Dynamics of agricultural groundwater extraction

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Abstract

Agricultural shallow groundwater extraction can result in desiccation of neighbouring nature reserves and degradation of groundwater quality in the Netherlands, whereas both externalities are often not considered when agricultural groundwater extraction patterns are being determined. A model is developed to study socially optimal agricultural shallow groundwater extraction patterns. It becomes clear that the current price of groundwater is inefficient and provides fewer incentives for the adoption of modern irrigation technology than does a system that considers the cost of desiccation and groundwater contamination in the price of groundwater. The study shows that including the impact of groundwater extraction on groundwater quality into a resource management model is particularly significant if the recharge of groundwater is large compared to stock size.

Key words: Dynamic renewable resource management; Groundwater quantity and quality; Price reform

1. Introduction

In the Netherlands, farmers extract shallow groundwater of a high quality for low-value use, like irrigation. This extraction can result in desiccation of neighbouring nature reserves due to falling groundwater levels and degradation of the quality of groundwater. These externalities are often not considered when groundwater extraction patterns are being determined.

Despite the seriousness of the pollution and desiccation problem in the Netherlands (about one-fourth of the Dutch utilised agricultural area is desiccated), economic literature on the internalisation of externalities from agricultural groundwater extraction has been limited. Two well-developed branches of economic literature focus on groundwater. One focuses on water quantity, and emphasises the comparison between optimal pumping paths and common property outcomes (e.g. Gisser and Sanchez, 1980, and Provencher and Burt, 1994). The other branch focuses on water quality and analyses contamination in a pollution-control perspective, giving special emphasis to non-point pollution as an externality imposed by agricultural production activities (e.g. Larson, 1996, Fleming and Adams, 1997 and Byström, 1998,). Economic literature has extensively covered water quantity and its quality, but usually separately, as illustrated by the apparent gap between joint quantity and quality management in these two branches of literature. Palma (1999) recently brought quality into a typical resource management model, but the model contains a number of unrealistic simplifications with respect to the hydrological component.

The aim of this paper is to study socially optimal agricultural groundwater extraction patterns and to show how desiccation and contamination can be integrated into an optimal control model. In contrast to other approaches, our approach considers changes in both quantity and quality of the stock simultaneously, because they are mutually interacting. Since we focus on the analytical aspects, the analysis remains theoretical and is not tested on the basis of an empirical application. We use an interdisciplinary model, which shows the interaction between economic, hydrological, and environmental variables. The model used in this paper builds upon models developed by Caswell and Zilberman (1985 and 1986), Dinar and Zilberman (1991), Shah and Zilberman (1992), and Zilberman et al. (1994).

The structure of the paper is as follows. Section 2 describes the setting of the agricultural groundwater extraction problem and shows how changes in stock quantity and quality over time can be modelled. Section 3 shows the open access outcome and the socially optimal outcome and basic features of the optimal control model. Section 4 shows the importance of joint quantity and quality management. Section 5 contains the conclusions.

2. Model approach

2.1 Basic set-up

To explain the impact of agricultural shallow groundwater extraction on groundwater quality and quantity, we start with a schematic representation of water flows in the unsaturated and saturated zone of agricultural soils in the Netherlands (see Figure 1). The figure shows the groundwater stock S as a function of width X, length Y, and height H; $S = XYH$ with dimension [m^3]. We indicate in square brackets the dimension. A smaller stock caused by agricultural shallow groundwater extractions, A [m^3/month], is associated with lower groundwater levels, H [m], for a given area, XY [m^2], which can cause desiccation. Only part h [-] of applied irrigation water A is utilised by the crop, the other part $(1-h)A$ [m^3/month] returns to the groundwater stock. Net natural groundwater recharge R [m^3/month] is equal to percolation minus capillary rise in that area during that time period. For simplicity, horizontal water flows are not considered.

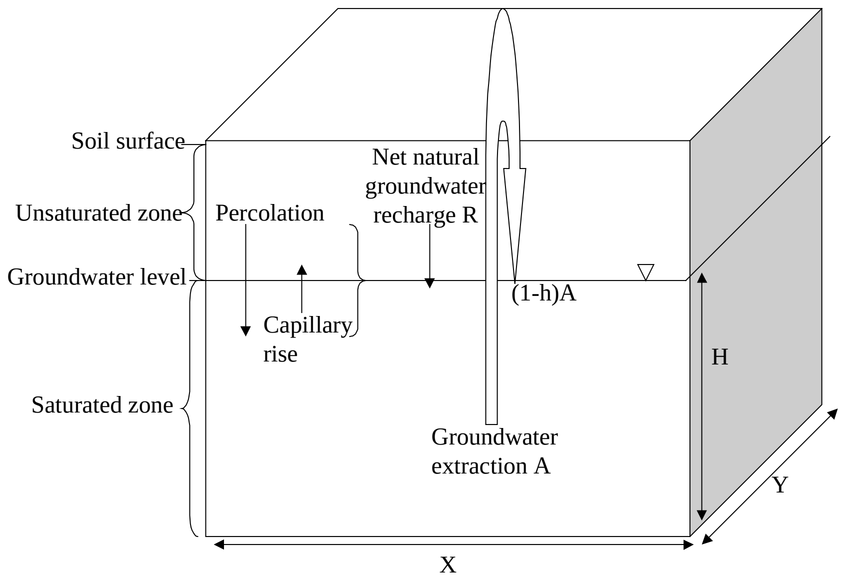

Fig. 1. Schematic representation of the water flows in the unsaturated and saturated zone. The subsoil consists of an open layer on top of an aquifer, which means that the hydraulic resistance of the top layer is low.

The equations of motion of changes in groundwater stock quantity and quality for a given area are based on balance equations of what goes in and out of the stock and are given by[1]:

$$\frac{\partial S}{\partial t} \equiv \dot{S}_t = R_t + (1-h)A_t - A_t = R_t - hA_t \text{, for } S_t \geq 0 \text{ and given an initial condition } S_0 \quad (1)$$

$$\frac{\partial C^{\mathrm{S}}}{\partial t} \equiv \dot{C}_t^{\mathrm{S}} = (C_t^{\mathrm{R}} - C_t^{\mathrm{S}}) \frac{(R_t - hA_t + A_t)}{(R_t - hA_t + S_t)} \text{, for } C_t^{\mathrm{S}} \geq 0 \text{ and given an initial condition } C_0^{\mathrm{S}} \quad (2)$$

Equation (1) indicates that changes in groundwater quantity over time $\dot{S}_t$ for a given area are equal to net natural recharge flows R_t plus recharge flows from applied water $(1-h)A_t$ that is not utilised by the crop minus agricultural extraction flows A_t (all terms in [m^3/month]). Equation (2) shows that changes in groundwater quality over time $\dot{C}_t^{\mathrm{S}}$ [g/month] for a given area consists of a quality and quantity component. As a quality indicator we use the nitrate concentration [g/m^3=mg/l]. The quality component is the difference between the nitrate concentration in recharge flows C_t^{R} and the nitrate concentration in extraction flows C_t^{S}. The latter is equal to the nitrate concentration in the groundwater stock. Groundwater quality will deteriorate, if recharge flows are of a lower quality (higher nitrate concentration) than extraction flows $C_t^{\mathrm{R}} > C_t^{\mathrm{S}}$. The nitrate concentration in recharge flows depends in our model on the concentration of nitrogen in the soil. For simplicity we have assumed that the nitrate concentration in recharge flows does not depend on the size of recharge flows. The quantity component shows that the smaller the ratio between recharge flows and groundwater stock,

[1]For convenience, we show the derivation of the equation of motion of groundwater quality in discrete time $C_{t+1}^{\mathrm{S}} S_{t+1} = C_t^{\mathrm{S}}(S_t - A_t) + C_t^{\mathrm{R}}(R_t - hA_t + A_t) \Rightarrow C_{t+1}^{\mathrm{S}} S_{t+1} = C_t^{\mathrm{S}} S_{t+1} + C_t^{\mathrm{S}}(S_t - A_t - S_{t+1}) + C_t^{\mathrm{R}}(R_t - hA_t + A_t) \Rightarrow$
$\dot{C}_t^{\mathrm{S}} = (C_t^{\mathrm{S}}(S_t - A_t - S_{t+1}) + C_t^{\mathrm{R}}(R_t - hA_t + A_t)) / S_{t+1}$. Substitution by $S_{t+1} = R_t - hA_t + S_t$ gives Equation (2).

the larger the dilution effect and the smaller the change in stock quality. In the special case where the groundwater stock is very large, extraction has hardly any impact on stock quality.

2.2 Irrigation technology

Farmers may apply various irrigation technologies that determine, which part h of applied water is utilised by the crop, often referred to as the irrigation effectiveness of the technology. Changes in stock quantity and quality depend on the effectiveness of irrigation technologies. To show that increases in water and output prices provide incentives for the adoption of modern irrigation technology, we turn to the following model (Zilberman and Lipper, 1999). Output per hectare q is, ceteris paribus, given by $q = f(e)$, where e is effective water[2], which is defined as the amount of irrigation water actually used by the crop, with $f' > 0$ and $f'' < 0$, i.e. $f(e)$ is an increasing and concave agronomic function. The irrigation effectiveness h_j of technology j is the ratio between effective and applied water, according to $h_j = e_j / A_j$, and depends on land quality[3], which we hold constant for the sake of simplicity. Two irrigation technologies are considered: a traditional one $(j = 1)$ and a modern one $(j = 2)$, which has a higher irrigation effectiveness $h_2 > h_1$. Quasi-rent π per hectare is equal to agricultural output price p times output per hectare, minus the price of applied water w times the quantity of water applied A and the cost of technology k_j per hectare. Maximum competitive quasi-rent π_j^* is obtained by solving for the optimal level of applied water A_j^*. The modern technology is chosen if $\pi_2^* > \pi_1^*$ and $\pi_2^* > 0$,

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[2] In case effective water use is a function of water quality, groundwater of a lower quality will reduce effective water use. Effective water use is not a function of water quality in our analysis, because effective water use does currently not depend on the nitrate concentration in groundwater in the Netherlands.

[3] Land quality is defined in terms of the land's ability to store water and depends on soil permeability, water-holding capacity, and the slope of the land. Irrigation effectiveness is higher on heavier clay soils, than on sandy soils, through which water passes rapidly. Differences in effectiveness are larger on sandy soils than on clay soils, and gains from a switch in technology will therefore be higher on sandy soils (cf. Shah et al., 1995).

$$\pi_j^*(A_j) = \max\{pf(h_j A_j) - wA_j - k_j\}, \text{ for } j = 1, 2 \qquad (3)$$

Quasi-rent maximisation under technology *j* occurs where the value of the marginal product of effective water is equal to the price of effective water use.

$$pf'(h_j A_j) = \frac{w}{h_j}, \text{ for } j = 1, 2 \qquad (4)$$

The analysis now allows to calculate the open access outcome of groundwater extraction and the socially optimal results, where both quality and quantity aspects are considered.

3. Open Access Outcome vs. Socially Optimal Outcome

Open Access Outcome

If a large number of competitive farmers exploit a stock as a common property resource, it is not unreasonable to suppose that farmers' behaviour is myopic. Individual farmers do not consider the impact of their pumping on the state of the resource and on the environment, and take the resource stock as given each period. Only their extraction costs are considered in the price of applied water. Farmers will maximise individual current profit each period, and it seems reasonable to assume that they pump water until the marginal net benefit is zero. Optimal groundwater use for a given technology at time t in the open access case is given by[4]:

$$pf'(hA_t) = \frac{c(S_t)}{h} \qquad (5)$$

The farmers will base their decisions only on the private cost and the resulting low price of water will provide fewer incentives for adoption of modern irrigation technology than a price, which reflects the social costs.

[4] We note that this result is independent of discount rates. Under open access, equilibrium rents are zero, whatever discount rates are used, and a static analysis will therefore give the right results (Perman et al., 1999).

Socially Optimal Outcome

The objective of a social planner is to maximise the sum of discounted net agricultural benefit and environmental damage over an infinite time horizon, taking into account the changes in quantity and quality of the groundwater stock over time. Shadow prices of changes in stock quantity and quality are considered in our continuous-time optimal control model. The level of damage to environmental amenities, given by $d = g(A_t, C_t^S)$, is assumed to increase if farmers extract more shallow groundwater since groundwater levels will fall and if the nitrate concentration of the stock increases, with $g'(A_t) > 0$ and $g'(C_t^S) > 0$. The increase in damage becomes smaller for higher levels of extraction and higher nitrate concentrations, with $g''(A_t) < 0$ and $g''(C_t^S) < 0$. The unit cost of groundwater extraction $c(S_t)$ increases as the size of the stock S_t declines, and the cost increase per unit is larger, the lower the remaining stock, with $c' < 0$ and $c'' > 0$, i.e. $c(S_t)$ is decreasing and convex. A small stock increases the unit cost of extraction and provides an incentive to reduce groundwater extraction. Further we assume a constant discount rate ρ. Finally, we define V as the annual monetary value of goods and services provided by environmental amenities per hectare and Φ as the ratio between the area of affected nature reserve and the area of farmland irrigated. To maximise the total present value of the objective function, the social planner's problem is to choose A_t for a given technology:

$$\max \int_0^\infty (pf(hA_t) - \Phi V g(A_t, C_t^S) - c(S_t)A_t) e^{-\rho t} dt \tag{6}$$

subject to the equations of motion (Equations (1) and (2)) of the two state variables. The maximum principle technique is used to solve the optimisation problem (Perman et al., 1999). The current value Hamiltonian function for the optimisation problem can be stated as:

$$H = pf(hA_t) - \Phi Vg(A_t, C_t^{\mathrm{S}}) - c(S_t)A_t + \lambda_t(R_t - hA_t) - \mu_t(C_t^{\mathrm{R}} - C_t^{\mathrm{S}})\frac{(R_t - hA_t + A_t)}{(R_t - hA_t + S_t)} \tag{7}$$

where λ_t and μ_t are the current value shadow prices or co-state variables associated with changes in the quantity and quality of the resource over time, i.e. the values of respectively a unit change in both the availability and the nitrate concentration of the groundwater stock at time t (cf. Conrad and Clark, 1987). Optimal allocation rules are given by:

$$\frac{\partial H}{\partial A_t} = pf'(hA_t)h - \Phi Vg'(A_t) - c(S_t) - \lambda_t h - \frac{\mu_t(C_t^{\mathrm{R}} - C_t^{\mathrm{S}})(R_t - hS_t + S_t)}{(R_t - hA_t + S_t)^2} = 0 \tag{8}$$

$$\dot{\lambda}_t = \rho\lambda_t - \frac{\partial H}{\partial S_t} = \rho\lambda_t + c'(S_t)A_t - \frac{\mu_t(C_t^{\mathrm{R}} - C_t^{\mathrm{S}})(R_t - hA_t + A_t)}{(R_t - hA_t + S_t)^2} \tag{9}$$

$$\dot{\mu}_t = \rho\mu_t - \frac{\partial H}{\partial C_t^{\mathrm{S}}} = \rho\mu_t + \Phi Vg'(C_t^{\mathrm{S}}) - \frac{\mu_t(R_t - hA_t + A_t)}{(R_t - hA_t + S_t)} \tag{10}$$

The first optimality condition (Equation (8)) can be rewritten as:

$$pf'(hA_t) = \frac{\Phi Vg'(A_t)}{h} + \frac{c(S_t)}{h} + \lambda_t + \frac{\mu_t(C_t^{\mathrm{R}} - C_t^{\mathrm{S}})(R_t - hS_t + S_t)}{h(R_t - hA_t + S_t)^2} \tag{11}$$

To achieve socially optimal agricultural groundwater extraction, the value of marginal damage to environmental amenities, the extraction costs and shadow prices of changes in the quantity and quality of the stock over time have to be considered in the price of water use. Agricultural groundwater extraction will have a negative impact on groundwater quality if $C_t^{\mathrm{R}} > C_t^{\mathrm{S}}$ and a positive impact if $C_t^{\mathrm{R}} < C_t^{\mathrm{S}}$. The price of water will be higher in the first case, when extraction causes a negative externality. The significance of this impact on the price of water will become smaller if stock size increases, due to the dilution effect.

The rate of change over time in shadow prices can be obtained from Equations (9) and (10).

$$\frac{\dot{\lambda}_t}{\lambda_t} = \rho + \frac{c'(S_t)A_t}{\lambda_t} - \frac{\mu_t(C_t^{\mathrm{R}} - C_t^{\mathrm{S}})(R_t - hA_t + A_t)}{\lambda_t(R_t - hA_t + S_t)^2} \tag{12}$$

$$\frac{\dot{\mu}_t}{\mu_t} = \rho + \frac{\Phi V g'(C_t^{\mathrm{S}})}{\mu_t} - \frac{(R_t - hA_t + A_t)}{(R_t - hA_t + S_t)} \tag{13}$$

The rate of change in the resource value associated with delayed extraction by one period (Equation (12)) (i.e. the cost of not mining the resource) is equal to the sum of three effects:

1) The discount rate, which is positive and serves as a compensation for delayed benefits;
2) The extraction-cost effect, where larger stocks reduce extraction cost; and
3) The dilution effect, where larger stocks tend to slow down changes in quality. The dilution effect will reduce the cost of maintaining stocks if $C_t^{\mathrm{R}} > C_t^{\mathrm{S}}$ and it will increase the cost if $C_t^{\mathrm{R}} < C_t^{\mathrm{S}}$. In the latter case, water quality is not improved due to delayed extraction.

If the initial stock size is relatively large, the extraction-cost and dilution effect may be negligible, because a marginal change in stock quantity is unlikely to cause a substantial change, neither in the unit pumping cost nor in the stock quality. In that case, the rate of change in the shadow price of stock quantity will be equal to the discount rate. If the initial stock size is small relative to recharge flows (i.e. if the extraction-cost and the dilution effect are stronger than the discount-rate effect), the rate of change in the shadow price will decline over time. It will decline over time because the extraction-cost and dilution effect will become stronger over time, if λ_t declines over time.

The rate of change in the shadow price of stock quality over time (Equation (13)) is also equal to the sum of three effects: 1) the discount rate, 2) environmental damage-effect, which is positive (higher nitrate concentrations increase damage costs) and 3) dilution effect. Appendix A shows the derivation of the steady state of the renewable groundwater stock.

We would like to emphasise that the rate of change over time in shadow prices, equation (12) and (13) differ from the results of the dynamics of renewable resource economics found in the literature (Zilberman et al., 1993). The rate of change in the resource value associated with delayed extraction by one period depends in the literature generally on a resource-growth effect (where maintaining stocks tends to increase resource growth), instead of on a dilution effect like in our analysis. When the resource is a population of some livestock species, for instance a fish population, population growth depends on the initial population size (reflected in the growth function). Insight into the importance of stock size to slow down changes in stock quality is therefore an extension of existing work in this field.

4. Usefulness of the approach

In this section, we show the importance of bringing the impact of groundwater extraction on groundwater quality into a resource management model. We study water-pricing reform, a key element in the proposed European Water Framework Directive (COM (97)164) in the presence of negative and positive externalities from agricultural groundwater extraction on stock quality. Such positive externalities may arise if C_t^{R} becomes smaller than C_t^{S}, which might for instance be the result of current restrictions for maximum allowable concentrations of nitrates. According to the Nitrate Directive (Council Directive 91/676/EEC), waters must be protected against pollution by nitrates from agricultural sources by not allowing the nitrate concentration in groundwater to exceed the legally accepted EU limit of 50 mg/l.

In the Netherlands, most farmers currently only pay the energy costs of lifting water from the stock to the field (i.e. about € 0.04 per m^3) although extraction is subject to two acts for a financial contribution to the government. Farmers are subject to a tax (of € 0.08 per m^3) under the 'Act Taxes on Environmental Basis' introduced in January 1995, but only a small percentage of farmers (about 2%) exceed the tax-free threshold of 40,000 m^3 of groundwater extraction per annum (Van Staalduinen et al., 1996). They are also subject to a *levy* under the

'Groundwater Act', adopted in 1983. The levy-free threshold and tariffs vary among provinces. The levy is relatively low compared to the tax. The main part of agricultural extraction is, however, not subject to the levy under the Groundwater Act. This means that the price of irrigation water is currently equal to the price in the open access case. Such a low price is inefficient from a social point of view in the presence of externalities such as desiccation and contamination and provides fewer incentives for the adoption of modern irrigation technology than optimal. The costs of these externalities have to be internalised in the price of water, to achieve socially optimal agricultural groundwater extraction patterns.

Article 12 of the proposed European Water Framework Directive obliges member states to implement 'full cost recovery', which means that the price of water should not only reflect the costs of the water-use services, but also environmental and resource depletion costs. This will provide incentives for the adoption of modern irrigation technology. Whether the modern technology will be adopted depends among others on the gap between relative costs of both irrigation technologies, like explained in section 2.2. The extent of divergence between the private and social price of water (Equation (5) and (11)) represents the optimal volumetric tax T that induces farmers to behave in the socially optimal way:

$$T = \frac{\Phi V g'(A_t)}{h} + \lambda_t + \frac{\mu_t (C_t^{\mathrm{R}} - C_t^{\mathrm{S}})(R_t - hS_t + S_t)}{h(R_t - hA_t + S_t)^2} \tag{14}$$

Agricultural groundwater extraction will have a negative impact on groundwater quality, if $C_t^{\mathrm{R}} > C_t^{\mathrm{S}}$ and a positive impact, if $C_t^{\mathrm{R}} < C_t^{\mathrm{S}}$. Contamination is reflected in a higher required tax on agricultural groundwater extraction and improvements in water quality are reflected in a lower required tax. The significance of this impact on the tax rate will become smaller if stock size increases, due to the dilution effect. If negative externalities of extraction are not internalised in the tax, contamination will be accelerated because the price will be too low and extraction may be higher than optimal. If positive externalities of extraction are not internalised in the tax, improvements in quality will be slowed down because the price will be too high, which may decrease extraction and increase both stock size and the irrigation effectiveness. In other words it will affect the time path of changes in stock quality over-time.

Larson *et al.* (1996) suggest that water may be the better input to regulate in terms of achieving non-point source reduction goals at lower cost, whereas often only a tax on nitrogen input is considered in the analysis for efficient pollution regulation, like in Fleming and Adams (1997). The cost-effectiveness of second-best policies in achieving joint quantity and quality management can be evaluated along the lines of Larson *et al.* (1996).

The theoretical framework of efficient water-pricing schemes is clear, but there are some caveats. Firstly, it is hard to determine the level of taxes, since monetary values have to be attached to damage caused by excessive use of groundwater, whereas perpetrators of externalities usually evaluate damage less severely than other interest groups. Solutions suggested for the monetary valuation of environmental damage caused by excessive groundwater extraction are very controversial, which makes direct application of Equation (11) and (14) fragile. Secondly, water-pricing schemes often ignore information needed for implementation. Implementation problems are linked to enforcement, monitoring, institutional limitations, conflicting policies, political interests, and welfare implications. Thirdly, the introduction of price reform is conditional upon the size of the social gains relative to the transaction costs. Finally, water-pricing reform only has a positive influence on water conservation if the price elasticity of water demand is significantly different from zero and is negative. Agricultural water demand is usually inelastic only up to a given price level (Garrido, 1999). This ‘price threshold’ depends on the productivity of water, the set of alternative production strategies, the proportion of land devoted to permanently-irrigated crops, and the irrigation technologies.

In this paper we only focused on water-pricing reform as an instrument in achieving socially optimal agricultural groundwater extraction patterns. Other instruments such as water markets can be used as well (see Giannias and Lekakis, 1997 and Wichelns, 1999), although they do not provide the same incentives for the adoption of modern irrigation technology. Policy instruments can be combined in such a way that they reinforce each other.

5. Conclusions

This study shows the importance of bringing the impact of agricultural shallow groundwater extraction on groundwater quality into a resource management model. It studies the dynamics of socially optimal agricultural shallow groundwater extraction management. This is not only of great interest in the Netherlands, but also for countries with a comparable hydrological setting and similar problems.

It becomes clear that the current low price of agricultural groundwater use is inefficient and provides fewer incentives for the adoption of modern irrigation technology than does a system that considers the cost of desiccation and contamination in the price of water.

It becomes also clear that internalisation of the negative as well as positive externalities from agricultural shallow groundwater extraction on stock quality in the price of groundwater is particularly significant if the recharge of groundwater is large compared to stock size. This impact will become smaller if stock size increases, due to the dilution effect. If these externalities are not internalised in the price of groundwater, contamination will be accelerated and quality improvements will be slowed down. It will affect the time path of changes in groundwater stock quality over-time. This stresses the importance of considering developments in nitrate policy when designing water-price reforms, as proposed under the European Water Framework Directive.

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Appendix A

Usually, inter-temporal optimisation models are closed by adding some sort of terminal condition. If there is no recharge, the stock would always be decreasing, so the problem would necessarily reach a point where nothing will be extracted, because either the stock is depleted or extraction has become prohibitively expensive. If groundwater is a renewable resource, it is possible to have a steady state with extraction, for which: $\dot{S}$ =0, $\dot{C}^{S}$ =0, $\dot{\lambda}$ =0, and $\dot{\mu}$ =0. If the quantity and quality of the stock do not change over time, and consequently shadow prices remain constant, a renewable resource system will be in a steady state. The results are expressed in the following equations:

$$A = \frac{R}{h} \tag{A1}$$

$$\frac{(C^{R} - C^{S})(R - hA + A)}{(R - hA + S)} = 0 \tag{A2}$$

$$\lambda = -\frac{c'(S)A}{\rho} + \frac{\mu(C^{R} - C^{S})(R - hA + A)}{\rho(R - hA + S)^{2}} \tag{A3}$$

$$\mu = -\frac{\Phi V g'(C^{S})}{\rho - (R - hA + A)/(R - hA + S)} \tag{A4}$$

If extraction and recharge flows are of the same size, the stock size will not change over time (Equation (A1)). Neither will stock quality change over time, if nitrate concentrations in recharge and extraction flows are equal $C^{R} = C^{S}$, if there is no recharge $R - hA + A = 0$, or if stock size is very large $S \to \infty$, (Equation(A2)). The shadow price of changes in the quantity of the resource over time will be smaller for larger stocks (Equation (A3)). The shadow price of changes in quantity are zero, if stock size is very large and a quality-only model will be appropriate. The smaller the ratio between the recharge flows and the groundwater stock, the smaller the shadow price of changes in quality of the resource (Equation (A4)).

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