Optimal Economic Management of Groundwater Quantity and Quality:

An Integrated Approach

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Short Abstract: A dynamic model is developed that jointly optimizes over groundwater quality and quantity for extractive municipal and non-extractive agricultural users. The model is applied to an aquifer in southern Ontario to analyze several policy scenarios, demonstrating that interactions between externalities can partially offset one another.

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Introduction

Abundant supplies of clean groundwater are essential to communities that rely on aquifers – for drinking, watering livestock, irrigation or industrial uses. Conflict is common in areas where the quantity or quality of water is compromised by over-extraction or contamination. Agricultural uses have often been blamed as sources of groundwater contamination, particularly by nitrates leached from the fertilized soil (Addiscott and Powlson, 1991). Depletion of groundwater quantity has usually been associated with municipal and industrial works, impacting on all water users who may require deeper wells, or face higher costs of importing water if wells run dry.

Policy analysts have at times proposed restrictions to limit groundwater contamination to a certain threshold, and/or to curtail rates of groundwater extraction, without considering the effects of the individuals policies on each other. Resource economists have often acknowledged linkages between groundwater quality and quantity management issues, but have not done much analysis of these relationships (Fleming and Adams, 1997). This paper applies dynamic optimization model developed by Zachariah (1999) to a case study of the Southwestern Ontario township of Wilmot to demonstrate that integrating quantity and quality relationships into a single economic problem of aquifer management would yield an optimal outcome, and individual policies by themselves may be inappropriate.

The paper uses an approach that combines water quality and quantity costs and benefits over extractive and non-extractive users into one intertemporal allocation problem. The non-extractive use is agricultural waste assimilation, and the extractive use is as drinking water for nearby municipalities with well-heads in surrounding rural regions. The externalities that are modeled include over-extraction due to municipal water pricing that only covers the costs of distribution and treatment, and overuse for waste assimilation due to the absence of controls on leaching of agricultural nutrients.

Empirical results, indicate that if attempts were made to resolve groundwater quantity and quality problems by addressing them independently, the overall loss would be greater than the current loss of allowing both problems to persist and allowing their cross effects to partially offset each other.

The rest of this paper is divided into three sections. Section One presents the rationale for integrating groundwater quantity and quality management policies and describes the theoretical model. Section Two presents the economic and physical data of Wilmot Township to which the model was applied, and the management scenarios considered. Section Three presents the results of the study, and concludes with a discussion of the research applications and policy implications.

Section One

Aquifers provide extractive benefits, associated with groundwater withdrawals for crop and livestock production, industrial production and domestic use, and non-extractive benefits derived by farmers when waste products from animal rearing and field fertilization are assimilated on-site (Bergstrom *et al.* 1996). Onsite disposal agricultural waste is a private benefit to farmers as it allows them to avoid waste handling costs that would lower profits. Thus, the pollution abatement cost avoided is counted as the benefit of waste assimilation.

Private and external costs are created from the extractive or non-extractive uses of aquifers. Excessive extraction drives the water table lower and causes other pumps to expend more energy to draw water over greater lifts, and may necessitate the deepening of shallow wells. Excessive extraction not only increases extraction costs but also reduces the stock of water available for other users in the future (Provencher and Burt, 1993). In a sense, current extractors create an externality that lowers the social value of groundwater for future generations. This is the central problem addressed by a number of studies (e.g., Negri, 1989, and Tsur and Zemel, 1995). On the other hand, waste assimilation creates external costs for groundwater extractors if, due to such assimilation, groundwater treatment becomes necessary (O'Neil and Raucher, 1990).[1]

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[1] Apart from costs incurred by groundwater extractors there may be costs related to the decreased value of surface waters affected by increase nutrient loading. This environmental cost has not been included in the analysis.

Lee (1998) as reviewed a number of studies proposing how the appropriate balance between waste assimilation benefits and clean water benefits of the aquifer should be achieved. Similarly, Zachariah (1999) has reviewed the main approaches proposed to address the problem of excessive extraction. In general, water quality models propose pollution reduction programs such as taxes, emissions charges, changes in agricultural practices to lower the cost of supplying drinking water. By concentrating solely on supplying drinking water, researchers attach all economic importance of the aquifer to its extractive uses. But clearly, an aquifer provides beneficial services other than that of supplying water. This is why Bergstrom *et al.*, (1996) recommend that the full range of environmental and economic services of groundwater needs to be accounted for in policy decisions. This involves measuring the benefits and costs of extractive and non-extractive uses of groundwater and their interrelated nature. The missing link in the groundwater economics literature is that little attention has been given to how extractive and non-extractive benefits and costs of groundwater use should be pulled together.

This economic model accounts for extractive and non-extractive benefits and costs of using the aquifer. The model accounts for the economic functions that measure the benefits of groundwater extraction and waste assimilation. Quantity and quality variables are linked through economic relationships of extractive and non-extractive uses, on one hand, and through physical relationships (stock dynamics, pollution dynamics, and hydrology), on the other hand.

Extractive uses affect groundwater quantity variables, creating extraction externalities on other users and may affect the quality of water remaining in the aquifer as a given amount of pollutant must be assimilated by a smaller volume of water. These extractors derive the benefits of groundwater for a range economic activities. Non-extractive uses affect groundwater quality parameters making it more expensive for extractive users, thus affecting groundwater quantity parameters. For example, more polluted water increases treatment cost and reduces the incentive to extract. The decreased incentive to extract helps to decrease the costs associated with water table depletion. Simultaneously, non-extractive users are benefitting from agricultural production derive benefits as costs of waste abatement are avoided. The converse on this reasoning is also true. Improved water quality serves to increase extraction rates.

The optimal solution is one that determines the allocation of activities that maximizes the net present value of economic benefits of services provided by the aquifer over the given planning horizon. Using dynamic programing, the Lagrangian function to be maximized is:

$$L = [N(g_t^p(w_t^p) - c_t^p(x_t, \psi_t^C) w_t^p + g_t^m(w_t^m) - c_t^m(x_t, \psi_t^C) w_t^m + \\ + g_t^d(\psi_t) + (N+1)\beta V_{t+1}(x_t - w_t^m - N w_t^p + r_t)] \\ + \lambda_t(x_t - w^m - N w^p) \tag{1}$$

where

g_t, c_t, are benefit and cost functions respectively, in period t; *p, m* and *d* are superscripts referring to privately supplied extraction, municipal extraction, and waste assimilation activities, respectively; w_t and ψ_t are rates of groundwater extraction and waste assimilation, respectively, $w_t \geq 0$ and $\psi_t \geq 0$; x_t is the stock of groundwater in the aquifer, N is the number of privately self-supplied extractors, r_t is the rate of groundwater recharge in period t, β is the discount factor, V_{t+1} is the function representing the value of the aquifer in period *t+1*, and λ is the Lagrangian multiplier for the stock constraint.

The cost of water for extractive purposes is a function of groundwater x_t (affects the pumping cost) and the rate of waste assimilation, ψ_t (which affects treatment cost). Agricultural cost avoided, g_t^d, is a function of waste assimilation since this is derived from the abatement cost function. The term:

$$x_{t+1} = x_t - N w_t^p - w_t^m + r_t \tag{2}$$

defines the groundwater stock equation of motion. And

$$x_t - w_t^m - N w_t^p \tag{3}$$

sets the constraint that total extraction should not exceed available stock.

The model uses linear inverse demand functions based on an own price elasticity of -0.569 estimated by Renzetti and Dupont (1997). Parameters for the non-extractive user's benefit function were obtained by regressing levels of nitrate leaching on foregone agricultural revenues as estimated by Yiridoe and Weersink (1998).

Several other simplifying assumptions about the hydro-geologic properties about the Wilmot aquifer were made along with assumptions about the fate of nitrate in groundwater and water treatment technology. The main parameters are summarized in Tables 1 and 2. The problem was solved for a 50 year planning horizon using General Algebraic Modelling System (GAMS) computer software. Other time horizons were solved as sensitivity checks.

Analytical results for the socially optimal solution from include the following:

i. The optimal time path of waste assimilation and the optimal time path of groundwater extraction are simultaneously determined and cannot be obtained by independent management of groundwater quality or quantity.

ii. Farm operators choose levels of activity (fertilizer application with the associated level of waste assimilation) where the marginal benefit is equal to the present value of the sum of all marginal effects of fertilizer application on the cost functions of all extractive users affected. These marginal effects are determined by size and duration of external costs visited on extractive users.

The primary implication of the analytical results of the integrated model is that while the existence of externalities may point to the need some adjustment in aquifer management, it may not be sufficient to improved groundwater management benefits by implementing policies that do not recognize the interrelationships of quality and quantity decisions.

Section Two: Empirical Model and Case Data

The model was applied to Wilmot Township in Southwestern Ontario where the maim regional aquifer is an important source of potable water for the 13,000 residents of the area and some of the 250,000 urban residents in nearby Kitchener-Wateroo (K-W). Wilmot Township is also a prime agricultural region. Farm cash receipts from the 307 farms located there in 1996 amounted to $61M. This represents a substantial contribution to local employment and other economic activities.

In 1996, a groundwater quality survey showed that nitrate levels in the area ranged from as low as 1 part per million (ppm) to 19 ppm (RMW, 1998). The Ontario drinking water objective for nitrate in water is 10 ppm. To protect future drinking water supplies, the Region contemplates wellhead protection policies intended to avoid future groundwater treatment expenses. Some policies may include restriction of agricultural activities in high risk areas (Murray, 1995). To reduce the problem of water table depletion due high withdrawal rates, extraction controls by Ministry of the Environment have been proposed. Though both authorities often consult each other, such consultations have generally not been for the purpose of defining the quantity quality program interrelationships of their proposed policies. The model is used to estimate what might be the optimal levels of extraction and waste assimilation activities if these relationships are connsidered.

To estimate the optimal levels of groundwater extraction and waste assimilation, the model was solved under the assumption that groundwater authorities had the necessary information and appropriate policy instruments at hand to maximize the net present value of benefits (extractive and non-extractive) from the aquifer over a given planning horizon.

Alternative management scenarios:

From the theoretical model, the solution of the integrated approach is optimal. To compare the extent to which other approaches would fall short of the optimal result four alternative management regimes for groundwater were considered. These scenarios were based actual or suggested policy activities of groundwater management authorities in Wilmot Township – The Regional Municipality of Waterloo and the provincial Ministry of Environment.

As the primary supplier of water The Region has the authority to protect groundwater recharge areas from potential sources of pollution. They may use landuse zoning by-laws, local operating standards and outright restrictions to prevent groundwater contamination form agricultural waste assimilation. The Ministry of Environment has the responsibility under the Ontario Water Resources Act to limit the amount of permitted extractions from aquifers. It may use various measures to reduce groundwater extraction that creates cost externalities on neighbouring wells or where the aquifer is threatened with depletion.

These two groundwater management authorities, together have the authority to design and implement policy tools that would bring about the optimal aquifer management result but generally do not act together to the extent necessary for an the optimal result. Rather, decisions may be based on the perceived need for action. The management scenarios evaluated in this paper were constructed to account for this reality.

A) Status Quo - The Region and the Ministry of Environment were assumed not to take any specific actions to reduce the current trends in groundwater extraction and waste assimilation due to crop fertilization activities. Municipal extractors supply water to residents at the cost of extraction and distribution without any specific charge for the scarcity value of water itself. Farm operators apply nutrients to their fields without accounting for the costs that could be passed on to extractive users.

B) Water Quality Protection Regime - The Region responds the high levels of nitrate recorded in some areas of Wilmot with a limit on the amount of nitrogen that can be applied of fields given crops. This water quality protection program is designed to limit nitrate leaching to no more than 15 kg nitrate nitrogen /ha/year.[2] Under this regime, the Ministry of Environment operates as under the status quo.

C) Groundwater Demand Management - In response to well interference complaints and to concerns about protecting base flow for ecosystems at risk, the Ontario Ministry of Environment embarks on a program to limit groundwater extraction by municipalities and industrial extractors. This would be done through the revocation or reduction of permitted extractions. Farmers as assumed to produce agricultural waste due form crop fertilization without penalties or disincentives from The Region.

D) Separately Implemented Demand Management and Water Quality Protection - This policy scenario considers the possibility that both The Region and Ministry of Environment may implement policy tools that address specific area of responsibility. Each authority implements policy to address the

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[2] Groundwater managers are assumed to know the marginal abatement cost functions per hectare of the agricultural community. A maximum amount of fertilizer per hectare or a precisely nutrient accounting system would be sufficient to ensure a binding constraint.

problem as is seen in isolated context; thus, no consideration is given to the possibility that interrelationships between policies could affect their suitability.

Section Three: Results

For every policy scenario considered, the model predicts levels of groundwater extraction, levels of agricultural production (for a given nitrate management plan), and total economic benefits derived from water use and agricultural fertilization in the township (summarized in Table 3).

According to the model, the scenarios ranked by benefits from highest to lowest were: integrated approach, status quo, groundwater quality protection policy, demand management to conserve aquifer stock, and separately administered groundwater quality protection and demand management policy.

In the ideal state, groundwater extraction rates would be set at exactly the amount that would maximize benefits to the area, and farming would be restricted to the level where the marginal environmental cost of farming was equal to the marginal environmental benefit of farming. If these were actually done, the benefits obtained under this scenario would be maximized. Thus, the integrated approach would yield optimal results.

- As can be seen, the optimal amount of extractions would exceed that amount under the status quo, but the optimal amount of waste assimilation would be less than that under the status quo.
- Under a demand management program to protect groundwater stocks, extractors absorb the major cost of the policy.
- When a water quality protection program is introduced the farming community bears the major cost of the action but this spurs on greater rates of extraction even beyond the optimal amount.

These results demonstrate that the activities are interrelated and changes in one may affect levels of the other.

Policy Implications & Research Applications

Consider the policy recommendation that stronger restrictions be placed on the farming community to keep nitrate levels below a given threshold. Depending on the extent of restriction, policy makers may be creating greater costs than benefits. By forcing the farming community to cut back its use of fertilizers, policy makers may help make groundwater cheaper but make farming less profitable. In this case the marginal cost of this policy would be larger than the marginal benefit.

To the municipal water user, the water quality program is beneficial. Compared to the optimal outcome, this policy would cause economic benefits of urban water users to increase by 17% while benefits of the farming community would fall by approximately 10% (see Table 3). However, as Table 3 shows, the overall economic well-being of Wilmot Township region would decrease by 4%.

Water quantity conservation does not necessarily increase economic benefits either. An extraction control policy would reduce total benefits by more than 1%. The full cost of this would be borne by municipal water users whose welfare would fall by 9%. Finally, the economic losses from groundwater use under current policy (status quo) are less than 1%. The municipal water users are clearly much worse off than they would be under a nitrate management policy. However, the status quo is the policy scenario that is closest to the optimal outcome predicted by the model.

Apart from implementing the ideal integrated approach to address the rural-urban groundwater conflict in Wilmot Township, it becomes clear that the best action for the perceived groundwater management problem is almost no action. This is explained by the interrelationship between water quality and quantity decisions. The policy implication is that all such regulations should be economically justified.

As Table 4 shows, these results are very sensitive to the area of land cultivated, the marginal benefit function for waste assimilation, the marginal benefits function for groundwater extracted, environmental constraints, and the treatment cost of water. For example, with a large and rapidly growing urban population in Wilmot Township, or high value industries that depended on large amounts of clean groundwater a water quality protection program may become economically feasible. Also, increased treatment costs for contaminated groundwater could justify the introduction of water quality programs.

Table 1 Hydrological Data Used In The Integrated Model

Area of aquifer = 38.48 km^2
Storativity = 0.15
Transmisivity = 1250 cubic m per day
Distance measurement for well interference (d_{ij}) = 300 m
Initial depth of water table from ground surface = 22 m
Initial thickness of aquifer = 105 m

Table 2 Explanation Of Functions and Coefficients Used in Base Solution of the Integrated Model

Expression	Notes
Gross benefit of private extraction = $N[2.5368w^p - 0.003246(w^p)^2/2]$	N = 300, number of self-supplied wells 2.5368 = intercept; 0.003246 = coefficient w^p = self-supplied groundwater extraction (m^3/year) Sources: Renzetti and Dupont (1997) and Tate and Lacelle (1995)
Gross benefit of municipal extraction = $2.5368w^p - 0.0000121(w^m)^2/2]$	2.5368 = intercept; 0.00000121 = coefficient w^m = municipal groundwater extraction (m^3/year) Sources: Renzetti and Dupont (1997) and Wilmot Township (pers. com.)
Gross benefit of onsite disposal = $165.044\psi - 7.196\psi^2/2$	E^d = agricultural land producing onsite disposal, 1924 hectares 165.286 = constant 7.196 = coefficient ψ = onsite disposal, kg nitrogen/ha Source of data: Yiiridoe (1997)
Total Pumping Cost = $PC^{p}\cdot(L+d^{p})w^{p}$ $PC^{m}\cdot(L+d_t^{m})w_t^{m}$	PC^{p} = self-supplied marginal cost of pumping 1 m^3 over vertical distance of 1m, \$0.0007. PC^{m} = municipal marginal cost of pumping 1 m^3 over vertical distance of 1m, \$0.0007. Source: Provencher and Burt (1994) $L_t + Dd_t$ = total vertical distance (static water table distance and effect of cone of depression respectively). Endogenously determined.
Total Variable Treatment Cost = $0.01455\ \psi^{C}_{t}$	0.01455 = coefficient, ψ^{C}_{t} = cumulative amount of nitrate in groundwater per hectare of land. Endogenously determined. Source: extrapolation based on data from AFCW Environmental Systems Services

Table 3: Summary of Solution Values of Model Applied To Wilmot Township, Ontario

Management Regime/Solution	Integrated Approach	Status Quo	Demand Management	Water Quality Protection	Separately Managed
Groundwater extraction rate (Million cubic meters)	1.4	1.2	1.04	1.54	1.37
Level of waste assimilation (kg nitrate/hectare/year leached)	20.5	22.9	22.9	15	15
Depth of water table at end of planning horizon (meters)	23.2	22.7	21.3	24.4	23
Marginal treatment cost of groundwater ($ per cubic meter)	0.6	0.68	0.68	0.45	0.45
Net present value of extractive and non-extractive benefits ($ Million)	62.9	62.3	60.3	62.1	60.1
Welfare loss associated with management approach as a percentage of social optimum	0.0%	0.9%	1.2%	4.0%	4.4%
Extractors share of total benefits in management scenario	24.4%	22.8%	22.5%	29.8%	29.6%
Farm operators’ share of total benefits in management scenario	75.6%	77.2%	77.5%	70.2%	70.4%
Change in extractors’ welfare compared with integrated approach	0.0%	-7.5%	-9.0%	17.0%	15.5%
Change in farm operators’ welfare compared with integrated approach	0.0%	1.2%	1.2%	-10.9%	-10.9%

Table 4

EFFECTS OF ECONOMIC, HYDRO-GEOLOGIC, AND WATER QUALITY VARIABLES ON DECISION VARIABLES

SENSITIVITY ELASTICITY = % Ä column / % Ä row	PERCENTAGE CHANGE IN BENEFITS	PERCENTAGE CHANGE IN TOTAL EXTRACTION	PERCENTAGE CHANGE IN AGRICULTURAL WASTE
Area of cultivated land vulnerable to leaching	0.753	-0.060	0.156
Marginal benefit function for agricultural cost avoided	0.745	-0.100	0.259
Marginal benefit function for groundwater extracted	0.503	0.068	-0.009
Maximum allowable nutrient loading	0.291	-0.250	0.959
Cost of treating water for nitrate contamination	-0.167	-0.356	-0.096

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