Cleaning the Water: a Smart Market for Nitrates

R. A. Ranga Prabodanie[1] and John F. Raffensperger[1]

[1] Department of Management, University of Canterbury, Christchurch
Email: R.Ranathunga@mang.canterbury.ac.nz

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EXTENDED ABSTRACT

Fresh water contamination from nitrates is a global crisis. Major contributors are large-scale commercial entities such as farms and factories. Water pollution from direct emissions into the streams is easy to control using technological treatments, but agricultural non-point or diffuse source pollution is difficult to control with those treatments. The organizations which discharge large amounts of nitrates into water systems (e.g., dairies) have economic justification, but their operations affect human health and ecosystem sustainability.

In this paper, we describe a tradable permit system to control non-point source discharges. The proposed system is quite different to other discharge market proposals, as trading would incur virtually no transaction costs, while correctly accounting for relevant externalities in a highly detailed way, over time and space.

We use the term “discharge” to refer to the pollutant mass loaded to the aquifer under study. The term “nitrate permit” refers to a permit which allows the owner to discharge nitrates at a given rate. Defining discharge rights and allowing them be traded in a market is an efficient mechanism to reveal the economic values of those rights, and to shift them from low value uses to high value uses. In this paper, we describe how a trading system for nitrate discharge permits is designed and applied at the catchment scale.

Trading nitrate discharge consents is not as simple as trading other products, because the discharge has spatial and temporal impacts on water quality. The key requirement for a nitrate discharge permit trading system is the ability to estimate these impacts of source loadings on concentrations at water quality control points. Any hydrological software with this capability such as MODFLOW and MT3D can be used to assist nitrate trading.

We propose an auction mechanism to facilitate trade in non-point source nitrate discharge permits. The land users in the catchment may buy and sell nitrate permits and adjust the type of land use to match the permits held during a year. The regional environmental authority will provide guidance on land use types and permit requirements for those land use types. The regional environmental authority is expected to oversee the trade.

The proposed trading system is a "smart market." A smart market is a trading system in which computer algorithms determine the prices and allocations that maximise the gains relative to submitted bids (McCabe et al., 1991). In our proposed system, the computer models are a hydrology model to measure the impacts of a given discharge on other points in the catchment, and a linear program (LP) to clear the market and calculate prices. The LP objective coefficients are simply the users' bids. The constraints correspond to minimum quality standards at a set of environmental control points. The LP finds a solution which satisfies the environmental standards at minimum cost to the users.

The results obtained for a hypothetical catchment model show that water quality constraints restrict the trades, while participant bids mainly influence the location specific prices. Initial allocation of permits matters in distribution of gains.

Our market considers both present and future effects on environment and other third parties. Thus it is capable of meeting water quality goals in both the short and long term. For the land users, this smart market provides flexibility in land use decisions. The online auction is a convenient way to buy and sell nitrate permits. Conceptually, our market model can be applied to other hydrological pollutants. The proposed smart market has potential to be expanded to include both point and non-point sources, water withdrawals and other factors which effect the concentration. It provides insight into the economic value of pollution reduction at different locations in the catchment.

Broadly speaking, this smart market is an application of science, economics, and operations research to make everyone better off: the economy, the environment, and society as a whole. It is a modern, sophisticated solution to the conventional problem of environmental pollution.

1. INTRODUCTION

The allocation and pricing of water pollution rights is complicated by location and time dependent impacts of pollution and by the difficulties in defining and enforcing water pollution rights. A comprehensive water quality trading system should consider point and diffuse sources, spatial and temporal effects of pollution, present and future water quality requirements, hydrological interaction of polluted groundwater and surface water, trade externalities, transaction costs, impacts of water withdrawals on quality, and the effects of uncertain weather. Apart from social and political considerations, this needs a close collaboration of science and economic theory.

Dales (1968) is among the pioneers who demonstrated the applicability of market solutions to the water pollution problem. Montgomery (1972) provided the theoretical foundation for markets of pollution rights. He introduced the use of a 'diffusion matrix' to address the spatial effects of pollution. Taylor (1975) discussed a market for permits to use nitrogen fertilizer. Neil et al. (1983), Eheart et al. (1987), and Leston (1992) designed water pollution trading systems for point source dischargers considering uncertain river conditions. In those works, water quality simulation models were used to build the diffusion matrix. Weber (2001) argued that both water withdrawals and discharges affect surface water concentration, and therefore, a market should be designed to facilitate simultaneous trading in water quality and quantity.

Markets for non-point or diffuse source water pollution are less discussed in the literature due to the difficulties of tracing the sources and quantifying the spatial and temporal effects. But diffused pollutants can be worst when they leach into ground water and flow to streams via surface runoff. Horan et al. (2002) designed a system for trading nitrogen, including agricultural non-point sources and point sources. In this system, a trade between two sources was based on a trading ratio. Morgan et al. (2000) and Collentine (2005) also discussed tradable water pollution permit systems for non-point sources. However, none of those studies has considered both spatial and temporal impacts of diffuse discharges, both present and future water quality requirements, trade externalities, and transaction costs.

The long term objective of the work described in this paper is to design a smart market for trading nitrate discharge permits which has all the above capabilities. In this paper, we report the outcomes of our first working model. In the next sections, we discuss how this market is designed, how it can be applied to a simple case study, preliminary results from the case study, limitations in the current model and future work required.

2. MARKET DESIGN (METHODS)

We use a smart market to solve the nitrate discharge permit allocation problem. McCabe et al. (1991) were the first apply smart markets in allocating environmental pollution permits. Raffensperger and Milke (2005) designed a smart market for allocating groundwater, using a hydrology model, an online auction, and an LP. The proposed smart market for nitrates is similar in design to Raffensperger and Milke (2005).

First, we simulate ground water flow and contaminant transport in the catchment with computer codes such as MODFLOW (Harbough et al., 2000) and MT3D (Zheng, 1990). The transport simulation generates a three dimensional "response matrix." The response matrix contains coefficients H_{ijt}, the increase in concentration at environmental control point j at time t from a unit discharge at pollution source i. This matrix is then used in water quality constraints in the LP. The size and number of time periods in the model depends on how long it takes for the pollutants applied within the catchment to flow away from the catchment.

We propose to obtain buy and sell bids from participants through an online auction and store the bids in a database. The database stores bids, initial allocations, and other important information. Theoretically, buy and sell bids define the demand and supply functions and thus the consumer and producer surplus. A computer code can be written to read the response matrix, the bids, and other relevant data from the database and write the LP. The LP maximises consumer and producer surplus, subject to environmental quality constraints and initial allocations.

2.1. Model Smart Nitrader-GW: a Smart Market for Nitrate Trading in Ground Water.

Indices: i =1,…, N traders.
j =1,…, M control points.
t =1,…, T time periods.

Parameters
A_i, initial allocation to trader i.
H_{ijt}, concentration occurs at control point j, time t, from 1 unit discharge at pollution source i, (g/ m^3).
S_{jt}, maximum acceptable concentration from this year's pollution at control point j, time t (g/ m^3).
UB_i (US_i) limit on buy (sell) bid from trader i.
PB_i (PS_i) buy (sell) price offered by trader i (\$).

Decision variables
B_i, purchases by trader *i*. S_i, sales by trader *i*.
Q_i, discharge by trader *i*.
P_i, market price discharge for trader *i*, from row 3.

Objective function
Maximise $\Sigma^N_{i=1}(B_iPB_i - S_iPS_i)$, subject to
Upper bounds on bids

$B_i \le UB_i$, for all $i = 1,\dots, N$ (1)

$S_i \le US_i$, for all $i = 1,\dots, N$ (2)

Compliance constraints

$Q_i + S_i - B_i = A_i$, for all $i = 1,\dots, N$ (3)

Water quality standards

$\Sigma^N_{i=1} H_{ijt}Q_i \le S_{jt}$, for all $j=1,\dots, M$, $t=1,\dots, T$ (4)

Non-negativity constraints

$Q_i, B_i, S_i \ge 0$, for all $i = 1,\dots, N$ (5)

It can be proved that the price generated by the above LP is at least the offer/reservation price or a better price. Thus, all dischargers can place buy and sell bids to maximise their gains. We assume that the regional environmental authority has appointed a *market manager* to coordinate this market. The manager runs the LP and displays the allocations and prices on the web site. Some preliminary tentative auctions may help the participants to generate expectations for the results. Once the final auction is run, the manager collects money from sellers, pays the buyers, and clears the auction. The proposed web interface, database system, and computer code which create the LP remain for future development.

3. A SIMPLE CASE STUDY

This case study is a modified version of the first sample groundwater flow and transport problem described in PMWIN 5.3 user guide (Chiang & Kinzelbach, 1998). The hypothetical catchment covers a rectangular area 600m by 580m. The catchment is bounded by impermeable rocks (no-flow boundaries) on the East and West sides. The North and South boundaries are considered as fixed head boundaries and the hydraulic heads are 10 m and 8 m respectively. The ground surface elevation is 10 m above reference level.

The model assumes three vertical isotropic layers. The top layer has uniform thickness of 4m. The bottom layer varies in thickness from 6m in the middle, to 3m at the West and East ends, where two irregular silt layers are sandwiched between the top and bottom layers. The aquifer receives a constant groundwater recharge of 0.691 mm/day. There are three groundwater wells from which water is abstracted at a constant rate of 50 m^3/day. Other aquifer parameters used for the flow simulation are given in Table 1. A plan view of the study site is shown in Figure 1.

Table 1. Properties of isotropic layers

Property	Top layer	Bottom layer	Silt layers
Horizontal hydraulic conductivity (m/day)	40	16	4
Vertical hydraulic conductivity (m/day)	4	8	0.4
Specific yield	0.05	NA	NA
Specific storage	NA	0.00005	0.00005
Effective porosity	0.25	0.2	0.1

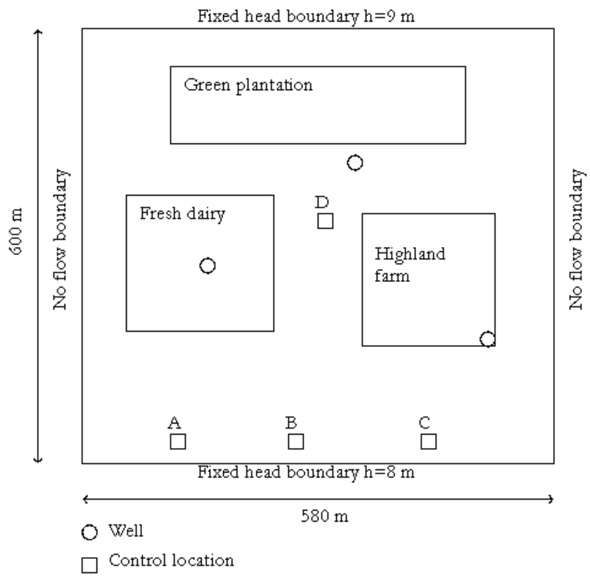

Figure 1. A plan view of the study site

Nitrate mobilization in the catchment is due to leaching and overland runoff is negligible. The initial concentration is zero. Nitrate transport in the aquifer is governed by advection, dispersion, and equilibrium controlled sorption. The longitudinal and transverse dispersivities are 10 m and 1 m respectively. Retardation factor is 2 and molecular diffusion coefficient and decay rate are zero.

The catchment has three nitrate sources (we assume three farmers) named Fresh, Green, and Highland. They have permits to discharge nitrates at a specified rate. The permit is valid for a year. The regional environmental authority has provided them with some guidelines on the potential discharge of nitrates from different crops, livestock, and farm management practices. At the start of the year, each farmer needs to decide which type of commercial farming (land use) is most profitable for the coming year and the amount of discharge permits needed.

The regional environmental authority wants to make sure that concentration levels at all control locations do not exceed the acceptable standards at any time due to trade. The authority has set a maximum acceptable increase in concentration at each control point at the end of each time period. The market solution must adhere to these limits.

3.1. Trading Nitrate Discharge Permits

To show how a trading system benefits the farmers, suppose the farmers have permits to discharge nitrates at a rate of 1.6 g/day/m^2. They have three options for this year:

- Option X: crop X, with discharge 0.5 g/day/m^2.
- Option Y1: crop Y using best management practice, with discharge 1.6 g/day/m^2.
- Option Y2: crop Y using conventional practice, with discharge 4.6 g/day/m^2. This discharge rate exceeds every farmer's permit.

Table 2 shows a farmer's profits for the options under different market prices of permits.

- If trade is not allowed, option Y1 is most profitable whereas option Y2 is impossible. Option Y2 would be most profitable, but is impossible because the discharge is higher than permitted.
- If trade is allowed and price is \$15/g/day/m^2, option Y2 is most profitable, with a profit of \$1,155. The farmer would buy 3 g/day/m^2.
- If trade is allowed and price is \$17/g/day/m^2, option Y1 is most profitable. The farmer would neither buy nor sell.
- If trade is allowed and price is \$50/g/day/m^2, option X is most profitable. The farmer would sell 1.1 g/day/m^2 of the permit.

Thus, at \$15, this farmer would bid to buy 3 g/day/m^2. At \$50, the farmer would offer to sell 1.1 g/day/m^2. This way, all farmers can estimate their profits and place bids accordingly.

3.2. Hydrological Simulation

Two hydrological simulation models were used to obtain the response matrix of the trading system. Groundwater flow in the catchment was simulated using the standard groundwater modelling program, MODFLOW (Harbough et al., 2000). The groundwater contaminant transport was simulated with MT3D (Zheng, 1990). All simulations were carried out on PMWIN 5.3 (Chiang & Kinzelbach, 1998), a freely available graphical user interface for MODFLOW and related transport models such as MT3D.

The MODFLOW model has 30 rows and 28 columns, in size varying from 30x30m at the boundaries to 10x10m at the well locations. The aquifer is represented in 5 layers. The top and bottom layers were 4m and 3m thick, respectively. Each had spatially uniform aquifer characteristics. Layers 2, 3, and 4 had heterogeneous aquifer properties. The transient simulation was set for 12 years (as trial simulations showed this was sufficient). Recharge and abstraction rates from wells were kept constant over this period.

Table 2. Profits by option for different prices

Option	X	Y1	Y2
Discharge, g/day/m^2	0.5	1.6	4.6
Profit from crop growing	\$1,100.0	\$1,200.0	\$1,200.0
Cost of best mgt practice	\$0	–\$50.0	\$0
Profit, trading nitrates at \$15/g/day/m^2	\$16.5	\$0	–\$45.0
Total annual profit	\$1,116.5	\$1,150.0	\$1,155.0
Profit, trading nitrates at \$17/g/day/m^2	\$18.7	\$0	–\$51.0
Total annual profit	\$1,118.7	\$1,150.0	\$1,149.0
Profit, trading nitrates at \$50/g/day/m^2	\$55.0	\$0	–\$150.0
Total annual profit	\$1,155.0	\$1,150.0	\$1,050.0

We assume that nitrate leaching occurs uniformly from the whole area of each farm at a constant rate throughout the year. Diffuse sources are simulated in MT3D with the recharge package, so recharge concentration was calculated as the discharge rate divided by the constant recharge to aquifer. The constant recharge to aquifer is 0.000691 m/day. If the pollutant is loaded to the aquifer at a rate of 0.691 g/day/m^2, the recharge concentration is 1000 g/m^3. For this study, a permit to apply nitrates at a rate of 0.691 g/day/m^2 is considered as a unit permit and 1000 g/m^3 as the source concentration occurs from a one unit permit.

To obtain the response matrix, we ran three simulations, one for each participant discharging one unit (equal to 0.691 g/day/m^2) throughout the first year of simulation. From each simulation, we observed the concentration at end of each year at 8 control points: A1, A5, B1, B5, C1, C5, D1 and D5, the character representing the control location and the digit representing the layer.

For the case study, the LP had 12 periods, 8 control points, and 12*8 water quality constraints. We identify each constraint as "yearYCP," representing the constraint for year Y at control point CP. The right hand side of each constraint, S_{jt}, can be viewed as a resource, i.e., the allowable increase in nitrate at location j in period t. We analysed the prices and allocations generated by the LP under three trading scenarios. The trading scenarios were distinguished by varying the initial allocations and participant's bidding behaviours.

4. RESULTS AND DISCUSSION

Scenario A: Initial allocation is 1 unit. Farmers have three options with potential discharges of 0.5 units, 0.9 units, and 1.2 units. Each farmer bids identically to buy up to 0.2 units at $10 (to make a total of 1.2) and sell up to 0.5 at $20 (to keep only 0.5 units. By the initial allocation of 1 unit to each discharger, constraint year5A5 would be violated. That is, this resource is over allocated. The extra allocation is calculated as 31.6739*1 + 5.4643*1 + 0*1 – 33.33 = 3.8081. This is shown as a negative initial surplus in Table 4, in the column "Initial surplus". The result for this scenario is in Table 3, with the binding constraints in Table 4.

Total payment to sellers ($3.09) is more than the total paid by buyers ($0.98), so the market manager pays a net of $2.11. This is because the resource year5A5 is initially over-allocated by 3.8081, as described above. The model would be infeasible without trading. Fortunately, all traders are willing to sell. So the market manager buys the extra allocation of 3.8081 units of resource year5A5 at its shadow price, $0.6314. In contrast, constraint year4C4 is under allocated initially by 1.0202 units. That is, before trading, the market manager has 1.0202 units excess of this resource. Everyone is willing to buy. Hence, the manager sells 1.0202 units of this resource at its shadow price, $0.2830. The manager's net payment is therefore $3.8081*0.6314 – 1.0202*0.2830 = $2.11.

Table 3. LP solution for scenario A.

	Fresh i=1	Green i=2	H'land i=3	Total
Buy (B_i)	0	0.2000	0.0224	
Sell (S_i)	0.1547	0	0	
Final allocation (Q_i)	0.8453	1.2	1.0224	
Bid price (P_i)	$20.00	$3.78	$10.00	
Receipts from buyers	$0.00	$0.76	$0.22	$0.98
Payments to sellers	$3.09	$0.00	$0.00	$3.09
Surplus to manager				−$2.11

Table 4. Binding constraints for scenario A

Identifier	Constraint	Initial surplus	Shadow price
year4C5	$0\ Q1 + 1.1479\ Q2 + 35.3319\ Q3 \leq 37.5$	1.0202	0.2830
year5A5	$31.6739\ Q1 + 5.4643\ Q2 + 0\ Q3 \leq 33.33$	−3.8081	0.6314

With this scenario, only Fresh can sell. Green and Highland can buy. But Highland can buy only a small amount (0.0224 units). It is not sufficient to adopt another farming option which needs 0.2 more units. Green gets all he wanted. The price for Green is the least, because his demand is less compared to what he could have bought.

Scenario B: Due to the over allocation in Scenario A, we changed the initial allocation so it is not overallocated. We obtained the maximum feasible initial allocation by changing the objective of the LP, to maximise the total allocation so that everyone gets the same, subject to the water quality constraints. The solution is 0.8943. This initial allocation does not violate any constraints. The binding constraint was year4A5. When the initial allocation varies, the demand varies, and the traders adjust the bids accordingly. Each farmer now bids to buy up to 0.3057 units at $15 (to make a total of 1.2 units) and sell upto 0.3943 at $30 (to keep only 0.5 units). The result is in Table 5 with binding constraints in Table 6.

Table 5. LP solution for scenario B.

	Fresh i=1	Green i=2	H'land i=3	Total
Buy (B_i)	0.0000	0.3057	0.1281	
Sell (S_i)	0.0490	0.0000	0.0000	
Final allocation (Q_i)	0.8453	1.2	1.0224	
Bid price (P_i)	$30.00	$5.66	$15.00	
Receipts from buyers	$0.00	$1.73	$1.92	$3.65
Payments to sellers	$1.47	$0.00	$0.00	$1.47
Surplus to manager				$2.18

Table 6. Binding constraints for scenario B

Identifier	Constraint	Initial surplus	Shadow price
year4C5	$0\ Q1 + 1.1479\ Q2 + 35.3319\ Q3 \leq 37.5$	4.8761	0.4245
year5A5	$31.6739\ Q1 + 5.4643\ Q2 + 0\ Q3 \leq 33.33$	0.1173	0.9472

Total paid by buyers is greater than the total due to sellers, so the manger has a surplus. This surplus can be explained using the binding constraints. Two constraints: year4C5 and year5A5 which were not binding in the initial allocation become binding after trade. They are initially under-allocated resources. The buyers first buy from manager's excess. The surplus money left after clearing the market is the buyer's payment for the resources they bought from the market manager. As expected, prices and trades change when the bids change. But as in scenario A, Fresh sells and others buy. Highland again can buy an insufficient amount while Green gets all he wanted.

Scenario C: What if Fresh wants to buy, Highland also wants to buy more, and Green wants to sell? Suppose they bid differently as in Table 7. Initial allocations are the same as in above scenario B.

The results in Table 8 indicate that even if Fresh is prepared to pay more he cannot buy (B_1 =0.0001 ≈ 0). Highland also cannot buy much more. Even though Green offers to sell at $10, he cannot sell.

This is reasonable, because the shadow price at Green is $2.96, and unless he drops the reservation price down to $2.96, he cannot sell. That is, if Green offers to sell at $2.95 while others don't change the bids, he can sell all 0.3943 units, and Fresh and Highland can buy 0.0132 units and 0.1508 units respectively. We observe that no matter how much Fresh and Highland are willing to pay, they cannot buy 0.2 units.

Table 7. Bid prices for scenario C.

	Buy (offer price)	Sell (reservation price)
Fresh (i=1)	$50	-
Green(i=2)	-	$10
H'land(i=3)	$40	-

Table 8. LP results for scenario C.

	Fresh i=1	Green i=2	H'land i=3	Total
Buy (B_i)	0.0001	0	0.1380	
Sell (S_i)	0	0	0	
Final allocation (Q_i)	0.8944	0.8943	1.0323	
Price(P_i)	$50.00	$2.96	$40.00	
Receipts from buyers	$0.00	$0.00	$5.53	$5.53
Payments to sellers	$0.00	$0.00	$0.00	$0.00
Surplus				$5.53
Binding constraints	year4A5 (shadow price = $1.2322) year4C5 (shadow price = $1.1321)			

The lack of flexibility is explained from the water quality constraints. For instance, the concentration at control point A in year 4 ($40.578\ Q1 + 1.3513\ Q2 + 0\ Q3 \leq 37.5$) is contributed entirely by farmer Fresh. There is no opportunity to increase the discharge at Fresh by reducing the pollution at Green and/or Highland. But higher demand at Fresh raises the worth of resource 'year4A4'. The shadow price of this constraint tells how much the quality standard imposed at control point A costs to the society. Similarly, the concentration at control point C in year 4 is contributed almost only by farmer Highland, and there is little opportunity to increase the pollution at Highland by reducing the pollution at Fresh and/or Green.

5. LIMITATIONS

For our case study, the concentration at a control point was accurately expressed as a linear function of the quantities discharged at distinct locations. Beyond this problem domain, the discharges may have non-linear responses. We considered the recharge to be spatially uniform and constant throughout the whole period. But certain parts of the catchment may receive higher/lesser recharge than the other parts due to varying rainfall, evaporation, and other inflow and outflows. Even though recharge is neither uniform spatially nor constant over time, MODFLOW can handle it. But the uncertainty of future recharge appears to be a challenge for this market.

Well abstraction rates and return flows also affect the concentration. We kept the well abstraction rates constant over the whole period, and assumed no return. But abstraction rates can vary over time, and a certain amount of abstracted water is possibly returned to the aquifer. The returned water may be much polluted. Again, uncertainty stands in both future withdrawal rates and returns. The wells take the contaminated water out. Therefore, high abstraction rates probably decrease the concentration. Thinking another way, when abstraction rates are high, there will be less water to dilute the pollutants and the concentration may increase. Thus, a farmer may be able to manipulate the impacts of his discharge by manipulating the well abstraction rate. Therefore, a market for both water and discharge may be a better solution.

The permits are defined as the pollutant mass (grams) that can be loaded on a unit surface area (square meter) of the aquifer per time period (day). But the real application of pollutants, for example chemical fertilizer, occurs at time lags. Leaching may be severe in rainy season and minor in dry season. Consequently, the timing of true water pollution depends on uncertain weather.

The major enforcement issue concerned with these permits is whether the owners of the permit know what they can and cannot do, based on the particular discharge profile associated with their particular land use. The simplest way to deal with this is through the regional environmental authority. The authority can provide guidelines on the daily discharge of the pollutant from different crops, livestock (number of cows, sheep, or other animals), and other potential sources and require the participants to have sufficient permits. Pollutant leaching from those sources under given geography and weather conditions can be estimated using software tools such as SWAT (Neitsch et al., 2005). How often the market should run depends on how often the participants change the type of land use. Obviously, farmers cannot do this too frequently.

The LP generates continuous buy and sell quantities. This may create conflict. For example if a farmer needs 5 units to grow a new crop and bids to buy 5, buying 4 units or anything less than 5 units may be useless. So if the bid is accepted, the farmer must get at least 5 units. The upper bounds can be supported by the current LP, but lower bounds may make the problem infeasible. The tentative auctions can help to some extent. But facilitating trade in discrete blocks will be useful.

The location and number of control points have a strong influence on this market. If a control point is close to one discharger and far from others, the close discharger would face a relatively higher price. The right hand sides of the water quality constraints are based on the environmental authority's pre-judgement of how much pollution this year's dischargers can forward to the future. It is not a guarantee that the water quality standard will be achievable in the future. Last, not least, the prices and allocations depend on the coefficients generated by the catchment hydrological models. Therefore, well calibrated MODFLOW and MT3D (or other) models are recommended.

6. CONCLUSIONS

This market generates location specific prices. With an arbitrary initial allocation, a positive or a negative trade surplus is possible, so the market manager may make a net payment or a gain. If the initial allocation is feasible, the market manager does not make a net payment and a surplus may or may not remain after clearing the market. As expected, the prices and allocations depend on bids and water quality constraints. But for the particular case study, the final distribution of permits is least dependent on the bids. Water quality constraints (H_{ijt} values) significantly restrict the allocations.

Participants do not have to find trading partners because they use the online auction. They do not need to negotiate with the affected parties as the model itself takes into account the impacts on environment and other participants. Information such as price history can be made freely available on the auction web. Therefore, transaction costs are almost eliminated. This market is efficient end effective as long as the participant behaviour is not illegal and the tools and data are available to obtain the response matrix values and the potential leaching from different land uses.

Protection of water quality, low transaction costs, flexibility for commercial land users, and adoptability for any hydrological pollutant are the key features of this smart market. Future work includes associating the effects of both point and diffuce sources, surface water and ground water interaction, water withdrawals, overland runoff, nutrient reduction technologies and uncertainty in water flow and nitrate transport.

7. REFERENCES

Chiang, W., & Kinzelbach, W. (1998), Processing Modflow: a simulation system for modelling groundwater flow and pollution.

Collentine, D. (2005), Including non-point sources in a water quality trading program, *Water Science and Technology*, 51(3-4), 47-53.

Dales, J. H. (1968), Land, water and ownership, *Canadian J. of Economics*, 1(4). 971-804.

Eheart, J.W., Brill, E.D., Lence, B.J., Kilgore, J.D., and Uber, J.G. (1987), Cost efficiency of time-varying discharge permit programs for water quality management, *Water Resources Research*, 23(2), 245-251.

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, USGS, Reston, VA.

Horan, R.D., Shortle, J.S., and Abler, D.G. (2002), Point-nonpoint nutrient trading in the Susquehanna River Basin, *Water Resources Res.*, 38(5).

Leston, D. (1992). Simulation of a two-pollutant, two-season pollution offset system for the Colorado River of Texas below Austin, *Water Resources Research, 28*(5), 1311-18.

McCabe, K.A., Rassenti, S.J., & Smith, V.L. (1991), Smart Computer-Assisted Markets, *Science*, 254(5031), 534-538.

Morgan, C.L., Coggins, J.S., & Eidman, V.R. (2000), Tradable permits for controlling nitrates in groundwater at the farm level, *J. Agr. and App. Econ*, 32(2), 249-258.

Neil, W.O., David, M., Moore, C., & Joeres, E. (1983). Transferable discharge permits and economic efficiency: The Fox River, *J. Env. Econ. and Mgt*, 10(4), 346-355.

Neitsch, S.L., Arnold, J.G., Kiniry, J.R., and Williams, J.R. (2005). Soil and Water Assessment Tool, Grassland, Soil, & Water Res. Lab. & Blackland Res. Centre, Texas.

Raffensperger, J.F., and Milke, M. (2005), A design for a fresh water spot market, *Water Sci. and Tech: Water Supply*, 5(6), 217-224.

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