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Managing Groundwater Quantity-Quality: Competitive Myopic Equilibrium Extraction, Competitive Extraction with Limited Foresight, and Optimal Extraction

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Abstract
The purpose of this paper is to cast the groundwater quality-quantity problem in a joint resource management model structure that captures the spatial features of groundwater extraction and pollution. Groundwater use is developed under three types of common property extraction criteria namely- myopic extraction, extraction with limited foresight and optimal extraction. The analytical solutions under the three cases show that under optimal extraction, spatial externalities influence the use of water and fertilizer while for the myopic case the marginal decision rule is impacted by the pumping decisions of competitors spatially in previous time periods, and is not accompanied by any user cost for later periods. The diffuse nature of the resource has policy implications in terms of managing groundwater across space and over time given both quantity and quality considerations.

Keywords: spatial resource externalities; myopic resource extraction; extraction with limited foresight, optimal extraction

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Managing Groundwater Quantity-Quality: Competitive Myopic Equilibrium Extraction, Competitive Extraction with Limited Foresight, and Optimal Extraction

Introduction

Management of groundwater with respect to water quality and quantity has a long and interesting history. This literature on this topic has taken on a number of interesting and important perspectives, but can be grouped into several broad categories. The first category represents those papers and reports that have only been concerned with the quantity of groundwater. This literature can be subdivided into those papers which are based on "bathtub" or single-cell models and those which view groundwater as a spatially heterogeneous resource. The second category of research only considers groundwater quality itself. The third category considers the quality and quantity of groundwater as a join resource management problem.

The list of authors who have used the "bathtub" model formulation to consider groundwater quality management issues include Feinerman and Knapp (1983), Gisser (1983), Gisser and Sanchez (1980), and Provencher and Burt (1993) to name a few. Koundouri (2004) provides an extensive review of the work which has been done using the "bathtub" model formulations.

Perhaps Provencher and Burt (1993) provide the most comprehensive and in-depth analysis of the groundwater quantity management issue based on the "bathtub" model formulation. As a beginning, two types of externalities are identified: the stock externality and the pumping cost externality. The stock externality arises because each agent's groundwater pumping decision is constrained by the total groundwater stock. If a firm extracts a marginal unit of groundwater in the current period, there is a corresponding (instantaneous) reduction in the quantity of groundwater available to all other agents having access to the groundwater source in the next period. The usual conclusion is that the "rule of capture" governs the allocation of groundwater in the sense that the only way an agent can capture a unit of groundwater is to pump it. An individual firm is not likely to be successful storing a unit of groundwater for next period because other firms have access to that stock of water.

The pumping cost externality arises because the cost of water withdrawals from the aquifer depends on the size of the groundwater stock. If a firm pumps a marginal unit of the groundwater stock in the current period, this firms decision impacts the costs at which other firms extract groundwater in the next period. This problem is that firms extract groundwater too quickly. This occurs because one firm's decision to reduce its rate of pumping lowers the pumping costs of all firms in the future, but this particular firm is not compensated for its conservation decision.

The "bathtub" model or single-cell model has been widely used for policy analysis as suggested previously, but has two serious shortcomings which have been extensively discussed by Brozovic et al (2004, 2010). First, the spatial location of agents who are pumping water from an aquifer is assumed to not matter. Second, path-independence of the groundwater stock is assumed. The later assumption means that the pumping activities from previous periods have not effect on the pumping decisions in the current period nor in future periods. The current status of an aquifer under these assumptions is usually represented by either the stock of water remaining or the depth to water. The later measure is called the pumping lift.

Brozovic et al (2004, 2010) depart from the usual single-cell or bathtub model and present a groundwater model structure that is explicitly spatial and hydrologically based. Groundwater levels are allowed to vary in a continuous fashion across a spatial dimension in response to local conditions. Each agent's pumping decision has a distinctive impact on other agents. Externalities are shown to vary across space and time as a function of the explicit spatial relationships between agents along with their respective pumping decisions. These authors use a fully integrated hydraulic response specification in their model structure to capture spatially heterogeneous behavior in an aquifer.

The exploitation of an aquifer is frequently accompanied by a corresponding problem of groundwater pollution. This is particularly true in regions where the primary use of an aquifer is irrigation. For example, when applied jointly with irrigation water, nutrients such as nitrogen can begin to create a groundwater pollution problem. One line of research, as noted previously, focuses on the pollution problem itself and does not consider the exploitation of the aquifer and the corresponding pollution problem as a joint resource issue. Examples include Anderson, et al (1985), Conrad and Olson (1992), Fleming, et al (1995), Kim et al (1993), Nkonya and Featherstone (2001), and Yadav (1997).

The second line of research models the groundwater quantity-quality issue as a joint resource management problem. Examples here include Dinar (1994), Dinar and Xepapadeas (1998), Hellegers, et al (2001) Raucher (2007), and Roseta-Palma (2002). All of these researchers use the bathtub model to address the joint resource management problem. No consideration is given to the spatial dimension of the groundwater water quality-quantity management problem.

The purpose of this paper is to cast the groundwater quality-quantity problem in a joint resource management model structure that represents the spatial features of groundwater extraction and pollution in the case of nitrogen fertilizer. The remainder of this paper is organized as follows. First, the joint resource management model is presented in the next section. This section includes the characterization of the socially optimal marginal decision rules. The third section is concerned with the myopic competitive equilibrium extraction and competitive extraction with limited foresight. This section will also consider the prospect of strategic behavior on the part of each decision maker. The next section will consider policy options and the last section provides a summary and set of conclusions.

Basic Model Structure and Socially Optimal Groundwater Extraction

The groundwater quantity-quality modeling for this paper is a based in part on the specifications found in the paper by Brozovic, et al (2004). The model for the "social planner" problem or the one that will maximize net benefits is provided in this section. The marginal decision rules for the joint maximization problem or social planner's problem are developed and discussed in this section as well.

The assumptions and notation are presented first. A spatial dimension is important in this research, so we use the identification of the firm or farm to represent the spatial location of water pumping activities and the stock of polluting activity. The measure of groundwater stock and the stock of nitrates in the groundwater source are both defined with respect to the location of each firm. Each firm is assumed to have only one well and the location of the well for each firm precludes the problem of well interference.

Let i, j $(i, j = 1, \dots, I)$ denote a firm which pumps groundwater for use in irrigation and also applies nitrogen fertilizer to a crop. Let t, s, τ be used to denote time with the time period for making decisions span the interval $(0, \dots, T)$. The remaining notation is defined as follows:

$u_{it} =$ $\quad amount\ of\ groundwater\ pumped\ and\ used\ for\ irrigation, firm\ i, period\ t;$

$m_{it} =$ $\quad amount\ of\ nitrogen\ fertilier\ used\ by\ firm\ i, period\ t;$

$x_{it} =$ $\quad pumping\ lift\ for\ firm\ i, period\ t;$

$C =$ $\quad average\ and\ marginal\ cost\ of\ pumping\ unit\ of\ groundwater;$

$\pi_{it} =$ $\quad net\ benefit\ function\ for\ firm\ i\ in\ period\ t$;

$\Gamma_t =$ $\quad net\ social\ benefit\ for\ period\ t$;

$\theta_{ji(t-s)} =$ $\quad well\ function$;

$M_{it} =$ $\quad Stock\ of\ nitrates\ in\ the\ aquifer\ at\ firm\ i\ in\ period\ t$;

$\alpha_{ji(t-s)} =$ $\quad nitrate\ spatial\ adjustment\ parameter\ at\ firm\ i\ location$;

The gross benefit function is $B_{it}(u_{it}, m_{it})$. We assume that $\frac{\partial B_{it}}{\partial u_{it}} > 0, \frac{\partial^2 B_{it}}{\partial u_{it}^2} < 0, \frac{\partial B_{it}}{\partial m_{it}} > 0$, and $\frac{\partial^2 B_{it}}{\partial m_{it}^2} < 0$. Damages arising from the presence of nitrates in groundwater are assumed to be measured at the location of each well. The damage function is represented by $D_{it}(M_{it})$ with $D'_{it}(M_{it}) > 0$ and $D''_{it}(M_{it}) < 0$. The net benefits for each firm i in any period t is defined as follows:

$$\pi_{it} = B_{it}(u_{it}, m_{it}) - Cx_{it}u_{it} - p_m m_{it} - D_{it}(M_{it}) \tag{1}$$

We assume that per unit pumping lift cost remains constant at C. (This same specification is also used by Brozovic et al (2004) as a model simplification.) The net social benefit function for each time period t is given as follows:

$$\Gamma_t = \sum_{i=1}^{I} \pi_{it} \tag{2}$$

Let the period discount rate be defined as $\beta^t = (1 + r)^{-t}$ where r is a market-determined interest rate. The social welfare or joint maximization problem to be solved is stated as

$$Max \quad Z = \sum_{t=0}^{T-1} \beta^t \Gamma_t \tag{3}$$

$subject\ to$

$$x_{it} = \sum_{s=0}^{t-1}\left[\sum_{j=1}^{J} u_{is}\theta_{ji(t-s)} - R_{it}\right] + x_{i0} \qquad (4)\ (\lambda_{it})$$

$$(i = 1, \dots, I)$$

$$(t = 0, \dots, T-1)$$

$$M_{it} = \sum_{s=0}^{t-1}\left[\sum_{j=1}^{I} \alpha_{ji(t-s)} l_{is}(u_{is}, m_{it})\right] + M_{io} \qquad (5)\ (\phi_{it})$$

$$(i = 1, \dots, I)$$

$$(t = 0, \dots, T-1)$$

The particular form of the state equations follows from discussions provided by Brozovic et al (2004, 2010). The current equations for the stock variables are expressed by adding up the period-by-period changes for each stock variable and the specification of the lag-determining parameters become explicit in these formulations. An important problem arises if we use a differential equation or difference equation approach for these specifications. The problem falls under the heading of "path dependency" and things become difficult to find solutions in these cases.

The stock of groundwater at each the ith user's location where pumping takes place in each period t is measured by the pumping lift. The pumping lift is defined as the distance water must lifted from the surface of the aquifer to the ground surface in each period. The state equation for the lift at location i, period t, is given by equation (4). Recharge for each user i in period i is assumed to be constant and is denoted as R_{it}. Significant recharge in each period reduces the lift at each location. The first set of terms on the right hand side of equation (4) represent the pumping activity impacts at location i in period t. It is apparent from equation (4) the pumping in each period increases the size of the lift. Moreover, current pumping activity has an adverse impact on all users in future years

The specification of pumping activity for each user at location i in period t shows that lift at that location is a function of extraction history of the that user as well as the history of other users pumping water from the aquifer. This history for the ith agent in period t is represented by $\theta_{ji(t-s)}$ in equation (4) which represents the drawdown or decrease imposed on agent i by agent j when agent this agent extracted an extra unit of groundwater s periods before the current period t. The nature of this impact can be shown by considering the sign of $\left(\theta_{ji(s+1)} - \theta_{jis}\right)$. If this sign is equal to zero, all pumping impacts occur immediately, similar to the bathtub model. If the sign is positive, there are cumulative effects from past extraction activities and the impacts on the groundwater resource for user i accrue and increase over time. If the sign is negative, the impacts on the groundwater resource on agent i are reduced overtime and there is a form of recovery from previous pumping actions overtime. It is assumed that the aquifer considered in this paper is characterized as diffused resource with this difference being positive. The spatial impacts by groundwater pumping at distant sites are lagged impacts.

Equation (5) is the state equation for the nitrate pollution stock variable. It is assumed that the pollution stock is characterized as a diffused stock variable. The generation of nitrate pollution in the aquifer in each time period at each location is represented by the pollution generation function $l_{it}(u_{it}, m_{it})$ with $\frac{\partial l_{it}}{\partial u_{it}} > 0, \frac{\partial^2 l_{it}}{\partial u_{it}^2} < 0$, and $\frac{\partial l_{it}}{\partial m_{it}} > 0, \frac{\partial^2 l_{it}}{\partial m_{it}^2} < 0$. It is also assumed that $\frac{\partial^2 l_{it}}{\partial u_{it} \partial m_{it}} > 0$. It is assumed that the pollution stock is characterized as a diffused stock variable. The impacts over time and space are represented in equation (5) by the $\alpha_{ji(t-s)}$ which are a response matrix variables.

Optimal behavior implied by the social planner's problem given above can be summarized by examining the marginal decision rules from the model. These decision rules for pumping groundwater and using it for irrigation along with the application of nitrogen fertilizer at each location in each time period are given by equations (7)and (8), respectively. The derivations for these equations are given in the Appendix.

$$\begin{aligned}\frac{\partial B_{k\tau}}{\partial u_{k\tau}} = C\left\{\sum_{s=0}^{\tau-1}\left[\sum_{j=1}^{I} u_{js}\theta_{jk(\tau-s)} - R_{k\tau}\right] + x_{k0}\right\} \\ + C\left[\sum_{s=\tau+1}^{T-1}\beta^{s-\tau}\sum_{j=1}^{I} u_{j\tau}\theta_{jk(s-\tau)}\right] \\ + \sum_{s=\tau+1}^{T-1}\sum_{j=1}^{I}\alpha_{kj(s-\tau)}\beta^{s-\tau} D'_{js}\frac{\partial l_{k\tau}}{\partial u_{k\tau}}\end{aligned} \tag{6}$$

$$(k = 1, \dots, I)$$

$$(\tau = 0, \dots, T-1)$$

$$\frac{\partial B_{k\tau}}{\partial m_{k\tau}} = p_m + \sum_{s=\tau+1}^{T-1}\beta^{s-\tau}\sum_{j=1}^{I}\alpha_{kj(s-\tau)} D'_{js}\frac{\partial l_{k\tau}}{\partial m_{k\tau}} \tag{7}$$

$$(k = 1, \dots, I)$$

$$(\tau = 0, \dots, T-1)$$

Consider first the marginal decision rule for pumping groundwater at location k in period τ. The left hand side of equation (7) represents the marginal benefit of pumping groundwater and using it for irrigation applications. This marginal benefit is similar to the marginal benefit expressions found in the typical bathtub model formulation.

The marginal opportunity cost of pumping groundwater is shown on the right hand side of equation (7) and consists of three components. The first component is the marginal cost of pumping a unit of groundwater at location k in period τ. It is interesting to note to see that current period unit cost of pumping groundwater is explicitly impacted by pumping decisions at other locations from previous periods. The second term represents the kth farmer's marginal user cost in period τ. It is clear that these decisions have spatial impacts at different pumping locations in each of the remaining years in the planning horizon.

The specification of groundwater assumes that irrigation water and nitrogen applications are nonseparable in nature. This means that a marginal increase in groundwater pumping and application will result in a marginal increase in the groundwater pollution stock. The last term shows the marginal opportunity cost measured as marginal damages related to the ith firm's decision to pump groundwater in the current decision which have spatial impacts in each of the remaining years in the planning horizon.

The marginal decision rule for optimal fertilizer application is given represented by equation (7). The left hand side of this equation represents the marginal benefit of fertilizer applications which the marginal opportunity costs are shown on the right hand side. The first term is the market price paid for a unit of nitrogen fertilizer. The second term shows that the current application of nitrogen fertilizer will increase the damages from nitrates in the groundwater at all pumping locations in each of the time periods over the remaining periods in the planning horizon.

Competitive Myopic Equilibrium Extraction

The competitive myopic equilibrium extraction model represents the decision making framework researchers usually use to model competitive behavior. This particular problem is also frequently cast as a non-cooperative game with strategy when the aquifer is assumed to be characterized as a bathtub or single-cell aquifer. In this case farmers pumping groundwater are viewed as symmetric and the uniform impact each user has on the aggregate stock of groundwater provides an easily observed variable of competitive use of groundwater.

The diffusional characteristic of a groundwater stock in this research makes it more difficult for competitors to accurately observe each other's impact on the stock of groundwater in each time period. As shown earlier, the state of the groundwater stock in each time period varies across space and is dependent on the complexities of the entire extraction history in periods prior to the current extraction period. It is thus concluded there is no aggregate variable to serve as a meaningful single measure for decisions being made competitors in a non-cooperative environment.

The most appropriate modeling strategy in this case for the decision problem to assume that each farmer will maximize his or her own single period objective function. Moreover, it also seems reasonable that the competitive myopic decision maker will not be cognizant of the pollution stock externalities, even at the location of its own groundwater well.

The ith farmer's single period decision problem is presented as the following:

$$Max \qquad \pi_{it} = B_{it}(u_{it}, m_{it}) - Cx_{it}u_{it} - p_m m_{it} \tag{8}$$

The marginal decision rules for this decision maker are given by the following:

$$\frac{\partial B_{it}}{\partial u_{it}} = C\left\{\sum_{s=0}^{t-1}\left[\sum_{j=1}^{I} u_{is}\theta_{ji(t-s)} - R_{it}\right] + x_{i0}\right\} \tag{9}$$

$$\frac{\partial B_{it}}{\partial m_{it}} = p_m \tag{10}$$

Equation (10) represents the marginal decision rule for the ith farmer's application of nitrogen fertilizer in each time period t. Equation (9) shows the marginal decision rule for pumping groundwater that the ith farmer will follow in each period. The right hand side of equation (9) shows explicitly how the marginal cost of current period pumping is impacted by the pumping decisions of competitors spatially in previous time periods, but the concept of an user cost is not present given the myopic behavior assumed here.

Equations (9) and (10) can easily be compared with equations (6) and (7) to see the marginal opportunity costs that are not taken into account by the ith decision maker in a myopic competitive decision making environment. This issue will be taken up in another section.

Competitive Extraction with Limited Foresight

The decision maker in this model is assumed to take into account its future pumping decisions on itself, but does not consider what the impacts will be now or in the future on its competitors who also pump water from the same aquifer. It is also assumed that the ith farmer does not any environmental impacts related to groundwater pumping and nitrogen fertilizer application decisions. Brozovic et al. (2004) note that this model formulation provides a useful comparison to optimal and myopic extraction decisions. Moreover, the effects of the pumping externality can be divided into own-effects and the impacts on other decision makers.

The decision model for the ith farmer is given by the following:

$$Max \qquad \Gamma_i = \sum_{t=0}^{T-1} \beta^t [B_{it}(u_{it}, m_{it}) - Cx_{it}u_{it} - p_m m_{it}] \qquad (11)$$

$subject\ to$

$$x_{it} = \sum_{s=0}^{t-1} \left[\sum_{j=1}^{I} u_{it}\theta_{ji(t-s)} - R_{it} \right] + x_{i0} \qquad (\lambda_{it})(12)$$

The marginal decision rules for the kth farmer are given by the following:

$$\frac{\partial B_{k\tau}}{\partial m_{k\tau}} = p_m \tag{13}$$

$$\frac{\partial B_{k\tau}}{\partial u_{k\tau}} = C\left[\sum_{s=0}^{\tau-1}\left[\sum_{j=1}^{I} u_{k\tau}\theta_{jk(\tau-s)} - R_{k\tau}\right] + x_{k0}\right] + \sum_{s=\tau+1}^{T-1} \beta^{(s-\tau)} C u_{ks}\theta_{kk(s-\tau)} \tag{14}$$

Equation (13) shows the marginal decision rule for optimal nitrogen fertilizer applications. Comparing this equation with equation (7) shows the over application of nitrogen fertilizer since the damages related to the groundwater pollution stock are not accounted for.

Equation (14) is the marginal decision rule for pumping groundwater for competitive extraction with limited foresight. The first term on the right hand side of this equation shows the explicit impact on per unit pumping cost in the current period of past pumping decisions by all decision makers. The second expression shows the impacts that current period pumping by farm k will have on its own pumping costs in future periods. These results can be contrasted with the marginal decision rule for groundwater pumping in the joint maximization of social optimum outcome as given by equation(6). It is apparent that terms capturing the spatial and temporal impact from the marginal damage functions that occur due to the ith user's pumping in the current period is absent in this model. Here the pumping impacts are considered more localized and independent.

Groundwater Quality and Quantity Policy When Groundwater is a Diffuse Resource

The diffuse naturel of a groundwater stock introduces a range of complexities into the resource management problem that makes it difficult to develop a comprehensive policy based on economic incentives alone. This problem becomes even more complex when the groundwater stock is in a long-term state of decline. One example of a major aquifer that is such a state of decline is the Ogallala Aquifer which covers a large area of the High Plains region in the United States (Miller and Appel, 1997). The resource management problem becomes even more complex with the diffuse nature of the water quality problem. This is because with time, as the stock of water decreases, the dispersion of the stock of the pollutant is affected and the effect also varies across space. Simulation flow models which capture the transport of pollutants across time become essential for these cases in the absence of actual data on pollutant loading and concentration. Recently water quality research has used models like SWAT and APEX to simulate water quality over watersheds and basins though the applicability of these models at a smaller spatial scale is uncertain.

The economic incentive-based frequently discussed when the groundwater resource is represented as a bathtub or single-cell aquifer do not exactly apply to the resource when it is modeled as a diffuse resource. First, economic incentives and approaches for controlling the stock of water may not be similar to those for controlling the level of the pollutant. Second, managing the pollutant stock as a non-point externality for agricultural pollution, may require policies quite different from managing the stock of water over time, especially when spatial considerations are important. Nevertheless, the economic incentive-based policies for the single-cell aquifer or aquifer with high transmissivity may provide some insight into the policy management problem for the diffuse resource characteristics case.

The property right system proposed by Smith (1977) is one example of a management system to consider here. In this system, the property rights for groundwater can be assigned to both the stock and flow elements of a groundwater system. The flow element of the groundwater system is the recharge of return flow to aquifer while the stock element is the stock of water that remains in the groundwater at any point in time. The key feature of this system is that property right system imposes a stock limitation on an individual's pumping decisions. Ghosh and Willett (2012) provide a detailed analysis of the system proposed by Smith when an aquifer is in the state of decline.

The management of an aquifer with the characteristics shown in this paper remain problematic. Skurray at al. (2012) draw attention to a number of important issues that must be addressed when an aquifer is modeled as a diffuse resource. These include establishing the consumptive boundaries of a pool, clarifying the relationships between extraction of the resource and the resulting impacts, and likely intertemporal effects.

Two primary factors influencing the stock of water and the amount of pollutant for a diffuse resource is the extent of the area covered by the aquifer and the amount of lagged impact caused by pumping in a certain period of time. If the area of the aquifer is large and the pumping impact diminishes over time due to high levels of recharge from surface water, then the magnitude of spatial impacts will be lower. Also, well spacing regulations are now common in most states under the High Plains Aquifer, but groundwater being a common property resource, spatial externalities exists locally. In this situation, the case of competitive extraction with limited foresight will be more frequently encountered.

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Appendix A

$$\mathcal{L} = \sum_{t=0}^{T-1} \sum_{i=1}^{I} \left\{ \beta^t [B_{it}(u_{it}, m_{it}) - Cx_{it}u_{it} - p_m m_{it} - D_{it}(M_{it})] + \lambda_{it} \left\{ \sum_{s=0}^{t-1} \left[\sum_{j=1}^{I} u_{is}\theta_{ji(t-s)} - R_{it} \right] - x_{it} + x_{i0} \right\} + \phi_{it} \left\{ \sum_{t=0}^{t-1} \left[\sum_{j=1}^{I} \alpha_{ji(t-s)} l_{is}(u_{is}, m_{is}) \right] + M_{i0} - M_{it} \right\} \right\} \quad (A.1)$$

$$\frac{\partial \mathcal{L}}{\partial u_{k\tau}} = \beta^\tau \left[\frac{\partial B_{k\tau}}{\partial u_{k\tau}} - Cx_{k\tau} \right] + \sum_{s=\tau+1}^{T-1} \sum_{j=1}^{I} \lambda_{j\tau}\theta_{kj(s-\tau)} + \sum_{s=\tau+1}^{T-1} \sum_{j=1}^{I} \phi_{j(s-\tau)} \frac{\partial l_{k\tau}}{\partial u_{k\tau}} = 0 \quad (A.2)$$

$$(k = 1, \dots, J)$$
$$(\tau = 0, \dots, T-1)$$

$$\frac{\partial \mathcal{L}}{\partial x_{k\tau}} = \beta^\tau C u_{k\tau} - \lambda_{k\tau} = 0 \quad (A.3)$$

$$(k = 1, \dots, I)$$
$$(\tau = 0, \dots, T-1)$$

$$\frac{\partial \mathcal{L}}{\partial m_{k\tau}} = \frac{\partial B_{k\tau}}{\partial m_{k\tau}} - \beta^\tau p_m + \sum_{s=\tau+1}^{T-1} \sum_{j=1}^{I} \phi_{j(s-\tau)} \frac{\partial l_{k\tau}}{\partial m_{k\tau}} = 0 \quad (A.4)$$

$$(k = 1, \dots, I)$$
$$(\tau = 0, \dots, T-1)$$

$$\frac{\partial \mathcal{L}}{\partial M_{k\tau}} = -\beta^\tau D'_{k\tau} + \phi_{k\tau} = 0 \quad (A.6)$$

$$(k = 1, \dots, I)$$
$$(\tau = 0, \dots, T-1)$$

$$\frac{\partial B_{k\tau}}{\partial u_{k\tau}} = C\left\{\sum_{s=0}^{\tau-1}\left[\sum_{j=1}^{I} u_{js}\theta_{jk(\tau-s)} - R_{k\tau}\right] + x_{k0}\right\} + C\left[\sum_{s=\tau+1}^{T-1}\beta^{s-\tau}\sum_{j=1}^{I} u_{j\tau}\theta_{jk(s-\tau)}\right] + \sum_{s=\tau+1}^{T-1}\sum_{j=1}^{I}\alpha_{kj(s-\tau)}\beta^{s-\tau} D'_{js}\frac{\partial l_{k\tau}}{\partial u_{k\tau}} \quad (A.7)$$

$$\frac{\partial B_{k\tau}}{\partial m_{k\tau}} = p_m + \sum_{s=\tau+1}^{T-1}\beta^{s-\tau}\sum_{j=1}^{I}\alpha_{kj(s-\tau)} D'_{js}\frac{\partial l_{k\tau}}{\partial m_{k\tau}} \quad (A.8)$$

Appendix B

$$\mathcal{L} = \sum_{t=0}^{T-1} \left\{ \beta^t [B_{it}(u_{it}, m_{it}) - C x_{it} u_{it} - p_m m_{it}] + \lambda_{it} \left[\sum_{s=0}^{t-1} \left[\sum_{j=1}^{I} u_{ji(t-s)} - R_{it} \right] - x_{it} + x_{i0} \right] \right\} \qquad (B.1)$$

$$\frac{\partial \mathcal{L}}{\partial u_{k\tau}} = \beta^\tau \frac{\partial B_{k\tau}}{\partial u_{k\tau}} - \beta^\tau C x_{k\tau} + \sum_{s=\tau+1}^{T-1} \lambda_{k\tau} \theta_{kk(s-\tau)} = 0 \qquad (B.2)$$

$$\frac{\partial \mathcal{L}}{\partial x_{k\tau}} = -\beta^\tau C u_{k\tau} - \lambda_{k\tau} = 0 \qquad (B.3)$$

$$\frac{\partial \mathcal{L}}{\partial m_{k\tau}} = \beta^\tau \frac{\partial B_{k\tau}}{\partial m_{k\tau}} - \beta^\tau p_m = 0 \qquad (B.4)$$