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Simulation-Optimization Approach for Trading Point and Non-point Source Nutrient Permits

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Abstract: Excess nutrients in surface water systems cause many environmental problems. Some governments restrict nutrient overloading through nutrient permits. Economic theory states that the best allocation of such permits is made via trading. However, nutrient permit trading is complicated by two factors associated especially with non-point sources: (1) time lags between loading and appearance in a water body and (2) differences between the load and the quantity transported to a water body. In a nutrient permit market, the prices and allocations depend heavily on these hydro-geological factors, so they should be incorporated into the trading system. Nutrient trading programs to date fail to include all factors simultaneously.

We present a new system for trading point and non-point source nitrate permits. The methodology of trading is based on a simulation-optimization approach which is similar to the simulation-optimization approaches used in other non-market based nutrient management programs. Simulations are used to incorporate the hydro-geological impacts and a simple optimization technique is used to clear the market. The system consists of four components. First, a farm simulation model estimates the nutrient leaching from farm practices. Second, a nutrient transport model simulates the fate of leached nutrients in the catchment. Third, traders bid to buy and offer to sell in a centralized online auction. Finally, a linear program finds optimal trades based on the bids and water quality standards.

Using a simple example, we show how this system facilitates trade among point and non-point sources. The illustration is for nitrates, but the concept applies to other contaminants such as phosphates. The example addresses the common case in which nitrates enter a river from both groundwater and direct point sources. The permits specify the maximum allowed nitrate loading into the aquifer for non-point sources and into the river directly for point sources. The results suggest that trade among point and non-point sources is desirable only under some hydrological and economic conditions. If nitrate transport in groundwater is sufficiently fast that a significant amount of nitrates leached from non-point sources reach the receiving surface water body within a year or few, the opportunities for trade between point and non-point sources are high.

We investigated trading under two market rules. First, the market allows trade in permits valid for a single year only (year-1 permits, permits for next year) and second, the market allows trade in different permits valid for distinct future years (year-1, year-2, …, year-5 permits, permits for next five years). We found that the latter provides more opportunities for trade between point and non-point sources, because the non-point source bids for recent permits have to compete with the point source bids for future permits. Therefore, point and non-point source nutrient trading is most suitable when nutrient flow in the catchment is relatively fast and/or point sources are willing to buy future permits.

The price assigned to each source reflects all its spatiotemporal impacts, transaction costs are negligible as the sources buy permits from a centralized auction without having to find sellers, and water quality standards are always maintained. However, in trading loading-based permits, the problem of resource allocation over time arises as nutrients loaded into the aquifer from distinct non-point sources may reach a surface water body gradually over many years. Defining permits based on the water quality constraints is a solution, but the sources will have to purchase a portfolio of permits to match their impacts on the constraints defined over time and the set of receptors. Linear Programming is applicable if the underlying assumptions hold; mainly, the relationship between the quantity of nitrates loaded and the quantity transported to a receptor is linear.

Keywords: *simulation-optimization, trading, nutrients, water quality*

1. INTRODUCTION

Nutrient overload in surface water systems is a global environmental concern (OCED, 2008; Onglay, 1999). Excess nutrients cause eutrophication (plant growth) and hypoxia (shortage of oxygen) in rivers and lakes. Commonly found nutrients in water are nitrogen in the form of nitrate and phosphorus in the form of phosphates.

Nutrients enter water ways from point sources and non-point sources. Point sources (PS) are direct emissions into surface water bodies from factories, sewage treatment plants, and waste water canals. Non point sources (NPS) are agricultural and other land uses from which pollutants migrate to water bodies via groundwater flux or surface runoff. Compared to point source nutrient pollution, non-point source nutrient pollution is difficult to measure and control because it occurs slowly over time and over a wide space. Many rivers and lakes under the threat of nutrient pollution usually receive nutrients from both PS and NPS.

Governments use different policies to control water pollution. The most common are direct controls, environmental charges, and tradable pollution permits. Starvins (2002) discusses many examples for each of these pollution control instruments. Tradable permits are licenses issued by an environmental authority allowing the holder to produce a specified amount of a specified type of pollution for a specified period. In theory, tradable pollution permits achieve the efficient or optimal distribution of pollution permits (Montgomery, 1972; McGarlends, 1988).

Today, governments and environmental authorities have recognized the need for nutrient trading programs which allow trade among point and non-point sources (D. Leston, 1992; Ribaudo et al., 1999; Faeth, 2000), but the world lacks experience with such nutrient trading systems. The United States is the only exception, and has made a significant effort to implement nutrient trading programs even though few trades actually take place (King and Kuch, 2003; US EPA, 2007).

Point and non-point source (PS and NPS) nutrient trading systems in the United States have many obstacles to trade. The first is that only point sources (mainly industrial) are regulated, while non-point sources (mainly agricultural) are not. Point sources, if they cannot meet the discharge limits specified by the permits, can pay upstream land users to implement best management practices which offset the excess nutrient load. Under the above circumstances, US nutrient trading systems are not true point and non-point source trading programs mainly because they do not require any purchases by NPS, and trades always occur in one direction.

In addition, point and non-point source nutrient trading is complicated due to the spatial and temporal impacts of NPS. In designing a nutrient trading system, the main difficulties that arise are incorporating the effects of:

- time lags between loading and appearance in a water body (for NPS, the time lag may be many decades while for PS, the time lag may be few days),
- differences between the load and the quantity transported to a water body (the quantity transported does not usually enter the receiving water body at once, but gradually over a relatively long period), and
- many distinct receptors (a receptor is a water body or a point on a water body where water quality is monitored).

In a well designed nutrient trading system, the price assigned to any source (point or non-point) should reflect all its effects on all receptors over time and space. Neither the existing trading systems nor the conceptual designs of nutrient trading systems proposed to date (US EPA, 2007; Kerr, Rutherford, & Lock, 2007; Morgan, Coggins, & Eidman, 2000) take into account all the above hydro-geological impacts simultaneously.

An interesting development is the use of simulation-optimization approaches as a means of incorporating hydro-geological impacts in non-market based nutrient management programs (Morgan and Everett, 2005; Amalsri and Kaluarachchi, 2005; and others). Morgan and Everett (2005) describe a simulation-optimization approach to determine optimal nitrate loading to an aquifer from decentralized waster water treatment plants. They use a groundwater model to simulate nitrate transport and obtain a response matrix which relates the source nitrate loading to the concentration at the receptors. The response matrix is then used in a linear optimization model which determines the optimal sustainable distribution of nitrate loading. Amalsri and Kaluarachchi (2005) present an integrated methodology for optimal management of non-point source nitrate loading. They use two simulation models: one which simulates soil nitrogen dynamics and estimates nitrate leaching from land uses, and another which simulates the fate and transport of leached nitrates in the aquifer. The physical simulations are coupled with an optimization module which utilizes genetic algorithms to determine optimal on-ground nitrogen loading subject to water quality standards. Morgan, Coggins, & Eidman (2000) present a methodology for trading nutrient permits among NPS. In their trading system, simulations are used to validate trades. Morgan et al. also use two simulations, one to simulate soil nitrogen dynamics and another to simulate nitrate transport in groundwater.

Extending these concepts, we propose a nutrient trading system which employs a simulation-optimization approach to facilitate nutrient trading within and among PS and NPS. In this paper, we address a commonly found nutrient pollution problem, where nutrients enter a surface water body from NPS via groundwater flux and from PS via direct emissions. All sources are regulated and they are required to possess a permit to match their nutrient loading on water resources. The system finds optimal prices and allocations while accounting for relevant hydrogeology.

2. A METHODOLOGY FOR TRADING NUTRIENT PERMITS

We describe a trading system specifically designed for trading nitrate permits in a river catchment. Point source permits specify the maximum allowed emission into the river per year in kg/year. Non-point source permits specify the maximum allowed loading to the aquifer in kg/ha/year. All permits are valid only for a year, but the sources can buy permits for future years.

The simulation approach proposed is similar to the simulation approaches proposed in Amalsri and Kaluarachchi (2005) and Morgan, Coggins, & Eidman (2000) in that we use simulations of soil nitrogen dynamics and nitrate transport. The difference is, rather than simulating every possible land use scenario or permit exchange, we use the simulation models on a one-off basis as in Morgan and Everett (2005). Below, we briefly describe the components of the trading system.

First, NPS use a leaching loss model to estimate the potential nitrate leaching from possible land uses. The model simulates the processes that determine the fate of organic and inorganic nitrogen in the root zone (mineralization, immobilization, nitrification, denitrification, and plant uptake) and estimates the nitrate leaching per hectare per year. Based on these estimates, NPS decide the size of the permit required for each land use option. Existing computer programs such as SWAT (Neitsch, Arnold, Kiniry, & Williams, 2005) and GLEAMS (Knisel, 1993) may be used to estimate the nitrate leaching. We recommend that all NPS should use a common authorized leaching loss model.

PS decide on the size of the permit required in kg/year from the quantity and nitrate concentration of the effluents they wish to discharge into the river during the year.

Second, an environmental authority or a government representative who oversees the trading system (hereafter referred to as the auctioneer), uses a catchment nitrate transport model to estimate transport coefficients which measure the mass nitrate input to the stream that occurs in each year during the planning horizon due to one kg/ha/year nitrate leaching from each non-point source. A separate transport matrix should be obtained for every receptor of interest. Commonly available computer codes such as MT3D (Zheng, 1990) and MF2K-GWT (U. S. Geological Survey, 2006) may be used to simulate nitrate transport.

Third, PS and NPS bid to buy permits in an online auction. Everyone buys from the centralized auction rather than from a particular seller. This online auction is designed as a smart market, which uses computer algorithms to determine the optimal prices and allocations relative to the submitted bids and the relevant constraints, using optimization techniques (McCabe, Rassenti, & Smith, 1991). Smart markets have been successfully applied in complicated multilateral trading situations such as electricity markets (Hogan, Read, & Ring, 1996) and conjectured for water markets (Raffensperger and Milke, 2005).

Fourth, we employ a linear program to determine the optimal prices and allocations, assuming that a linear relationship exists between mass nitrate loading into the aquifer, and mass nitrate input into the river or concentration at each receptor. The linear program determines the optimal trades subject to water quality standards and submitted bids.

2.1. A Linear Program to Clear the Market

Indices: $i = 1,\ldots, N$ sources; $j = 1,\ldots, M$ receptors; t, $s = 1,\ldots, T$ years; and $k = 1,\ldots, K$ bids.

Parameters:

H_{ijt}: concentration that occurs at receptor j, at the end of the year that is $t-1$ years after a "unit nitrate loading" occurred at source i. Unit nitrate loading is defined as 1 kg nitrate emission during a year in the case of PS or 1 kg/ha nitrate leaching during a year in the case of NPS.

$\hat{H}_{it}$: mass nitrate input into the stream that occurs during the year that is t–1 years after a unit nitrate loading occurred at source i. The river may be considered as another receptor indexed by a particular j_0, but to distinguish the main receptor on which point source emissions are directly loaded, we use a separate set of transport coefficients for the river. This is the receptor which affects trade the most. If nitrates do not reside in the river for more than a year, for PS, $\hat{H}_{it} = 1$ for $t = 1$ and 0 for $t > 1$.

C_{jt}: the concentration that occurs at receptor j, at the end of year t, from all non-tradable sources.

$\hat{C}_t$: mass nitrate input into the stream that occurs at receptor j, during year t, from all non-tradable sources.

S_{jt}: the maximum acceptable concentration at receptor j at the end of year t.

$\hat{S}_t$: the maximum acceptable mass nitrate input into the stream during year t.

U_{itk}: upper bound on the k^{th} bid placed by trader i for year-t permits.

P_{itk}: bid price of k^{th} bid placed by trader i for year-t permits.

Decision variables:

x_{itk}: quantity accepted from the k^{th} bid placed by trader i for year-t permits.

q_{it}: maximum loading allowed for source i, during year t; this is the size of the year-t permit held by source i after trade.

μ_{it} = price of year-t permit assigned to source i. This is the shadow price of constraint 2 below.

Objective function: Maximize $\sum_i \sum_t \sum_k (P_{itk} x_{itk})$

Subject to constraints:

Upper bounds on bids:	$x_{itk} \le U_{itk}$	for all i, t and k	(1)	θ_{itk}
Compliance constraints:	$q_{it} - \sum_k x_{itk} = 0$	for all i and t	(2)	μ_{it}
Water quality standards:	$\sum_i \sum_{s=1}^{t} H_{ij(t-s+1)} q_{is} \le S_{jt} - C_{jt}$	for all j and t	(3)	λ_{jt}
	$\sum_i \sum_{s=1}^{t} \hat{H}_{i(t-s+1)} q_{is} \le \hat{S}_t - \hat{C}_t$	for all j and t	(4)	γ_t
Other non-negativity constraints:	$x_{itk} \ge 0$	for all i, t and k	(5)	β_{itk}

The above linear program determines the distribution of nitrate loading among the sources in each year which maximises the total utility subject to water quality constraints. It is formulated as a gross pool market in which any initial permit holdings are ignored. The bids reflect the preferred resource position at the particular price. However, the sources who possess initial holdings can offer to sell. Then the preferred resource position is calculated by subtracting the offered quantity from the initially held quantity (for example, if a source initially holds a permit of 50 kg and offers to sell 20 kg at \$1, then the preferred resource position at price \$1 is 50-20 = 30 kg). After clearing the market, the net purchases or sales are calculated relative to the optimal loading. In this paper, we assume that there are no initial holdings, and everyone has to buy the permit he or she needs from the auctioneer, who keeps all revenue from the auction.

$S_{jt} - C_{jt}$ and $\hat{S}_t - \hat{C}_t$ are the net amounts of pollution capacity available for allocation in the auction. We can estimate expected values for C_{jt} and $\hat{C}_t$ using the same transport simulation model discussed under the methodology. However, determining S_{jt} and $\hat{S}_t$ should be done carefully. Water quality standards usually specify the maximum acceptable pollutant load into a water body during a period or the maximum acceptable concentration at a time. If we set S_{jt} and $\hat{S}_t$ equal to those standards, and some constraint for year t_0 becomes binding in the solution, we may not be able to allocate any permit that affects period t_0 in the future. We are currently studying the optimal method to determine S_{jt} and $\hat{S}_t$, which is a problem of resource allocation over time. In this paper we assume that $S_{jt} - C_{jt}$ and $\hat{S}_t - \hat{C}_t$ are given, as the total amounts of resources available for allocation in the auction.

The variables listed in the right hand side of the constraints, θ_{itk}, μ_{it}, λ_{jt}, γ_t, and β_{itk}, are the dual variables associated with the constraints. Each of them reflects how much the objective function will improve if the right hand side of the constraint were increased by 1 unit. From the linear programming dual, we can derive the price, $\mu_{it} = \sum_j \sum^{T}_{s=t} H_{ij(s-t+1)} \lambda_{js} + \sum^{T}_{s=t} \hat{H}_{i(t-s+1)} \gamma_s$. The price of source i is determined by its impacts on all the receptors over the planning horizon. If only the mass nitrate input into the stream in every year is capped, and no other receptors are considered, $\mu_{it} = \sum^{T}_{s=t} \hat{H}_{ij(s-t+1)} \gamma_s$.

For PS, the price $\mu_{it} = \hat{H}_{i1} \gamma_t = 1 \times \gamma_t = \gamma_t$. Given $\mu_{it} = \gamma_t$ for all PS, unless a considerable portion of nitrates loaded from NPS reach the river in the same year of loading, the point source price for a particular year-t_0 permit is independent of the non-point source prices for year-t_0 permits and therefore, it is quite likely that two independent markets will operate. In the illustration below, we show how a market for a particular year-t_0 permit will operate differently from a market in which year-t_1, year-t_2, …, year-t_T permits are traded simultaneously.

3. ILLUSTRATION: TRADING NITRATES AMONG PS AND NPS

3.1. Hypothetical Case Study

To demonstrate the trading system, we use a hypothetical river catchment of 5 × 5 km^2 area with some PS and NPS. In Figure 1, circles indicate PS, and rectangles indicate NPS. We simulated nitrate transport in the catchment using MT3D with the flow terms obtained from a groundwater flow simulation. The flow model was developed with MODFLOW (Harbaugh, Banta, Hill, & McDonald, 2000). The hydro-geological parameters used in the simulation are listed in Table 1. We have assumed that nitrate transport in the aquifer is due to advection, dispersion, and first order decay.

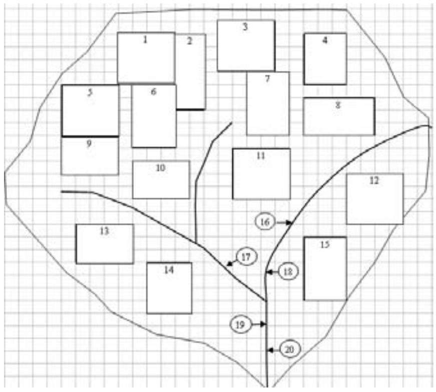

Figure 1. Hypothetical catchment.

Using the model, we simulated 1 kg/ha/year nitrate loading from each non-point source and obtained the mass nitrate input into the river that occurs in each year during a planning horizon of 50 years. These values are the transport coefficients $\hat{H}_{ijt}$s in the linear program (Table 2). A 50-year horizon is sufficient because almost all nitrates applied in year 1 at any non-point source in the catchment reach the river by 50 years.

In this demonstration, we do not estimate the potential leaching losses from land uses and we assume that the NPS have estimated the size of the permits required using a leaching loss model.

We assume that once nitrates enter the river from PS or NPS, they do not reside in the river for more than a year, so there is no need to simulate the nitrate transport in the river, and all PS are identical in their total impact during a year.

Only one water quality standard applies: every year, the total mass nitrate input into the river should not exceed the pre-specified standard. Taking into account the water quality standard and expected non-tradable source contributions including the nitrates already in the aquifer, the auctioneer can allocate only 1000 kg of the annual nitrate intake capacity of the river. Hence, $\hat{S}_t - \hat{C}_t$ = 1000 kg for all t, for this example. No other receptors are considered.

Table **1**. Hydro-geological properties used in groundwater models.

Parameter	Value
Hydraulic conductivity (longitudinal)	0.0006 m/s
Hydraulic conductivity (vertical)	0.0001 m/s
Storage coefficient	0.0001 1/m
Effective porosity	0.2
Longitudinal dispersivity	5 m
Ratio: H/L dispersivity	0.1
Ratio: V/L dispersivity	0.01
Molecular diffusion coefficient	0.00005
First order decay coefficient	0.0002 1/day
Recharge (uniform)	100 mm/year
No. of layers in the models	1
Cell size in the models	200×200 m^2

Table **2**. Transport coefficients ($\hat{H}_{ijt}$s) for t = 1, 2, 3, and 50.

Yr	Transport coefficients for non-point sources (kg)														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0.000	0.038	0.003	0.000	0.007	0.046	0.111	0.704	1.090	1.698	0.089	0.287	0.026	0.006	0.045
2	0.002	0.406	0.054	0.003	0.098	0.480	0.553	3.411	4.354	4.921	0.558	1.129	0.179	0.059	0.288
3	0.021	1.170	0.231	0.022	0.369	1.418	0.919	5.135	5.332	5.290	1.138	1.687	0.401	0.169	0.622
.															
50	0.623	2.452	1.293	0.405	1.632	3.438	1.192	3.434	2.406	2.441	1.946	1.767	0.904	0.609	1.444

We modeled the linear program using the algebraic modeling language AMPL, and included the transport coefficients in the AMPL data file. The auction is cleared by running the linear program with submitted bids. Next, we demonstrate the results generated by the auction for a set of hypothetical bids.

3.2. Results and discussion

Assume the sources bid as given in Table 3 and everyone bids only for year-1 permits. The results are given in the first three columns of Table 4. PS can buy all that they bid for, 175 kg/year at a small price of $0.03. Only some NPS can buy all they bid.

Total point source allocation is 875 kg. Accordingly, the expected nitrate contribution to the river in year 1 is 875 kg from PS and 125 kg from NPS. Some NPS have immediate impacts on the river. Even though the non-point source bids are identical, NPS 8 and 10 get the least allocations. The reasons are (1) source 10 has the highest impact on the year-1 constraint ($\hat{H}_{10,1}$ = 1.698 kg) and have to compete with the PS in the market, and (2) source 8 has the highest total impact on all constraints ($\sum_t \hat{H}_{8,t}$ = 38.57 kg).

Table **3**. Hypothetical bids.

Price	Quantity	
	PS	NPS
$1.00	30 kg/year	6 kg/ha/year
$0.70	15 kg/year	4 kg/ha/year
$0.40	20 kg/year	10 kg/ha/year
$0.20	60 kg/year	16 kg/ha/year
$0.10	50 kg/year	12 kg/ha/year

If non-point bid prices were increased by 10 times, source 10 can buy 36 kg while the total point source allocation is reduced from 875 kg to 859.5 kg. By paying more, non-point source 10 can buy another 36−25.396=10.604 kg which would otherwise have been purchased by the point sources. These results provide evidence that there is some trading in year-1 permits between point and non-point sources, but not much.

If all sources bid as given in Table 3 for year-1 to year-5 permits simultaneously, the results are shown in columns 4 to 13 in Table 4. All NPS can buy less year-1 permits than they would have bought if everyone had bid only for year-1 permits. When PS bid to buy future permits, NPS are burdened with their bids for recent permits (for example, year-1 permits) competing with the point source bids for future permits (for example, year 5-permits) because recent non-point source permits and future point source permits affect the same constraints.

Table **4**. Results of trading: prices and allocations.

Src	Bid for year-1 permits		Bid for year-1 to year-5 permits									
	Buy	Price	Buy					Price				
	yr-1	yr-1	yr-1	yr-2	yr-3	yr-4	yr-5	yr-1	yr-2	yr-3	yr-4	yr-5
	48.000	$0.02	10.000	20.000	20.000	20.000	36.000	$0.42	$0.37	$0.31	$0.25	$0.19
2	36.000	$0.12	6.000	6.000	6.000	10.000	10.000	$0.84	$0.80	$0.72	$0.68	$0.68
3	48.000	$0.05	10.000	10.000	10.000	10.000	20.000	$0.53	$0.48	$0.44	$0.41	$0.37
4	48.000	$0.01	20.000	20.000	36.000	36.000	36.000	$0.25	$0.22	$0.19	$0.16	$0.12
5	48.000	$0.07	8.412	10.000	10.000	10.000	10.000	$0.70	$0.64	$0.57	$0.52	$0.47
6	36.000	$0.17	0.000	0.000	6.000	6.000	6.000	$1.11	$1.06	$0.98	$0.94	$0.96
7	48.000	$0.06	10.000	10.000	10.000	20.000	20.000	$0.50	$0.49	$0.45	$0.39	$0.34
8	20.000	$0.22	0.000	0.000	0.000	0.000	0.700	$1.37	$1.49	$1.43	$1.15	$1.00
9	36.000	$0.18	0.000	0.000	0.000	0.000	6.000	$1.09	$1.30	$1.35	$1.04	$0.76
10	25.396	$0.20	0.000	0.000	0.000	0.000	6.000	$1.07	$1.28	$1.41	$1.17	$0.83
11	48.000	$0.10	6.000	6.000	10.000	10.000	10.000	$0.75	$0.72	$0.66	$0.59	$0.55
12	40.968	$0.10	10.000	6.000	10.000	10.000	10.000	$0.69	$0.71	$0.67	$0.58	$0.52
13	48.000	$0.04	20.000	20.000	20.000	20.000	20.000	$0.37	$0.35	$0.31	$0.28	$0.26
14	48.000	$0.03	20.000	20.000	20.000	36.000	36.000	$0.28	$0.25	$0.22	$0.20	$0.17
15	48.000	$0.07	10.000	10.000	10.000	10.000	10.000	$0.59	$0.56	$0.51	$0.45	$0.41
16	175.000	$0.03	175.000	175.000	175.000	125.000	125.000	$0.00	$0.00	$0.00	$0.10	$0.10
17	175.000	$0.03	175.000	175.000	175.000	155.262	125.000	$0.00	$0.00	$0.00	$0.10	$0.10
18	175.000	$0.03	175.000	175.000	175.000	175.000	125.000	$0.00	$0.00	$0.00	$0.10	$0.10
19	175.000	$0.03	175.000	175.000	175.000	175.000	125.000	$0.00	$0.00	$0.00	$0.10	$0.10
20	175.000	$0.03	175.000	175.000	175.000	175.000	151.225	$0.00	$0.00	$0.00	$0.10	$0.10

4. CONCLUSIONS

Even though there is a growing demand for P&NPS nutrient trading systems, dispersed and delayed impacts of NPS make the market design difficult and complicated. One-to-one bilateral trading is not acceptable because each NPS may have a unique pollution scenario over time and space which could not be offset by another single point or non-point source.

The purpose of this paper is to demonstrate a methodology for trading nutrient permits among PS and NPS. We propose a simulation-optimization approach which is similar to the simulation-optimization approaches used in other non-market based nutrient management programs. Simulations are used to estimate the spatiotemporal impacts of NPS and a linear program is used to clear the market. The linear program finds the optimal prices and allocations taking into account the relevant hydro-geological impacts.

According to our results, the extent to which trade occurs among the two types of sources depends on the properties of NPS, mainly the time lags associated with NPS. The faster the NPS loads reach their destination, the greater the opportunities for trade between point and non-point sources. However, a market for a specific year-t_0 permit provides fewer opportunities for trade between point and non-point sources because NPS permits have effects on many future years while PS have effects on a single immediate year. Hence, two markets are likely to exist, unless the NPS have significant impacts in the same year of the permit. When different permits for different future years are traded simultaneously in the same market, non-point source bids for recent years will compete with the point source bids for future years, and the non-point source prices are pushed up by the distributed nature of their impacts. Therefore, the NPS have to set their bid prices high enough compared to PS to buy more permits.

Point and non-point source nutrient trading appears to be most suitable when nitrate transport in groundwater is sufficiently fast and/or point sources are willing to buy future permits.

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REFERENCES

Almasri, M. N., and Kaluarachchi, J. J. (2005), Multi-criteria decision analysis for the optimal management of nitrate contamination of aquifers. Journal of Environmental Management, 74, 365-381.

Faeth, P. (2000). Fertile ground: nutrient trading's potential to cost effectively improve water quality. World Resources Institute, Washington DC.

OCED (2008). Environmental performance of agriculture in OECD countries since 1990. Paris, France.

Ongley, E. D. (1996). Control of water pollution from agriculture. Food and Agri. Organization of the UN.

Harbaugh, B. A. W., Banta, E. R., Hill, M. C., and McDonald, M. G. (2000). MODFLOW-2000: The U.S. Geological Survey Modular Groundwater Model. U.S. Geological Survey.

Hogan, W. W., Read, E. G., and Ring, B. J. (1996). Using mathematical programming for electricity spot pricing. *International Transactions in Operations Research, 3*, 243-253.

Kerr, S., Rutherford, K., & Lock, K. (2007). Nutrient trading in Lake Rotorua: goals and trading caps (Motu working paper 07-08). Motu Economic and Public Policy Research.

King, D. M., and Kuch, P. J. (2003). Will nutrient credit trading ever work: an assessment of supply and demand problems and institutional obstacles. *Environmental Law Reporter*: News and Analysis, 5-2003.

Knisel, W. G. E. (1993). GLEAMS, Groundwater Loading Effects on Agricultural Management Systems.

Leston, D. (1992). Point/nonpoint source pollution reduction trading: an interpretative survey. *Natural Resources Journal NRJOAB*, 32(2), 219-232.

McCabe, K. A., Rassenti, S. J., and Smith, V. L. (1991). Smart computer-assisted markets. *Science, 254*(5031), 534-538.

Morgan, C. L., Coggins, J. S., and Eidman, V. R. (2000). Tradable Permits for controlling nitrates in groundwater at the farm level. *Journal of Agricultural and Applied Economics*, 32(2), 249-258.

Morgan, D. S., and Everett, R. (2005). Application of simulation-optimization methods for management of nitrate loading to groundwater from decentralized wastewater treatment systems. U.S. Geological Survey.

Neitsch, S. L., Arnold, J. G., Kiniry, J. R., & Williams, J. R. (2005). Soil and Water Assessment Tool.

Raffensperger, J. F. and M. Milke (2005). A Design for a Fresh Water Spot Market. *Water Science and Technology.* 5(6), 217-224.

Ribaudo, M. O., Horan, R. D., and Smith, M. E. (1999). Economics of water quality protection from non-point sources: theory and practice. Washington, DC: U.S. Department of Agriculture.

Stavins, R. N. (2001). Experience with market-based environmental policy instruments. *Resources for the Future*.

U. S. Geological Survey (2006). Data Input Instructions for Groundwater Transport Process (GWT).

US EPA (2007). Water Quality Trading toolkit for Permit Writers.

Zheng, C. (1990). MT3D - A modular three-dimensional transport model for simulation of advection, dispersion and chemical reaction of contaminants in groundwater systems.