	7.808
Milton Waldbaum Co.	0.4	0.688	4.177	30.515
City of Montevideo	3	3.330	4.989	14.487
City of New Richland	0.6	2.494	1.789	13.662
City of New Ulm	6.77	2.307	13.553	24.949
City of Norwood Young America	0.908	3.485	1.834	11.380
City of Olivia	0.98	1.848	3.501	19.399
City of Redwood Falls	1.321	1.401	5.759	26.607
City of Renville	0.853	7.565	0.854	6.053
City of Sacred Heart	0.237	3.338	0.650	9.368
City of Springfield	0.78	1.113	4.640	27.281
City of St. Clair	0.212	1.828	1.025	13.184
City of St. James	2.96	4.937	3.415	9.819
City of St. Peter	4	0.649	29.158	81.367
City of Starbuck	0.35	1.459	1.889	17.463
City of Trimont	0.186	0.500	2.974	27.035
City of Truman	0.78	2.201	2.479	15.944
City of Walnut Grove	0.203	3.044	0.624	9.636
City of Waseca	3.5	1.626	11.052	30.591
City of Welcome	0.26	2.423	0.936	11.642
City of Willmar	7.5	5.855	6.100	9.025
City of Winnebago	1.7	1.457	6.818	27.691
MRVPUC	1.842	0.458	21.340	81.503
Buffalo Lake Energy LLC	0.509	0.542	6.333	39.965
Knollwood Mobile Home Park	0.0178	2.950	0.091	6.202
Guardian Energy LLC	0.25	0.308	5.892	41.739
POET Biorefining – Lake Crystal	0.1296	1.239	1.100	14.928

2 Average phosphorous concentrations over the course of the program are used for determining costs.

Figure 2 shows the predicted OM costs for the WWTFs on the Minnesota River using the equation generated with the data from Jiang *et al.* (2005) along with 3 lines representing the regression function solved for three selected design flow levels: .5 MGD, 5 MGD, and 10 MGD. The Majority of WWTFs on the Minnesota River are close to the .5 MGD size, with very few reaching larger sizes. Figure 3 presents the predicted OM costs for the Minnesota River WWTFs using the Sado *et al.* (2009) equation without alterations and with similar regression lines for the three selected design flow levels. While the results are very similar Sado *et al.* (2009) has higher estimates of the costs. This difference in the OM costs should not be large between the models because even with the different base technology assumptions the OM costs should end up being relatively similar, with a more noticeable difference occurring when capital costs are examined.

This can be observed by comparing Figure 4 and Figure 5. Figure 4 presents the predicted capital costs for the Minnesota River WWTFs using the regression equation from Table 4, while Figure 5 presents these same costs estimated using the Sado *et al.* (2010) regression. Once again each graph includes curves that represent the regression equations solved at each of the three selected design flow levels. Sado *et al.* (2010)'s results actually estimate much lower capital costs than Jiang *et al.* (2005). This is not surprising given the assumption that reduction would happen primarily through chemical additions. It is somewhat surprising that Sado *et al.* (2010) assumed that low phosphorus concentrations would be possible using this method and it is clear from the results that this led to a lower estimate of Capital Costs than Jiang *et al.* (2005) across the board.

Figure 2: Predicted OM Costs on MN River Data with Fitted Regression Lines

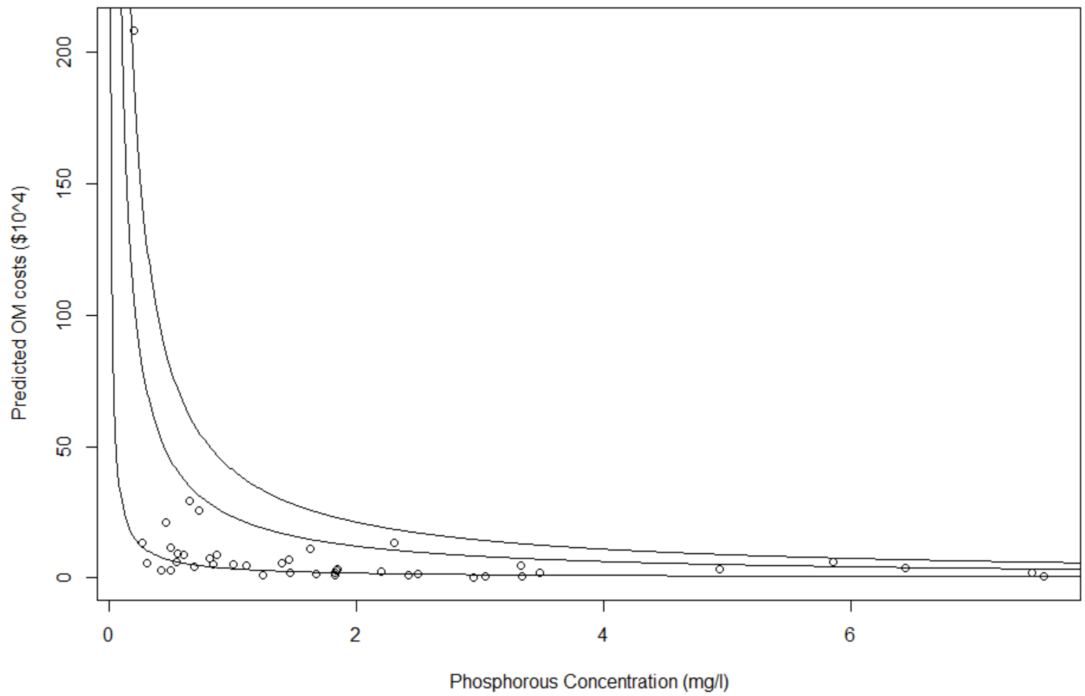


Figure 3: Predicted OM Costs on MN River Data Using Regression From Sado et al. (2009)

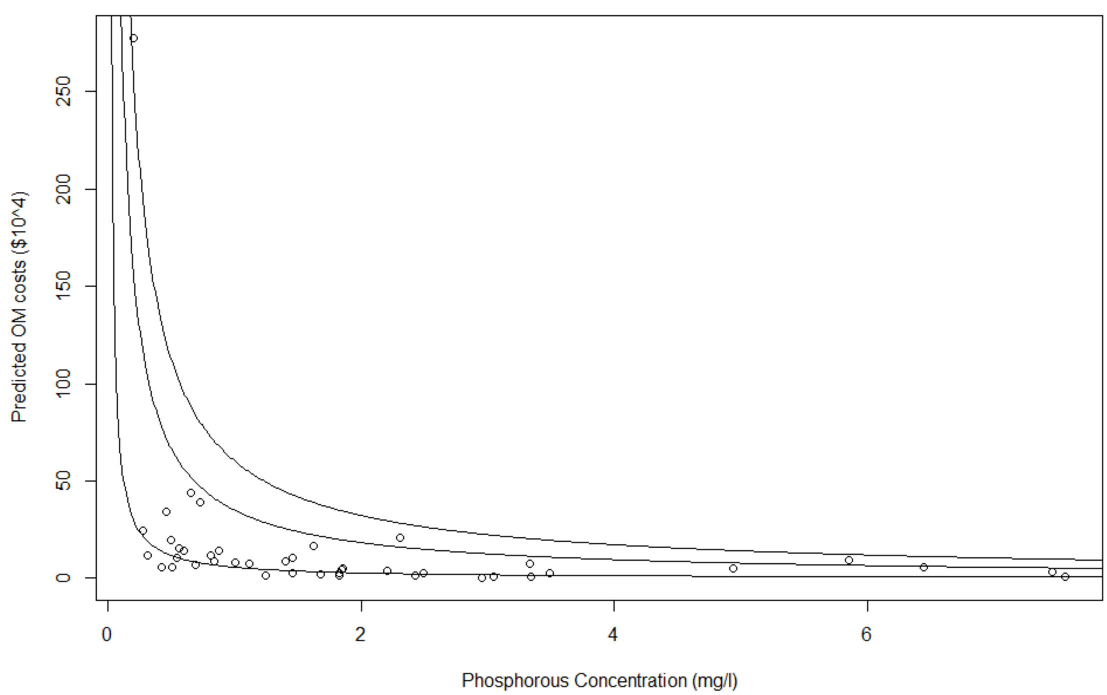


Figure 4: Predicted Capital Costs on MN River Data with Fitted Regression Lines

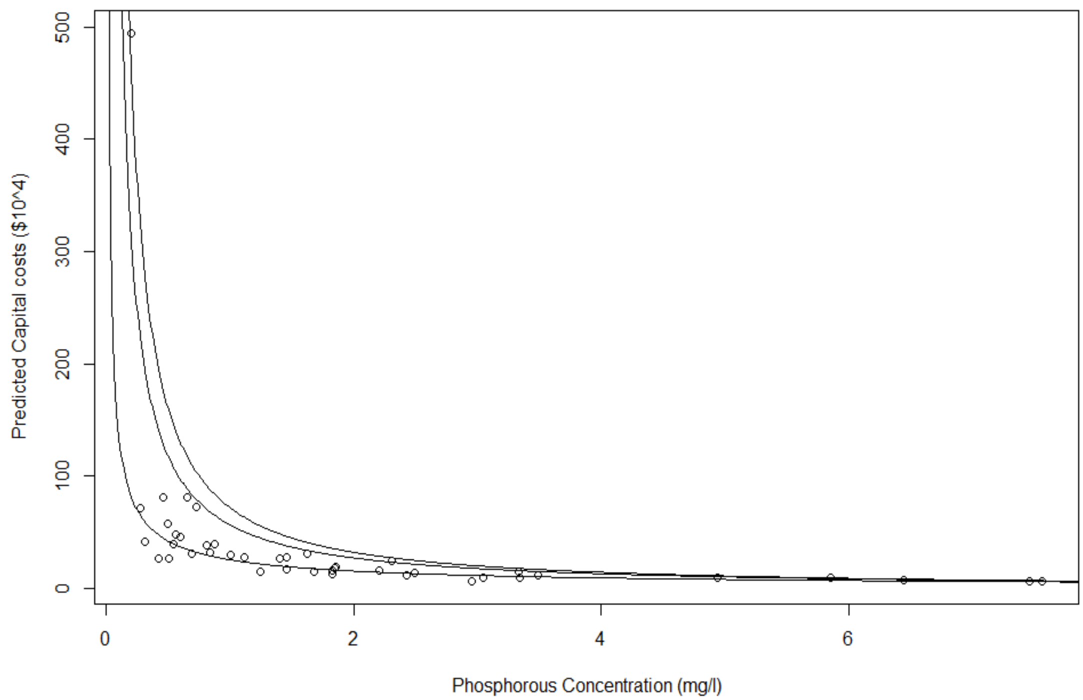
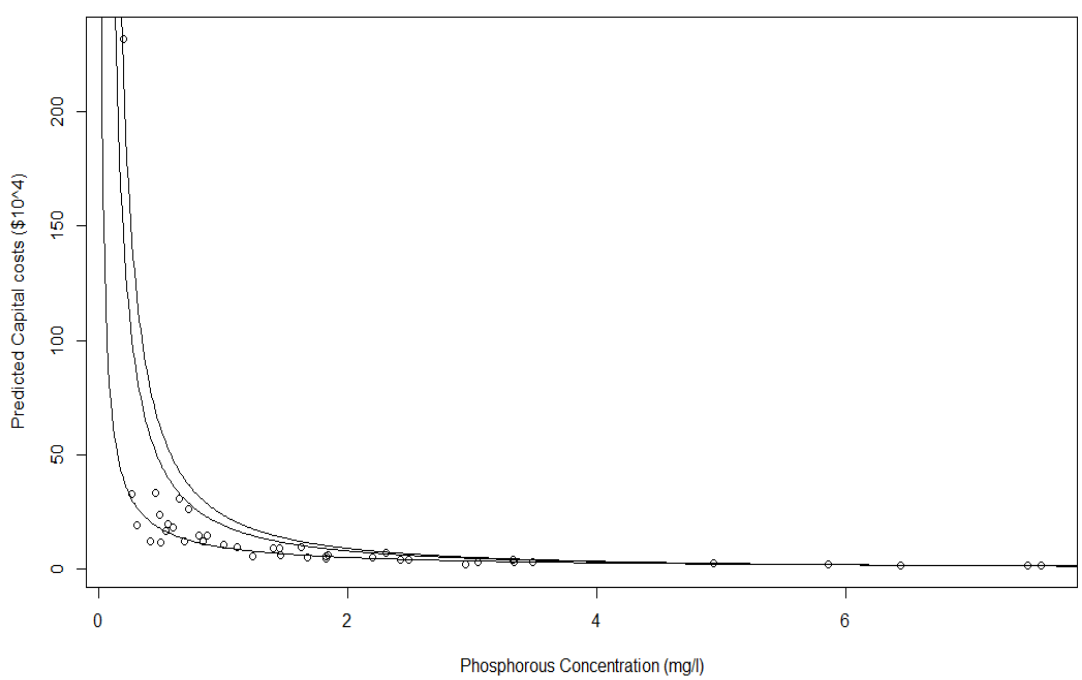


Figure 5: Predicted Capital Costs on MN River Data Using Regression Results from Sado et al. (2009)



Since the regression based on Jiang *et al.* (2005) seems to be a good fit we can then calculate the marginal cost for pollution abatement. Sado *et al.* (2010) do this in their paper with their results, and thus since their equation is the source for this regression the marginal cost equation can be computed in a similar way. Plugging in values to equations (23) and (24) from above we can create the following functions to represent the marginal cost for pollution abatement:

$$\partial OM/\partial C = (-.92282-.01134*\ln F)*OM/C \tag{26}$$

$$\partial OM/\partial F = (0.81566-.01134*\ln C)*OM/F \tag{27}$$

$$\partial CC/\partial C = (-.82418-.145*\ln F)*CC/C \tag{28}$$

$$\partial CC/\partial F = (.34555-.145*\ln C)*CC/F \tag{29}$$

In (26)-(29) C is the final phosphorus concentration and F is the design flow of the WWTF. This results in a curved marginal cost function showing that costs increase slowly as concentration falls until a point below a concentration of 1 mg/l where costs begin to rise rapidly. In the future we will only be concerned with the costs as concentration changes as we will assume that the size of the facilities remains constant throughout trading. Since there are different marginal costs for OM and CC costs we can create a function representing total marginal costs.

$$MC_i(C_i) = ((-.92282-.01134*\ln F_i)*OM_i + (-.82418-.145*\ln F_i)*CC_i)/C_i \tag{30}$$

Finally it should be noted that all marginal cost values should be negative, as they estimate the slope of the cost curve as phosphorus concentration increases.

Jiang *et al.* (2005)'s data provides a decent estimation for OM costs of the Minnesota River and will provide adequate values to allow a trading program's ideal solution to be calculated. While the costs estimated for Mankato do not match those calculated by the plant itself the numbers are still acceptable. Since Jiang *et al.* (2010)'s data came from a case study of one facility costs will vary, as many factors will not be the same at WWTF's in Minnesota. Nevertheless these estimates are more useful than those generated using data from Sado *et al.* (2010). As long as costs vary and show increasing marginal costs then the results should allow the trading program to be solved without too much error. The basic assumptions from Sado *et al.* (2010) make using their estimated numbers impractical. The basic equation from their paper is still useful, however, and combined with the data from Jiang *et al.* (2005) led to a more useful regression. Thus Jiang *et al.* (2005) provides a good starting ground for analyzing the cost of phosphorus reduction at wastewater treatment facilities for the purpose of studying pollution permit trading using data from the Minnesota River.

Estimating the Jordan Trading Program's Success:

Using the estimated cost functions the success of the Jordan Trading Program can be estimated by comparing the current total costs for the facilities with the estimated costs of a no-trade alternative. No-trade costs can be estimated by choosing a year, in this case 2011, and undoing the trades that occurred, then calculating the costs. The costs of our no trade scenario actually are lower than the results after trading for 2011, but this might be due to the fact that these facilities are not attempting to maximize profits, and thus some of the facilities selling permits might not actually increase pollution rates if they were not selling permits. To simulate this costs were also calculated keeping any facility that sells permits at their 2011 post trade pollution level if that facility was already emitting less pollution than their permits allowed them to even if they did not trade. This was the case for most sellers. The results of these estimations are presented in table 5, with the total costs of this second no-trade scenario, labeled No Trade Cost 2. In this scenario there was actually cost savings from trades. We are leaving one major thing out, however, in this analysis. New facilities that were granted 0 permits were not included in these cost estimates as our cost functions react poorly to 0 values and adjusting these to be very low phosphorous concentrations might not be practical due to high costs. Most likely a no trade system would have to adjust permits to give these facilities some, and if these values were low it might result in increased savings from a trading program.

Tables 5: Cost Comparison of Trading Program Vs no Trade Scenarios[3]

Permittee Name	2011 Phos (mg/L) Avg	JTU Program 2011 ($10^4)	No trade cost ($10^4)	No trade cost 2 ($10^4)
City of Amboy	1.6124	16.9239	16.9239	16.9239
ADM Co. - Marshall	8.758	7.3992	19.7695	19.7695
City of Arlington	0.578	50.3549	50.3549	50.3549
City of Belle Plaine	0.4908	64.2601	64.2601	64.2601
City of Benson	0.8692	43.1619	43.1619	43.1619
City of Blue Earth	0.395	83.4215	83.4215	83.4215
City of Clara City	0.748	34.7543	34.7543	34.7543
Darling Int.	0.3068	36.0032	36.0032	36.0032
Del Monte Corporation	0.4422	66.7864	66.7864	66.7864
City of Fairmont	0.8042	88.0331	70.4996	88.0331
City of Granite Falls	0.8072	41.8517	41.8517	41.8517
City of Lake Crystal	0.1674	123.5788	35.6989	123.5788
City of Le Center	0.6584	50.0699	50.0699	50.069
City of Madelia	0.9716	44.4365	44.4365	44.4365
City of Mankato	0.2928	461.295	358.3786	461.295
City of Marshall	4.5288	16.4408	16.4408	16.4408
Milton Waldbaum Co.	0.5686	39.7952	39.7952	39.7952
City of Montevideo	1.291	48.884	48.884	48.884
City of New Richland	2.066	17.8591	18.0089	18.0089
City of New Ulm	0.7054	133.5072	133.5072	133.5072
City of Norwood Young America	2.8966	15.3932	9.3701	15.3932
City of Olivia	1.2064	32.7255	32.7255	32.7255
City of Redwood Falls	1.5004	30.4846	30.4846	30.4846
City of Renville	1.6354	24.1497	13.0776	13.0776
City of Sacred Heart	1.8808	14.4277	14.8841	14.8841
City of Springfield	0.74	44.3959	44.395	44.3959
City of St. Clair	0.5074	31.6928	31.6928	31.6928
City of St. James	4.0854	15.9004	15.9004	15.9004
City of St. Peter	0.6872	104.3545	86.0106	104.3545
City of Starbuck	0.961	25.8792	26.0025	26.0025
City of Trimont	0.3688	36.1909	36.1909	36.1909
City of Truman	0.7432	44.2414	44.2414	44.2414
City of Walnut Grove	2.7274	10.9738	16.5471	16.5471
City of Waseca	0.9548	70.4459	70.4459	70.4459
City of Welcome	1.7238	15.6963	16.9134	16.9134
City of Willmar	1.063	91.2458	91.2458	91.2458
City of Winnebago	1.0682	45.711	45.711	45.711
MRVPUC	0.4492	104.6661	104.6661	104.6661
Buffalo Lake Energy LLC	0.5584			
Knollwood Mobile Home Park	2.8148			
Guardian Energy LLC	0.2412			
POET Biorefining – Lake Crystal	0			
	Total:	2227.3914	2003.5118	2236.2086

3 All costs are in $ 10^4

Chapter 5: Damage Estimations:

In order to evaluate the Farrow et al. (2005) trading program a value for damages due to pollution must be estimated. Farrow et al.'s (2005) paper presents the following equation for damages:

$$d_i = \sum_{n=0}^{N} (WTP * H_N) * l_n \frac{C_{\text{in}}^b}{C_{0\text{i}}^b} \frac{1}{Q_{0\text{i}}} \tag{31}$$

Where d_i is the damage caused by each unit of emissions, WTP is the willingness to pay for pollution abatement, H_n is the number of households affected by the water quality change, $l_n * C^b_{ni} / C^b_{0i}$[4] is a substitute value for the transfer coefficient and can be represented as $\tau_i(n)$, and Q_{0i} represents the flow of the river at the point that emissions occur (Farrow *et al.* 2005). This is represented by Konishi et al. (2013) as:

$$d_i = \sum_{m=1}^{M} WTP * H_m * \tau_{mi} * \frac{1}{Q} \tag{32}$$

where the same definitions hold for each of the variables. Farrow *et al.* (2005) justify a constant value for WTP by arguing a linear relationship to pollution concentrations and water quality and they state that "the household marginal willingness to pay for a small improvement in water quality, WTP, is constant... over the range of water quality conditions considered in this study." Essentially this states that as long as the extremes are not included (eliminating the very last bit of pollution, or evaluating an extremely dirty river) WTP should be close to constant, and thus it is not unreasonable to set it to a constant value.

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4 L_n is a discrete distance interval, while C^b_{ni} and C^b_{0i} represent the new and initial load concentrations respectively.

Evaluating for damages would be relatively easy, but for one primary issue: there are currently very few available and reliable estimations of the willingness to pay for phosphorus abatement on rivers. While there are a number of papers on the WTP for phosphorus abatement in lakes, such as the one by Minnesota Pollution Control Agency (2008), and even some data on the WTP for nitrogen reduction in lakes, there is only one academic paper that we could find on the benefits of phosphorus pollution reduction. Fortuitously this paper, by Mathews, Homans, and Easter, estimated WTP for a 40% reduction in phosphorus on the Minnesota River. Their results estimated that households had a WTP of $140 per year for phosphorus reductions on the Minnesota River (Mathews et al. 2002). Since this is for a 40% reduction in phosphorus we must first transform this value to be in dollars per kilogram phosphorus removed. The result is a WTP of approximately $0.01 per household per year per kilogram Phosphorus removed. This is a low value, but represents a great deal of money when multiplied by the number of households in a watershed. We can use this value as a baseline WTP, but since it is only one study we intend to test the sensitivity of trading programs to this number.

Since only one value of WTP could be estimated we choose to use several values of WTP both above and below our estimated value. Damages were then calculated using WTP values of starting at $0.009 and increasing to the value of $0.1. The population of Scott County (where Jordan is located) is used to approximate those effected by pollution at Jordan Minnesota, and this value was divided the average number of people per household in Minnesota, which was 2.48 people (United States Census Bureau 2010), giving an estimate of 52390.3 households in Scott County**.** Jordan BOD factors were used as transfer coefficients and the flow of the river was set at 272 cubic feet per second, which is the average flow of the Minnesota River during low flow conditions at Jordan Minnesota (Minnesota Pollution Control Agency 2004). To calculate damages the flow must first be adjusted into liters per second, which gives a value of 7701.952 . The results of this estimation are presented below in Table 6.

Damages are presented in dollars of damage at Jordan Minnesota per kilogram phosphorus emitted by each source. Sources closer to Jordan will cause more damage per kilogram, and thus abatement closer to Jordan reduces damage the most per unit of abatement. These damage values will be used in our model simulations in Chapter 6.

Table 6: Damages Per Kilogram Phosphorus Emitted by Facilities

Faciltiy	WTP=0.009	WTP=0.01	WTP=0.011	WTP=0.013	WTP=0.02	WTP=0.1
City of Amboy	1.10	1.22	1.34	1.58	2.44	11.94
ADM Co. - Marshall	0.32	0.35	0.39	0.46	0.71	3.47
City of Arlington	1.19	1.32	1.45	1.71	2.63	12.90
City of Belle Plaine	1.77	1.97	2.16	2.56	3.93	19.26
City of Benson	0.19	0.22	0.24	0.28	0.43	2.12
City of Blue Earth	0.48	0.53	0.58	0.69	1.06	5.20
City of Clara City	0.23	0.26	0.28	0.33	0.51	2.50
Darling Int.	0.34	0.37	0.41	0.49	0.75	3.66
Del Monte Corporation	0.60	0.67	0.74	0.87	1.34	6.55
City of Fairmont	0.39	0.43	0.48	0.56	0.86	4.24
City of Granite Falls	0.18	0.20	0.22	0.26	0.39	1.93
City of Lake Crystal	1.27	1.42	1.56	1.84	2.83	13.87
City of Le Center	1.80	2.00	2.21	2.61	4.01	19.65
City of Madelia	0.51	0.57	0.63	0.74	1.14	5.59
City of Mankato	1.27	1.42	1.56	1.84	2.83	13.87
City of Marshall	0.32	0.35	0.39	0.46	0.71	3.47
Milton Waldbaum Co.	1.13	1.26	1.38	1.64	2.52	12.33
City of Montevideo	0.16	0.18	0.19	0.23	0.35	1.73
City of New Richland	0.64	0.71	0.78	0.92	1.42	6.93
City of New Ulm	0.83	0.92	1.02	1.20	1.85	9.05
City of Norwood Young America	1.77	1.97	2.16	2.56	3.93	19.26
City of Olivia	0.30	0.33	0.37	0.43	0.67	3.27
City of Redwood Falls	0.48	0.53	0.58	0.69	1.06	5.20
City of Renville	0.30	0.33	0.37	0.43	0.67	3.27
City of Sacred Heart	0.30	0.33	0.37	0.43	0.67	3.27
City of Springfield	0.42	0.47	0.52	0.61	0.94	4.62
City of St. Clair	1.22	1.36	1.49	1.76	2.71	13.29
City of St. James	0.39	0.43	0.48	0.56	0.86	4.24
City of St. Peter	1.61	1.79	1.97	2.33	3.58	17.53
City of Starbuck	0.18	0.20	0.22	0.26	0.39	1.93
City of Trimont	0.27	0.29	0.32	0.38	0.59	2.89
City of Truman	0.34	0.37	0.41	0.49	0.75	3.66
City of Walnut Grove	0.35	0.39	0.43	0.51	0.79	3.85
City of Waseca	1.04	1.16	1.28	1.51	2.32	11.36
City of Welcome	0.27	0.29	0.32	0.38	0.59	2.89
City of Willmar	0.23	0.26	0.28	0.33	0.51	2.50
City of Winnebago	0.53	0.59	0.65	0.77	1.18	5.78
MRVPUC	1.80	2.00	2.21	2.61	4.01	19.65

Chapter 6: Model Estimations:

Using the damage values we now have all the information necessary to calculate a solution to our trading models. There is one issue, however, that appears due to the calculation method selected at this time. The current method creates a large matrix with dimensions equal to the number of facilities involved in trading, and will not be able to be solved for 42 WWTFs at one time. Thus we estimate a subsection of 3 WWTFs at this time. Future work will explore alternative methods so as to solve for the 42 firm model. This subset was made up of Mankato WWTF, Redwood Falls WWTF, and the ADM Marshall due to their variety of size and emissions levels. Of the WWTFs included Mankato is the cleanest facility, while Redwood falls is slightly above the 1mg/l end goal of the TMDL. ADM Marshall is a agricultural processing facility that is extremely dirty, with a phosphorus concentration in its emissions higher than normal untreated waste.

Due to its size and high capital investment costs (that can adversely effect the trading program) it was decided to drop the capital costs for Mankato during the simulations. This should have little impact on the results, as higher costs for Mankato would push it to become a buyer of permits, and as will be shown Mankato will do that even with the capital costs excluded. It should also be noted that firms were not allowed to become dirtier than their 2007 emissions levels during the trading program. While it is allowed in Farrow and the Jordan Trading Program for a firm to become dirtier than their starting levels as long as they purchase enough permits, this trading program ran into issues where a firm would have such high costs that the program would have these facilities increase their pollution and buy permits to the extent where they were actually emitting more pollution than normal waste water contains. This obviously makes little sense and thus the cap was implemented. Table 7 lists the various traits of each of these selected facilities. For this project we also focused on solving the Farrow trading model.

Table 7: Trading Simulation Facility Subset

Facility	Jordan BOD	Design Flow (MGD)	Phos Con 2007 (mg/l)
ADM Marshall	.18	2.64	7.16
Mankato	.72	11.25	.4064
Redwood Falls	.27	1.32	1.48

Farrow DTRS Model:

For simplicity's sake, cumulative damages to the river were assumed to be linear. This is most likely incorrect as studies have shown that thresholds on pollution exist beyond which damages increase exponentially, but the Farrow Model currently does not function correctly when faced with non-linear damages. This is addressed by Konishi *et al.* (2013) as stated earlier. Thus the damages estimated in Chapter 5 are usable and can generate ranges of damages based on each firms possible emissions levels. Combining these damages with the costs of abatement from our cost functions the social optimum -- a set of emissions levels that minimize the sum of costs and damages -- can be estimated. This serves as a target to evaluate the efficiency of the trading program. The program calculates the number of permits that should be used at the social optimum and then proceeds to distribute them to the facilities so that they are as evenly distributed as possible without giving any firm more permits than their maximum allowed emissions level. The costs and damages of this allocation are estimated so as to present the no trade outcome of the program. This makes for another good basis of comparison as it represents what has happened in most water quality trading programs in the country (no trades occurring) as well as showing what might happen in a normal command and control situation. It should be noted that in some cases the damages at this initial allocation will be lower than the social optimum, and due to the way the farrow trading program functions this results in the program not being able to result in the social optimum due to the trading ratios. This is not a problem for our simulation as in most cases the social optimum would be unknown and a implemented trading program would be trying to approximate a best guess at this value. If the social optimum was known then there would be no need for a trading program, as permits could be assigned to meet it exactly.

Our simulation to estimate the results of a Farrow trading inputs the damages and the costs of abatement and uses this to estimate the prices firms should pay one another for pollution permits. With this added variable the pollution abatement of each firm can be estimated, and thus compared to the social optimum and a no trade scenario. At our estimated value of WTP, the simulation comes to an equilibrium that has Mankato buying permits from both other sources and high levels of abatement at ADM Marshall and Redwood Falls. Mankato is not, however, able to buy as many permits as it would like and thus must abate a small amount. This is primarily due to the above mentioned issue with allocating permits, as our current allocation provides to few permits then needed to allow the trading program to solve for the social optimum. As WTP values increase the program continues to institute cost effective trades that, while leading to no decreases in damages from the no trade scenario, reduce costs substantially.

Some issues arose with the trading program however, and as a result the cost equation needed to be edited. While the simulation should come to a solution where the ratios of damages and marginal costs are equal to one another, the program continually failed in this regard. To make matters worse at higher WTP values the program actually encouraged poor trades that result in losses. As firms are seeking to minimize costs these trades should not occur as no one is being made better off. The reason for these errors stems from difficulties with the cost function. While the cost function estimated in Chapter 4 is fairly good at estimating the costs of abatement for the facilities, it is hard to work with. In order to estimate abatement in the simulation the marginal cost function is used with the idea that at the equilibrium marginal cost should equal price and that we can then replace our emissions variable with our maximum emissions values (which is known) minus our level of abatement. We then solve the equation for the level of abatement. The issue is that the marginal cost included the OM and CC cost equations in their entirety and therefore includes the variable for emissions. This equations is too complicated to be solved for abatement, and thus initially it was decided to hold OM and CC costs constant at the optimal emissions levels.[5] Because of this the results were only an approximation of the actual results and can have the above stated errors occur. This suggests that while our cost function is useful, it might not be well suited for use in trading simulations. To solve for this in the simulation Capital Costs were dropped to simplify the marginal cost equations, leading to a solvable abatement cost function. This

5 Several emissions levels were attempted, and variable were included to allow this result to be shifted to attempt to approximate the true abatement levels.

corrected the issues that had appeared in the previous versions of the simulation, but result in less accurate cost estimations unless you assume that facilities in the trading program will not upgrade their facilities, and instead reduce pollution through other methods, such as chemical additions.

The program shifts the firm's requirement for abatement into kilograms, while previously we had been examining it in terms of phosphorus concentration. This is because most trading programs will be interpreted in terms of permits that represent some amount of pollution, such as 1 permit allows 1 kg phosphorus to be emitted. Thus now the output of the program is the estimated number of kilograms that each source should emit after trading. The simulations result for our baseline WTP value suggest that ADM Marshall should reduce until they emit around 951.54 kgs phosphorus each period, Mankato should buy permits until they are at their maximum allotment of 1686.6 kgs phosphorus per period, and Redwood falls should reduce their emissions to 463.11 kgs phosphorus per period. These results make some intuitive sense as Mankato not only is extremely large, but is also already very clean, suggesting it would be quite costly for them to abate further. Mankato does not reduce to below their maximum until WTP is 1.2 $/kg Phosphorous reduction per household or higher. Results for several WTP levels are presented in table 8 below. If no trades were allowed and permits were split as equally as possible between the three firms so that none would have more than their maximum emissions level. For a WTP of .01 $/kg Phosphorous reduction per household the results in ADM Marshall receiving 1298 permits, Mankato receiving 1062.5 permits, and Redwood Falls receiving 826.99 permits. Each facility would be required to abate pollution either by chemical additions or by installing new machinery to improve their physical or biological phosphorus removal rates to meet these levels if no trades occurred.

Table 8: Farrow Simulation Results

Results	WTP = 0.009	WTP=0.01	WTP= 0.011	WTP= 0.013	WTP= 0.02	WTP=.1
Social Opt Firm 1 (Total Kg P)	1012.9	951.54	890.15	828.76	675.29	276.26
Social Opt Firm 2 (Total Kg P)	1686.6	1686.6	1686.6	1610.7	1290.2	573.44
Social Opt Firm 3 (Total Kg P)	487.92	463.11	458.98	405.23	322.53	140.59
Social Opt Damages ($10^4)	95.61	105.01	113.86	128.18	158.18	340.56
Social Opt Costs ($10^4)	13.027	14.179	15.063	21.874	53.331	249.56
Firm 1 Equilibrium (Total Kg P)	363.24	344.23	332.73	317.36	257.43	110.17
Firm 2 Equilibrium (Total Kg P)	1552.5	1513.2	1463.1	1396.1	1134.4	492.74
Firm 3 Equilibrium (Total Kg P)	137.9	134.37	135.39	123.84	100.36	43.037
Equilibrium Damages ($10^4)	76.322	82.655	87.805	99.127	123.9	262.76
Equilibrium Costs ($10^4)	61.345	65.64	70.295	79.847	121.84	405.73
No Trade Firm 1 (Total Kg P)	1298	1240.5	1196.8	1069.5	762.69	330.1
No Trade Firm 2 (Total Kg P)	1062.5	1033.8	1011.9	948.23	762.69	330.1
No Trade Firm 3 (Total Kg P)	826.99	826.99	826.99	826.99	762.69	330.1
No Trade Damages ($10^4)	76.324	82.653	87.806	99.126	123.9	262.76
No Trade Costs ($10^4)	65.5	70.24	74.029	86.11	132.77	431.69
Price Firm 1 ($10^4)	71.44	75.1	80.2	87.88	131.73	679.93
Price Firm 2 ($10^4)	289.84	304.69	325.38	356.54	534.45	2717.8

Chapter 7: Conclusions and Lessons:

The Jordan trading program has been the most successful water quality trading program in terms of total number of trades. While most other programs call having one trade a great success the Jordan trading program has averaged 17 trades a year during its lifetime, and his met its goal of reducing phosphorus, and thus BOD concentrations at Jordan Minnesota. With some assumptions the program appears to have succeeded in lowering the costs of pollution abatement compared to general command and control methods. This only occurs at the current level of trading because facilities are not profit maximizers. If they were different trades would most likely be expected. Towns such as Sacred Heart that would have had to spend millions on new facilities have been able to avoid costly upgrades by paying other firms to abate for them. In 2010 Sacred Heart had a population of only 548 people, but to upgrade their WWTF would have cost millions. Instead each year they spend a small fraction of this much to purchase permits from Mankato, and thus avoid trying to work millions out of a tiny tax base to replace an aging facility.

As we have seen, the Jordan Trading Program emerged because of a mandate by the EPA to solve BOD issues at Jordan Minnesota. From our analysis we can glean several lessons from this program. The first is that trading programs are most effective when there are few to no transaction costs. The Jordan Trading program limited trading costs by only allowing trades between WWTFs, thus cutting out the costly process of determining how much abatement actually occurs from various non-point pollution reduction strategies, and by making the trading process as simple as filling out one form.

Trades require no special personnel, no lengthy studies, and can be completed as quickly as the two firms can sign a piece of paper. This method has allowed trades to flourish, reducing the costs of the program. Non-point sources, however, in most cases are the majority of the problem when it comes to water pollution, often to the extent that without some non-point source abatement the water body will not be able to be brought into compliance. Thus a way must be found to include non-point source that minimizing transaction costs.

Currently most trading programs assume that point sources would somehow find non-point sources that are willing to trade. In most cases this is a difficult process, taking time and special personnel even before analysis of a potential trade partner can take place to determine how much abatement can take place. To alleviate these issues several things can be tried. Since finding trading partners is difficult, an organization could be created to group together non-point sources under a single entity for trading purposes. While there might be some resistance to the formulation of such an entity, if the benefits are clearly stated, i.e. payments for implementation of best management practices, then headway might be made. With one organization representing non-point sources it should be easier to find trading partners, potentially solving one of the issues that prevent non-point source trading from working. The next step would be to develop some general guidelines for the approximate pollution reduction results from various best management practices or other abatement efforts. While some margin of error would need to be built into these estimates if you had an approximate amount of phosphorus reduced from say, a buffer strip on a piece of land, you could set a value of permits that could be sold if the upgrade was implemented. Even if values are set at half of their expected reductions (giving a wide margin of error) if costs are low enough on non-point sources trades could greatly reduce the cost of pollution abatement and even allow programs to push past what would be possible with point source only abatement. While there would still be a lot of work to do organizing a program such as this, these are possible ideas that could make a non-point source trading program actually work.

The Second major lesson that can be learned from the Jordan Trading Program is one of modeling. While Hung and Shaw (2005) and Farrow *et al.*(2005) both struggle with various aspects of the nature of rivers, the Jordan Trading Program avoids this by focusing on one part of the river. While most trading programs are devoted to cleaning up large portions of rivers, the Jordan Trading Program is only concerned with the stretch of the river between Jordan and Shakopee Minnesota. This allows the program more flexibility in allowing trades, allowing some areas of the Minnesota River to actually get dirtier through trading if need be, while the river on a whole improves. Hung and Shaw (2005) constrains trades to prevent any one area from passing a limit to the point where a properly allocated permit program might see no trades at all due to the various factors preventing trades. This then effectively becomes a command and control program rather than a trading program. Farrow *et al.* (2005) is concerned with monetary damages, but there is very little data on actual valuations for these, and often estimates will be very low due to issues such as the free rider effect lowering household's willingness to pay for pollution abatement. While Farrow is also concerned about each part of the river they place fewer restraints on trading that Hung and Shaw, but they also face issues when dealing with nonlinear damages. The BOD problem at Jordan Minnesota represents one of these nonlinear damage situations, and the Jordan Trading Program was able to fix this by reducing the total pollutants, thus achieving the goal without becoming overwhelmed by attempting to estimated monetary damages.

The final lesson to be learned from the Jordan trading program is one that we should already know: any trading program we do institute will not yield the theoretical results. Costs will not be minimized, but can be approximately achieved. This can be seen by simply looking at how Mankato goes about their trades ("Minnesota Pollution Control Agency Interviews." 2012). Mankato is the seller in almost half the trades, and many of the largest, in our market, and yet they do not choose to use the market power they have. Instead of charging a price that will earn Mankato some profit they instead charge the estimated average cost per kilogram phosphorus reduction for each of their trades based on the number of kilograms of phosphorus Mankato needed to abate to provide the necessary permits (Fralish 2012). To make this result even more mystifying is that our estimated trading simulations actually suggest that due to its size Mankato will most likely have higher costs that other firm, and should thus actually be a buyer of permits. This draws attention to an issue with our trading simulations. Costs will vary widely between facilities, and thus Mankato abating and selling permits might actually be cost effective. As it is by selling permits Mankato prevented costly projects, such as the Sacred Heart example from earlier, and thus reduced some costs of pollution abatement on the river. It should also be noted that if the trading program had not been implemented Mankato might have very well abated to a similar level of phosphorus emissions. Most likely the trading program only served to reduce Mankato's emissions by a little, possibly represented by the drop in concentration from .4064 mg/l in 2007 to around .2928 mg/l in 2011. While expensive, they might stave off future regulations that could be more hurtful by cleaning their emissions before future programs come into effect. In some cases trading programs might not function as expected, even with numerous trades.

There is likely more that can be learned from examining the Jordan trading program, but that is to be left for future study. The current program will eventually be superseded by a new TMDL to deal with pollution issues on Lake Pepin, further downstream past where the Minnesota and Mississippi Rivers connect. Thus the most successful water-quality trading program in the nation may soon end. Hopefully the lessons that it has taught us will not go unnoticed, and can help shape policy in the future.

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Appendix A: Linear Damage Program

```
e1 = 0:30.695:6200.39;
e2 = 0:8.433:1703.466;
e3 = 0:4.13495:835.2599;

BOD=[.18 .72 .27];
Design=[2.64 11.25 1.321];
p2007=[7.1604 .4064 1.4766];
flow3=[855010556.7 4133815350.99 559529780.002];

%Using Willingness to pay as estaimated;
%.9*Paper Estimation WTP = .9*0.01020389;
%dam1=.315/28.316;
%dam2=1.278/28.316;
%dam3=.477/28.316;

% Paper Estimation WTP = 0.01020389;
%dam1=.35/28.316;
%dam2=1.42/28.316;
%dam3=.53/28.316;

% 1.1*Paper Estimation WTP = 1.1*0.01020389;
dam1=.385/28.316;
dam2=1.562/28.316;
dam3=.538/28.316;

% 1.2*Paper Estimation WTP = 1.2*0.01020389;
%dam1=.42/28.316;
%dam2=1.704/28.316;
%dam3=.636/28.316;

% 1.3*Paper Estimation WTP = 1.3*0.01020389;
%dam1=.455/28.316;
%dam2=1.846/28.316;
%dam3=.689/28.316;

% 2*Paper Estimation WTP = 2*0.01020389;
%dam1=.7/28.316;
%dam2=2.84/28.316;
%dam3=1.06/28.316;

%WTP = .1
%dam1=3.47/28.316;
%dam2=13.87/28.316;
%dam3=5.20/28.316;
%WTP=.5
%dam1=17.34;
%dam2=69.34;
%dam3=26;
%WTP=1
%dam1=34.67;
%dam2=138.68;
%dam3=52.01;
```

```
%WTP=5
%dam1=173.35/28.316;
%dam2=693.4/28.316;
%dam3=260.03/28.316;
%WTP = 10;
%dam1=346.7;
%dam2=1386.80;
%dam3=520.05;
%
%WTP = 25;
%dam1=866.75/28.316;
%dam2=3467.01/28.316;
%dam3=1300.13/28.316;
%WTP Selected 50;
%dam1=1733.50;
%dam2=6934.01;
%dam3=2600.25;
%WTP Selected 100;
%dam1=3467.01;
%dam2=13868.03;
%dam3=5200.51;
%WTP Selected 200;
%dam1=6934.01;
%dam2=27736.05;
%dam3=10401.02;


%Selected Damage levels; %Should these have some ratio to each other?;
%Selected high values of damages;
%dam1=150;
%dam2=350;
%dam3=200;
%Selected value set constant for each facility;
%dam1=100;
%dam2=100;
%dam3=100;
%Very High Damages
%dam1=1000;
%dam2=1000;
%dam3=1000;


d = dam1*e1+dam2*e2+dam3*e3;

q=zeros(length(e1),length(e2),length(e3));
for i=1:length(e1)
   for j=1:length(e2)
      for l=1:length(e3);
      q(i,j,l)=dam1*(e1(i))+dam2*(e2(j))+dam3*(e3(l));
      end;
   end;
end;
```

Appendix B: Excess Demand Program

```
% Calculating excess demand for 3-firm case

function ex = ed3nocap(p1,d1,d2,d3,x1,x2,x3)

emax1 = 6138.975797106;
emax2 = 1686.59666320392;
emax3 = 826.985014842956;

% parameters for MC approx
c1=0;
c2=0;
c3=0;

p2 = p1*(d2/d1); % effective price for receptor 2
p3 = p2*(d3/d2); % effective price for receptor 3
r1 = (-3211.92/(p1^(50000/96691)))+emax1;
r2 =(-28410.6/(p2^(10000/19503)))+emax2;
r3 = (-1569.35/(p3^(0.5192170184486103)))+emax3;
if r1 < 0;
   r1 = 0;
elseif r1 > emax1;
   r1 = emax1;
end
if r2 < 0;
   r2 = 0;
elseif r2 > emax2;
   r2 = emax2;
end
if r3 < 0;
   r3 = 0;
elseif r3 > emax3;
   r3 = emax3;
end
ex1 = d1*(emax1-x1-r1); % firm 1's excess demand
ex2 = d2*(emax2-x2-r2); % firm 2's excess demand
ex3 = d3*(emax3-x3-r3); % firm 3's excess demand
ex = ex1 + ex2 + ex3; % aggregate excess demand
```

Appendix C: Trading Simulation Program

```
format SHORT g;

e1 = 0:30.695:6200.39;
e2 = 0:8.433:1703.466;
e3 = 0:4.13495:835.2599;

load q.mat; % load damages
md1 = q(2:length(e1),1:(length(e2)-1),1:(length(e3)-1)) - q(1:(length(e1)-1),1:(length(e2)-1),1:(length(e3)-
1));
md2 = q(1:(length(e1)-1),2:length(e2),1:(length(e3)-1)) - q(1:(length(e1)-1),1:(length(e2)-1),1:(length(e3)-
1));
md3 = q(1:(length(e1)-1),1:(length(e2)-1),2:length(e3)) - q(1:(length(e1)-1),1:(length(e2)-1),1:(length(e3)-
1));

clear e1 e2 e3; % re-define (e1,e2,e3) to match size of matrix
e1 = 0:30.695:6139;
e2 = 0:8.433:1686.6;
e3 = 0:4.13495:826.99;

emax1 = 6138.975797106;
emax2 = 1686.59666320392;
emax3 = 826.985014842956;

% damage calculation
q = q(1:length(e1),1:length(e2),1:length(e3));

% marginal cost calculation
mc1=((-.92282-.01134*log(2.64))*exp(1.8361-.92282*log(e1*1000000/855010556.7)+.81566*log(2.64)-.
01134*(log(e1*1000000/855010556.7)*log(2.64)))))./(e1*1000000/855010556.7);

mc2=((-.92282-.01134*log(11.25))*exp(1.8361-.92282*log(e2*1000000/4133815350.99)+.81566*log(11.
25)-.01134*(log(e2*1000000/4133815350.99)*log(11.25)))))./(e2*1000000/4133815350.99);

mc3=((-.92282-.01134*log(1.321))*exp(1.8361-.92282*log(e3*1000000/559529780.002)+.81566*log(1.3
21)-.01134*(log(e3*1000000/559529780.002)*log(1.321)))))./(e3*1000000/559529780.002);

% cost calculation
C = zeros(length(e1),length(e2),length(e3));
for i=1:length(e1);
   for j=1:length(e2);
   C(i,j,:) =
exp(1.8361-.92282*log(e1(i)*1000000/855010556.7)+.81566*log(2.64)-.01134*(log(e1(i)*1000000/85501
0556.7)*log(2.64)))-
2.24489495629119+exp(1.8361-.92282*log(e2(j)*1000000/4133815350.99)+.81566*log(11.25)-.01134*(l
og(e2(j)*1000000/4133815350.99)*log(11.25)))-
105.868791+exp(1.8361-.92282*log(e3*1000000/559529780.002)+.81566*log(1.321)-.01134*(log(e3*10
00000/559529780.002)*log(1.321)))-5.48162192849477;
   end;
end;
```

```
% find minimum
m = min(min(min(C+q)));
ind1 = -inf;
ind2 = -inf;
ind3 = -inf;
for i=1:length(e1);
   for j=1:length(e2);
      for l=1:length(e3);
         if C(i,j,l)+q(i,j,l) == m;
         ind1 = i; ind2 = j; ind3 = l; break
         end;
      end;
   end;
end;

fprintf('optimal-emiss')
[e1(ind1),e2(ind2),e3(ind3)]

% Farrow et al trading equilibrium

x2 = min(emax2,(e1(ind1)+e2(ind2)+e3(ind3))/3); % allowable emissions limits
x3 = min(emax3,(e1(ind1)+e2(ind2)+e3(ind3))/3); % allowable emissions limits
x1 = ((e1(ind1)+e2(ind2)+e3(ind3))-(x2+x3));    % allowable emissions limits

   % evaluate marginal damages at initial allocation
   d1 = dam1;
   d2 = dam2;
   d3 = dam3;

p1 = 0:0.01:1000; % possible price range
ed = zeros(length(p1),1);
for i = 1:length(p1);
   ed(i) = abs(ed3nocap(p1(i),d1,d2,d3,x1,x2,x3)); % aggregate excess demand
end;
[v,ind4] = min(ed);
fprintf('excess demand')
ed3nocap(p1(ind4),d1,d2,d3,x1,x2,x3)

% parameters for MC approx
c1=0;
c2=0;
c3=0;

clear ed v;
p1(ind4); p2 = p1(ind4)*(d2/d1); p3 = p2*(d3/d2); % equilibrium price
r1 = (-3211.92/(p1(ind4)^(50000/96691)))+emax1;
r2 =(-28410.6/((p2)^(10000/19503)))+emax2;
r3 = (-1569.35/(p3^(0.5192170184486103)))+emax3;

if r1 < 0;
   r1 = 0;
elseif r1 > emax1;
   r1 = emax1;
```

```
end
if r2 < 0;
   r2 = 0;
elseif r2 > emax2;
   r2 = emax2;
end
if r3 < 0;
   r3 = 0;
elseif r3 > emax3;
   r3 = emax3;
end
e1eq = emax1 - r1;
e2eq = emax2 - r2;
e3eq = emax3 - r3;

% Equilibrium permit purchases, row i buys from col j

zeq = dam1*e1eq+dam2*e2eq+dam3*e3eq;
zopt = dam1*e1(ind1)+dam2*e2(ind2)+dam3*e3(ind3);
ceq =
exp(1.8361-.92282*log(e1eq*1000000/855010556.7)+.81566*log(2.64)-.01134*(log(e1eq*1000000/85501
0556.7)*log(2.64)))-
2.24489495629119+exp(1.8361-.92282*log(e2eq*1000000/4133815350.99)+.81566*log(11.25)-.01134*(l
og(e2eq*1000000/4133815350.99)*log(11.25)))-
105.868791+exp(1.8361-.92282*log(e3eq*1000000/559529780.002)+.81566*log(1.321)-.01134*(log(e3eq
*1000000/559529780.002)*log(1.321)))-5.48162192849477;
copt =
exp(1.8361-.92282*log(e1(ind1)*1000000/855010556.7)+.81566*log(2.64)-.01134*(log(e1(ind1)*100000
0/855010556.7)*log(2.64)))-
2.24489495629119+exp(1.8361-.92282*log(e2(ind2)*1000000/4133815350.99)+.81566*log(11.25)-.0113
4*(log(e2(ind2)*1000000/4133815350.99)*log(11.25)))-
105.868791+exp(1.8361-.92282*log(e3(ind3)*1000000/559529780.002)+.81566*log(1.321)-.01134*(log(
e3(ind3)*1000000/559529780.002)*log(1.321)))-5.48162192849477;
fprintf('equil emissions')
[e1eq,e2eq,e3eq]

fprintf('optimal emissions')
[e1(ind1),e2(ind2),e3(ind3)]

fprintf('equil damages, costs')
[zeq,ceq]

fprintf('optimal damages, costs')
[zopt,copt]

fprintf('Permit allocations')
[x1, x2, x3]

%fprintf('No-trade damages');
zno = dam1*x1+dam2*x2+dam3*x3;

%fprintf('No-trade total costs');
cno =
```

```
exp(1.8361-.92282*log(x1*1000000/855010556.7)+.81566*log(2.64)-.01134*(log(x1*1000000/855010556.7)*log(2.64)))-2.24489495629119+exp(1.8361-.92282*log(x2*1000000/4133815350.99)+.81566*log(11.25)-.01134*(log(x2*1000000/4133815350.99)*log(11.25)))-105.868791+exp(1.8361-.92282*log(x3*1000000/559529780.002)+.81566*log(1.321)-.01134*(log(x3*1000000/559529780.002)*log(1.321)))-5.48162192849477;

fprintf('No-trade damages total costs')
[zno, cno]

mc1eq =
((-.92282-.01134*log(2.64))*exp(1.8361-.92282*log(e1eq*1000000/855010556.7)+.81566*log(2.64)-.01134*(log(e1eq*1000000/855010556.7)*log(2.64)))).I(e1eq*1000000/855010556.7);
mc2eq =
((-.92282-.01134*log(11.25))*exp(1.8361-.92282*log(e2eq*1000000/4133815350.99)+.81566*log(11.25)-.01134*(log(e2eq*1000000/4133815350.99)*log(11.25))))/(e2eq*1000000/4133815350.99);
mc1opt =
((-.92282-.01134*log(2.64))*exp(1.8361-.92282*log(e1(ind1)*1000000/855010556.7)+.81566*log(2.64)-.01134*(log(e1(ind1)*1000000/855010556.7)*log(2.64)))).I(e1(ind1)*1000000/855010556.7);
mc2opt =
((-.92282-.01134*log(11.25))*exp(1.8361-.92282*log(e2(ind2)*1000000/4133815350.99)+.81566*log(11.25)-.01134*(log(e2(ind2)*1000000/4133815350.99)*log(11.25))))/(e2(ind2)*1000000/4133815350.99);

fprintf('d1/d2, mc1eq/mc2eq, mc1opt/mc2opt')
[d1/d2,mc1eq/mc2eq,mc1opt/mc2opt]
fprintf('equil prices')
[p1(ind4), p2, p3]

cost1=exp(1.8361-.92282*log(e1eq*1000000/855010556.7)+.81566*log(2.64)-.01134*(log(e1eq*1000000/855010556.7)*log(2.64)))-2.24489495629119;
cost2=exp(1.8361-.92282*log(e2eq*1000000/4133815350.99)+.81566*log(11.25)-.01134*(log(e2eq*1000000/4133815350.99)*log(11.25)))-105.868791;
cost3=exp(1.8361-.92282*log(e3eq*1000000/559529780.002)+.81566*log(1.321)-.01134*(log(e3eq*1000000/559529780.002)*log(1.321)))-5.48162192849477;
fprintf('Equil costs by firm')
[cost1, cost2, cost3]

no1=exp(1.8361-.92282*log(x1*1000000/855010556.7)+.81566*log(2.64)-.01134*(log(x1*1000000/855010556.7)*log(2.64)))-2.24489495629119;
no2=exp(1.8361-.92282*log(x2*1000000/4133815350.99)+.81566*log(11.25)-.01134*(log(x2*1000000/4133815350.99)*log(11.25)))-105.868791;
no3=exp(1.8361-.92282*log(x3*1000000/559529780.002)+.81566*log(1.321)-.01134*(log(x3*1000000/559529780.002)*log(1.321)))-5.48162192849477;
fprintf('No-trade costs by firm')
[no1,no2,no3]
trade1=x1-e1eq;
trade2=x2-e2eq;
trade3=x3-e3eq;
earn1=trade1*p1(ind4);
earn2=-trade1*p1(ind4)-trade3*p3;
earn3=trade3*p3;
[earn1, earn2, earn3];
ceq-earn1-earn2-earn3;
```

Appendix D: Cost Estimation Program

```
setwd("C:\\Users\\Michael Zajicek\\Desktop")
data<-read.csv("Jiang small data.csv", header=T)
attach(data)
lnCC=log(CC)
lnOM=log(OM)
lncon=log(Con)
lnsize=log(Size)
lnCS=lncon*lnsize
reg1<-lm(lnCC~lncon+lnsize+lnCS)
reg2<-lm(lnOM~lncon+lnsize+lnCS)
summary(reg1)
summary(reg2)

data3<-read.csv("Jiang small data change.csv", header=T)
attach(data3)
lnCC2=log(CC2)
lnOM2=log(OM2)
lncon2=log(Con2)
lnsize2=log(Size2)
lnCS2=lncon2*lnsize2
reg3<-lm(lnCC2~lncon2+lnsize2+lnCS2)
reg4<-lm(lnOM2~lncon2+lnsize2+lnCS2)

data4<-read.csv("MN Working Data Mankato edit.csv", header=T)
head(data4)
attach(data4)
data4=edit(data4)
;change design flow for POET Biorefining Lake Crystal to .1296
lnDF=log(DF)
lnPhoscon=log(Phoscon)
lncross=lnDF*lnPhoscon

LNMNCC=3.47660-.82418*lnPhoscon+.34555*lnDF-.145*lncross
MNCC=exp(LNMNCC)
LNMNOM=1.8361 -.92282*lnPhoscon+.81566*lnDF-.01134*lncross
MNOM=exp(LNMNOM)

lnSadoMNOM=log(9.870)-.997*lnPhoscon+.785*lnDF+.043*lncross
SadoMNOM=exp(lnSadoMNOM)
lnSadoMNCC=log(11.878)-.995*lnPhoscon+.302*lnDF-.164*lncross
SadoMNCC=exp(lnSadoMNCC)

testom=log(1.8361)-.92282*lncon+.81566*lnsize-.01134*lnCS
exp(testom)
testcc=log(3.47660)-.82418*lncon+.34555*lnsize-.145*lnCS
exp(testcc)
testSadoOM=log(9.870)-.997*lncon+.785*lnsize+.043*lnCS
exp(testSadoOM)
testsadocc=log(11.878)-.995*lncon+.302*lnsize-.164*lnCS
exp(testsadocc)

LNMNOM2=1.8361-.92282*lncon+.81566*lnsize-.01134*lnCS
```

```
exp(LNMNOM2)

testcc2=3.47660-.82418*lncon+.34555*lnsize-.145*lnCS
exp(testcc2)

OMC<-MNOM/Phoscon
domdc=(-.92282+.01134*lnDF)*OMC
domdc
OMF<-MNOM/DF
domdf=(.81566+.01134*lnPhoscon)*OMF
domdf

plot(Phoscon,MNOM)
scatter.smooth(x=Phoscon, y=MNOM, xlab="Phosphorous Concentration (mg/l)",ylab="Predicted OM
costs ($10^4)", main="Predicted OM Costs for Wastewater Facilities on the Minnesota River")
plot(Phoscon,MNCC)
scatter.smooth(x=Phoscon, y=MNCC, xlab="Phosphorous Concentration (mg/l)",ylab="Predicted Capital
costs ($10^4)", main="Predicted Capital Costs for Wastewater Facilities on the Minnesota River")
scatter.smooth(x=Con,exp(predict(reg2)),xlab="Phosphorous Concentration (mg/l)",ylab="Predicted OM
costs ($10^4)", main="OM costs Generated from Regression on Jiang Data")
scatter.smooth(x=Con,exp(predict(reg1)),xlab="Phosphorous Concentration (mg/l)",ylab="Predicted
Capital costs ($10^4)", main="Capital costs Generated from Regression on Jiang Data")

scatter.smooth(x=DF, y=MNOM, xlab="Facility Design Flow (MGD)",ylab="Predicted OM costs
($10^4)", main="Predicted OM Costs for Wastewater Facilities on the Minnesota River")
scatter.smooth(x=DF, y=MNCC, xlab="Facility Design Flow (MGD)",ylab="Predicted Capital costs
($10^4)", main="Predicted Capital Costs for Wastewater Facilities on the Minnesota River")

x=seq(0,8,by=.01)

CCDFLOW=exp(3.47660-.82418*log(x)+.34555*log(.5)-.145*log(x)*log(.5))
OMDFLOW=exp(1.8361-.92282*log(x)+.81566*(log(.5))-.01134*log(x)*(log(.5)))
OMDFMED=exp(1.8361-.92282*log(x)+.81566*(log(5))-.01134*log(x)*(log(5)))
OMDFHIGH=exp(1.8361-.92282*log(x)+.81566*(log(10))-.01134*log(x)*(log(10)))
CCDFMED=exp(3.47660-.82418*log(x)+.34555*log(5)-.145*log(x)*log(5))
CCDFHIGH=exp(3.47660-.82418*log(x)+.34555*log(10)-.145*log(x)*log(10))

plot(Phoscon,MNOM, xlab="Phosphorous Concentration (mg/l)",ylab="Predicted OM costs
($10^4)",main="Figure 2: Predicted OM Costs on MN River Data with Fitted Regression Lines")
lines(x,OMDFLOW)
lines(x,OMDFMED)
lines(x,OMDFHIGH)

plot(Phoscon,MNCC,xlab="Phosphorous Concentration (mg/l)",ylab="Predicted Capital costs ($10^4)",
main="Figure 4: Predicted Capital Costs on MN River Data with Fitted Regression Lines")
lines(x,CCDFLOW)
lines(x,CCDFMED)
lines(x,CCDFHIGH)

scclow=exp(log(11.878)-.995*log(x)+.302*log(.5)-.164*log(x)*log(.5))
sccmed=exp(log(11.878)-.995*log(x)+.302*log(5)-.164*log(x)*log(5))
scchigh=exp(log(11.878)-.995*log(x)+.302*log(10)-.164*log(x)*log(10))
somlow=exp(log(9.870)-.997*log(x)+.785*log(.5)+.043*log(x)*log(.5))
```

```
sommed=exp(log(9.870)-.997*log(x)+.785*log(5)+.043*log(x)*log(5))
somhigh=exp(log(9.870)-.997*log(x)+.785*log(10)+.043*log(x)*log(10))

plot(Phoscon,SadoMNOM, xlab="Phosphorous Concentration (mg/l)",ylab="Predicted OM costs
($10^4)",main="Figure 3: Predicted OM Costs on MN River Data Using Regression From Sado et al.
(2009)")
lines(x,somlow)
lines(x,sommed)
lines(x,somhigh)
plot(Phoscon,SadoMNCC, xlab="Phosphorous Concentration (mg/l)",ylab="Predicted Capital costs
($10^4)", main="Figure 5: Predicted Capital Costs on MN River Data Using Regression Results from Sado
et al. (2009)")
lines(x,scclow)
lines(x,sccmed)
lines(x,scchigh)

margOMF=(.81566+.01134*log(x))*(exp(1.8361-.92282*log(x)
+.81566*(log(.5))-.01134*log(x)*(log(.5)))/.5)
plot(Phoscon, MNOM)
lines(x, margOMF)
plot(x, margOMF)
```

Appendix E: Jordan Cost Estimation Program:

```
Phos=[1.6124
8.758
0.578
0.4908
0.8692
0.395
0.748
0.3068
0.4422
0.8042
0.8072
0.1674
0.6584
0.9716
0.2928
4.5288
0.5686
1.291
2.066
0.7054
2.8966
1.2064
1.5004
1.6354
1.8808
0.74
0.5074
4.0854
0.6872
0.961
0.3688
0.7432
2.7274
0.9548
1.7238
1.063
1.0682
0.4492
];

Phosnotrade=[1.6124
3.1374979708
0.578
0.4908
0.8692
0.395
0.748
0.3068
0.4422
1.0043671396
0.8072
0.833836746
```

```
0.6584
0.9716
0.3680923863
4.5288
0.5686
1.291
2.0437050101
0.7054
5.2850363628
1.2064
1.5004
3.462048381
1.7911427156
0.74
0.5074
4.0854
0.8334232904
0.9544704933
0.3688
0.7432
1.3980556858
0.9548
1.5371949444
1.063
1.0682
0.4492
];

design=[0.287
2.64
0.67
0.84
0.985
0.98
0.46
0.15
0.768
3.9
0.8
0.59
0.824
1.31
11.25
4.5
0.4
3
0.6
6.77
0.908
0.98
1.321
0.853
0.237
```

```
0.78
0.212
2.96
4
0.35
0.186
0.78
0.203
3.5
0.26
7.5
1.7
1.842
];

notradeassump=[1.6124
3.1374979708
0.578
0.4908
0.8692
0.395
0.748
0.3068
0.4422
0.8042
0.8072
0.1674
0.6584
0.9716
0.2928
4.5288
0.5686
1.291
2.0437050101
0.7054
2.8966
1.2064
1.5004
3.462048381
1.7911427156
0.74
0.5074
4.0854
0.6872
0.9544704933
0.3688
0.7432
1.3980556858
0.9548
1.5371949444
1.063
1.0682
0.4492
```

```
];

CC2011=exp(3.4766-.82418*log(Phos)+.34555*log(design)-.145*(log (Phos).*log(design)));
OM2011=exp(1.8361-.92282*log(Phos)+.81566*log(design)-.01134*(log (Phos).*log(design)));
Cost2011=CC2011+OM2011;

CCno=exp(3.4766-.82418*log(Phosnotrade)+.34555*log(design)-.145*(log (Phosnotrade).*log(design)));
OMno=exp(1.8361-.92282*log(Phosnotrade)+.81566*log(design)-.01134*(log
(Phosnotrade).*log(design)));
Costno=CCno+OMno;

CCno2=exp(3.4766-.82418*log(notradeassump)+.34555*log(design)-.145*(log
(notradeassump).*log(design)));
OMno2=exp(1.8361-.92282*log(notradeassump)+.81566*log(design)-.01134*(log
(notradeassump).*log(design)));
Costno2=CCno2+OMno2;
```