Three Essays on the Economics of Groundwater Extraction

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Declaration

Except where otherwise acknowledged, the material presented in this thesis is, to the best of my knowledge and belief, original and has not been submitted for a degree at any other university.

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Abstract

The primary contribution of this thesis is to develop a series of hydroeconomic models to act as solution-oriented tools to conduct integrated groundwater management and provide fresh policy insights. Using spatially detailed economic and hydrologic data from a real-world aquifer, this thesis examines key groundwater management problems and suggests policies that might be used to control such systems.

The thesis consists of three main essays focusing on issues in groundwater spatial dynamics and the design of optimal regulations. The first essay explores the importance of including well location decisions in spatially differentiated groundwater models to provide robust estimates of the gains from optimal management. Using a spatially differentiated and dynamic model of endogenous well location, this essay compares optimal and competitive extraction paths and well location decisions under alternative hypotheses as to the spatial distribution of groundwater.

The second essay presents an integrated assessment of first- and second-best management tools to regulate extraction from spatially heterogeneous aquifers. The trade-offs involved in each policy choice between welfare gains, redistribution effects, hydrological sustainability and implementation costs are examined. The essay also considers new approaches to groundwater management and analyses coordination between users via a generalisation of unitisation. Although

decentralised profit-sharing systems have arisen organically for the exploitation of other spatially heterogeneous resources such as fisheries, no theoretical or empirical studies have formalised decentralised unitisation schemes in a modeling framework of groundwater extraction.

The third essay investigates the use of multiple instruments for optimal groundwater management under the risk of occurrence of irreversible saltwater intrusion. This essay quantifies the trade-off between risk and efficiency involved in different instrument combinations implemented in an uncertain world. Using a numerical solution to a stochastic dynamic optimisation problem, the use of multiple policy instruments in aquifer management is justified in economic terms.

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Chapter 1 Introduction

1.1 Intensive use of groundwater: emerging challenges and strategies

The water situation today

Water is a unique natural resource because it is key to meeting our fundamental needs and to sustaining our planet's ecosystems, while it also contributes to economic development. The strong link between economic development and water resources suggests that the primary driver of stress in our planet's water systems is increasing human water demand and thus, increasing competition among water users. Developing solutions for water challenges around the world requires addressing these interlinkages with joint efforts by key actors in and outside the water domain. Although the challenges are enormous, so are the opportunities for effective action (UNESCO 2009).

Why is groundwater important?

Groundwater is increasingly being used for agricultural, industrial and domestic water supplies, with one third of the world's population depending on this resource for its daily supply. Furthermore, groundwater is an important support of *in situ* services by its circulation and general ubiquity. The economic value of groundwater is increasing as a response to higher water demands, but also as a substitute for surface water resources (Burke et al. 1999).

The expansion in groundwater use can be explained by the comparative features of groundwater and surface water. Firstly, the cost of groundwater development is generally modest, while surface water projects often require important public or joint private investments. Secondly, the natural quality of groundwater is generally high and it is less vulnerable than surface water to pollution threats. Thirdly, groundwater provides a more reliable water supply as the direct impact of climate change is negligible[1]. This reliability decreases the risks for users dependent on groundwater, thus favouring investment decisions and enhancing socioeconomic development. In fact, in many places, groundwater is the only reliable means of obtaining water and entire regions in developing and developed countries depend on it (The World Bank 2006a).

Groundwater over extraction: from a 'vicious' to a 'virtuous' circle

During the last century, the advantages of groundwater development have been exploited by groundwater users and governments at all levels. However, extensive resource development, uncontrolled discharges and agricultural intensification have

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[1] However, the indirect impacts of climate change on groundwater reserves may be important. Reduced rainfall and increased evapotranspiration can result in less recharge, especially in unconfined aquifers.,

resulted in the once abundant and cheap groundwater resource getting scarcer and increasingly polluted. The problems range from falling water tables and irreversibly salinised water to land subsidence and reduction of groundwater flow to sustain ecosystems (Kemper 1999). Furthermore, due to the linkages between groundwater and surface water, extraction and pollution of groundwater can affect the quantity and quality of water in streams, lakes and wetlands.

To respond to old and emerging problems, the causes of underlying groundwater depletion and pollution require analysis. Firstly, aquifers are common to large surface areas which can be accessed by small individual landholders in a highly decentralised manner. As with other common pool resources, the condition of groundwater (quantity and quality) is dependent on the action of many users. If exploitation is uncontrolled, users of the resource receive all the benefits of groundwater use but do not fully realise external and opportunity costs of their extraction and waste disposal. Thus, groundwater exploitation is often economically inefficient. Secondly, the hidden nature of groundwater has resulted in a persistent lack of data and understanding of the limits under which groundwater is available (The World Bank 2006a). Finally, on shared aquifers no single entity has the authority to control all pumpage; this increases the incentives for uncoordinated development and the 'race to the bottom' intensifies.

Supply-driven groundwater development may lead to a 'vicious' circle, whereby uncontrolled extraction leads to quantity and quality deterioration, exacerbating drawdown and misuse by existing users. To transform this 'vicious' circle into a 'virtuous' circle, the peculiarities of groundwater must be fully accounted in use. An integrated management approach is required that includes both the socioeconomic dimension (demand-side management) and the hydrogeological dimension (supply-side management) in a specific institutional and policy context (The World Bank 2006a).

1.2 Economics of groundwater extraction

Social research related to groundwater use is just as important as hydrological research so as to develop appropriate water management solutions in an integrated framework. In particular, economic analysis can help the decision-making process and promote more efficient resource use. Despite their importance, the number of economic studies on groundwater remains limited.

Economics is concerned with the allocation of scarce resources. At the microeconomic level, it helps to design effective regulatory measures by changing the way people view, and use, scarce groundwater resources. At the macroeconomic level, groundwater use is affected by economic forces, while the level of consumption and state of groundwater resources can have a strong feedback to the economy.

Classical vs. recent groundwater economics

Table 1.1 presents key studies on the field of groundwater economics by topic. Classical economic studies of groundwater exploitation have recognised the ongoing public concern about rapid resource depletion, and derived optimal management formulas for a wide variety of water uses and demand and cost functions (Brown & Deacon 1972; Burt 1967, 1970; Gisser & Sanchez 1980; Worthington et al. 1985; Zeitouni & Dinar 1997). However, most of the economic literature on optimal groundwater management faces two constraints in light of today's emerging challenges. Firstly, most of these studies focus on refining the economic component of their analysis at the expense of strong simplifications of the hydrologic component. Secondly, their policy prescriptions tend to be of a 'top-down' nature, failing to acknowledge that, contrary to surface water, groundwater is usually developed in a highly decentralised manner. In this context, central control measures are often beyond government's capacity to enforce and/or users' capacity to comply

Table 1.1 **Key references in the groundwater economics literature**

Topic	Main references
Dynamic optimal allocation	Burt (1964, 1966, 1967, 1970)
Gisser Sanchez effect (GSE)	Gisser and Sanchez (1980)
Robustness of GSE	Brill and Burness (1994) Burness and Brill (2001) Feinerman and Knapp (1983) Nieswiadomy (1985) Noel et al. (1980) Worthington et al. (1985)

Game theoretic models of pumping behaviour	Dixon (1989) Negri (1989) Provencher and Burt (1993)
Economic instruments for managing groundwater	*Reviews:* Pearce and Koundouri (2003) Zilberman et al. (1997) *First-best tools:* Brown and Deacon (1972) Burness & Brill (2001) Nieswiadomy (1985) Noel et al. (1980) *Water markets:* Anderson and Hill (1997) Howitt (1997) Zilberman et al. (1994) *Equity aspects:* Burness and Brill (2001) Feinerman (1988) Feinerman and Knapp (1983) Shah (1993)
Groundwater management under uncertainty	*Conjunctive use of surface water and groundwater:* Burt (1964, 1966, 1967, 1970) Tsur (1990) Tsur and Graham-Tomasi (1991)

	Irreversible groundwater pollution: Tsur and Zemel (1997)
Spatial dynamics in groundwater economic models	Bredehoeft and Young (1970) Brozovic et al. (2006, 2010) Faisal et al. (1997) Young et al. (1986)

Recent research has tackled these two drawbacks by operationalising economic concepts together with hydrological, engineering and environmental aspects of water resources systems within a coherent framework (Brouwer & Hofkes 2008; Cai et al. 2008; Lund et al. 2006; McKinney et al. 1999). The idea is to develop hydroeconomic models to act as solution-oriented tools to conduct integrated management and provide fresh policy insights. This thesis aims to contribute to this line of research by discovering new strategies to advance efficiency and transparency in groundwater use.

Literature contribution and research gaps

Economic research on groundwater management has developed rapidly in a number of areas. Among others, there have been significant contributions in testing the robustness of the Gisser-Sanchez effect (GSE)[2] under several modeling assumptions and different empirical applications (Brill & Burness 1994; Burness & Brill 2001;

[2] The GSE refers to the claim of Gisser and Sanchez (1980) that the no-management dynamic solution of groundwater exploitation is almost identical to the efficient management solution.

Kim et al. 1989; Knapp & Olson 1995; Koundouri 2004a; Provencher 1993); and in designing centralised policy instruments to induce users to improve their groundwater-related performance (Shortle & Horan 2001; Zilberman et al. 1997). However, a number of issues require further theoretical and empirical work.

The first gap this thesis intends to address relates to the welfare implications of optimal well location. Although the significance of including realistic spatially differentiated hydrological components in groundwater economic models has been widely recognised (Brozovic et al. 2010; Faisal et al. 1997), the existing literature provides only a general sense of the economic effects of hydrological simplifications and typically, assumes that extraction is the only management variable. As a result, it is essential to develop spatially differentiated dynamic optimisation models that also allow for spatially based decision variables (such as well location or depth). Further empirical work is also needed to inform real-world management on the design and performance of first- and second-best spatially based regulations.

The second research gap is the lack of integrated assessments of alternative groundwater extraction policies. Most groundwater economic models have taken economic efficiency as the only criterion when comparing alternative policies to address over extraction problems. This single-focus approach is in sharp contrast to the three main drivers of integrated groundwater management: economic efficiency, environmental sustainability and social equity. As more information on the variation of extraction externalities over space and time becomes available, integrated assessments of alternative central and decentralised instruments are essential to effectively inform policy design in complex settings.

The third gap this research investigates is the implications of irreversible impacts of overexploitation, such as the encroachment of saline water, for the design of multiple-instrument policies. Climate change and demographic dynamics make risk management vital to analysis and decision making. Although a few theoretical studies have derived the sensitivity of optimal management policies to the details of the hazard and damage specifications (Tsur & Zemel 1996, 2004), none has quantified the trade-off between risk-taking and economic efficiency of alternative policy measures in a theoretical or empirical setting.

1.3 Bridging the gap: three essential groundwater management issues

The present thesis provides a multi-disciplinary framework to examine some key groundwater management issues. The first contribution is to develop a spatially differentiated and dynamic model of endogenous site location for groundwater extraction. Optimal and competitive extraction paths and well location decisions are then compared under alternative hypotheses as to the spatial distribution of groundwater. This analysis explores the importance of including well location decisions in spatially differentiated groundwater models so as to provide estimates of the gains from optimal management, and to inform groundwater policies in the design of spatial regulations.

Building on the finding that unregulated groundwater extraction from spatially heterogeneous aquifers is inefficient, a comparison of optimal first- and second-best management tools to regulate extraction is undertaken. The aim is to inform policy design in three respects. Firstly, the efficiency of second-best policies relative to first-best policies is evaluated in a dynamic and spatially explicit framework of groundwater extraction. Secondly, an integrated assessment of policy options is provided by quantifying their welfare distributional and hydrological effects and discussing implementation costs. Thirdly, the ability of unitisation to correct externalities across spatial property right owners is explored.

The final issue investigated in this thesis is the use of multiple instruments for optimal groundwater management under the risk of occurrence of irreversible saltwater intrusion. The goal of this analysis is to explore the sensitivity of optimal instrument mixes to the introduction of uncertainty, and to quantify the trade-off between risk and efficiency involved in different instrument combinations.

1.4 Case study: the Guarani Aquifer System

The Guarani Aquifer System (GAS) is a huge hydrogeological system that extends over an area of at least 1,200,000 km^2 of Brazil, Paraguay, Uruguay and Argentina. Although the total volume of freshwater in storage is estimated to be around 40,000

km^3 with a natural recharge of 166 km^3,, the current level of exploitation is relatively modest. The climate is mainly sub-tropical, and the area has abundant (but often polluted) surface water resources, which experience a significant dry season and an occasional drought. Thus, the need for reliable water supply sources could grow considerably, and a demand for high-value agricultural and industrial uses is also likely to increase substantially (The World Bank 2006b).

A project funded by the Global Environmental Facility (GEF) was conducted on the GAS between 2003 and 2009. This project set up four pilot areas with representative problems, and one of these is used as the case study for this thesis. The Concordia / Salto pilot project occupies an area of 500 km^2 on either side of the Rio Uruguay, which forms the international frontier between Argentina and Uruguay. The Guarani Aquifer here is found beneath 800-1000 metres of volcanic basalt flows and its groundwater exhibits overflowing artesian heads and marked geothermal potential (The World Bank 2006b).

The Concordia / Salto area was chosen to illustrate empirically the theoretical insights of the thesis. The case study is important because, firstly, the main groundwater problems in the area are hydraulic interference between neighbouring wells, which reduces (and may even eliminate) the overflowing artesian heads, and saltwater intrusion from the south-south-east, where the GAS contains thermal groundwater of high natural salinity. Secondly, appropriate spatially detailed economic and hydrologic data is available. Thirdly, the transboundary nature of the aquifer in the area means that other considerations beyond economic efficiency, such as implementation costs and equity considerations, need to be taken into account.

1.5 A brief roadmap

This thesis is organised as follows. The following three chapters constitute the core of the thesis and present three independent, but interrelated essays on vital issues in the economics of groundwater extraction. Each chapter establishes its own research space, develops a theoretical model, applies it to the GAS case study and discusses the policy implications of its results. The first chapter examines the welfare gains from optimal management of spatially heterogeneous aquifers when the choice variable set is expanded to include well location decisions. The second chapter re-emphasises the importance of the spatial dynamics of aquifers by evaluating alternative policy options with a spatially explicit groundwater extraction model. This chapter contributes to real-world policy implementation by investigating how different policies perform in terms of equity, sustainability and transaction costs and by considering decentralised management approaches, such as unitisation. The final core chapter introduces uncertainty as a crucial constraint policymakers face in the real world and, under its presence, justifies in economic terms the use of multiple policy instruments in aquifer management. The last chapter concludes the thesis, discusses policy implications and provides ideas for further research.

Chapter 2 Groundwater spatial dynamics and optimal well location

2.1 Introduction

A wide variety of spatial regulations have been implemented around the world to mitigate the effects of groundwater over extraction. These include zoning systems, minimum well distances, spatially variable extraction depths and locations for artificial recharge (Burchi 1999). Despite the use of spatial instruments in practice, the groundwater economics literature has primarily focused on extraction control measures. This policy-theory mismatch can be explained, in some cases, by the frequent use of 'bath-tub' models in practice, where spatial considerations are irrelevant (Brown & Deacon 1972; Burt 1967, 1970; Gisser 1983; Koundouri 2004b; Tsur & Graham-Tomasi 1991). Even when heterogeneous spatial representations have been used in natural resource exploitation, optimal spatial regulations have yet to be studied in the context of groundwater depletion problems (Bredehoeft & Young 1970; Brozovic et al. 2006, 2010).

I fill the gap in the groundwater literature by comparing optimal versus competitive extraction paths, and also location decisions under alternative scenarios regarding the distribution of aquifers over space. I show that the welfare gains from optimal management can be under- or over-estimated if the dynamics of a heterogeneously distributed resource are represented by a homogeneous specification. The results of this chapter suggest that unregulated location choices can result in substantial welfare losses even when groundwater extraction rates are set optimally.

Recent studies have analised the spatial nature of extraction externalities (Bockstael 1996; Brozovic et al. 2006, 2010; Chakravorty et al. 1995; Gaudet et al. 2001; Goetz & Zilberman 2000; Knapp & Schwabe 2008; Parker 2007; Smith et al. 2009). Nevertheless, despite developments in the modeling of site choice using random utility models in both fisheries and recreational (Haab & Hicks 1997; Hauber & Parsons 2000; Kaoru et al. 1995; Scrogin et al. 2004; Smith 2005), until now there has been no dynamic and optimal analysis relevant to endogenous user location in terms of groundwater extraction. My contribution is to develop a deterministic and spatially dynamic model of endogenous well location for groundwater extraction, and to contrast the results from this approach to the standard presumption that aquifers are homogeneously distributed spatially, and this distribution is independent of past extractions.

The theoretical model I develop is applied to a real-world aquifer. I show that the typical assumption of a homogeneous 'bath-tub' representation of groundwater flow substantially underestimates the welfare and hydrological costs from unregulated well location. I demonstrate that optimal well location does matter when a spatially differentiated model is used if the 'interference' areas are properly acknowledged in the modeling context. Thus, a regulation that locates new wells in areas with low hydraulic interference may result in significant welfare gains even if extraction rates are unregulated. These findings are important given the dependency on groundwater resources and their rapid rate of depletion in various parts of the world. By applying the insights developed from the model and also the insights from its application for a particular aquifer, decision makers should be able to improve the outcomes in terms of groundwater extraction.

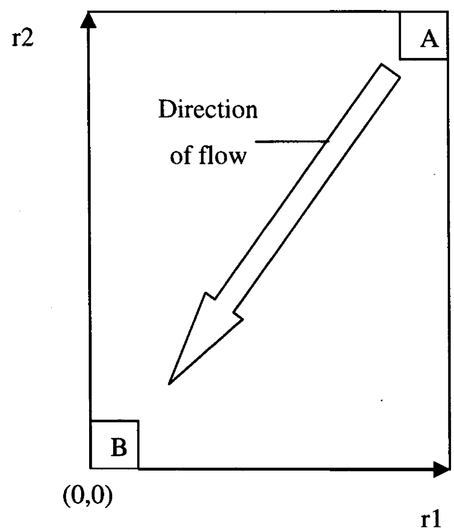
In the following section, I present a theoretical model for optimal dynamic groundwater extraction and well location under two aquifer spatial representations. I discuss and compare optimal and competitive extraction and well location conditions from this model under each spatial representation. In section 2.3 I describe spatial representations in existing economic models of groundwater, while in section 2.4 I illustrate the theoretical model with real data from the Guarani Aquifer System (GAS). I demonstrate that the assumption of spatial homogeneity on the distribution of groundwater affects both optimal extraction and location rules and policy prescriptions. Section 2.5 provides important policy implications while section 2.6 concludes.

2.2 The Model

A theoretical model of optimal dynamic groundwater extraction and well location is developed under two spatial representations of the dynamics of the resource's response: uniform and immediate (UI) and non-uniform and lagged (NUL). I analyse the case of an exogenously growing demand. Instead of assuming a specific growth structure (Brill & Burness 1994; Brown & Deacon 1972), I represent growth as a given per-period rise in the number of wells. Hence, the problem becomes one of choosing both optimal extraction paths and locations for new wells.

Consider an aquifer initially exploited by N spatially distributed users who own only one well each. In any period, the number of wells increases by an exogenous number n_t, conforming a total of $n(t)$ wells. A new well i at time t is located at an endogenously decided two-dimensional point $(r_{i1}, r_{i2}) \in \Omega$, where Ω is an exogenously bounded feasible region. The location decision has to satisfy two kinds of restrictions: firstly, wells should not be too close to any urban area or other forbidden region (facilities, natural resources, and so on) and secondly, a well cannot be placed exactly in the same place (or arbitrarily close to) where another well is located. The former is exogenously given, since the cities and facilities are assumed to be previously located when the well location decision is made, whereas the latter is an endogenous constraint because deciding the location of any well influences the location possibilities for the remaining wells.

Figure 2.1 **Exogenously bounded area (Ω).**



In order to surpass the non-convexity of the problem and attain an analytical solution, I make a series of reasonable assumptions. Firstly, I set the feasible region Ω to be constant, allowing wells to be, in principle, arbitrarily close to one another. Secondly, Ω is depicted as a rectangle such that the general direction of groundwater flow runs from one corner (A in Figure 2.1) to the opposite (B in Figure 2.1). This last corner is set as the origin (0,0) of both directions (r_{i1}, r_{i2}).

The decision variable u_{it} is well $i's$ per-period groundwater extraction at time t. The state variable y_{it} is defined as the hydraulic head at well i and time t. y_{it}^* and u_{it}^* are time dependent constraints on minimum values of head and use rates.

The net benefit from groundwater extraction is given by the function $G_{it}(y_{it}, u_{it})$ for each initial well and $G_{it}(y_{it}, u_{it}, (r_{i1}, r_{i2}))$ for each new well. Note that this function is allowed to vary across wells and time. I assume $\frac{\partial G_{it}(.)}{\partial y_{it}} > 0$ and $\frac{\partial G_{it}(.)}{\partial u_{it}} > 0$, so that per-period net benefits increase with both hydraulic head and extraction levels. Also $\frac{\partial G_{it}^{2}(.)}{\partial y_{it}^{2}} \leq 0$ and $\frac{\partial G_{it}^{2}(.)}{\partial u_{it}^{2}} \leq 0$, so that net benefits decrease at least linearly with head loss and falling extraction rates. For new wells, location enters directly the benefits function to allow for spatial variability in resource quality. I assume $\frac{\partial G_{it}(.)}{\partial r_{i1}} > 0$, $\frac{\partial G_{it}(.)}{\partial r_{i2}} > 0$ and $\frac{\partial G_{it}^{2}(.)}{\partial r_{i1}^{2}} \leq 0, \frac{\partial G_{it}^{2}(.)}{\partial r_{i2}^{2}} \leq 0$ so that the resource's quality and ease of extraction increases (at a diminishing rate) as we approach the origin of groundwater flow in the area.

Spatial representations of the dynamics of groundwater flow

The UI and NUL sub-models determine specific equations of motion describing the evolution of the state variable over time at every well. According to the UI representation, hydraulic heads respond to extraction in a temporally and spatially homogeneous fashion. The per-period hydraulic head at well i at time $t+1$ (y_{it+1}) is given by the function $f_t\left[\sum_{k=1}^{t}\sum_{j=1}^{n(t)} u_{jk}, y_{i1}, w\right]$ where w is the deterministic and constant recharge rate of groundwater. At any time period, hydraulic heads change by the same amount at every well. Additionally, variations in extraction rates at t have an effect only on head changes from t to $t+1$, which is independent of the location of extraction. Hence, $\frac{\partial(f_t[.]-f_{t-1}[.])}{\partial u_{jm}}=0 \quad \forall m=1,...,t-1$ and defining $u=\sum_{k=1}^{t}\sum_{j=1}^{n(t)}u_{jk}$,

$\frac{\partial(f_t[.]-f_{t-1}[.])}{\partial u_{it}}=\frac{\partial(f_t[.]-f_{t-1}[.])}{\partial u_{jt}}=\frac{\partial f}{\partial u}<0$ for any pair of wells j and i.

The NUL representation is more general and assumes that hydraulic heads are spatially heterogeneous and dependent upon the complete history of extraction. User $i's$ head at $t+1$ is given by $f_{it}\left[u_{jk}\Big|_{j=1}^{n(t)}\Big|_{k=1}^{t},\left(r_{j1},r_{j2}\right)\Big|_{j=N+1}^{n(t)},y_{i1},w\right]$. The aquifer dynamics is hereby characterised by four distinctive features. Firstly, head changes are allowed to be non-uniform across space, that is $f_{it}[.]-f_{it-1}[.]$ may be different from $f_{jt}[.]-f_{jt-1}[.]$. Secondly, extractions by two wells j and i may have a different effect on a third well $k's$ stock: $\frac{\partial f_{kt}[.]}{\partial u_{it}}\neq\frac{\partial f_{kt}[.]}{\partial u_{jt}}$. Thirdly, extraction by j at t may affect $i's$ hydraulic head at $t+m$ and this effect depends on m: $\frac{\partial(f_{it}[.]-f_{it-1}[.])}{\partial u_{jt-k}}\neq\frac{\partial(f_{it}[.]-f_{it-1}[.])}{\partial u_{jt-l}}$ where $k\neq l$. Fourthly, I assume a new well $j's$ impact on well $i's$ head increases at least linearly, the closer it is located to the origin of groundwater flow: $\frac{\partial f_{it}}{\partial r_{j1}}<0$, $\frac{\partial f_{it}}{\partial r_{j2}}<0$ and $\frac{\partial f_{it}^{2}}{\partial r_{j1}^{2}}\leq 0$, $\frac{\partial f_{it}^{2}}{\partial r_{j2}^{2}}\leq 0$.

The socially optimal equilibrium

The deterministic discrete time model consists of the maximisation of

$$(2.1)\ J = \sum_{t=1}^{T} \beta_t \left[\sum_{i=1}^{N} G_{it}(y_{it}, u_{it}) + \sum_{i=N+1}^{n(t)} G_{it}(y_{it}, u_{it}, (r_{i1}, r_{i2})) \right]$$

subject to

$$(2.2)\ \beta_t = \frac{1}{(1+\rho)^t}$$

$$(2.3)\ n(t) = n(t-1) + n_t \qquad t = 1,\dots,T$$

$$(2.4)\ n(0) = N$$

$$(2.5)\ (r_{i1}, r_{i2}) \in \Omega(t) \qquad i = n(t-1)+1,\dots,n(t)\ ;\ t = 1,\dots,T$$

$$(2.6)\ y_{it}^* - y_{it} \le 0 \quad i = 1,\dots,n(t)\ ;\ t = 2,\dots,T$$

$$(2.7)\ u_{it}^* - u_{it} \le 0 \quad i = 1,\dots,n(t)\ ;\ t = 1,\dots,T$$

$$(2.8a)\ y_{it+1} = f_t \left[\sum_{k=1}^{t} \sum_{j=1}^{n(t)} u_{jk}, y_{i1}, w \right] \quad i = 1,\dots,n(t)\ ;\ t = 1,\dots,T-1 \qquad \text{[UI representation]}$$

$$(2.8b)\ y_{it+1} = f_{it} \left[u_{jk} \Big|_{j=1}^{n(t)} \Big|_{k=1}^{t}, (r_{j1}, r_{j2}) \Big|_{j=N+1}^{n(t)}, y_{i1}, w \right] i = 1,\dots,n(t) \quad ; \quad t = 1,\dots,T-1 \quad \text{[NUL}$$

representation]

where $(r_{i1}, r_{i2})\Big|_{i=N+1}^{n(T)}, (u_{it})\Big|_{i=1}^{n(t)}\Big|_{t=1}^{T}$ are the decision variables, the y_{i1}'s and n_t's are given and ρ is the time discount rate.

A discrete time model was chosen because it is more realistic than a continuous time calculus of variations approach and generates management policies that can be easily implemented (Culver & Shoemaker 1992). The aquifer's equations of motion are usually estimated as a linear set of difference equations. Since in a discrete time formulation these equations become summations, the method of Lagrange multipliers can be used to derive the necessary conditions for the problem defined by (2.1)-(2.7) under (2.8a) or (2.8b) (Brozovic et al. 2010).

The Lagrangian expressions under the UI and NUL representations are respectively:

(2.9a)

$$L^{ui} = J + \sum_{t=1}^{T-1}\sum_{i=1}^{n(t)} \lambda_{it}^{ui}\left[f_t\left[\sum_{k=1}^{t}\sum_{i=1}^{n(k)} u_{jk}, y_{i1}, w\right] - y_{it+1}\right] + \sum_{t=2}^{T}\sum_{i=1}^{n(t)} \delta_{it}^{ui}\left[y_{it} - y_{it}^{*}\right] + \sum_{t=1}^{T}\sum_{i=1}^{n(t)} \gamma_{it}^{ui}\left[u_{it} - u_{it}^{*}\right]$$

(2.9b)

$$L^{nul} = J + \sum_{t=1}^{T-1}\sum_{i=1}^{n(t)} \lambda_{it}^{nul}\left[f_{it}\left[u_{jk}\Big|_{j=1}^{n(k)}\Big|_{k=1}^{t}, \left(r_{j1}, r_{j2}\right)\Big|_{j=N+1}^{n(t)}, y_{i1}, w\right] - y_{it+1}\right] + \sum_{t=2}^{T}\sum_{i=1}^{n(t)} \delta_{it}^{nul}\left[y_{it} - y_{it}^{*}\right]$$

$$+ \sum_{t=1}^{T}\sum_{i=1}^{n(t)} \gamma_{it}^{nul}\left[u_{it} - u_{it}^{*}\right]$$

where $\lambda_{it}^{ui}, \delta_{it}^{ui}, \gamma_{it}^{ui}, \lambda_{it}^{nul}, \delta_{it}^{nul}$ and γ_{it}^{nul} are the Lagrange multipliers. Some of the necessary conditions for an interior solution are detailed below. Sufficient conditions for global optimality are satisfied by concavity of the Lagrangian with respect to the decision and state variables and the transversality conditions $\beta_T \lambda_{jT} y_{jT} = 0$.

In order to state the conditions in current value form, I define the transformations $\lambda_{jk} = \beta_k \mu_{jk}$, $\delta_{jk} = \beta_k v_{jk}$ and $\gamma_{jk} = \beta_k \varpi_{jk}$.

(2.10a) $\dfrac{\partial L^{ui}}{\partial y_{it+1}} = 0 \Rightarrow \dfrac{\partial G_{it+1}(.)}{\partial y_{it+1}} + v_{it+1}^{ui} = \mu_{it}^{ui}\beta_{-1} \quad i = 1,\dots,n(t) \;\; ; \;\; t = 1,\dots,T-1$

(2.10b) $\dfrac{\partial L^{nul}}{\partial y_{it+1}} = 0 \Rightarrow \dfrac{\partial G_{it+1}(.)}{\partial y_{it+1}} + v_{it+1}^{nul} = \mu_{it}^{nul}\beta_{-1} \quad i = 1,\dots,n(t) \;\; ; \;\; t = 1,\dots,T-1$

(2.11a) $\frac{\partial L^{ui}}{\partial u_{it}} = 0 \Rightarrow \frac{\partial G_{it}(.)}{\partial u_{it}} + \varpi_{it}^{ui} = -\frac{\partial f}{\partial u}\sum_{k=t}^{T-1}\sum_{j=1}^{n(k)} \mu_{jk}^{ui}\beta_{k-t} \quad i = 1,...,n(t) \;\; ; \;\; t = 1,...,T$

(2.11b) $\frac{\partial L^{nul}}{\partial u_{it}} = 0 \Rightarrow \frac{\partial G_{it}(.)}{\partial u_{it}} + \varpi_{it}^{nul} = -\sum_{k=t}^{T-1}\sum_{j=1}^{n(k)} \mu_{jk}^{nul}\beta_{k-t}\frac{\partial f_{jk}[.]}{\partial u_{it}} \quad i = 1,...,n(t) \;\; ; \;\; t = 1,...,T$

If i is a new well from period t onwards:

(2.12a) $\frac{\partial L^{ui}}{\partial r_{im}} = \sum_{k=t}^{T}\frac{\partial G_{i,k}(.)}{\partial r_{im}}\beta_k = 0 \qquad i = n(t-1)+1,...,n(t) \;\; ; \;\; m = 1,2$

(2.12b) $\frac{\partial L^{nul}}{\partial r_{im}} = \sum_{k=t}^{T}\frac{\partial G_{i,k}(.)}{\partial r_{im}}\beta_k + \sum_{k=t}^{T-1}\sum_{j=1}^{n(k)}\lambda_{jk}^{nul}\frac{\partial f_{jk}[.]}{\partial r_{im}} = 0 \qquad i = n(t-1)+1,...,n(t) \;\; ;$

$m = 1,2$

Conditions (2.10a) and (2.10b) show that for an optimal allocation, the shadow price of groundwater at time t must equal the discounted marginal net benefit of a unit increase in hydraulic heads in $t+1$. Since heads at $t+1$ are determined by decisions at t, if the shadow price at t were larger (smaller), benefits would increase by saving less (more) stock for $t+1$. Note that the net marginal benefit of a greater hydraulic head is conformed by the user's extra profits and the relaxation of the constraint on the minimum value of the head if it is binding (ν_{it+1}).

Conditions (2.11a) and (2.11b) equate the private marginal net benefit of extracting an additional unit of the resource with the discounted future costs of that extraction on all wells. If the private net marginal benefits of an extra unit of extraction are constant across time, then both equations indicate an increasing optimal path of extraction. However, lower heads are likely to increase marginal extraction costs over time. Hence, the shape of the optimal extraction path will depend on the importance of higher marginal extraction costs relative to lower future external costs on all other wells.

The following proposition defines the effect of the spatial representation on the estimation of optimal extraction paths.

Proposition 2.1. Optimal extraction paths are likely to be incorrect if a heterogeneous aquifer is depicted by a homogeneous spatial representation. Simplifying the resource's response to an average rate $\left(\frac{\partial f}{\partial u}\right)$ over (under) estimates the optimal extraction paths of wells who are relatively more (less) harmful to other wells' heads, ceteris paribus.

Proof.

Condition (2.11a) in the UI representation implies that the optimal extraction paths of two wells with the same net benefits function will be exactly equal. This is because the marginal stock depletion caused on other wells is independent of the location of the extraction source. Conversely, under the NUL representation, condition (2.11b) shows that even if two wells share the same net benefits function, their optimal extraction paths will vary if the resource is heterogeneously distributed $\left(\frac{\partial f_{jk}}{\partial u_{it}} \neq \frac{\partial f_{lm}}{\partial u_{pn}}\right)$. In particular, if $\frac{\partial f_{jk}}{\partial u_{it}} > \frac{\partial f}{\partial u}$ $\forall j,t,k$ (the external effects of well i are higher than average), well $i's$ optimal extraction path will be underestimated by the UI representation.

The next proposition determines the effect of the spatial representation used on the estimation of optimal locations of new wells.

Proposition 2.2. The optimal location of new wells will be incorrect if a homogenous representation of the aquifer is used, unless the evolution of the groundwater's stock is independent of the location of new users $\left(\frac{\partial f_{jk}}{\partial r_{im}} = 0 \right)$.

Proof.

Conditions (2.12a) and (2.12b) determine the optimal location of new wells. If the head's response to extractions is assumed uniform throughout the resource site, only private marginal net benefits of the new well are taken into account $\left(\frac{\partial G_{ik}}{\partial r_{im}} \right)$. By contrast, if the NUL representation is used, new wells are optimally distributed across space *only* when total marginal net benefits of changing the location of a new well are zero. These net benefits consist of the private benefits accruing to the new user and the social benefits derived from choosing locations that interfere less with other wells' hydraulic heads. Thus, unless $\frac{\partial f_{jk}}{\partial r_{im}} = 0 \quad \forall i, j, k, m$, conditions (2.12a) and (2.12b) will differ and the UI representation will provide wrong estimates of the location of new wells.

I examine the conditions for (2.11a), (2.11b), (2.12a) and (2.12b) to yield very similar solutions. When the externality imposed on others by each well's extraction is not diffuse in nature, the effects of extraction are uniformly and immediately transmitted throughout the whole aquifer. In this case, $\frac{\partial f_{jk}[.]}{\partial u_{it}}$ is virtually unchanged for different values of (i,t) and (j,k) and $\frac{\partial f_{jk}}{\partial r_{i1}}$ and $\frac{\partial f_{jk}}{\partial r_{i2}}$ are very close to zero. In such settings, the aquifer is more akin to a homogeneous physical characterisation (such as the UI representation) and few further insights can be obtained from a more complex description of the physics of the aquifer system (NUL representation).

Competitive scenario

I investigate the effect of the spatial representation of the aquifer on the estimation of inefficiencies resulting from unregulated extraction and location decisions. For simplicity, I only examine an open-loop equilibrium. That is, I assume that in the absence of regulation, users commit themselves at the start of the program to a complete time path of extraction that maximises the present value of their stream of profits given the extraction paths of rival users. Given that access to most common property resources is restricted by a series of legal and institutional constraints, the incentive to conserve and recognise the interdependence of extraction paths is limited but not absent from private decision making.

The necessary conditions characterising well i's problem under the UI and NUL representations of the resource system are as follows:

(2.13a) $\frac{\partial L_i^{ui}}{\partial y_{it+1}} = 0 \Rightarrow \frac{\partial G_{it+1}(.)}{\partial y_{it+1}} + v_{it+1}^{ui} = \mu_{it}^{ui} \beta_{-1}$

(2.13b) $\frac{\partial L_i^{nul}}{\partial y_{it+1}} = 0 \Rightarrow \frac{\partial G_{it+1}(.)}{\partial y_{it+1}} + v_{it+1}^{nul} = \mu_{it}^{nul} \beta_{-1}$

(2.14a) $\frac{\partial L_i^{ui}}{\partial u_{it}} = 0 \Rightarrow \frac{\partial G_{it}(.)}{\partial u_{it}} + \varpi_{it}^{ui} = -\frac{\partial f}{\partial u} \sum_{k=t}^{T-1} \mu_{ik}^{ui} \beta_{k-t}$

(2.14b) $\frac{\partial L_i^{nul}}{\partial u_{it}} = 0 \Rightarrow \frac{\partial G_{it}(.)}{\partial u_{it}} + \varpi_{it}^{nul} = -\sum_{k=t}^{T-1} \mu_{ik}^{nul} \frac{\partial f_{ik}}{\partial u_{it}} \beta_{k-t}$

If i is a new well from period t onwards:

(2.15a) $\frac{\partial L_i^{ui}}{\partial r_{im}} = \sum_{k=t}^{T} \frac{\partial G_{ik}(.)}{\partial r_{im}} \beta_k = 0 \qquad m = 1,2$

(2.15b) $\frac{\partial L_i^{nul}}{\partial r_{im}} = \sum_{k=t}^{T} \frac{\partial G_{ik}(.)}{\partial r_{im}} \beta_k + \sum_{k=t}^{T-1} \lambda_{it}^{nul} \frac{\partial f_{ik}[.]}{\partial r_{im}} = 0 \qquad m = 1,2$

Once again, I define the transformations $\lambda_{jk} = \beta_k \mu_{jk}$, $\gamma_{jk} = \beta_k \varpi_{jk}$ and $\delta_{jk} = \beta_k v_{jk}$.

The following proposition identifies conditions when the gap between optimal and competitive extraction paths will be wrongly estimated by a simplified spatial representation of the aquifer.

Proposition 2.3. The UI representation will:

a) Overestimate the divergence between optimal and competitive extraction paths if the aquifer's response to each well's extraction is localised to the immediate vicinity of that well.

b) Under (over) estimate the gap between optimal and competitive extraction paths of wells who are relatively more (less) harmful to other wells' heads if externalities are diffusional over space.

c) Give a correct estimation of the gap between optimal and competitive extraction paths if the effects of extraction are widely transmitted throughout the resource in a uniform fashion.

Proof.

a) If the aquifer's response to each well's extraction is localised to the immediate vicinity of that well ($\frac{\partial f_{jk}}{\partial u_{it}} \approx 0$ and $\frac{\partial f_{jk}}{\partial r_{i1}} \approx 0$, $\frac{\partial f_{jk}}{\partial r_{i2}} \approx 0$ for all (k,t) and $j \neq i$), then by comparing (2.11b) with (2.14b), it can be concluded that the solutions yielded by the optimal and competitive extraction schemes under the NUL representation will be close. Hence, inefficiencies from competitive allocation are small. However, by comparing (2.11a) with (2.14a), the UI representation may still find an important divergence between the optimal and competitive schemes and overestimate the policy scope for regulation of the resource. The simpler representation of the physical system fails to acknowledge that the aquifer is close to private property to begin with.

b) If $\sum_{k=t}^{T-1}\sum_{j\neq i}\frac{\partial f_{jk}}{\partial u_{it}} > (<)\sum_{k=t}^{T-1}\sum_{j\neq i}\frac{\partial f}{\partial u}$ $\forall t$, well $i's$ external effects are higher (lower) than average and the difference between the right hand side of (2.11a) and (2.14a) is smaller (larger) than the difference between (2.11b) and (2.14b). Thus, the UI representation under (over) estimates the gap between optimal and competitive extraction paths of wells who are relatively more (less) harmful to other wells' heads.

c) If $\frac{\partial f_{it}}{\partial u_{it}} \approx \frac{\partial f_{it}}{\partial u_{jk}} \approx \frac{\partial f}{\partial u}$ $\forall i \neq j$, the difference between conditions (2.11a) and (2.14a) and (2.11b) and (2.14b) is the same. Thus, the UI representation is able to adequately capture the behavior of the aquifer.

I emphasise that even if the gap estimated between optimal and competitive extraction paths is the same regardless of the spatial representation used, the gains from optimal management will be underestimated by the UI model. This result can be derived by comparing (2.15a) with (2.12a) and (2.15b) with (2.12b). Since stock depletion at both the own and others' locations is independent of the location of the extraction source in the UI representation, the optimality conditions for the location of new wells only differ between the optimal and competitive scenarios if the NUL representation is used.

Discretisation of spatial aspects of extraction

The introduction of space in a dynamic optimisation framework is more challenging than the consideration of time because of its multiple dimensions. Economic spatial models of resource management have dealt with continuous one-dimensional representations of space that are sufficiently tractable to be analysed with traditional optimisation techniques. These models fix spatial heterogeneity over time (Chakravorty et al. 1995; Gaudet et al. 2001; Goetz & Zilberman 2000; Knapp & Schwabe 2008; Kolstad 1994). However, problems with endogenously determined spatial heterogeneity in multiple dimensions cannot be solved analytically (and empirically applied) unless space is discretised.

One way of discretising the continuous feasible region for the location of users is to convert it into an index set and enumerate specific locations of relevance by their geographical coordinates. Next, outcomes at these locations can be estimated through statistically validated parametric forms. This method is called metamodelling (developing a model of the model) and provides a functional relation between the response (stock changes) and the excitation (extraction pattern) at points where the information has economic value (user locations).

2.3 Spatial dynamics in groundwater

Groundwater extraction links economic actors over space and time in a spatial-dynamic process that generates spatial-dynamic externalities (Wilen 2007). The spatial structure of these externalities is represented by 'cones of depression' where the water table is drawn down in the area adjacent to each pumping well. Where many wells exist, their intersecting cones of depression create complicated patterns in the surface of the groundwater table that evolve through time. Hence, drawdown in any point of an aquifer depends on the location and history of extractions.

Many economic studies of groundwater management use single-cell (or 'bath-tub') aquifer models that assume an aquifer responds uniformly and instantly to groundwater extraction. These models suppose that the response of the aquifer depends only upon hydrological parameters and ignore the positioning of development within the system. Various optimal control methods have been applied to derive dynamic optimal groundwater allocations using this hydrological representation (Brown & Deacon 1972; Burt 1967, 1970; Gisser 1983; Koundouri 2004b; Tsur & Graham-Tomasi 1991).

A similarly large body of literature has used bath-tub models to measure welfare losses if groundwater allocation is left to the free market. Under quite restrictive economic, hydrologic and agronomic assumptions, Gisser and Sanchez (1980) found that there is no substantive quantitative difference between optimal rules for pumping water and competitive rates (the Gisser-Sanchez effect (GSE)). Their conclusion has led to a number of investigations on the robustness of the GSE which perform sensitivity analysis on all of its assumptions with the exception of the spatial uniformity of the aquifer. Some of these studies found a significant divergence between optimal and competitive extraction paths (Brill & Burness 1994; Feinerman & Knapp 1983; Kim et al. 1989; Provencher & Burt 1994; Shah et al. 1995; Worthington et al. 1985) while others did not (Allen & Gisser 1984; Knapp & Olson 1995; Nieswiadomy 1985).

Two-cell models offer a more realistic interpretation of groundwater hydraulics by dividing the simulation region in two cells and allowing flow between them in proportion to the difference in stock levels. Nevertheless, these models only examine interdependency between two areas (such as two adjacent aquifers) and ignore micro-level incentives of individual users within each area (Chakravorty & Umetsu 2003; Saak & Peterson 2007; Zeitouni & Dinar 1997).

A closer approximation to realistic groundwater dynamics has been achieved by a few economic studies that model aquifers as multi-cell basins. These studies represent water movement between cells with finite difference approximations of groundwater flow equations and linearise the system to include it in the economic optimisation. The shortcoming of these models is that only the previous period's extractions (and not the whole extraction history) are assumed to influence groundwater stock changes at any time period (Chakravorty & Umetsu 2003; Noel et al. 1980; Noel & Howitt 1982).

Finally, four important contributions to the modeling of spatial heterogeneity and path-dependency in groundwater extraction must be noted. Brozovic et al. (2006, 2010) built a theoretical model for the optimal extraction of groundwater by spatially distributed users. They conclude that some aquifers may be more akin to private than common property and may be subject to significant lagged effects from pumping. A few decades earlier, Bredehoeft and Young (1970) incorporated spatially dynamic characteristics of aquifer behavior into a simulation program and directly embedded it into an economic optimisation problem. However, they only investigated the effects of volumetric taxes fixed in space and time. Young et al. (1986) generated response functions to different excitations (for example, extracting from a single well at a unit rate for the first period of time and no extraction thereafter) from a finite-difference model and analysed several institutional alternatives for managing a groundwater-surface water system. Finally, Faisal et al. (1997) used a discrete kernel-based hydrological model to compare socially optimal and open access extraction schemes from a hypothetical basin.

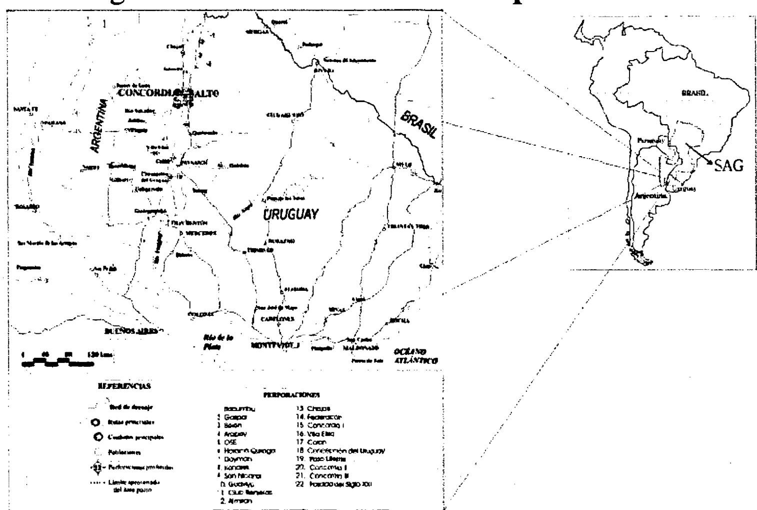
Notwithstanding the existing groundwater modeling literature, there still has been no study that examines the sensitivity of the results to different spatial and temporal specifications of the aquifer's response when the location of new wells is also a choice variable. Most importantly, there are no empirical studies using actual data from aquifers that evaluate the mismeasurement of the inefficiencies from unregulated groundwater extraction and well location while assuming a homogeneous physical representation in a real-world context. The findings do not simply arise from improved information from knowing the nature of groundwater flows, but from modeling the endogenous decision by groundwater users in terms of the location of their wells and pumping rates.

2.4 Model application

The Guarani Aquifer System (GAS) is located in the sedimentary Parana Basin in the subsoil of the east and center-south of South America. As shown by Figure 2.2, I focus on a section of the aquifer identified as the Concordia-Salto pilot project (The

World Bank 2006b). The seven wells in the area extract thermal groundwater for hydrogeothermal tourism. Although access is limited by extraction permits, tourism operators own groundwater as a common property resource subject to the rule of first capture. Thus, the rate of groundwater mining and recycling and the location of new wells are the result of private decision making.

Figure 2.2 **The Concordia-Salto pilot area.**



Source: The World Bank, 2006, *The Guarani aquifer initiative for transboundary groundwater management*, The GW MATE Case Profile Collection no. 9, The World Bank, Washington D.C.

The numerical model of the Concordia-Salto pilot area

Two general types of groundwater models are in use today: analytical and numerical models. Conditional on a high degree of understanding of the processes by which stresses on a system produce subsequent responses, analytical models provide exact solutions can be obtained to the partial differential equations of the model. However, rigid idealised conditions are required about parameters and boundaries. Numerical methods can relax these idealized conditions by yielding approximate solutions to the governing equations through the discretisation of space and time. Within the discretised problem domain, the variable internal properties, boundaries, and stresses of the system are approximated.

Given their accuracy, analytical solutions are usually preferred to numerical modeling wherever possible. When the complexity of the groundwater system prevents an analytical analysis, numerical models have become increasingly popular by offering a versatile approach to groundwater problems. These models incorporate assumptions and simplifications to grasp complex management problems. Thus, the accuracy of the answer depends on how realistic these assumptions are on the model application. Even if the model input data and the discretization restrictions are reasonable, the system should be studied carefully and the implications of the model's assumptions properly acknowledged (Spitz & Moreno 1996).

A study of a Global Environmental Facility (GEF)'s project developed and parameterized a numerical model of the Concordia-Salto area. A finite difference model, using the MODFLOW numerical simulation code was selected, and a multilayered model constructed to represent the Guaraní Aquifer System within the pilot area. The aquifer is overlain by a thick basalt sequence that acts as an aquiclude to the sandstones of the Rivera, Tacuarembó and Buena Vista Formations. These range in age from late Permian to Jurassic and represent a sedimentary sequence which developed from primarily fluvial in the early stages to primarily aeolian at the end. The model also included the underlying Paleozoic deposits which act primarily as an aquitard, but with some low-yielding water-bearing units. The top of the

Precambrian crystalline basement served as the lower boundary of the model. (Charlestworth et al. 2008).

In the Concordia-Salto pilot area, given the geological scenario of a large confined aquifer without an obvious natural division close to the pilot area, arbitrary limits were selected for the model's domain. The only condition on the domain was that it had to be sufficiently large to avoid the effect of tensions within the model's perimeter and cones of depression extending to the border during modelling. Three modelling approaches were used with different boundary conditions and distributions of active cells inside the domain:

1) Model with boundaries of constant head (controlled)
2) Mixed boundary conditions (constant head and controlled flow)
3) Mixed boundary conditions (constant head and no flow)

The third approach was considered to be the most appropriate one for the Concordia-Salto pilot area because it avoids the restrictions of all four boundaries with constant heads, covers a larger domain and provides a more conservative response to represent pumping tests.

The hydrological sub-model: UI and NUL representations

Following Morel-Seytoux and Daly (1975), the finite difference model is run 50 times by applying different levels of stress at the seven existing and seven potential stress locations. Due to computational constraints, the duration of the study (40 years) is divided in two management/stress periods of 20 years during which extraction rates are held constant. The different stress levels applied in the runs are obtained by randomly generating percentage variations of the actual extraction rates[3] from a normal distribution.[4]

The three-dimensional flow simulation package MODFLOW is used to simulate the aquifer numerically (McDonald & Harbaugh 1988). After the model is allowed to run in transient mode, drawdowns are recorded at the end of each time interval (20 and 40 years) and well location.

Let $Q_{k,1}$ and $Q_{k,2}$ be the extraction rates (in m^3/h for a 16-hour daily extraction regime) applied at location k during the first and second stress periods respectively. Let $s_{i,1}$ and $s_{i,2}$ be the aquifer's response at location i after 20 and 40 years due to all such stresses. The UI representation entails estimating drawdown as:

(2.16) $s_{i,1} = \beta \sum_{k=1}^{14} (Q_{k,1})$

(2.17) $s_{i,2} = \beta \sum_{k=1}^{14} (Q_{k,1} + Q_{k,2})$

[3] Extraction rates at the seven potential sites for well location were set at $150m^3/h$ for a 16-hour daily extraction regime.

[4] The normal distribution used had a mean of 0.5 and a standard deviation of 0.3, as users in the area agreed on the likelihood of an increasing extraction pattern over the next years.

Note that the drawdown of the water table is uniform throughout the aquifer and the contribution of each well's extraction is constant across time and space (the coefficient β is constant).

The NUL sub-model is derived by adapting Theis' (1935) solution for transient well response to pumping and using the principle of superposition[5] to estimate drawdowns $s_{i,1}$ and $s_{i,2}$ as a linear function of $Q_{k,1}$ and $Q_{k,2}$ $\forall k = 1,...,14$ (well locations) as:

(2.18) $$s_{i,1} = \sum_{k=1}^{14} Q_{k,1}\beta_{i,k,1}$$

(2.19) $$s_{i,2} = \sum_{k=1}^{14} \left[Q_{k,1}\beta_{i,k,2} + \left(Q_{k,2} - Q_{k,1}\right)\beta_{i,k,1}\right]$$

The coefficients $\beta_{i,k,1}$ and $\beta_{i,k,2}$ are commonly cited as the 'well functions', which depend on the time since extraction started at well k and the distance between wells i and k. These represent drawdowns at location i after 20 and 40 years since well k started its extraction, caused by a permanent unit increase in the constant extraction rate applied at location k (Brozovic et al. 2006).

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[5] The principle of superposition means that for linear systems, the solution to a problem involving multiple inputs (or stresses) is equal to the sum of the solutions to a set of simpler individual problems that form the composite problem.

Formulation of the socially optimal and competitive management cases

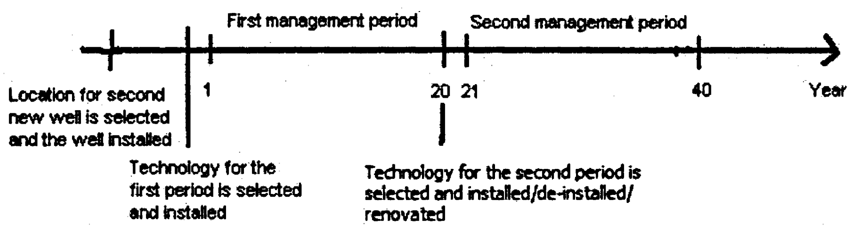
Since users fulfill their demand for water by self-extraction from the aquifer (facing no external price for it), the optimal design policy is derived by converting problem (2.1) into a cost-minimisation problem. Thus, I examine the case where the demand for water is inelastic and water requirements are fixed. The decision variables are (a) where to install two new wells from a set of potential locations[6], (b) whether to install/de-install a water recycling system at each existent and new location in the first or second period, (c) whether to install/de-install a pumping system at each existent and new location in the first or second period. The constraints are that (a) extraction at each well exceeds a given demand minus the equivalent recycled water (if any), (b) hydraulic heads at all operative well locations must exceed the aquifer's depth by more than 10m if no equipment is installed and more than 3m if water recycling systems but no pumps are installed, and (c) the aquifer's response to extraction patterns represented by equations (2.16-2.17) or (2.18-2.19).

In the competitive management scenario, one of the locations for the new wells is given by a well that has already been drilled in the area. The other location is assumed to be selected in a 'myopic' fashion based on the largest head excess—expected after the first 20 years—of the distance between ground surface and the lower datum of the aquifer. Two potential locations (one in Argentina and one in Uruguay) are analysed for the second new well.

[6] The locations used are the ones proposed by Charlesworth et al. (2008).

A decision timeline is depicted on Figure 2.3. All users have perfect information on the equation of motion of hydraulic head at their own wells, and on the water requirements of every other user. New well locations are selected beforehand (and these are public information). Well drilling and construction starts and finishes at time zero. For the first management period, all users assume the rest will extract their total water requirements. However, ex-post, agents can observe each other's decisions so that at the start of the second period, they assume that extraction will remain at period one levels.

Figure 2.3 **Decision and installation timeline for the competitive extraction scenario**



The optimisation algorithm

As stated by Goldberg (1989), three main types of search and optimisation techniques are identified by the current literature: calculus-based, enumerative and random.

Calculus-based methods have been applied extensively. However, these methods seek local optima and depend upon the existence of derivatives. Thus, they are suitable for a very limited problem domain. Enumerative techniques look at objective function values at every point in a certain search space, one at a time. Dynamic programming is the most commonly used technique but it suffers from the 'curse of dimensionality' when search spaces are too large or complex to search. Finally, randomised search efficiently exploits historical information to search new points with expected improved performance.

The present problem involves the solution of a mathematical programming problem that has a highly non-linear and discontinuous objective function and constraint set. This makes it difficult to calculate or estimate derivatives of these functions with respect to the decision variables, hampering the application of traditional optimisation methods used in groundwater management problems. As an alternative, non-linear programming has been used for the past decade. These algorithms refine a single trial design by updating search directions with computationally expensive gradient information. However, this technique does not guarantee the finding of a global optimum and tends to be non-robust (McKinney & Lin 1994).

Complex groundwater management problems such as optimal reservoir systems operation and remediation/monitoring designs have recently been studied by optimising Monte Carlo techniques such as Genetic Algorithms (GAs), Simulated Annealing (SA) and Neural Networks (NN) (Cieniawski et al. 1995; Hsiao & Chang 2002; McKinney & Lin 1994; Ritzel et al. 1994; Rogers & Dowla 1994; Wang &

Zheng 1998; Wardlaw & Sharif 1999). This chapter will investigate the ability of Genetic Algorithms to solve a non-linear groundwater management problem. Although the three Monte Carlo techniques mentioned have proved to be equally robust, Gas were chosen over SA or NN because they are easier to compute, which explains their popularity as the main evolutionary algorithm used in the groundwater management literature.

GAs, as first suggested by Holland (1975), are search algorithms based on the mechanics of natural selection and operate on a population of decision variable sets. To solve an optimisation problem, a GA encodes decision variable values as strings of an initial population. The objective function is valued for each individual string and those that perform better ('fittest') are more likely to 'reproduce' and appear in the next generation. Through the application of three genetic operators: selection, crossover and mutation, a GA population 'evolves' through successive generations until a termination criterion is met.

Goldberg (1989) delineates the main differences between GAs and traditional optimisation methods:

1) GAs use a coding of the decision variable set, not the decision variables themselves.

2) GAs search from a population of decision variable sets, not a single variable set. This increases the probability of locating global rather than local optima.

3) GAs use the objective function itself, not derivative or auxiliary information. Thus, they are independent of the structure of the particular problem being analysed.

4) GAs use probabilistic, not deterministic, search rules.

GAs help search for optimal (or near-optimal) constrained groundwater designs by easily incorporating constraints into the formulation and do not require derivatives with respect to the decision variables as in non-linear programming.

Coding of the optimisation algorithm

A simple GA is described in Figure 2.4. It works following the next steps:

1) Firstly, it creates a random initial population. A population size of 100 individuals led to the best results. To lower the chances of convergence to a local minimum, an initial range was set approximately in the neighbourhood of the expected minimal point. The initial population was set to have no recycling or pumping systems installed ($R_{i1}, R_{i2}, P_{i1}, P_{i2}|_{i=1...14} = 0$), extraction rates equal to the fixed demand levels ($Q_{i,1}, Q_{i,2} = d_{i,1}, d_{i,2}|_{i=1...14}$) and a positive chance of each location being chosen for a new well ($0 \leq L_i \leq 1|_{i=8...14}$).

2) The algorithm then creates a sequence of new populations by using the individuals in the current generation to create the next population:

a) It computes the fitness value of each member of the current population.

b) The raw fitness scores are scaled based on the rank of each individual (position in the sorted scores) instead of its score.

c) Selects members, called parents, based on their fitness. A tournament selection was specified as the selection function. Sets of four individuals were chosen at random and the best individual of each set are made parents.

d) Two individuals are guaranteed to survive to the next generation ('Elite children').

e) As shown by Figure 2.4, children are produced either by making random changes to a single parent—mutation—or by combining the vector entries of a pair of parents—crossover.

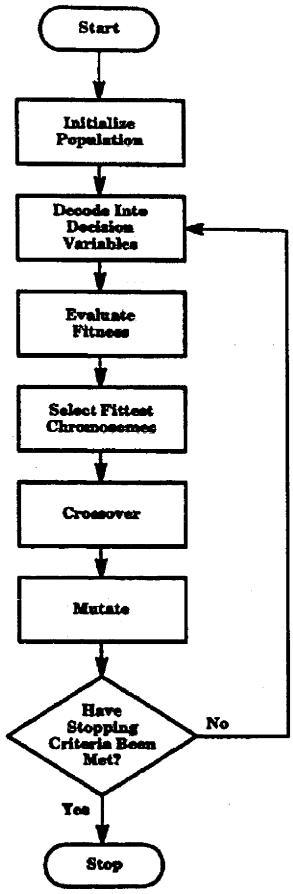
Mutations are introduced to prevent the algorithm from converging early to a local optimum. The mutation function used for constrained problems is the 'adaptive feasible'. This randomly generates adaptive directions within a feasible region bounded by the constraints of the problem.

The fraction of the next generation that is produced by crossover was set to 0.8. The function chosen to perform the crossover was the 'scattered'. This function creates a random binary vector and selects the genes where the vector is a 1 from the first parent and the genes where the vector is a 0 from the second parent and combines the genes to form the child.

f) The current population is replaced with the children to form the new population.

3) The algorithm stops when the iteration process exceeds the maximum number of generations (set at 50) or when the weighted average change in the fitness value over 20 generations is less than 1e-06.

Figure 2.4 **Flowchart describing a GA**



Source: McKinney, DC & Lin, M 1994, 'Genetic algorithm solution of groundwater management models', *Water Resources Research,* vol. 30, no. 6, pp. 1897-1906.

For the present problem, several constraints have to be satisfied. The method used by GAs to handle constrained optimisation problems is to add penalty terms to the objective function. The GA assigns a lower fitness value to individuals that violate constraints. Various penalty factors were tested. The appendix provides details of the GA coding.

Data

The appendix presents the economic and hydrologic data used in the empirical application, which was derived from reports published as a result of the aforementioned GEF project (Barbazza 2006; Castagnino 2008; Charlesworth et al. 2008). Hydrological parameters (surface level, initial hydraulic heads, current extraction rates, and so on) were obtained from the numerical model developed as part of the pilot project in the area (Charlesworth et al. 2008).

Simulation results

The coefficients β, $\beta_{i,k,1}$ and $\beta_{i,k,2}$ from equations (2.16-2.17) and (2.18-2.19) were estimated by linear regressions on data obtained by simulating different extraction scenarios and recording responses at each well[7].

A graphical analysis of drawdown at one of the wells (well 5) provides evidence of spatial interdependency and the lagged nature of the groundwater externality. The well function analysed is representative of the response at every other well. Figure 2.5 presents the impacts through time and space on drawdown at well 5 of a permanent unit change in extraction from each well at the first and the 20th year of the program. Following Brozovic et al. (2006), the 'well function' is discounted to the time when the extraction rate is incremented.

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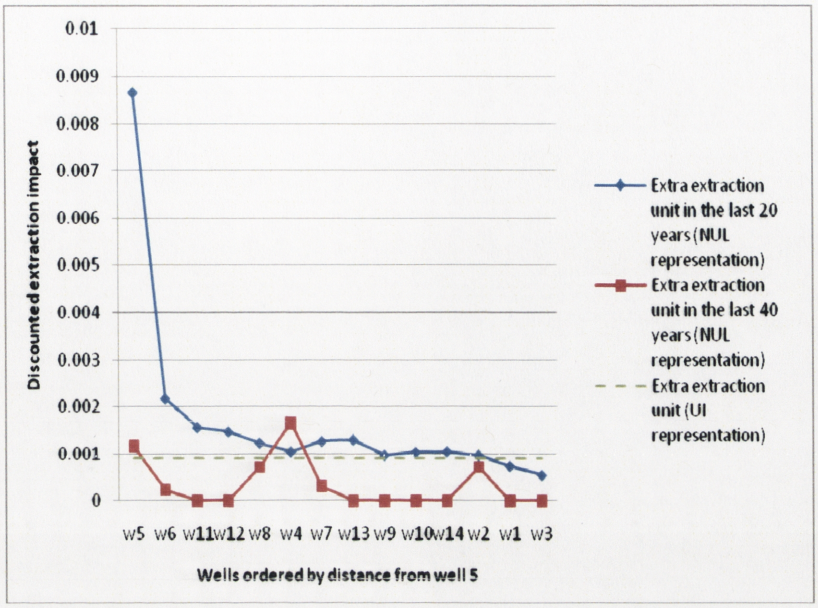
[7] Refer to the appendix for the results of these estimations.

Figure 2.5 **Impact of extractions on well #5**



Result 2.1. This aquifer is an example of an intermediate case where externalities are diffusional over space. Hence, a spatially uniform policy is most likely to bring few gains over no intervention and perhaps a simple spatial regulation may be more effective[8].

Initially, I consider the effect of distance on the magnitude of the externality imposed by one user on another. A permanent increase in any user's extraction from the 20th year has a lower impact on well 5 the further the user is from it. However, the relationship between drawdown and the position of extraction diminishes when extraction rates are incremented from the start of the planning period.

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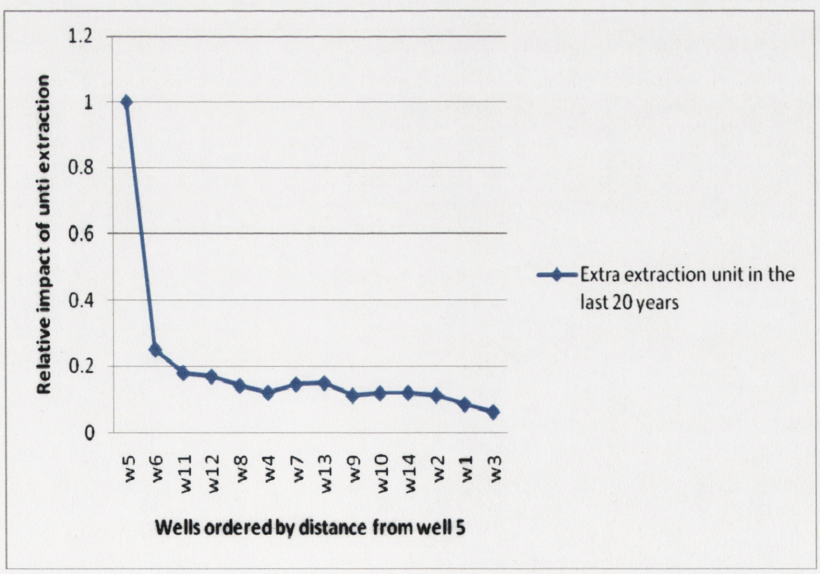
[8] Furthermore, a simple spatial regulation, such as minimum well distance, may be less costly to implement and less likely to be contested by users than a uniform volumetric tax.

This finding brings us to the relevance of lagged groundwater extraction externalities on a path-dependent resource. The NUL representation predicts that at larger distances from an extraction well, the effects of changes in extraction that occurred several periods ago may be more significant than more recent changes, even with discounting.

We can compare the impacts resulting from a change in extraction 20 and 40 years ago of the closest and furthest wells from well 5. If the extraction schedule of one of the three closest wells changes from the initial period, the impact is 96 per cent lower than a more recent change (in the 20th year). However, in the case of one of the three furthest wells the impact is 75 per cent lower. The rich spatial dynamics explained in previous paragraphs cannot be captured by the simple UI representation of the aquifer.

Figure 2.6 **NUL representation: relative impact of extractions on well #5**



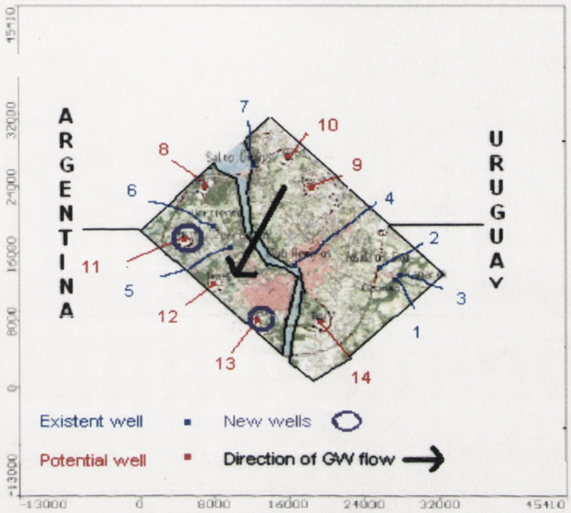
In Figure 2.6, the solid 'well function' is normalised by a user's own well function. The NUL representation shows that how much a user cares about another user's groundwater withdrawals depends inversely on the distance between the two. The relative well function decreases rapidly with distance, implying that groundwater users may be concerned only about extraction by very proximate users.

Result 2.2. While the UI and NUL representations derive different optimal new well locations, the location of new wells in the competitive management scenario is the same regardless of the aquifer's representation.

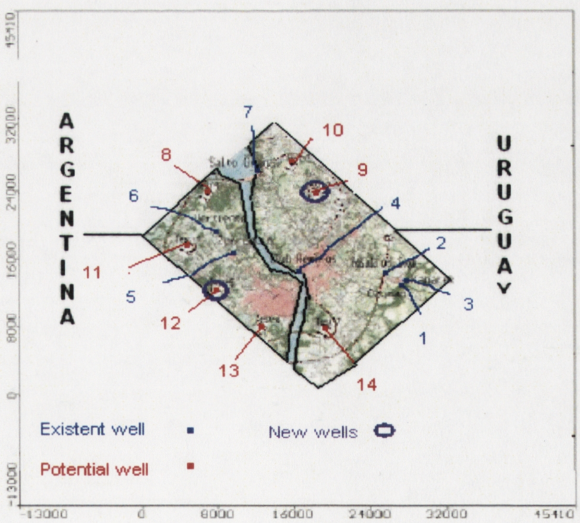
The UI and NUL representations derive different optimal new well locations as expected by the difference between optimality conditions (2.12a) and (2.12b). Under the NUL representation, costs are minimised when the new wells are located at sites #11 and #13 because head and demand constraints are satisfied without the need to invest in any technology in either the first or the second management period. Conversely, as Figure 2.7 shows, under the UI representation, optimal well locations are at sites #9 and #12 and no technology is needed given the drawdown predictions of this physical specification.

The location of new wells in the competitive management scenario is the same regardless of the aquifer's representation used. At the start of the first management period, all users expect their hydraulic heads to be sufficient to cover their water needs during the period, and no equipment is installed. During the second 20 years, drawdown in the north-western corner of the area increases dramatically if measured with the NUL representation. It is worth noticing that this happens regardless of the position of the second new well. Hence, two users in that area are forced to invest in recycling systems. Because the UI representation averages out drawdown throughout the aquifer, it fails to acknowledge the interference area in the north-western corner of the aquifer.

Figure 2.7 **Optimal new well locations and technology installed**



(A) NUL representation



(B) UI representation

Result 2.3. Given result 2.1, the UI representation underestimates both the welfare and hydrological gains of optimal well location even when the demand for water is inelastic.

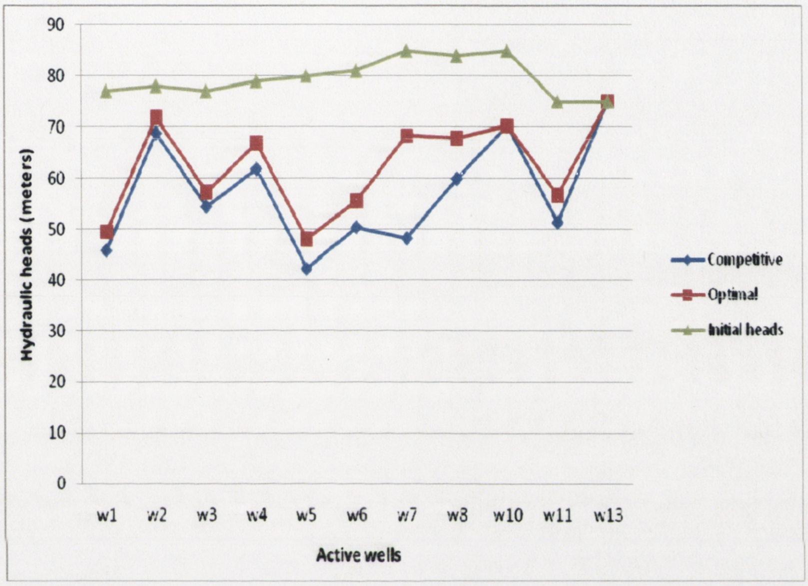
As summarised in Table 2.1, total costs are reduced by almost one-fifth if the two new wells are optimally located. Cost-savings are due to avoided technology costs which directly depend on changes in water drawdown. Conversely, the UI representation underestimates the welfare losses, finding no cost-savings after optimally locating new wells.

Table 2.1 **Optimal vs. competitive groundwater management.**

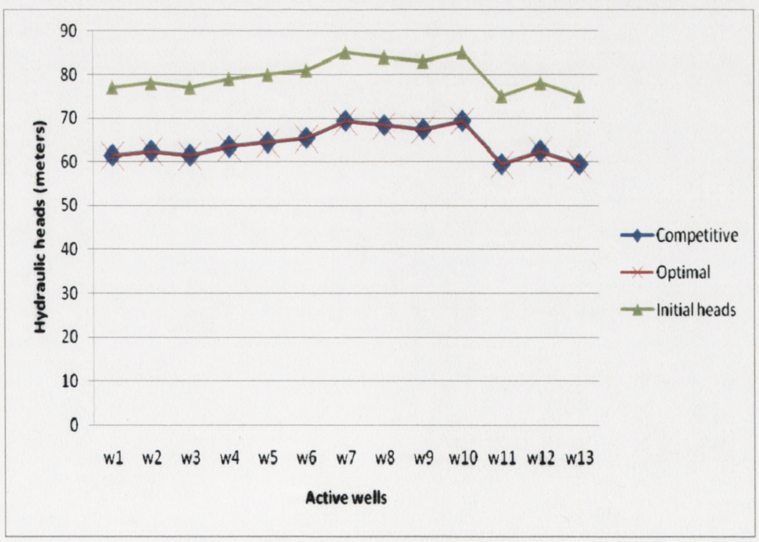
	Management scheme		
	Competitive	**Optimal**	**Difference**
A. NUL representation			
Location of new wells	8 and 10 or 13	11 and 13	YES
Location of recycling systems	7 and 8	None	YES
Location of pumping systems	None	None	NO
Total discounted cost	US$2,330,554	US$2M	+16.53%
Average drawdown after 40 years	22.41m	17.56m	+27.62%
B. UI representation			
Location of new wells	8 and 10 or 13	9 and 12	YES
Location of recycling systems	None	None	NO
Location of pumping systems	None	None	NO
Total discounted cost	US$2M	US$2M	0%
Average drawdown after 40 years	15.57m	15.68m	-1%

Simplifying the aquifer dynamics by a homogeneous representation underestimates the hydrological losses of competitive extraction (difference in average drawdown) by 30 per cent. This result can be also seen in Figure 2.8. Panel A shows that in most wells, the competitive management-induced drawdowns are more than five metres greater than the optimal policy-induced drawdowns. By contrast, the UI representation on panel B calculates an equal difference between initial and final heads for every location irrespective of the positioning of new users and management scheme.

Figure 2.8 **Potentiometric head at active wells at the end of the planning period**



(A) NUL representation



(B) UI representation

2.5 Policy implications

In the Concordia-Salto area presented in this study, an interim minimum well separation of two kilometres has been adopted. Although this policy represents an important advance, it is not the result of an informed policymaking process. In fact, I find that not only the distance among wells, but also the direction of groundwater flow, should inform policymaking to maximise welfare gains from regulation. The two-kilometre limit may be too limiting in some areas and insufficient in others. Thus, this decision may generate conflicts and controversies, especially in a transboundary context where the geographical demarcation and regulation of hydrological units is a difficult task.

The spatio-temporal aspect of external impacts among users of an aquifer adds an extra layer of complexity to the challenge of changing resource policy in the face of emerging physical, economic and environmental realities. Geospatial data systems are still under development and models of agricultural/resource economics have not been linked at a high spatial resolution to physical models (Steward et al. 2009). However, decentralised spatial groundwater policies such as location norms and zoning systems have a record of success in countries like India, characterised by a high degree of spatial variation in local storage characteristics and recharge processes (The World Bank 2010). Where the drawdown effects of many small users are localised, spatial regulations are comparatively easy to enforce by local communities, and also offer flexibility in that an area can be abandoned after drilling without considerable financial loss (Zektser & Everett 2004).

The frequent use in practice of spatial policies for groundwater management suggests that the definition of first- and second-best policies should be revised. Modeling aquifers as spatial systems means that first-best policies entail utilising separate instruments for each spatial unit (for example, different extraction paths), but also optimally regulating spatial variables such as well location/depth. Optimal second-best policies need not be an undifferentiated version of their first-best counterparts but rather regulations on time-invariant variables. As a result, by considering non-extraction control variables, it is still possible to take into account hydrological information about spatial interconnections and design second-best policies that realise most of the rents from optimal management.

Spatially explicit groundwater economic models are also needed to evaluate the economic effects of groundwater policies *ex post*. For instance, in the Ogallala Aquifer, county-specific water policies were found to have a lower implicit cost of conserving saturated thickness than policies for the region as a whole (Terrell et al. 2002). As our modeling experience on spatial policies grows over time, we will have opportunities to test how different combinations of spatial instruments differ in their impacts on rents, extraction levels and groundwater stocks.

Finally, the incorporation of spatially based control variables in the modeling of groundwater depletion problems raises important institutional design questions. The use of spatial regulations means that the position of decision makers in space matters for the system outcome. Hence, the implementation of rent-maximising spatial policies will often require cooperation among agents and agencies in different regions or nations. In this context, transboundary institutions should be designed so as to incorporate these policies in integrated water management schemes.

2.6 Conclusions

Spatial regulations, such as well location and zoning systems, are a key component of aquifer management initiatives around the world. Despite this empirical fact, groundwater economic models have refined optimal extraction rules while lagging behind in the study of optimal spatial policies. This policy-theory miss-match can be explained if studies use a spatially homogeneous representation of the aquifer's dynamics. However, if spatially explicit representations are used, optimal location of new wells may result in significant welfare and hydrological gains, even if total extraction is not capped. My contribution is to provide theoretical results and also empirical evidence that highlights the importance of optimal well location choice to internalise intertemporal externalities.

The modeling approach developed compares the divergence between competitive and optimal extraction time-paths and location of new wells under alternative spatial representations of aquifers. The first representation resembles those most frequently used by economic studies which assume an immediate and uniform response to extraction. By contrast, the alternative and more realistic representation allows for a dynamic spatial heterogeneous response, more akin to the behaviour encountered in real-world aquifers.

The theoretical results reveal that simplifying heterogeneously distributed aquifers with homogeneous spatial representations leads to over (under) estimation of optimal extraction paths of users whose extractions are relatively more (less) harmful to others' stocks. Under the assumption of a spatial homogeneity, the well location decision is irrelevant. Thus, while the predicted welfare gap may be reasonably approximated when the number of wells is fixed, this is not the case with a growing number of endogenously located new users.

I apply the model to a real-world aquifer for which detailed spatial data is available. The empirical findings show that significant welfare and hydrologic costs from unregulated well location are overlooked if the aquifer is assumed to be a homogeneously distributed resource. This is because such a representation fails to capture well interference areas. Thus, the location of new wells is an irrelevant decision for users in both the optimal management and competitive scenarios.

From a policy perspective, the present study raises several important issues. By expanding the regulatory set to include spatially based variables, it is possible to design second-best policies that realise most of the rents from optimal management. Hence, welfare gains from management may be substantial even if extraction rates are unregulated.

Another implication, at least in terms of the aquifer studied, is that second-best economically defined spacing regulations may possibly have better efficiency results (and lower implementation costs) than uniform taxes or quotas. This is because uniform policies average or blend the optimal differentiated results, while spacing regulations do take into account hydrological information about spatial interconnections. However, these regulations need to be economically defined by spatially explicit groundwater models that allow for multiple choice variables, more akin to the real world of groundwater development. Thus, the transaction costs of acquiring spatially detailed data should also be taken into consideration when comparing alternative policies with different efficiency results.

Appendix

Table A 2.1 **Hydrologic and economic parameters per well**

Well location	**Capital Costs (US$)**			**Surface level minus Lower Datum (m)**	**Water requirements (m^3/h)**		**Initial head (m)**
	Drilling and casing	**Recycling system**	**Pump**		**First period**	**Second period**	
1	N/A	300,000	200,000	20	210	210	77
2	N/A	160,000	80,000	20	90	90	78
3	N/A	160,000	80,000	19	120	120	77
4	N/A	160,000	80,000	16	60	60	79
5	N/A	300,000	200,000	34	150	150	80
6	N/A	300,000	200,000	29	300	300	81
7	N/A	300,000	200,000	40	200	200	85
8	2M	300,000	200,000	56	150	150	84
9	2M	300,000	200,000	50	150	150	83
10	2M	300,000	200,000	40	150	150	85
11	2M	300,000	200,000	37	150	150	81
12	2M	300,000	200,000	30	150	150	78
13	2M	300,000	200,000	11	150	150	75
14	2M	300,000	200,000	32	150	150	75

Table A 2.2 **Coding of the GA**

Option	Value
Crossover fraction	0.8
Mutation function	Adapt feasible
Selection function	Tournament
Number of generations	50
Stall generations	50
Population size	100
Initial penalty	100
Penalty factor	200

Table A 2.3 **'Well function' coefficient estimates and standard errors**

k	$\beta_{1,k,1}$	$\beta_{1,k,2}$	$\beta_{2,k,1}$	$\beta_{2,k,2}$	$\beta_{3,k,1}$	$\beta_{3,k,2}$	$\beta_{4,k,1}$	$\beta_{4,k,2}$	$\beta_{5,k,1}$	$\beta_{5,k,2}$	$\beta_{6,k,1}$	$\beta_{6,k,2}$	$\beta_{7,k,1}$	$\beta_{7,k,2}$
1	**0.1292***	**0.1165***	**0.0232***	0.015	**0.0414***	**0.0368***	**0.0099***	-0.002	**0.0061***	-0.012	**0.0054***	-0.006	**0.0053***	-0.005
	(0.000)	(0.011)	(0.000)	(0.01)	(0.001)	(0.009)	(0.001)	(0.013)	(0.001)	(0.014)	(0.001)	(0.014)	(0.000)	(0.014)
2	**0.0215***	0.033	**0.0498***	**0.0686***	**0.0255***	**0.0363***	**0.0119***	**0.047***	**0.008***	**0.0487***	**0.0079***	0.033	**0.0067***	0.021
	(0.000)	(0.022)	(0.001)	(0.022)	(0.002)	(0.019)	(0.001)	(0.028)	(0.002)	(0.03)	(0.003)	(0.029)	(0.001)	(0.03)
3	**0.023***	0.009	**0.0232***	0.009	**0.081***	**0.0725***	**0.0091***	-0.01	**0.0045***	-0.024	0.0012	-0.025	**0.0046***	-0.024
	(0.000)	(0.016)	(0.001)	(0.016)	(0.001)	(0.013)	(0.001)	(0.02)	(0.001)	(0.021)	(0.002)	(0.021)	(0.001)	(0.021)
4	**0.0084***	0.051	**0.0093***	0.056	**0.007***	0.042	**0.0682***	**0.1324***	**0.0086***	**0.1114***	0.0007	**0.0872***	**0.0059***	**0.1134***
	(0.001)	(0.036)	(0.001)	(0.036)	(0.001)	(0.03)	(0.001)	(0.046)	(0.003)	(0.048)	(0.005)	(0.048)	(0.001)	(0.049)
5	**0.0067***	0.003	**0.0073***	0.014	**0.0078***	0.005	**0.0122***	0.017	**0.0712***	**0.0787***	**0.0169***	0.022	**0.0095***	0.021
	(0.000)	(0.011)	(0.000)	(0.011)	(0.003)	(0.01)	(0.001)	(0.014)	(0.001)	(0.015)	(0.002)	(0.015)	(0.000)	(0.015)
6	**0.0059***	0.006	**0.0065***	0.002	**0.0056***	0.007	**0.0103***	0.011	**0.0179***	**0.0163***	**0.0534***	**0.0528***	**0.0106***	0.004
	(0.000)	(0.007)	(0.000)	(0.007)	(0.001)	(0.006)	(0.000)	(0.009)	(0.001)	(0.009)	(0.001)	(0.009)	(0.000)	(0.009)
7	**0.0061***	**0.0154***	**0.0066***	0.014	**0.0044***	0.012	**0.0086***	0.019	**0.0104***	**0.0211***	**0.0108***	**0.0218***	**0.0378***	**0.0493***
	(0.000)	(0.009)	(0.000)	(0.009)	(0.001)	(0.008)	(0.000)	(0.012)	(0.001)	(0.012)	(0.001)	(0.012)	(0.000)	(0.012)
8	**0.0043***	**0.0309***	**0.0048***	**0.0231***	**0.0052***	**0.0224***	**0.0071***	**0.0383***	**0.0101***	**0.0482***	**0.0108***	**0.0394***	**0.0111***	0.026
	(0.000)	(0.014)	(0.000)	(0.014)	(0.001)	(0.012)	(0.001)	(0.017)	(0.001)	(0.018)	(0.002)	(0.018)	(0.001)	(0.019)

9	**0.0079***	0.005	**0.009***	0.002	**0.0106***	0.005	**0.0094***	0.002	**0.008***	-0.001	**0.0098***	0.001	**0.0113***	0.001
	(0.000)	(0.013)	(0.000)	(0.013)	(0.001)	(0.011)	(0.001)	(0.016)	(0.001)	(0.017)	(0.002)	(0.017)	(0.001)	(0.017)
10	**0.0064***	0.002	**0.0068***	0.002	**0.0054***	0.007	**0.008***	-0.003	**0.0085***	-0.004	**0.0098***	0.005	**0.0154***	0.022
	(0.000)	(0.013)	(0.000)	(0.013)	(0.001)	(0.006)	(0.001)	(0.017)	(0.001)	(0.018)	(0.002)	(0.017)	(0.001)	(0.018)
11	**0.0046***	0.009	**0.005***	0.01	**0.0047***	0.003	**0.0078***	0.018	**0.0128***	0.022	**0.0122***	0.018	**0.0075***	0.01
	(0.000)	(0.011)	(0.000)	(0.011)	(0.001)	(0.011)	(0.001)	(0.014)	(0.001)	(0.014)	(0.002)	(0.014)	(0.000)	(0.015)
12	**0.0051***	0.01	**0.0054***	0.008	**0.004***	0.006	**0.0091***	0.01	**0.0121***	0.019	**0.0086***	0.011	**0.0059***	0.015
	(0.000)	(0.012)	(0.000)	(0.012)	(0.001)	(0.009)	(0.001)	(0.016)	(0.001)	(0.016)	(0.002)	(0.016)	(0.000)	(0.017)
13	**0.0074***	0.003	**0.0077***	-0.002	**0.0088***	0.003	**0.0116***	-0.006	**0.0107***	-0.018	**0.0113***	-0.01	**0.006***	-0.014
	(0.000)	(0.014)	(0.000)	(0.014)	(0.001)	(0.01)	(0.001)	(0.018)	(0.001)	(0.019)	(0.002)	(0.019)	(0.001)	(0.019)
14	**0.0111***	-0.012	**0.0114***	-0.028	**0.0082***	0.001	**0.0126***	-0.026	**0.0086***	-0.029	**0.0097***	-0.022	**0.0056***	-0.023
	(0.000)	(0.017)	(0.001)	(0.016)	(0.001)	(0.012)	(0.001)	(0.021)	(0.002)	(0.022)	(0.002)	(0.022)	(0.001)	(0.023)

k	$\beta_{8,k,1}$	$\beta_{8,k,2}$	$\beta_{9,k,1}$	$\beta_{9,k,2}$	$\beta_{10,k,1}$	$\beta_{10,k,2}$	$\beta_{11,k,1}$	$\beta_{11,k,2}$	$\beta_{12,k,1}$	$\beta_{12,k,2}$	$\beta_{13,k,1}$	$\beta_{13,k,2}$	$\beta_{14,k,1}$	$\beta_{14,k,2}$
1	**0.0046***	-0.007	**0.0082***	-0.002	**0.006***	-0.002	**0.0047***	-0.011	**0.0048***	**-0.0678***	**0.0068***	0.015	**0.0107***	0.009
	(0.001)	(0.011)	(0.000)	(0.014)	(0.001)	(0.021)	(0.001)	(0.012)	(0.002)	(0.031)	(0.001)	(0.038)	(0.000)	(0.013)
2	**0.006***	0.028	**0.0101***	0.024	**0.0061***	0.008	**0.0062***	**0.0424***	**0.0083***	**0.1664***	**0.008***	0.025	**0.0113***	0.04
	(0.001)	(0.023)	(0.001)	(0.029)	(0.003)	(0.044)	(0.001)	(0.025)	(0.004)	(0.065)	(0.001)	(0.08)	(0.001)	(0.027)

3	**0.0035***	-0.019	**0.0077***	-0.019	**0.0043***	-0.033	**0.0035***	-0.021	0.0035	-0.069	**0.006***	-0.006	**0.01***	0.016
	(0.001)	(0.016)	(0.001)	(0.021)	(0.002)	(0.032)	(0.001)	(0.018)	(0.003)	(0.046)	(0.001)	(0.057)	(0.001)	(0.019)
4	**0.0056***	**0.0897***	**0.0084***	**0.1104***	0.0054	**0.1424***	**0.0065***	**0.0976***	0.0098	**0.2902***	**0.0098***	0.027	**0.0101***	0.06
	(0.001)	(0.037)	(0.002)	(0.048)	(0.004)	(0.073)	(0.002)	(0.041)	(0.006)	(0.106)	(0.002)	(0.013)	(0.001)	(0.043)
5	**0.0115***	**0.0191***	**0.0093***	0.02	**0.0098***	0.023	**0.0135***	**0.021***	**0.016***	0.053	**0.0102***	-0.033	**0.0079***	0.008
	(0.001)	(0.011)	(0.000)	(0.015)	(0.001)	(0.023)	(0.001)	(0.013)	(0.002)	(0.033)	(0.001)	(0.04)	(0.000)	(0.013)
6	**0.0148***	**0.012***	**0.0092***	0.004	**0.0083***	-0.001	**0.0147***	**0.013***	**0.0127***	0.003	**0.0086***	0.028	**0.0068***	0.007
	(0.000)	(0.007)	(0.000)	(0.009)	(0.001)	(0.014)	(0.000)	(0.008)	(0.001)	(0.02)	(0.000)	(0.025)	(0.000)	(0.008)
7	**0.0125***	**0.0214***	**0.0123***	**0.0236***	**0.0138***	**0.0311***	**0.0092***	**0.018***	**0.0105***	0.019	**0.0065***	0.042	**0.0061***	0.013
	(0.000)	(0.009)	(0.000)	(0.012)	(0.001)	(0.018)	(0.001)	(0.01)	(0.002)	(0.027)	(0.000)	(0.033)	(0.000)	(0.011)
8	**0.0428***	**0.0644***	**0.0078***	0.022	**0.0095***	0.017	**0.0107***	**0.0437***	**0.0075***	**0.1249***	**0.0057***	0.071	**0.0047***	0.02
	(0.001)	(0.014)	(0.001)	(0.018)	(0.002)	(0.028)	(0.001)	(0.015)	(0.002)	(0.04)	(0.001)	(0.05)	(0.001)	(0.017)
9	**0.008***	0.001	**0.0237***	0.014	**0.0112***	-0.003	**0.0063***	-0.001	0.0025	-0.007	**0.0052***	-0.024	**0.0061***	0.003
	(0.001)	(0.013)	(0.001)	(0.017)	(0.001)	(0.026)	(0.001)	(0.014)	(0.002)	(0.037)	(0.001)	(0.046)	(0.001)	(0.015)
10	**0.0094***	0.006	**0.0147***	0.021	**0.0238***	0.043	**0.0072***	-0.004	**0.0065***	-0.06	**0.0053***	-0.015	**0.005***	-0.001
	(0.001)	(0.014)	(0.001)	(0.018)	(0.002)	(0.027)	(0.001)	(0.015)	(0.002)	(0.039)	(0.001)	(0.048)	(0.001)	(0.016)
11	**0.0109***	0.016	**0.0065***	0.009	**0.0074***	0.007	**0.018***	**0.0269***	**0.0112***	0.048	**0.0075***	0.019	**0.0058***	0.009
	(0.001)	(0.011)	(0.000)	(0.014)	(0.001)	(0.022)	(0.001)	(0.12)	(0.002)	(0.032)	(0.001)	(0.039)	(0.000)	(0.013)
12	**0.0073***	0.013	**0.0058***	0.014	**0.0042***	0.014	**0.0106***	0.017	**0.0407***	**0.0768***	**0.0106***	-0.028	**0.0069***	0.015
	(0.001)	(0.013)	(0.000)	(0.016)	(0.001)	(0.025)	(0.001)	(0.014)	(0.002)	(0.036)	(0.001)	(0.044)	(0.000)	(0.015)
13	**0.0069***	-0.013	**0.0065***	-0.012	**0.0075***	-0.013	**0.0087***	-0.017	**0.0118***	**-0.0819***	**0.0467***	0.029	**0.0121***	0.002
	(0.001)	(0.015)	(0.001)	(0.019)	(0.002)	(0.29)	(0.001)	(0.016)	(0.003)	(0.042)	(0.001)	(0.051)	(0.001)	(0.017)

14	**0.006***	-0.02	**0.0072***	-0.022	**0.0058***	-0.027	**0.0069***	-0.025	**0.009***	**-0.0846***	**0.012***	-0.029	**0.0492***	-0.004
	(0.001)	(0.017)	(0.001)	(0.022)	(0.002)	(0.033)	(0.001)	(0.019)	(0.003)	(0.049)	(0.001)	(0.06)	(0.001)	(0.02)
β	**0.0056***													
	(0.000)													

*Notes: * denotes significance at the 10% level.*

Chapter 3 An integrated assessment of extraction policies on spatially heterogeneous aquifers

3.1 Introduction

As discussed in Chapter 2, extraction from spatially heterogeneous aquifers is likely to be inefficient in the absence of regulation. If water extraction is inefficient, all users may benefit through the implementation of a management tool to regulate groundwater withdrawals. The variation of extraction externalities across space and their evolution over time means that optimal corrective measures have to match this heterogeneity if economic efficiency is to be maximised (Xabadia et al. 2008). However, the rarity of these finely tuned policies in real world schemes raises interesting questions for economists about how their analysis can effectively inform policy design in complex settings (Weinberg & Wilen 2000).

Spatially and temporally differentiated policies are technically difficult to design and costly to implement. Although information and monitoring technologies have significantly evolved in recent years, differentiated policies are more likely to be opposed by affected populations with negotiation costs being too high relative to efficiency gains (Xabadia et al. 2008). Hence, during the policymaking process, management tools are compared not only in terms of efficiency but also in terms of their welfare distributional effects and implementation costs (Brill & Burness 1994).

Despite this empirical fact, most studies on groundwater management have focused on the derivation of first-best tools and consider only the efficiency of water use (Burness & Brill 2001; Nieswiadomy 1985; Noel et al. 1980). To the best of my knowledge, the exceptions are Feinerman (1988), Feinerman and Knapp (1983) and Shah (1993), who analyse the equity aspect of tax options by comparing different rebate schemes, and Burness and Brill (2001) who propose an ad-hoc method to design a tax that minimises the negative effect on private returns while generating a pumping schedule close to the planning schedule. In this chapter, I intend to fill this gap by presenting a typical model of groundwater extraction and comparing several optimal first- and second-best policies (taxes, unitisation and markets) to control groundwater extraction. I examine the trade-offs involved in each policy choice between welfare gains, redistribution effects, hydrological sustainability and implementation costs. While this model directly applies to a groundwater extraction problem, it can be easily modified to any common pool resource where extraction externalities are both dynamic and spatial.

The analytical results confirm that spatial property rights alone do not yield efficient outcomes because the pumping externality persists after the allocation of rights (Koundouri 2004a). To correct the externality, I compare an optimal temporally and spatially differentiated tax with an optimal dynamic and spatially uniform tax and find that the economic and hydrological gains from a spatially differentiated tax are more modest the lower the spatial variation of pumping externalities. Additionally, an optimal differentiated tax may not be more hydrologically sustainable than an optimal spatially uniform tax.

I also consider new approaches to groundwater management and analyse coordination between users via a generalisation of unitisation. First-best efficient extraction can be achieved with unitisation and contractual obligation is not required if shares are properly varied across space. Also, acceptability is not an issue, since it is a voluntary regime (Koundouri 2004a).

I employ a numerical example based on thermal groundwater extraction from the Guarani Aquifer System to rank different policies according to their performance in terms of efficiency, equity and hydrological sustainability. The empirical results show that a spatially uniform policy results in a small efficiency loss (15 per cent) but a gain in private profits of 85 per cent, relative to a differentiated tax. Thus, a uniform tax would be much more easily acceptable by users at the expense of small efficiency losses. A full unitisation scheme appears to be the policy that minimises efficiency and hydrological losses while maintaining competitive private profits and avoiding adverse distributional effects. However, further work should be done on the quantification of transaction costs of negotiation and reduction of information asymmetries to prevent unitisation failure.

The contribution of this chapter is three-fold. Firstly, I evaluate the efficiency of second-best policies relative to first-best policies in a dynamic and spatially explicit framework of groundwater extraction. To my best knowledge, previous studies on groundwater extraction examined second-best policy options in an ad-hoc manner without making explicit analytical comparisons with first-best options (Burness & Brill 2001; Feinerman 1988; Feinerman & Knapp 1983; Shah 1993). Hence, I draw on the literature for pollution control that compares the optimally set second-best policies in terms of their efficiency, transaction costs, fiscal effects and distributional impacts (Claassen & Horan 2001; Weinberg & Wilen 2000; Xabadia et al. 2008).

Secondly, I provide an integrated assessment of policy options by quantifying their welfare distributional and hydrological effects and discussing implementation costs. These criteria may dominate the decisions about support of, or opposition to, groundwater management. Hence, they must be incorporated if economic analysis is to inform real-world policymaking.

Finally, I explore the ability of unitisation to correct externalities across spatial property right owners. Although unitisation is a well-known solution in the context of mineral rights to an oil or gas field (Libecap & Wiggins 1984, 1985), it has been rarely applied or studied to control groundwater extraction (Anderson & Hill 1997). One reason is that in traditional unitisation schemes, management is centralised in a single operator and this runs counter to modern decentralised approaches to water management. A profit-sharing system need not imply centralised management. In fact, decentralised profit-sharing systems have arisen organically for the exploitation of other spatially heterogeneous resources such as fisheries (Cancino et al. 2007; Uchida & Wilen 2007). However, no theoretical or empirical studies have formalised decentralised unitisation schemes in a modeling framework of groundwater extraction.

This chapter is organised as follows. The first section discusses the indicators used to assess alternative policy instruments in terms of different aspects. Then, I introduce the groundwater extraction model and define the optimal and competitive outcomes. Next, I describe a first-best tax and identify conditions when a dynamic spatially uniform tax may replace the former at low efficiency and hydrological losses. I then describe the ability of a unitisation scheme to achieve efficiency when participation is voluntary, and make a brief reference to groundwater markets. The following section presents the empirical application and discusses the obtained results. The chapter closes with some policy recommendations and conclusions.

3.2 Indicators for integrated assessment

To provide the comparisons across different policy approaches I use a quantitative framework in three key categories: equity, economic efficiency and hydrological sustainability.

The first category is assessed by calculating private profits of users under each policy (relative to a no policy scenario) and measuring their inequality with the coefficient of variation (CV). This criterion was selected based on its simplicity and independence of relative shifts in income. The more popular Gini coefficient is not used because, to be validly computed, no user can have a negative profit and this is not satisfied in this study.

Secondly, average head drawdown (relative to the socially optimal case) was chosen as the criteria to measure hydrological sustainability. Sustainability has proved to be an elusive concept to define in a precise manner and with universal applicability. In this chapter, I define hydrological sustainability as the development and use of groundwater in a manner that can be maintained for an indefinite time without causing unacceptable consequences such as reduction of baseflow to streams and rivers, unstable water balance, saltwater intrusion, reduction of rainfall runoff and land subsidence. Given that a reduction of the hydraulic head increases the extent of the previous adverse effects, I define a loss of hydrological sustainability (after a certain policy has been applied) as a reduction in the hydraulic head with respect to the socially optimal case.

Finally, economic efficiency was assessed as usually with the increase in aggregate welfare. In this analysis, I also discuss the transaction costs of implementing each policy in qualitative terms but leave their quantification for future work.

3.3 A spatial model of an aquifer

Consider an aquifer where there is a fixed quantity N of spatially distributed users in known, fixed locations. Each of these extracts water from a single well over an infinite horison. Tenure is assumed to be guaranteed and infinite.

The state variable y_{it} is defined as the hydraulic head in user $i's$ well at time t. y_i is bounded by $0 < y_i < \bar{y}$, where $\bar{y}$ is the aquifer's capacity limit. Without loss of generality, it is assumed initial heads are the same for every user: $y_{i1} = y_{j1} = y_1 \ \forall i, j$. The decision variable u_{it} is user $i's$ per-period water extraction at time t. Drawdown at location i and time t is given by a function d_{it} that depends on the extraction from every well such that

$$(3.1)\ d_{it+1} = y_{it+1} - y_{it} = \sum_{j=1}^{N} u_{jt} w_{ij}$$

where w_{ij} is the well function denoting the effect of user $j's$ extraction on user $i's$ head at time t. Note that $w_{ij} \le 0 \ \forall i, j$. For simplicity, I have assumed the recharge rate is equal to zero for every time period[9]. Thus, the equations of motion describing the hydraulic head in each well and time period are

[9] However, when comparing farms of different soil types, recharge rate becomes critical and should be included in the analysis.

$$(3.2)\ y_{it+1} = \sum_{j=1}^{N} u_{jt} w_{ij} + y_{it}; \quad i = 1,\ldots,N \quad t = 1,\ldots,T-1$$

This linear physical model captures spatial heterogeneity but changes in the resource's state depend only on the previous period's extraction. Simplifying the groundwater extraction model to be path-independent is not hydrologically accurate as adjustments to extraction are usually gradual. The results would provide few further insights at the expense of considerable computational difficulty if path dependency were incorporated.

Net benefits for user i are defined as benefits minus extraction costs. To simplify, I assume all users share the same net benefits function. I assume a linear quadratic function as recommended by Noel and Howitt (1982) for water resources problems:

$$(3.3)\ NB_{it}(y_{it}, u_{it}) = au_{it} - \frac{1}{2}bu_{it}^{\ 2} - c(\bar{y} - y_{it})$$

where a denotes the water demand intercept, b is the water demand slope and c is a stock opportunity cost intercept. $\bar{y}$ denotes the aquifer's maximum capacity. I assume $\frac{\partial NB_{it}(.)}{\partial y_{it}} > 0$ and $\frac{\partial NB_{it}(.)}{\partial u_{it}} > 0$, so that per-period net benefits increase with head and extraction levels. $\frac{\partial NB_{it}^{\ 2}(.)}{\partial u_{it}^2} \leq 0$, so that net benefits increase less than linearly with extraction.

3.4 Benchmark cases

The sole owner equilibrium

Consider the case where a sole owner simultaneously manages all N wells. The sole owner's objective is to maximise the present discounted value of groundwater extraction over time while taking into account the spatial heterogeneity of the aquifer.

The sole owner's problem is

$$(3.4)\ \max_{u_{it}} \sum_{t=1}^{T} \sum_{i=1}^{N} \delta^t NB_{it}(y_{it}, u_{it})$$

subject to (3.2).

After substituting (3.2) in the objective function, a solution of problem (3.4) has to satisfy the following necessary conditions for an interior solution[10]:

$$(3.5)\ \delta^t(a - bu_{it}) + c\sum_{s=t+1}^{T} \delta^s \sum_{j=1}^{N} w_{ji} = 0.$$

[10] Sufficient conditions for global optimality are satisfied by concavity of the objective function with respect to the decision variables.

Equation (3.5) governs the optimal choice of per-period extraction from each well. Groundwater should be extracted up to the point where the private marginal benefit of extracting an additional unit equals the discounted sum of the marginal costs in lower future payoffs to all users from that increase in extraction. The first order condition reduces to

$$(3.6)\; u_{it}^{SO} = \frac{a}{b} + \frac{c}{b}\sum_{j=1}^{N} w_{ji}\frac{\delta\left(1-\delta^{T-t}\right)}{(1-\delta)}.$$

The optimal level of extraction under a sole owner u_{it}^{SO} is increasing in a and c and decreasing in the marginal drawdown at other wells w_{ji}. Two factors explain that the optimal amount of groundwater extraction increases over time: (1) extraction costs increase for the remainder of the planning horizon and (2) lower marginal values are obtained from additional quantities of water used in any time period (Noel & Howitt 1982).

Competitive equilibrium

In the case of uncoordinated, decentralised ownership of the N wells, each of the owners maximises her returns over the whole period, taking as given the behavior of other users. The dynamic problem for user i is

$$(3.7)\ \max_{u_{it}} \sum_{t=1}^{T} \delta^t NB_{it}(y_{it}, u_{it})$$

subject to (3.2).

A solution of problem (3.7) has to satisfy the following necessary condition:

$$(3.8)\ \delta^t(a - bu_{it}) + c\sum_{s=t+1}^{T} \delta^s w_{ii} = 0.$$

The second term on the right hand side of (3.8) is smaller than the equivalent in the sole owner's condition (3.5). This is because user i's choice does not account for the effect of her decision on all other users' future extraction costs.

Equation (3.8) reduces to

$$(3.9)\ u_{it}^{CO} = \frac{a}{b} + \frac{c}{b} w_{ii} \frac{\delta(1-\delta^{T-t})}{(1-\delta)}.$$

As predicted by several groundwater economic studies (Kim et al. 1989; Knapp & Olson 1995; Provencher 1993; Provencher & Burt 1994), under decentralised ownership and no coordination, extraction by any user at any time period is higher than if the aquifer is managed by a sole owner: $u_{it}^{CO} > u_{it}^{SO}\ \forall i,t$. Because user i's choice is independent of other users' extractions, equation (3.9) defines a subgame perfect Nash equilibrium for each user in competitive equilibrium.

Proposition 3.1. The difference between the sole owner and competitive equilibrium is determined by the magnitude of the extraction externalities. If the effects of extraction are transmitted throughout the aquifer ($w_{ij} < 0$), the inefficiency of spatial property rights in the absence of coordination is very large. Conversely, if the resource's response to extraction is localised to the immediate vicinity of each user ($w_{ij} = 0$ $\forall i \neq j$), uncoordinated spatial property rights completely solve the commons problem.

Proof.

The dependence of inefficiency on external drawdown can be examined with the wedge between the sole owner's extraction choice and a competitive user

$$(3.10)\ u_{it}^{CO} - u_{it}^{SO} = -\frac{c}{b}\sum_{j \neq i} w_{ji} \frac{\delta\left(1-\delta^{T-t}\right)}{(1-\delta)}.$$

If the aquifer is managed by a sole owner, not only is economic welfare maximised, but groundwater stocks conserved. As with the inefficiency of uncoordinated ownership, hydraulic losses also increase with c and w_{ij} $(i \neq j)$:

$$(3.11)\ y_{it}^{SO} - y_{it}^{CO} = \frac{c}{b}\sum_{s=1}^{t-1} \frac{\delta\left(1-\delta^{t-1-s}\right)}{(1-\delta)}\left[\sum_{j=1}^{N} w_{ij} \sum_{j \neq i} w_{ji}\right]$$

3.5 Central control approaches

A number of instruments have been proposed to correct third-party effects associated with uncoordinated groundwater extraction. Economists have traditionally prescribed the introduction of extraction taxes or quotas to achieve an improved temporal allocation of the resource. In this section I compare the performance of a differentiated (first-best) and a uniform (second-best) tax in regards to efficiency, equity, hydrological sustainability and administration costs.

First-best policies

The following proposition defines a tax policy that assures at every moment in time the optimal amount of groundwater is extracted from every location (note that the optimal extraction quotas may be straightforwardly set at u_{it}^{SO}).

Proposition 3.2. The first-best outcome can be achieved by a dynamic and spatially differentiated volumetric tax given by

$$(3.12)\ \tau_{it}^{*} = -c\sum_{j\neq i} w_{ji}\frac{\delta\left(1-\delta^{T-t}\right)}{(1-\delta)}.$$

Proof.

When a tax is implemented, user $i's$ private decision problem becomes:

$$(3.13)\ \max_{u_{it}} \sum_{t=1}^{T} \delta^t NB_{it}(y_{it}, u_{it}) - \tau_{it} u_{it}$$

subject to (3.2).

The optimal private choice for a given tax is

$$(3.14)\, u_{it}^{CO}(\tau_{it}) = \frac{a}{b} + \frac{c}{b} w_{ii} \frac{\delta(1-\delta^{T-t})}{(1-\delta)} - \frac{\tau_{it}}{b}.$$

Equating $u_{it}^{CO}(\tau_{it})$ to u_{it}^{SO} from the social planner's problem, the tax should be defined by (3.12). Since the optimal tax induces extraction at the socially optimal level, the hydrological gains of implementing this policy are given by (3.11).

If both the spatial and temporal distributions of the hydrological response are incorporated in the design of policy, the social optimum is achieved and hydraulic heads preserved. However, differentiated policies do have some disadvantages. Firstly, the financial impact may not be equitably distributed among parties and may drive some users out of business within a few years. This is because users whose extraction causes relatively larger external effects on others (for example, if extraction is very concentrated in certain locations) would be taxed more heavily. In these cases, serious resistance may be raised against the introduction of a differentiated tax without rebate[11]. The following proposition identifies conditions when the negotiation costs of a dynamic and spatially differentiated tax are likely to be higher.

Proposition 3.3. In the case of no tax rebates, user i is more likely to have its profits reduced (relative to a competitive scenario) after paying the differentiated tax τ_{it}^*

a) The higher the external marginal effect of its extractions in absolute value $\left(\left|\sum_{j\neq i} w_{ji}\right|\right)$.

b) The lower the external marginal effect of others' extractions on user $i's$ stock in absolute value $\left(\left|\sum_{j\neq i} w_{ij}\right|\right)$.

Proof.

At any period t, user $i's$ profits after paying the dynamic, spatially differentiated tax will be higher than its profits under competition if

$$(3.15)\quad A_i\left(c\gamma_t^2 w_{ii} - \frac{1}{2}\gamma_t^2 cA_i - \gamma_t\left(a - cw_{ii}\gamma_t\right)\right) > c\sum_{s=1}^{t-1}\gamma_s\sum_j A_j w_{ij}$$

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[11] We leave for future work the consideration of the impact of different rebate schemes on benefits redistribution. For an examination of various groundwater rebate schemes see Feinerman (1988).

where $\gamma_t = \frac{\delta(1-\delta^{T-t})}{(1-\delta)}$ and $A_i = \sum_{j \neq i} w_{ji}$. Refer to the appendix for a full derivation of (3.15).

The higher $|A_i|$, by (3.12) user i will be paying a higher tax rate and will more likely oppose its introduction. Similarly, the lower $\sum_j A_j w_{ij}$, the less affected user i will be from increased extraction in a competitive scenario, thus less likely to support policy intervention.

Secondly, differentiated policies are also costly to implement because they have to vary among users and require adjustments over time. This double variation entails high transaction costs of policy design, negotiation, monitoring, and control. Thus, in the world of real policy implementation, the relevant question becomes which system is efficient after accounting for transaction costs. This raises interesting questions about the costs of so-called 'inefficient' uniform policies. In the next sub-section I characterise second-best policies and identify conditions when the associated efficiency losses are relatively small compared to first-best policies. In these cases, 'inefficient' policies may be preferred to efficient policies, such as those defined above, if the savings in transaction costs exceed the efficiency losses.

Second-best policies

Three non-differentiated policies may be considered: a dynamic spatially uniform tax (τ_t^*), a static spatially differentiated tax (τ_i^*), and a static and spatially uniform tax (τ^*). However, I examine the first one in detail and leave the other two to future research. According to each specific occasion, it may not be feasible to vary the tax over time, space, or both. These regulations require less information or adjustments over time and are less likely to encounter political constraints. The following proposition characterises the optimal spatially uniform tax and identifies situations when efficiency losses of this policy (relative to the first-best tax) can be important.

Proposition 3.4. The optimal spatially uniform tax with the lowest loss in efficiency compared to all other spatially uniform tax rates is given by $\tau_t^* = -\frac{1}{N} c \frac{\delta\left(1-\delta^{T-t}\right)}{(1-\delta)} \sum_{i=1}^{N} \sum_{j \neq i} w_{ij}$. This policy results in higher efficiency losses the higher the variation of third-party effects over space.

Proof.

The derivation of the tax is presented in the appendix. A spatially uniform tax causes a distortion by averaging out the external effects of extraction of all users. Thus, users with relatively high external effects ($\sum_{i \neq j} w_{ij} > \frac{1}{N}\sum_{j=1}^{N}\sum_{i \neq j} w_{ij}$) will be extracting beyond optimal and vice versa.

The efficiency losses of the optimal spatially uniform policy are characterised by the difference in aggregate net benefits of all users (taking into account that taxes revert to society)[12]:

$$(3.16)\quad \sum_{t=1}^{T}\sum_{i=1}^{N}\delta^{t}\left[NB\left(u_{it}^{SO}\right)-NB\left(u_{it}^{CO}\left(\tau_{t}^{*}\right)\right)\right]=\sum_{t=1}^{T}\delta^{t}\frac{c^{2}}{b}\left[N\,\mathrm{var}\left(A_{i}\right)\right]\left[\sum_{s=1}^{t-1}\gamma_{s}-\frac{1}{2}\gamma_{t}^{2}\right]$$

where $A_i = \sum_{j \neq i} w_{ji}$ and $\gamma_t = \frac{\delta\left(1-\delta^{T-t}\right)}{\left(1-\delta\right)}$. Note that this policy is first-best only when $A_i = A\ \forall i$, that is, external effects are uniformly distributed over the aquifer.

How does the optimal spatially uniform tax compare to the differentiated tax in terms of the preservation of hydraulic heads? The following proposition indicates that a spatially differentiated tax need not be hydrologically beneficial for every user of the resource.

Proposition 3.5. An optimal differentiated tax may not be more hydrologically sustainable than an optimal spatially uniform tax. Users whose stocks are relatively more sensitive to the extraction of those with lower than average marginal external extraction effects may suffer a lower drawdown under a uniform tax than under a

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[12] For analytical simplicity, I assume $w_{ij} = w_{ji}$ and $w_{ii} = 1$.

spatially differentiated one (and vice versa). This is because users with lower than average marginal external extraction effects extract less than under a spatially differentiated tax (Proposition 3.4).

Proof.

The difference of user $i's$ head at time t under a spatially differentiated and a uniform tax is given by

$$(3.17)\quad y_{it}^{CO}(\tau_{it}^{*})-y_{it}^{CO}(\tau_{t}^{*})=\frac{c}{b}\sum_{s=1}^{t-1}\frac{\delta(1-\delta^{t-1-s})}{(1-\delta)}\sum_{j}\left[A_j-\frac{1}{N}\sum_{j}A_j\right]w_{ij}.$$

If $\sum_{j}\left[A_j-\frac{1}{N}\sum_{j}A_j\right]w_{ij}<0$ (that is, user i is less sensitive to increases in extraction from users k where $|A_k|>\left|\frac{1}{N}\sum_{j}A_j\right|$), the spatially uniform policy actually conserves the groundwater stock of user i.

Based on hydrological sustainability, some users will support a spatially uniform tax rather than a differentiated tax. I next examine situations when a spatially differentiated tax results in private economic losses relative to a uniform tax.

Proposition 3.6. In the case of no tax rebates, user i will have its profits reduced under the differentiated tax τ_{it}^{*} relative to spatially uniform tax τ_{t}^{*} if the next three conditions are satisfied:

a) User $i's$ marginal drawdown is higher than average in absolute value;

b) User $i's$ stock is relatively more sensitive to the extraction of those with lower than average marginal external extraction effects;

c) User $i's$ extraction under the spatially uniform tax is sufficiently high.

Proof.

Assuming $A_i - \frac{1}{N}\sum_i A_i < 0$, at any period t, user $i's$ profits after paying the dynamic, spatially differentiated tax will be lower than its profits under the spatially uniform tax if

$$(3.18)\ -\frac{c}{b}\gamma_t^2\left[w_{ii} - \frac{1}{2}\left(A_i + \frac{1}{N}\sum_i A_i\right)\right] + \frac{1}{D_i}\frac{1}{b}\sum_{s=1}^{t-1}\gamma_s\sum_j D_j w_{ij} + \gamma_t\left[u_{it}^{CO}(\tau_t^*) + A_i\frac{c}{b}\gamma_t\right] > 0$$

where $\gamma_k = \dfrac{\delta(1-\delta^{T-k})}{(1-\delta)}$, $A_i = \sum_{j \neq i} w_{ji}$ and $D_i = A_i - \frac{1}{N}\sum_i A_i$. Refer to the appendix for a full derivation of (3.18).

Note that the first term of (3.18) is always positive, the second is positive if $\sum_j D_j w_{ij} < 0$ (condition b in Proposition 3.6) and the third one is positive if $u_{it}^{CO}(\tau_t^*) > -A_i\frac{c}{b}\gamma_t$ (condition c in Proposition 3.6). Hence, users who oppose the differentiated tax on hydrological sustainability grounds, will also do so because their profits are reduced if their optimal extraction rates are lower under the differentiated tax.

3.6 Decentralised regulatory approaches

More flexible decentralised controls through the use of economic incentives have gained acceptance over the past decade. I now turn to investigate the potential promotion of efficient groundwater management and allocation from unitisation schemes and water markets.

Unitisation

In this section, I examine the effects of unitising the aquifer. Unitisation is a contractual agreement that evolved in oil recovery to mitigate common pool problems. In the case of groundwater, unitisation is typically regarded as a solution to excessive drawdown where a single unit operator extracts from and develops the reservoir. All other parties then share in the net returns as shareholders (Libecap 2005).

This view of unitisation is equivalent to complete centralisation of managemen in a basin and runs counter to an agreed trend of non-intrusive policies which encourage decentralised resource allocation decisions. Thus, in this study I explore the effects of a unitisation scheme where users consolidate a percentage of their profits in a pool but do not surrender operation of their wells. A key issue in this type of unitisation contract is that general uncertainty and asymmetrical information regarding profits may block consensus on value estimates that determine unit shares. However, empirically we observe that unitisation schemes are usually agreed to late in field development when information problems are reduced.

I assume users have an identical profit function and unitisation comes late in field development. Thus, uncertainty about lease values collapses around true parameter values and there is perfect information and monitoring on the productivity of each lease. No new wells are added to the field. In this scenario, I follow Kaffine and Costello (2010) and consider a unitisation scheme where all wells are still privately operated. User i makes a contribution $0 < \alpha_i < 1$ of her profits to a pool and gets in return a dividend of $0 < \mu_i < 1$.

The dynamic problem for user i is:

$$(3.19)\ \max_{u_{it}} \sum_{t=1}^{T} \delta^t \left[(1-\alpha_i) NB_{it}(u_{it}, y_{it}) + \mu_i \sum_{j=1}^{N} \alpha_j NB_{jt}(u_{jt}, y_{jt}) \right]$$

subject to (3.2).

The necessary conditions are given by:

$$(3.20)\ \delta^{t}(1-\alpha_i+\mu_i\alpha_i)(a-bu_{it})+(1-\alpha_i)c\sum_{s=1}^{t-1}\delta^{s}w_{ii}+\mu_i c\sum_{j=1}^{N}\alpha_j\sum_{s=1}^{t-1}\delta^{s}w_{ji}=0.$$

Each user internalises the effect of its extraction on others' stocks to the extent that part of their profits is obtained as dividend. Thus, the external cost of a further unit of extraction includes the dividend foregone from a smaller aggregate pool given by the last term in (3.20).

Since user i's extraction rate remains independent of any other user's extraction, equation (3.20) defines a subgame perfect equilibrium for each user under a given unitisation scheme:

$$(3.21)\ u_{it}^{U}=\frac{a}{b}+\frac{c\frac{\delta(1-\delta^{T})}{(1-\delta)}\left[(1-\alpha_i+\mu_i\alpha_i)w_{ii}+\mu_i\sum_{j\neq i}\alpha_j w_{ji}\right]}{b(1-\alpha_i+\mu_i\alpha_i)}.$$

Note that extraction rates under this unitisation scheme (u_{it}^{U}) are decreasing with α_i. Sharing a larger fraction of profits leads to more conservative extraction paths because a larger dividend pool makes users internalise third-party effects of their extraction to a greater extent.

Proposition 3.7. The magnitude of the difference between the sole owner and the unitisation equilibrium decreases with α_i and disappears when $\alpha_i=1$ (all profits are shared). Thus, efficiency increases with the contribution α_i and full unitisation ($\alpha_i = 1$) achieves first-best, regardless of the dividend μ_i. This is because under full unitisation each user maximises the sum of profits from all locations.

Proof.

The difference between unitisation extraction paths and those under sole owner management is given by:

$$(3.22)\ u_{it}^{U} - u_{it}^{SO} = -\frac{c}{b}\frac{\delta\left(1-\delta^{T}\right)}{(1-\delta)}\sum_{j\neq i} w_{ji}\left[1-\frac{\mu_i}{1-\alpha_i+\mu_i\alpha_i}\right]$$

Note that (3.22) is increasing in α_i and if $\alpha_i = 1$ (full unitisation), the difference becomes zero.

I assume that at the start of the period each user has the option of entering the unitisation scheme. If every user decides to enter, the scheme is put in place and users are legally bound to share profits in a fully unitised manner for the rest of the period[13]. Note that if the scheme is implemented, all users choose the efficient extraction levels since when unitisation is full, extraction efficiency is independent of dividends.

[13] I leave to future work the cases of partial unitisation and implementation of unitisation schemes without agreement by all users.

By endogenising the participation decision, each user considers the long-term difference in profits between sharing a cooperative equilibrium and going it alone. The question is whether a set of dividends exists that encourages full participation and is feasible. The minimum μ_i such that user i prefers to participate is given by

$$(3.23)\ \hat{\mu}_i = \frac{\sum_{t=1}^{T} NB_{it}\left(u_{it}^{CO}, y_{it}^{CO}\right)}{\sum_{t=1}^{T}\sum_{j=1}^{N} NB_{jt}\left(u_{jt}^{SO}, y_{jt}^{SO}\right)}.$$

In general, the minimum dividends required to join the unitisation scheme will be lower the higher the external effects of extraction. However, those users who suffer larger drawdowns from third-party extraction will require lower dividends.

Proposition 3.8. Fully efficient exploitation can be voluntarily achieved by self-interested parties if (1) unitisation is full, (2) each user receives a minimum fraction of the dividends, (3) the scheme is legally binding, and (4) there is perfect information on lease values (profits from each well's extraction).

Proof.

In order for the dividend structure to be feasible, the individual dividends must sum to less or equal to unity:

$$(3.24)\sum_{i=1}^{N}\hat{\mu}_i = \frac{\sum_{t=1}^{T}\sum_{i=1}^{N} NB_{it}^{CO}\left(u_{it}^{CO}, y_{it}^{CO}\right)}{\sum_{t=1}^{T}\sum_{i=1}^{N} NB_{it}^{SO}\left(u_{it}^{SO}, y_{it}^{SO}\right)} \leq 1.$$

Since full unitisation achieves first-best, the denominator of Equation (3.24) is greater than the numerator, the dividends given by (3.23) are feasible and full participation with full unitisation is supportable.

A voluntary unitisation scheme will, by definition, make every party better off. If profits are distributed such that each party receives the amount it would under competition, the question arises as to what to do with the excess. The remaining profits could be invested across the basin in maintenance/upgrading of extraction systems, finance monitoring/data collection technologies, or distributed among users according to some equity criterion. This flexibility of unitisation schemes enables better policy formation by governments by tailoring regulation to different resource and socio-economic contexts.

The transaction costs of unitising an aquifer will depend on the type of scheme implemented. If during exploration individual users agree to give authority to a single entity to develop the basin, monitoring and enforcement costs are reduced because the resource is recovered from a few, strategically located wells. However, transportation costs of water to the land on which it is used may be high. Conversely, if unitisation takes place late in field development, monitoring and enforcement costs will be higher if all wells are kept in operation. However, distribution costs will be reduced (Anderson & Snyder 1997).

Finally, the transaction costs of cooperative agreement may be high, particularly if the number of users is large. These could be reduced by taking advantage of existing user organisations such as municipalities, water districts, and other groundwater associations (Anderson & Snyder 1997).

Groundwater markets

The introduction of water markets is another prescription economists usually offer due to their well documented promotion of efficiency (Anderson & Hill 1997; Howitt 1997; Zilberman et al. 1994). I do not cover this type of water management here analytically because the use of tradable rights for groundwater is complicated in practice. This difficulty arises when changes in the groundwater level and the impact of those changes on production and the environment depend on location-specific characteristics.

Any system for privatising groundwater and allowing transfers between willing buyers and sellers must be restricted to protect third parties and avoid transferring rights between locations of heterogeneous characteristics. Market transactions encourage private decision makers to seek mutually beneficial trades, but if third parties are affected by the transactions, restrictions on transfers may be necessary (Anderson & Snyder 1997).

On one hand, if the market approach is embraced with no restrictions, the burden on administrative capacity may be low but at the expense of small improvements in economic efficiency and an inequitable distribution of financial impact. On the other hand, restricting trade may correct spatial externalities in extraction, but defeats the non-intrusive nature of markets with the need of a trade institution for guided trading (Koundouri 2004a). To avoid resistance from pumpers, at least a hearing process must be provided by a central agency where third parties can challenge market transfers. Otherwise, allowable extraction/interference rates must be determined. Thus, the high demand for administrative institutions is a major disadvantage for the introduction of markets on spatially heterogeneous aquifers.

3.7 Empirical application

The hydrological parameters of the model are based on a real-world aquifer.[14] The number of wells and well functions were obtained from Chapter 2 (Appendix). I use $\bar{y} = 100$ and $y_0 = 70$.

[14] This aquifer is the Concordia-Salto section of the Guarani Aquifer System. For more details see Charlesworth et al. (2008).

For the net benefits function I specify $a = 20{,}000$, $b = 100$ and $c = 26{,}000$. The discount rate is set at 5 per cent ($\rho = 0.05$). The model was parameterised so as to obtain competitive extraction rates similar to the ones currently observed in the area and documented by Charlesworth et al. (2008).

Benchmark cases

The following two figures illustrate the variation of the socially optimal extraction rates over space and time. Figure 3.1 shows that optimal extraction rates for the first year decrease with the marginal external extraction effects at every location, while Figure 3.2 illustrates the upward trend of optimal extraction paths over time.

Figure 3.1 **Optimal extraction rates in the first year: variability over space**

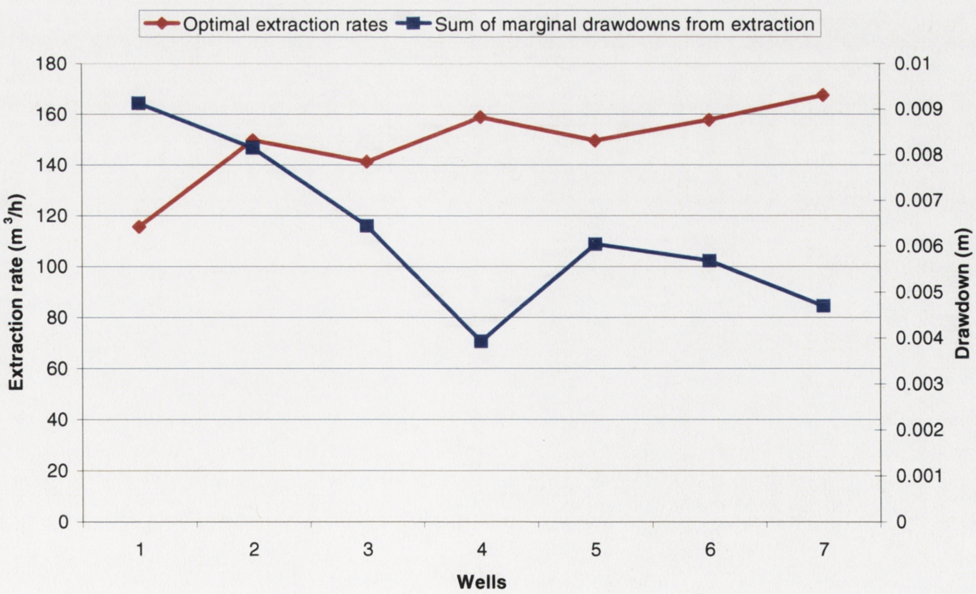
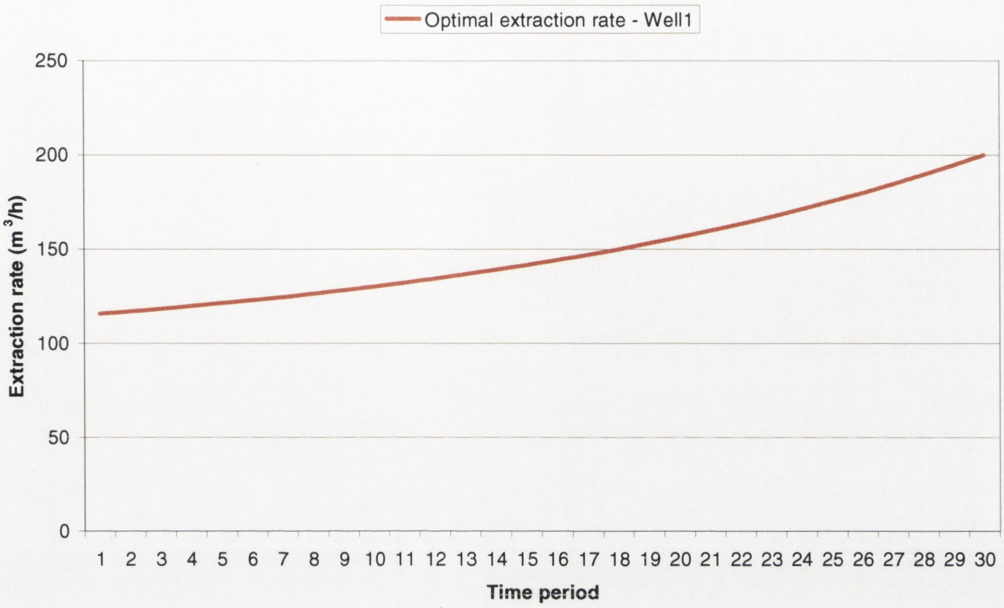


Figure 3.2 **Optimal extraction path for Well 1: variability over time**



Figures 3.3 and 3.4 depict the variation in the difference between competitive and optimal extraction paths over space and time. As predicted by Proposition 3.1, the difference between the sole owner and competitive equilibrium increases with the magnitude of extraction externalities. However, this wedge falls over time as the effects of increased extraction are felt over a shorter time horizon.

Figure 3.3 **Wedge between competitive and optimal extraction rates over space**

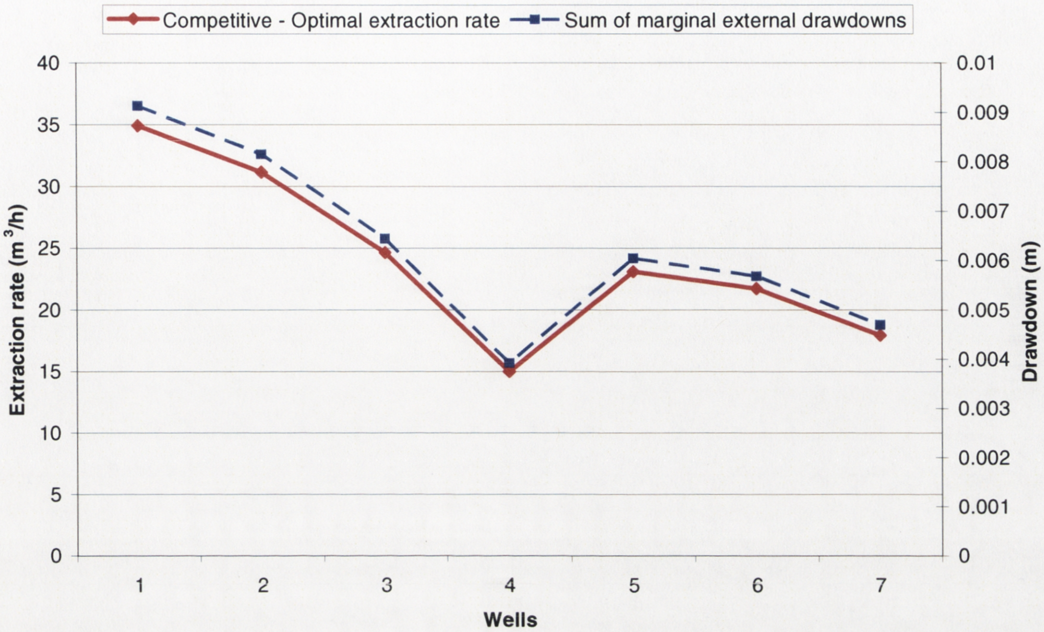
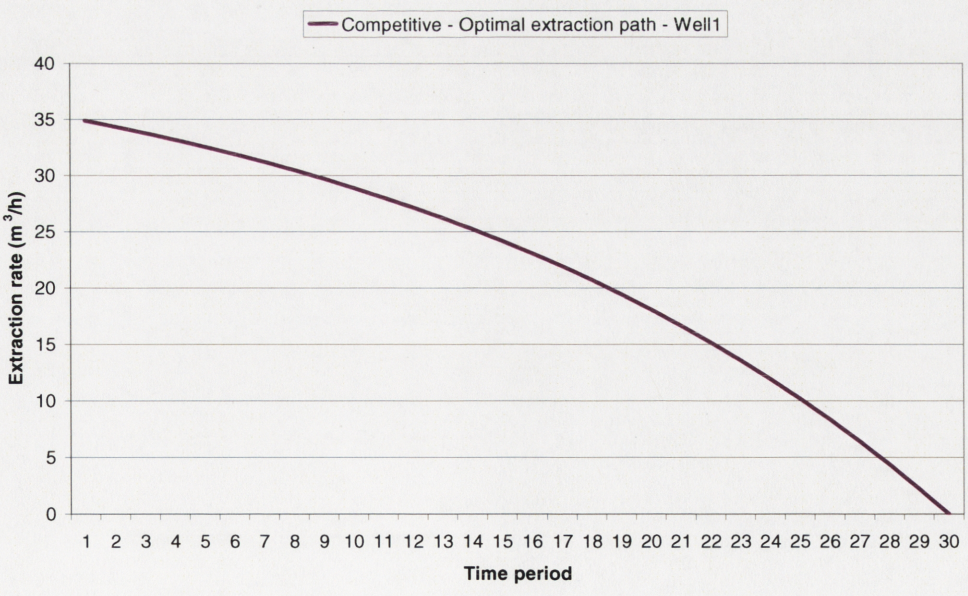


Figure 3.4 **Wedge between competitive and optimal extraction rates over time**



Comparison of differentiated versus non-differentiated policies

After computing the optimal private outcome and the social outcome, I analyse the performance of alternative tax policies. Table 3.1 summarises the optimal taxes considered and illustrates the implications of these policies on extracted water, private profits, and welfare.

Table 3.1 **Effects of alternative tax policies on private profits and welfare**

	Spatially and temporally differentiated tax	**Dynamic and spatially uniform tax**	**Private outcome (No policy)**
Tax rate 1st year (US$/m^3/h)	3,491–1,498	2,406	-
Coefficient of variation of tax rate in 1st year	0.27	0	-
Tax rate final year (US$/m^3/h)	225–96	155	-
Extracted water 1st year (m^3/h)	1,041	1,041	1,209
Aggregate private profits (US$)	923,495	1,700,109	49,430,515
Tax payments (US$)	51,366,218	50,147,687	-
Total welfare (US$)	52,289,714	51,847,796	49,430,515
Welfare gain[a] (%)	5.8	4.9	0
Efficiency loss[b] (%)	0	15.5	100

Notes: [a] Welfare gain is computed as the percentage difference in total welfare with respect to the private outcome; [b] Efficiency loss is computed as the percentage difference in welfare gain with respect to the spatially and temporally differentiated tax.

In this example, the optimal spatially and temporally differentiated tax rates in the first year vary between US$3491/m^3/h to US$1498/m^3/h[15]. The coefficient of variation of these tax rates is 0.27, implying that the distribution of the tax burden is considerably unequal. Extracted water decreases initially by 16 per cent compared to the case where no policy is implemented. As shown by Proposition 3.2, the optimal spatially and temporally differentiated tax decreases over time.

Table 3.1 shows that the optimal dynamic spatially uniform tax is initially set at US$2406/m^3/h, which is the average of the tax rates under the optimal spatially and temporally differentiated policy. Although the spatially uniform policy is able to cut the initial water extraction by the same percentage as the socially optimal policy (16 per cent), the welfare gain is lower (5 per cent). The efficiency loss of this second-best policy relative to the first-best policy, given by $EL(\tau_t^*) = \dfrac{WG(\tau_{it}^*) - WG(\tau_t^*)}{WG(\tau_{it}^*)}$, is 15 per cent. This result implies that the imposition of the uniform tax achieves about 85 per cent of the welfare gains that would be obtained with the optimal spatially and temporally differentiated tax, and 15 per cent of the potential welfare gains are lost. Under the optimal spatially uniform policy, tax payments still account for almost the totality of welfare (over 96 per cent).

The next three figures illustrate the comparison between the optimal spatially differentiated tax and the spatially uniform tax in terms of efficiency, hydrological

[15] Based on a 16-hour daily regime.

sustainability and private welfare. Figure 3.5 depicts the differences over space between extraction rates under the first-best and second-best tax policies in the first year. I have also graphed the difference between each user's marginal effects and the average. As shown in Proposition 3.4, users with relatively high external effects $(\sum_{i \neq j} w_{ij} > \frac{1}{N} \sum_{j=1}^{N} \sum_{i \neq j} w_{ij})$ extract beyond optimal and viceversa. The small difference between extraction rates (and hence relatively small difference in efficiency) can be explained by the small variance in marginal external drawdown (3.35986E-06), in accordance to Proposition 3.4.

Figure 3.5 **Difference in extraction rates between differentiated and uniform tax – First year**

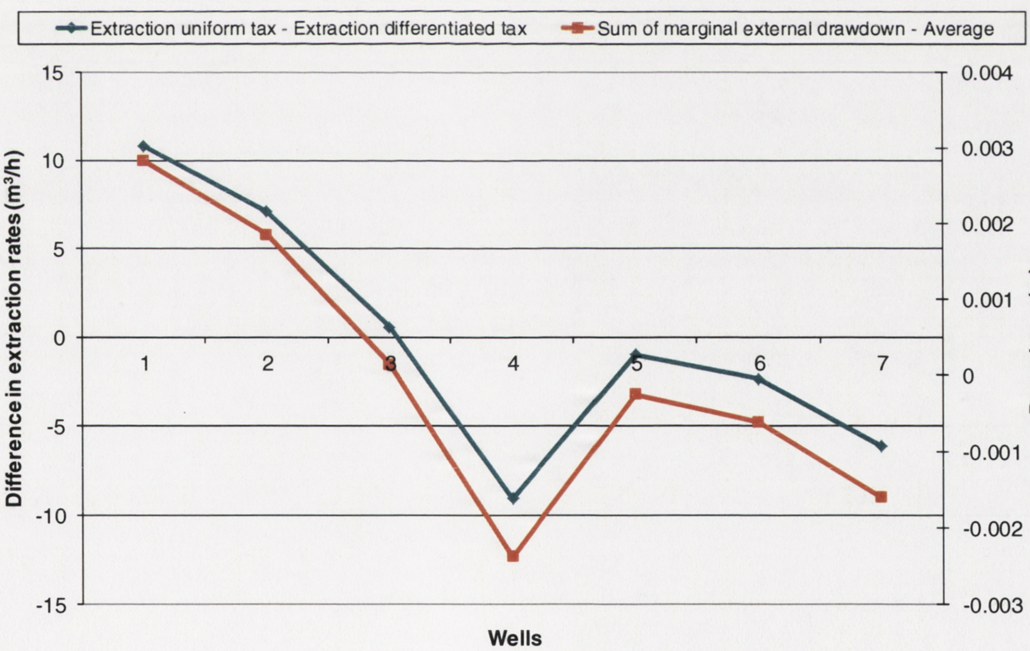
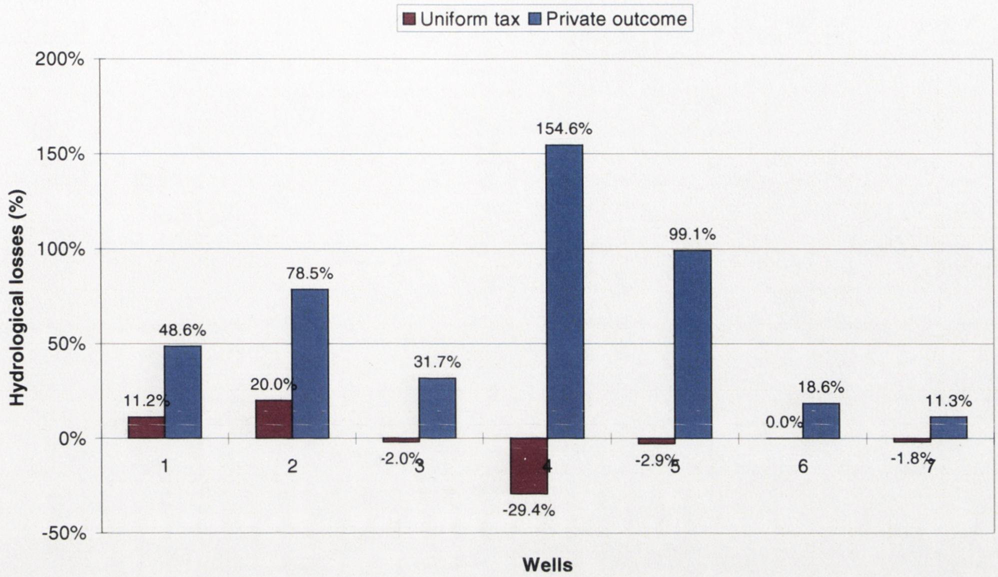


Figure 3.6 allows us to compare the hydrological sustainability of both tax policies. The bars represent the hydrological losses under the optimal spatial uniform tax and under no policy with respect to the optimal spatially differentiated policy, given by $HL_i(\tau_t^*) = \frac{y_{iT}^{CO}(\tau_{it}^*) - y_{iT}^{CO}(\tau_t^*)}{y_{iT}^{CO}(\tau_{it}^*)}$ and $HL_i(0) = \frac{y_{iT}^{CO}(\tau_{it}^*) - y_{iT}^{CO}(0)}{y_{iT}^{CO}(\tau_{it}^*)}$ respectively. If at some wells, the reduction of hydraulic head is smaller under a spatially uniform tax than under a differentiated tax, the hydrologic loss is negative (a uniform policy may actually reduce drawdown at some locations).

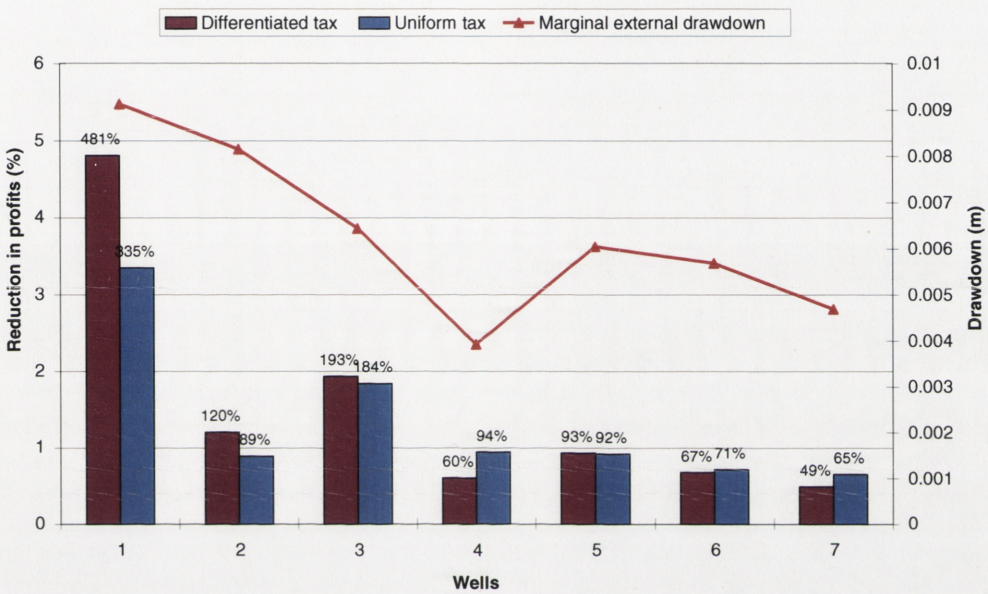
Firstly, note that the optimal spatially uniform policy decreases drawdown at every well by a considerable percentage relative to the private outcome. As shown by Proposition 5, the optimal spatially and temporally differentiated tax may not result in lower drawdowns at every location. In fact drawdown at wells 3 to 7 is lower under the spatially uniform policy.

Figure 3.6 **Hydrological losses of a spatially uniform tax**



Finally, Figure 3.7 compares the tax policies in regards to the percentage fall in private income relative to the no policy scenario, as measured by $PIL(\tau_{it}^*) = \frac{PI(0) - PI(\tau_{it}^*)}{PI(0)}$ and $PIL(\tau_t^*) = \frac{PI(0) - PI(\tau_t^*)}{PI(0)}$ with $PI(0)$ being the private profits in the no policy scenario. Under both tax schemes, the loss in private income varies widely across space with more than half the income reduced at every location. However, for those users who suffer relatively high private income losses, the loss is even higher under the optimal spatially and temporally differentiated tax, indicating that the spatially uniform tax leads to a more equitable distribution of the tax burden. As shown by Proposition 3, those users with higher marginal external drawdown (A_i), are subject to higher income losses under the optimal spatially and temporally differentiated tax.

Figure 3.7 **Reduction in profits of alternative tax policies**

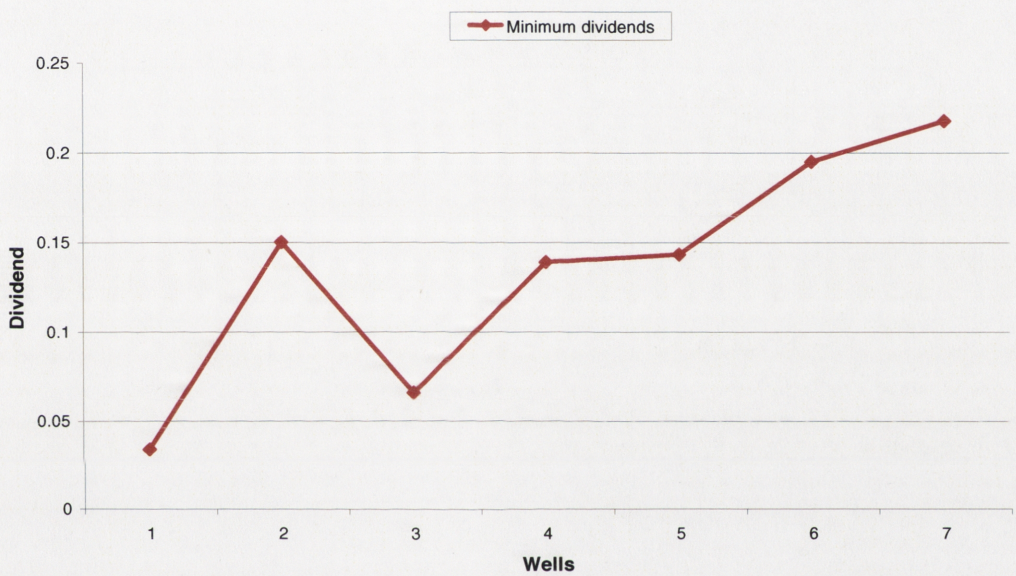


Unitisation

Users can also be induced to behave optimally from a social point of view, if the aquifer is unitised and welfare is appropriately distributed so that no user is worse off than in the private outcome. Figure 3.8 depicts the minimum shares needed at every location for a voluntary unitisation scheme to be feasible. The shares range between 0.03 and

0.22, and sum up to 0.95 so that 5 per cent of the welfare is an excess which can be distributed back among the users or used for alternative purposes, such as monitoring, research, well maintenance, et cetera.

Figure 3.8 **Minimum dividends required for a voluntary full unitisation scheme**



Trade-offs and policy choice

Finally, Table 3.2 compiles the performance of the three policies studied in terms of economic efficiency, hydrological sustainability, private profits, and equity of the private profits distribution. This table is a useful tool in the policymaking process where the relevant question is which system is efficient and politically feasible after accounting for all transaction costs.

Table 3.2 **Efficiency, hydrological, private and equity losses of alternative groundwater extraction policies**

	Social planner	**Differentiated tax**	**Full unitisation**	**Spatially uniform tax**	**Private outcome**
Welfare (US$)	52,289,714	52,289,714	52,289,714	51,847,796	49,430,515
Efficiency loss[a] (%)	-	0	0	15.5	100
Average head drawdown (m)	65.27	66.7	65.27	67.03	73.06
Hydrological loss[b] (%)	-	0	0	0.69	63.22
Aggregate private profits (US$)	52,289,714	923,495	49,430,515	1,700,109	49,430,515
Private loss[c] (%)	-	98.1	0	96.6	0
Coefficient of variation in private profits	0.42	30.27	0.45	11.09	0.45
Equity loss[d] (%)	-	66.3	0.1	23.6	0

Notes: [a] Efficiency loss is the percentage difference in welfare gain with respect to the spatially and temporally differentiated tax; [b] Hydrological loss is the percentage difference in average head drawdown with respect to the social planner equilibrium; [c] Private loss is the percentage difference in aggregate private profits with respect to the private outcome; [d] Equity loss is the percentage difference in the coefficient of variation in private profits with respect to the private outcome.

The spatially and temporally differentiated tax is usually the first (if not the only) solution proposed by economic studies, as it leads to a win-win situation with no efficiency or hydrological losses. However, this tax requires costly monitoring and constant modification and results in a private loss of 98 per cent relative to the private outcome. An important question is who would support such a policy. Even if a tax rebate scheme is implemented to increase political support, this would entail high design and negotiation costs. Furthermore, not only are private profits greatly reduced, but their inequality increases, as shown by an equity loss of 66 per cent relative to the private outcome, where $EQL(\tau_{it}^{*}) = -\frac{CV(0) - CV(\tau_{it}^{*})}{CV(0)}$ and $CV(0)$ and $CV(\tau_{it}^{*})$ indicate the coefficient of variation of private profits under no policy and under the spatially and temporally differentiated tax respectively.

Adopting an optimal spatially uniform tax entails efficiency and hydrological losses relative to the first-best tax. These losses must be contrasted with the advantages of this scheme and the regulator will ultimately make a decision specific to each case. Firstly, the user opposition to this policy may be lower as a spatially uniform tax rate is likely to be perceived as more equitable. Secondly, the inequality in the distribution of private profits does not increase as much, as seen by a lower equity loss of 24 per cent. Thirdly, a spatially uniform tax may entail lower monitoring and implementation costs.

Finally, a full unitisation scheme appears to entail no trade-offs in regards to the indicators in Table 3.2. This policy achieves first-best extraction rates while maintaining the distribution of private profits from the private outcome. However, for a more complete assessment, further investigation needs to be done on the negotiation and monitoring costs of a unitisation scheme and their determinants.

3.8 Policy implications

Despite improved data availability (for example, wireless communications), reduced computational cost, and better monitoring techniques (for example, GIS, remote sensing), implementation of finely-tuned policies to control groundwater extraction has been minimal. Well documented reasons for this mismatch are that information and implementation costs of spatially and temporally variable policies remain high and that such idiosyncratic policies are unlikely to be accepted by stakeholders. Hence, the welfare gains of first-best groundwater management are often outweighed by transaction and negotiation costs. In this light, the relevant question is in what situations are first-best solutions worth the economic and political effort and which second-best instruments are more politically and technically feasible at the expense of low efficiency losses.

This chapter proxies stakeholder acceptance of first-best policies vs. second-best by quantifying their effects on private profits. The results suggest that a first-best spatially differentiated policy drastically reduces private profits and increases the inequality of private profits relative to a spatially uniform policy. In addition, I investigate two more reasons that justify the lack of popularity of first-best differentiated policies.

Firstly, a spatially differentiated policy is also likely to be opposed by stakeholders because it leads to higher water drawdown at certain locations. Hence, both the loss in private profits and in hydrological sustainability may be considerably unequal under a first-best policy. Secondly, and perhaps most importantly, unless the spatial variation in externalities is high, a first-best spatially differentiated policy will offer small additional welfare gains relative to a uniform policy. In fact, accounting for the temporal variation in externalities may actually recover most of the potential gain from first-best management and encounter fewer political constraints.

The high transaction and political costs of centralised government-led fully differentiated policies has also redirected the approach to environmental protection towards proactive and decentralised initiatives. In the case of groundwater extraction, the introduction of water markets and voluntary agreements (such as unitisation schemes) has the potential to improve economic efficiency and minimise transaction costs, since they rely on specialised knowledge of participants about local conditions (Koundouri 2004a). This analysis shows that while groundwater markets cannot internalise spatial third-party effects, unitisation is able to achieve the first-best outcome if shares are properly designed and legal obstructions to the evolution of such agreement are removed. The experience from Territorial User Rights Fisheries (TURFs) suggests that rent gains from decentralised profit-sharing institutions are likely to exceed the transaction costs of coordination (Cancino et al. 2007).

Further investigation of other second-best instruments, such as uniform quantity regulations and well spacing requirements, is needed to provide a comprehensive assessment of policy options for groundwater management. The analysis in this chapter is not intended to recommend a particular management scheme, but to quantify the efficiency, equity and hydrological effects of alternative instruments to better inform groundwater management in practice.

3.9 Conclusions

Most economic analyses of groundwater extraction that find an important potential for groundwater management, go on to prescribe first-best policy instruments to induce users to internalise the external effects of their extraction. Implementing these instruments may be easy if the aquifer responds uniformly to groundwater extraction, as the regulation need only vary over time. However, most aquifers are heterogeneously distributed so that first-best policies must be adjusted over space and time, entailing extra economic and political efforts. In this light, it is worthwhile to consider alternative solutions that are either uniform over space or time or non-intrusive (decentralised). This chapter contributes to the literature on groundwater policy design by comparing differentiated and uniform, central and decentralised instruments in four aspects: efficiency, equity, hydrological sustainability and implementation costs.

Optimal spatially differentiated and uniform taxes are derived from a spatially explicit dynamic model of groundwater extraction. Comparison of these instruments suggests that a dynamic but spatially uniform tax is able to recover most of the potential gains from optimal management if the spatial variation of externalities is small. In addition, a uniform tax does not result in higher stock depletion at every location. The analytical results also show that unitising the aquifer via a decentralised profit-sharing institution achieves first-best and its voluntary formation is feasible.

The model is applied to an example based on thermal groundwater extraction from the Guarani Aquifer System. The empirical results show that a spatially uniform policy results in a small efficiency loss (15 per cent) but a gain in private profits (post-tax) of 85 per cent, relative to a differentiated tax. Thus, a uniform tax would be much more easily acceptable by users at the expense of small efficiency losses. A full unitisation scheme appears to be the policy that minimises efficiency and hydrological losses while maintaining competitive private profits and avoiding adverse distributional effects.

The results of this chapter aim to better inform policymakers of the trade-offs involved in different policy measures to control groundwater extraction. Because in the world of real policy implementation designing and implementing first-best policies is often either technically or politically infeasible, an integrated assessment of a broad suite of first and second-best solutions is needed. This chapter represents one step in that direction but future research should consider other non-differentiated policy instruments and quantify transaction costs of different policies and unitisation schemes.

Appendix

Proposition 3.3

Proof of (3.15)

To derive (3.15) I start by calculating for each user the per-period difference in profits between the spatially and temporally differentiated tax and the competitive case:

(3.25)

$$NB_{it}\left(u_{it}^{CO}\left(\tau_{it}^{*}\right), y_{it}^{CO}\left(\tau_{it}^{*}\right)\right) - NB_{it}\left(u_{it}^{CO}, y_{it}^{CO}\right) = a\left[u_{it}^{CO}\left(\tau_{it}^{*}\right) - u_{it}^{CO}\right] - \frac{1}{2}b\left[\left[u_{it}^{CO}\left(\tau_{it}^{*}\right)\right]^{2} - \left[u_{it}^{CO}\right]^{2}\right]$$

$$+ c\sum_{s=1}^{t-1}\sum_{j} w_{ij}\left[u_{is}^{CO}\left(\tau_{is}^{*}\right) - u_{is}^{CO}\right] - \tau_{it}^{*}u_{it}^{CO}\left(\tau_{it}^{*}\right)$$

Noting that $u_{it}^{CO}\left(\tau_{it}^{*}\right) = u_{it}^{SO}$, I substitute for $u_{it}^{CO}\left(\tau_{it}^{*}\right)$, u_{it}^{CO} and τ_{it}^{*}. User $i's$ profits will increase after the implementation of the spatially and temporally differentiated tax if

(3.26)

$$-\frac{c^{2}}{b}w_{ii}\gamma_{t}\left(\sum_{j\neq i} w_{ji}\gamma_{t}\right) - \frac{c^{2}}{2b}\left(\sum_{j\neq i} w_{ji}\gamma_{t}\right)^{2} + \frac{c^{2}}{b}\sum_{s=1}^{t-1}\gamma_{s}\sum_{j} w_{ij}\sum_{i\neq j} w_{ij} + c\sum_{j\neq i} w_{ji}\gamma_{t}\left(\frac{a}{b} + \frac{c}{b}\sum_{j} w_{ji}\gamma_{t}\right) > 0$$

I define $A_i = \sum_{j\neq i} w_{ji}$ and after some minor re-arrangements, I get (3.15).

Proposition 3.4.

To derive τ_t^*, I choose the value that maximises aggregate net benefits taking into account the response of users to the tax $u_{it}^{CO}(\tau_t^*)$:

$$(3.27)\ \max_{\tau_t} \sum_t \sum_i \delta^t \left[a u_{it}^{CO}(\tau_t) - \frac{1}{2} b \left[u_{it}^{CO}(\tau_t) \right]^2 - c\left(\bar{y} - \sum_{s=1}^{t-1} \sum_j w_{ij} u_{js}(\tau_s) - y_{i0} \right) \right]$$

Deriving with respect to τ_t and noting that $\frac{\partial u_{it}^{CO}(\tau_t)}{\partial \tau_t} = -\frac{1}{b}$ (from equation (3.14)) I get the first-order condition

$$(3.28)\ \sum_i \delta^t \left[-\frac{a}{b} + u_{it}^{CO}(\tau_t) \right] + \sum_{s=t+1}^{T} \delta^s \sum_i \sum_j w_{ij} \left(-\frac{c}{b} \right) = 0$$

Substituting $u_{it}^{CO}(\tau_t)$ from (3.14) and re-arranging I get

$$(3.29)\ \sum_i \delta^t \left[\frac{c}{b} w_{ii} \frac{\delta(1-\delta^{T-t})}{(1-\delta)} - \frac{\tau_t}{b} \right] - \frac{c}{b} \sum_i \sum_j w_{ij} \sum_{s=t+1}^{T} \delta^s = 0$$

τ_t^* can be easily derived from (3.29) after some re-arrangements. We are guaranteed a maximum because the derivative of (3.29) with respect to τ_t is negative and the derivative with respect to τ_s with $s \neq t$ is zero.

Proposition 3.6

Proof of (3.18)

To derive (3.18) I start by calculating for each user the per-period difference in profits between the spatially and temporally differentiated tax and the spatially uniform tax

(3.30)

$$NB_{it}\left(u_{it}^{CO}\left(\tau_{it}^*\right), y_{it}^{CO}\left(\tau_{it}^*\right)\right) - NB_{it}\left(u_{it}^{CO}\left(\tau_t^*\right), y_{it}^{CO}\left(\tau_t^*\right)\right) = a\left[u_{it}^{CO}\left(\tau_{it}^*\right) - u_{it}^{CO}\left(\tau_t^*\right)\right] - \frac{1}{2}b\left[\left[u_{it}^{CO}\left(\tau_{it}^*\right)\right]^2 - \left[u_{it}^{CO}\left(\tau_t^*\right)\right]^2\right]$$

$$+ c\sum_{s=1}^{t-1}\sum_j w_{ij}\left[u_{is}^{CO}\left(\tau_{is}^*\right) - u_{is}^{CO}\left(\tau_t^*\right)\right] - \tau_{it}^* u_{it}^{CO}\left(\tau_{it}^*\right) + \tau_t^* u_{it}^{CO}\left(\tau_t^*\right)$$

I substitute for $u_{it}^{CO}\left(\tau_{it}^*\right)$, $u_{it}^{CO}\left(\tau_t^*\right)$, τ_t^* and τ_{it}^*. User $i's$ profits will be lower under the spatially and temporally differentiated tax relative to the spatially uniform tax if

(3.31)

$$-\frac{c^2}{b}\gamma_t^2 w_{ii}\left(A_i - \frac{1}{N}\sum_i A_i\right) - \frac{c^2}{2b}\gamma_t^2\left[A_i^2 - \frac{1}{N^2}\left(\sum_i A_i\right)^2\right] + \frac{c}{b}\sum_{s=1}^{t-1}\gamma_s\sum_j w_{ij}\left(A_j - \frac{1}{N}\sum_j A_j\right)$$

$$+c\gamma_t\left[A_i\left(\frac{a}{b}+\frac{c}{b}w_{ii}\gamma_t+\frac{c}{b}A_i\gamma_t\right)-\frac{1}{N}\sum_i A_i\left(\frac{a}{b}+\frac{c}{b}w_{ii}\gamma_t+\frac{1}{N}\frac{c}{b}\gamma_t\sum_i A_i\right)\right]<0$$

(3.31) may be re-arranged to give (3.18).

Chapter 4 Optimal groundwater extraction under uncertainty: resilience versus economic payoffs

4.1. Introduction

This chapter examines the use of multiple instruments for optimal resource management under risk of occurrence of catastrophic events. I develop a spatially differentiated dynamic model of groundwater extraction that incorporates stochastic recharge processes and the risk of saltwater intrusion when hydraulic heads fall below some threshold level. I demonstrate that, under the uncertain threat of irreversible adverse events, the use of multiple instruments (that is, extraction and depth controls) yields higher economic benefits than a single instrument. Furthermore, although the use of a single instrument (extraction control) leads to more conservative extraction paths, the risk of crossing the threshold is actually higher than when multiple instruments are used. Thus, a cautionary single extraction policy results in a double loss in economic benefits and in the resilience of the aquifer's system. These results have direct policy implications for resource management problems in general where multiple instruments are available. This chapter informs policy design in an uncertain world by quantifying the trade-off between economic efficiency and resilience involved in alternative instrument mixes.

The economic theory of instrument choice for optimal environmental management has typically focused on the use of one instrument or compared two or more instruments. This literature is based on a key assumption that dates back to a classical result of the theory of economic policy. Tinbergen (1952) states that a policymaker with more instruments than targets is free to discard the excess instruments, and it makes no difference which ones he discards. The validity of this result is questioned in practice by the frequent use of multiple policy instruments over a broad range of environmental and resource issues. For instance, multiple instruments are often used to manage many aquifers over the world under the threat of saltwater intrusion—extraction controls, well depth limits, well locations, freshwater reinjection, electricity quotas (Custodio 2005; Ferreira da Silva & Haie 2007; Spechler 1994; Zekri 2008). Faced with this theory-practice disconnection, can the use of multiple policy instruments be justified in economic terms?

The use of multiple instruments may be optimal in a second-best world (Bennear & Stavins 2007). In the presence of multiple market failures and/or exogenous constraints, the use of multiple policy instruments may be more efficient than the use of a single instrument (Grafton & Silva-Echenique 1997). A crucial constraint of policymakers in the real world is the presence of uncertainty in the response of their target to policy actions and/or exogenous variables. Pertaining to economic systems in general, Brainard (1967) was first to show that optimal policy in the presence of uncertainty differs significantly from optimal policy in a world of certainty. In particular, he shows that all instruments available should be used in pursuing one target.

In the context of climate change and pollution control policy, a number of studies have shown that combining a price and a quantity instrument generally dominates the use of only one of these (Grafton & Devlin 1994; Jacoby & Ellerman 2004; Pizer 2002; Weitzman 1978). However, the implications of uncertain environmental irreversibilities on the selection of multiple policy instruments have not been examined in resource extraction problems.

This chapter examines optimal instrument mixes for groundwater extraction under the uncertain threat of irreversible saltwater intrusion. Its contribution is three-fold. Firstly, I show that under uncertainty, with one target (economic benefits) and two instruments (extraction and depth controls), it will generally be optimal to use some combination of both instruments. Secondly, I test whether irreversible environmental damage leads to a more 'conservationist' policy than would be otherwise (Arrow & Fisher 1974; Henry 1974; Tsur & Zemel 1996). I find that additional instruments complement extraction controls, simultaneously increasing the resilience of the system and the economic returns of users. By expanding the regulatory options of groundwater, I challenge the claim that event uncertainty necessarily induces conservative management. Thirdly, I quantify the relationship between the risk of loss of resilience and the economic benefits from extraction. Thus, the chapter aids policymakers in explicitly accounting for the trade-off between risk and efficiency involved in different instrument combinations implemented in an uncertain world.

This chapter is organised as follows. The next section delineates the hydro-economic model used and characterises hydrological uncertainty in the form of two shocks. Section 4.3 presents a numerical solution to the stochastic dynamic optimisation problem with perturbation methods. Section 4.4 outlines the main results of the simulations and discusses the contribution of the chapter to optimal instrument selection. The final section concludes the chapter.

4.2. The model

The model consists of a fresh groundwater reserve exploited by a fixed quantity N of spatially distributed wells in known, fixed locations. The freshwater reserve is underlain by a denser saline aquifer. The initial depth to the freshwater table is α_i and a_i is the distance from the surface to the initial freshwater-saltwater (FW-SW) interface at i. Denote by s_i the distance from the bottom of a well to the initial, undisturbed FW-SW interface at location i. Thus, $s_i = a_i - d_i$ where d_i is the depth of the well.

I assume user i owns a single well and must first determine the initial distance to the interface (s_i) by choosing the depth of its well (d_i). Note that s_i is bounded by the location of the freshwater and saltwater aquifers: $0 \leq s_i \leq a_i - \alpha_i$. At each t, user $i's$ per-period choice of water extraction is u_{it}.

The state variable y_i represents the hydraulic head at each location and time period. Heads are constrained to be positive, otherwise the aquifer does not yield any more freshwater and extraction is stopped. Thus, y_{it} is bounded by $0 < y_{it} < \bar{y}$, where $\bar{y}$ is the aquifer's capacity limit. The net benefit for user i are defined as benefits minus extraction costs. These are represented by the function:

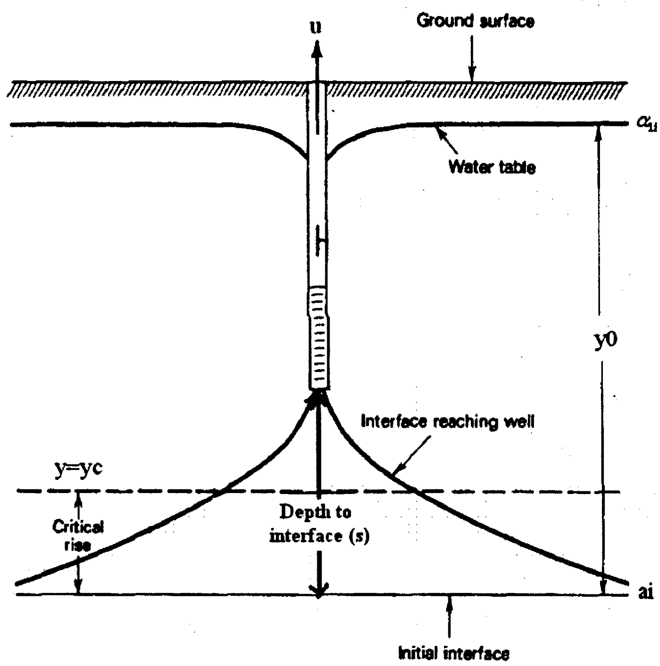
(4.1) $G_i(y_i, u_i, s) = k_0\left(\frac{(a_i - s_i)}{\alpha_i}\right)^{\theta} u_i^{\omega} - k_1 u_i(\bar{y} - y_i)$

where k_0 and k_1 are positive constants and $0 < \omega < 1$ indicates diminishing marginal extraction benefits. I have now excluded the 't' dimension from the equations for simplicity.

I assume $\frac{\partial G_i(.)}{\partial y_i} > 0$ and $\frac{\partial G_i(.)}{\partial u_i} > 0$, so that the per-period net benefit increases with head and extraction levels. I also assume $\frac{\partial G_i(.)}{\partial(a_i - s_i)} > 0$: wells installed at lower depths yield colder water (due to a lower geothermal potential) and are subject to faster quality deterioration due to pollutant leaching through topsoil. $\frac{\partial^2 G_i(.)}{\partial u_i^2} < 0$ and $\frac{\partial^2 G_i(.)}{\partial y_i^2} \leq 0$ so that extraction costs increase at least linearly with head losses and $\frac{\partial^2 G_i(.)}{\partial(a_i - s_i)^2} \leq 0$ so that revenue foregone from shallower wells becomes more important for wells at lower depths.

As Figure 4.1 shows, as the wells screened in the freshwater discharge water, the underlying saltwater migrates vertically upward in the shape of a cone (mirroring a cone of depression from extraction)[16].

Figure 4.1 **Saltwater upconing beneath a pumping well**



Source: Reilly, TE & Goodman, AS 1987, 'Analysis of saltwater upconing beneath a pumping well', *Journal of Hydrology*, vol. 89, no. 3–4, pp. 169–204.

[16] The water table may also rise as a result of saltwater upconing and salinity decrease crop yield and overall crop productivity. This issue is left for future research.

If the extraction rates lead to a stable positioning of the cones, with their apexes some distance below the bottom of the well, the wells discharge only freshwater. Decreases in hydraulic heads produce higher equilibrium cone positions until a critical level is reached. If any well's hydraulic head falls below this critical head level, the stable FW-SW interface is disrupted and discharge from all wells becomes saline irreversibly. This catastrophic event is irreversible in that freshwater cannot be extracted after its occurrence.

The certainty case

I consider first the management of an aquifer under full certainty. The critical head below which saline water intrudes into the freshwater aquifer is known and denoted by y_c. As saltwater migrates upwards in response to head differences between the freshwater and saltwater aquifers, the interface becomes a transition zone where the two fluids mix[17]. I assume this mix ('brackish' water) exceeds the maximum level of salt concentration when the hydraulic head at any location falls below a known critical level. Then, the discharge of all wells becomes saline.

[17] Pumping from the aquifer decreases the hydraulic head in the freshwater aquifer, and the interface advances upwards. As the interface advances, the transition zone widens until a new equilibrium is reached, where the head difference becomes zero. This equilibrium may occur before or after the pumping wells are contaminated.

I focus on the case where the event risk has bearing on the optimal policy, thus $y_i < y_c < y_i^{ne}$ where y_i^{ne} is the unique steady state to which the optimal heads converge when no event interrupts groundwater extraction (Tsur & Zemel 2004). Under certainty, the groundwater head's dynamic constraint is given by the following deterministic differential equation

$$(4.2)\; dy_i = \left(r(y_i) - \sum_{j=1}^{N} w(\varphi_{ij}) u_j \right) dt$$

where $(r(y_i))$ denotes the head-dependent deterministic recharge rate given by

$$(4.3)\; r(y_i) = (\bar{y} - y_i)^{\beta} \quad \text{if} \quad y_i > 0$$

$$r(y_i) = 0 \qquad \text{if} \quad y_i \leq 0$$

with $0 < \beta < 1$[18]. The following assumptions are made: (1) $r(\bar{y}) = 0$ and (2) $r(y_i)$ is decreasing and concave (as the hydraulic head falls, recharge increases at a diminishing rate). Note that negative hydraulic heads are plausible physically as they are measured above an arbitrary datum.

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[18] β is a power smaller than 1 because recharge rate is usually a concave function of hydraulic head or stock.

Extraction by all users is weighted by the 'well function' $w(\varphi_{ij})$ (Theis 1935). Although I allow for spatially heterogeneous responses to extraction, to keep the problem tractable I assume that lagged effects of extraction are negligible[19]. Then, the effect of user $j's$ extraction on user $i's$ head is defined as

$$(4.4)\ w(\varphi_{ij}) = \frac{1}{4\pi T} \int_{\frac{\varphi_{ij}^2 S}{4T}}^{\infty} \frac{e^{-z}}{z} dz$$

where φ_{ij} is the Euclidean distance between wells i and j, S is storativity and T is transmissivity.

The uncertainty case

In reality, there is no critical head level at which the 'brackish' water exceeds the maximum salt concentration. Instead, stochastic environmental conditions, such as subsurface flows, affect the concentration of saltwater in the transition zone. Thus, hydraulic heads affect the hazard of occurrence of the event, but no head level is completely safe. Although saltwater intrusion is ultimately determined by stochastic environmental conditions, these are assumed to be correlated to the distance between

[19] This assumption does not affect the main results of the analysis. If I allow for lagged effects, net benefits and the persistence of the aquifer would decrease, but the ranking of management options (with respect to size of net benefits and the time until saltwater intrudes) would remain unaltered.

the bottom of the wells and the initial interface. Thus, if wells are drilled at a greater distance from the initial interface, the probability of occurrence due to a small head decrease will be lower.

To analyse the importance of uncertainty, I assume the manager forms beliefs over possible values of the head threshold, and acts accordingly. I model uncertainty with two distinct and independent shocks which affect all wells equally. The first is a positive or negative shock representing natural climate variability that exerts influence on recharge and runoff. This is modeled by a Wiener diffusion process (Brownian motion) that follows a normal distribution[20] (W_t). The proportional effect of a random realisation dW of -1 or +1 on hydraulic heads is given by $\sigma_0 y_i = \sqrt{2\sigma_1} y_i = 0.01 y_i$. Thus, this process may increase or decrease heads by 1% of their value.

The second shock represents the crossing of the head threshold with a major negative shock to all wells at some stochastic time in the future. This jump process (q) follows a Poisson distribution with jumps of fixed amplitude dq. The uncertainty of this shock is described in terms of the hazard rate, which measures the conditional density of occurrence due to a small head decrease given that the event has not occurred yet. I

[20] A Brownian motion process has three important properties. First, it is a Markov process, that is, the probability distribution of all future values depends only on its current value. Second, changes over different time intervals are independent. Third, changes are normally distributed, with a variance that increases with the time interval (Dixit & Pindyck 1994).

assume the hazard rate is a separable function of average head and distance to the initial interface defined by

(4.5) $\lambda(avg(y), s) = \gamma(avg(y)).\varphi(s)$

where $\gamma(avg(y)) = \dfrac{f(avg(y))}{F(avg(y))}$. $F(avg(y)) = \Pr(y_c \leq avg(y))$ and $f(avg(y)) = \dfrac{\partial F(avg(y))}{\partial avg(y)}$ are the probability distribution and probability density associated with the critical level y_c. $\gamma(avg(y))$ is an increasing function of $avg(y)$ at a diminishing rate $\dfrac{\partial^2 \gamma}{\partial (avg(y))^2} < 0$. $\varphi(s)$ is a decreasing function of s and $0 < \varphi(s) < 1$. Then, $\lambda(avg(y), s) davg(y) \approx \Pr(y_c \in [avg(y), avg(y) + davg(y)] y_c < avg(y))$ for $davg(y)$ sufficiently small. For simplicity, I assume $\lambda(avg(y), s)$ is autonomous. The specific functional forms of $\gamma(avg(y))$ and $\varphi(s)$ are:

(4.6) $\gamma(avg(y)) = \left(1 - \left(\dfrac{avg(y)}{y_0}\right)^{kc}\right)$

(4.7) $\varphi(s) = \dfrac{\left(e^{avg\left(\frac{a_i - s_i - \alpha_i}{\alpha_i}\right)} - 1\right)}{kb}$

where $kb > 1$ and $kc > 1$ are constants. Note that the hazard rate drops to zero only if heads remain at their initial levels $(y_i = y_0)$, or if wells are drilled at maximum distance to the interface $(s_i = a_i - \alpha_i)$. Then the Poisson process (q) can be defined as $dq = 0$ with probability $(1 - \lambda(avg(y), s))dt$ and $dq = -1$ with probability $\lambda(avg(y), s)dt$. The sensitivity of the hydraulic head at well i to this process is given by $\sigma_2 y_i = -y_i$. Thus, saltwater intrusion is modeled as a jump to zero of all hydraulic heads and, thereby, extraction is stopped. The event is guaranteed to be irreversible by the deterministic dynamics of hydraulic heads: recharge ceases for non-positive heads and extraction from other wells further depresses hydraulic heads to negative values. The event occurrence thus renders the resource obsolete.

Under uncertainty, the groundwater head's dynamic constraint is given by a shock-expanded differential equation

(4.8) $dy_i = h_i + \sigma_0 y_i dW + \sigma_2 y_i dq$.

4.3. Optimal management of the aquifer system

I examine two management schemes. In the first case, a single instrument, in the form of time-varying extraction controls, is used to maximise total economic benefits from water extraction. With no regulation on the distance to the interface, wells are drilled at the minimum distance to the interface $(s_i = 0)$ so that economic returns from a certain extraction level are greatest while the threshold is not crossed[21].

The second management scheme incorporates distance to the initial interface as an additional control instrument. To simplify, I assume the distance limit implemented is the same for every well. Optimal extraction functions are determined for feasible distances to the interface. Later, the optimal distance to the interface is found by selecting the depth that generates the highest economic value from extraction. Note that, in reality, the freshwater and/or saltwater aquifers are usually located at different depths across space. Thus, the optimal distance will result in spatially differentiated optimal well depths.

Following Gaspar and Judd (1997), I adapt the Einstein tensor notation to the problem to deal with notational problems of multidimensional expressions. The state variables at multiple wells are represented by components of a vector y, the multiple extraction rates are represented by components of u and the aggregate net benefits of multiple users are represented by $G(y,u)$. Superscripts will refer to different components of a vector-valued function, whereas subscripts will refer to derivatives of those component functions.

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[21] Following previous economic studies on saltwater intrusion, I assume perfect myopia of private users concerning the imminent irreversible event occurrence (Koundouri & Christou 2006).

Optimal management under certainty

Let T denote the event's occurrence time. The optimal plan may be derived from

$$(4.9)\ V(y) = \max_{u,T}\left\{\int_0^T e^{-\rho t} G(y,u)dt\right\}$$

subject to $dy^i = h^i(y,u)$ ($h^i(y,u)$ is a column vector denoting the deterministic law of motion of the state variables), $u^\alpha \geq 0$, $y_T^i = y_c$ for at least one i and $y_0 > y_c$ given.

If extraction levels are such that heads fall to y_c, it is preferable to freeze extraction at those levels rather than to increase extraction at any well, trigger the event in all wells, and lose all future benefits. Thus, the event should be avoided and problem (4.9) becomes

$$(4.10)\ V(y) = \max_{u}\left\{\int_0^\infty e^{-\rho t} G(y,u)dt\right\}$$

subject to equation $dy^i = h^i(y,u)$, $u^\alpha \geq 0$, and $y^i \geq y_c$. The Bellman equation for the value function is

$$(4.11)\ 0 = \max_{u} G(y,u) + V_i(y)h^i(y,u) - \rho V(y)$$

subject to $y^i \geq y_c$.

To solve the constrained dynamic programming problem in (4.11), I construct the Lagrangian

$$(4.12)\ L = G(y,u) + V_i\ h^i - \rho V\ \ + \mu(y_c - y)$$

where μ is a vector of Lagrange multipliers for the constraint on heads. The first order condition with respect to u^α, $\alpha = 1,\ldots,N$ is

$$(4.13)\ \ 0 = G_\alpha(y,u) + V_i\ h^i_\alpha$$

Equations (4.13) define the optimal control $u = U(y)$ and the Bellman equation becomes

$$(4.14)\ 0 = \max_u G(y,U(y)) + V_i\ (y)h^i(y,U(y)) - \rho V(y)$$

subject to $y^i \geq y_c$. The Lagrangian in (4.12) becomes

$$(4.15)\ L = G(y,U(y)) + V_i\ (y)h^i(y,U(y)) - \rho V(y) + \mu(y_c - y)$$

and the first order condition with respect to y^j is (using the envelope theorem)

(4.16) $\rho V_j = G_j + V_{ij} h^i + V_i h^i_j + \mu^j$.

Since the system of equations given by (4.13) and (4.16) cannot be solved analytically, I employ a perturbation solution to solve it[22].

Optimal management under uncertainty

The dynamic optimisation problem for determining the optimal time-varying extraction rates under uncertainty is

(4.17) $V(y) = \max_u \left\{ \int_0^\infty e^{-\rho t} G(y,u) dt \right\}$

subject to (4.8) and $u^\alpha \geq 0$.

Using Ito's lemma, the Hamilton-Jacobi-Bellman equation of optimality can be used to solve (4.17) for the optimal extraction paths

(4.18) $\rho V(y) = \max_u G(y,u) + V_i(y) h^i(y,u) + V_{ij}(y) \sigma_1^2 y^i y^j + \lambda(y,d)[V(0) - V(y)]$

[22] Refer to the appendix for further details on the numerical approximation used.

For the uncertainty case, I introduce two auxiliary variables defined as ε and η for the Wiener and Poisson processes respectively. Problem (4.17) can now be expressed as

(4.19) $\max\limits_{u} E\left\{\int_0^\infty e^{-\rho t} G(y,u)dt\right\}$

subject to $dy^i = h^i(y,u)dt + \sqrt{2\sigma_1\varepsilon}\, y^i dW + \sigma_2 \eta y^i dq$.

The Bellman equation to (4.19) is

(4.20) $0 = \max\limits_{u} G(y,u) + V_i\, h^i + \sigma_1 \varepsilon V_{ij} + \lambda\left(V\,(y) - V\,(y(1-\eta))\right) - \rho V$

and the first order condition with respect to u^α, $\alpha = 1,\ldots,N$ is

(4.21) $0 = G_\alpha(y,u) + V_i\,(y,\varepsilon,\eta) h^i_\alpha(y,u)$

Equation (4.21) implicitly defines the optimal control $u = U(y,\varepsilon,\eta)$, so we have the system

(4.22) $0 = G_\alpha(y, U(y,\varepsilon,\eta)) + V_i\,(y,\varepsilon,\eta) h^i_\alpha(y, U(y,\varepsilon,\eta))$

(4.23) $0 = G(y, U(y,\varepsilon,\eta)) + V_i\,(y,\varepsilon,\eta) h^i(y, U(y,\varepsilon,\eta)) + \sigma_1 \varepsilon V_{ij}\,(y,\varepsilon,\eta)$

$+ \lambda(V(y,\varepsilon,\eta) - V(y(1-\eta),\varepsilon,\eta)) - \rho V(y,\varepsilon,\eta)$

This system is again solved using a perturbation method.

4.4 Numerical simulation

The hydrological parameters of the model are based on a real-world aquifer.[23] I set $\bar{y}=100$, $y_c=40$, $y_0=70$ and $\beta=0.5$. I assume each well is located at the same depth throughout the area, that is $\alpha_i=1000\ \forall i$ and $a_i=2000\ \forall i$. The number of wells and well functions are the same as Chapter 2. For the hazard rate I specify $kb=10$ and $kc=4$. Thus, the probability of a negative shock equals 0.025 when $avg(y)=40$ for the deepest possible well $(2000m)$ and equals 0 for the shallowest possible well $(1000m)$.

For the net benefits function I specify $\omega=0.8$, $\theta=0.025$, $k_0=70{,}000$ and $k_1=7{,}000$. I set the discount rate at 5% ($\rho=0.05$).

[23] This aquifer is the Concordia-Salto section of the Guarani Aquifer System. For more details see Charlesworth et al. (2008).

Certainty: a single instrument is optimal

I first examine optimal groundwater extraction for the case when the critical head level for maximum saltwater concentration is known. Here, the intrusion of saltwater depends only on the relative potential of freshwater, given by hydraulic heads.

As shown in Figure 4.2 and Table 4.1, the value function increases as the distance between the wells' screens and the initial interface decreases, that is, wells are drilled at greater depths. With no uncertainty on the critical head level and with optimal extraction, setting a limit on the distance from the wells to the initial interface generates no economic benefits. Thus, the use of a single regulatory instrument is optimal in a certainty scenario where the occurrence of an irreversible event depends entirely on the extraction paths chosen.

This result supports the actions of many users who drill their wells as deep as possible to avoid surface pollution infiltration and ensure water quality. It is also consistent with most economic studies on saltwater intrusion which ignore the distance between pumping and the interface as a necessary regulatory target if extraction controls are set optimally.

Figure 4.2 **The value function for different distances to FW-SW interface**

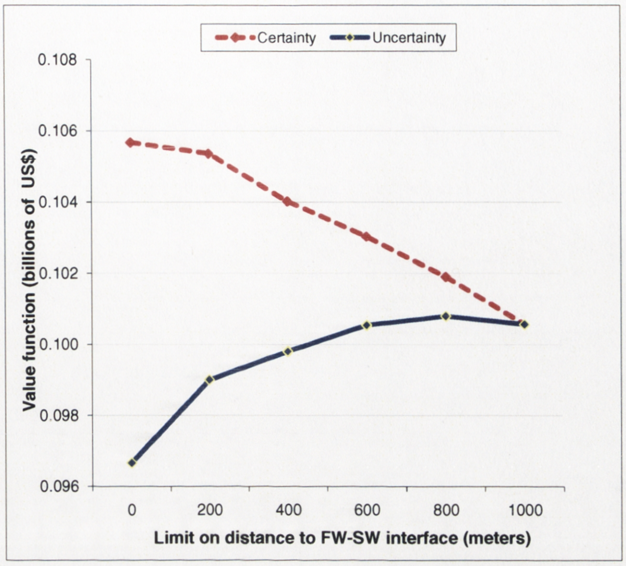


Table 4.1 **The value function for different distances to FW-SW interface (billions of US$).**

Distance limit (m)	**0**	**200**	**400**	**600**	**800**	**1000**
Certainty	**0.1057**	0.1054	0.1040	0.1030	0.1019	0.1006
Uncertainty	0.0967	0.0990	0.0998	0.1005	**0.1008**	0.1006
Note: The cells in bold represent the highest payoffs for each scenario.						

Figures 4.3 and 4.4 show that with a constant environment and optimal extraction, hydraulic heads drop until the threshold is reached. At that time, optimal extraction

drops in every well so that drawdown equals recharge and heads are maintained at the threshold level.

Figure 4.3 **Optimal head levels under certainty**

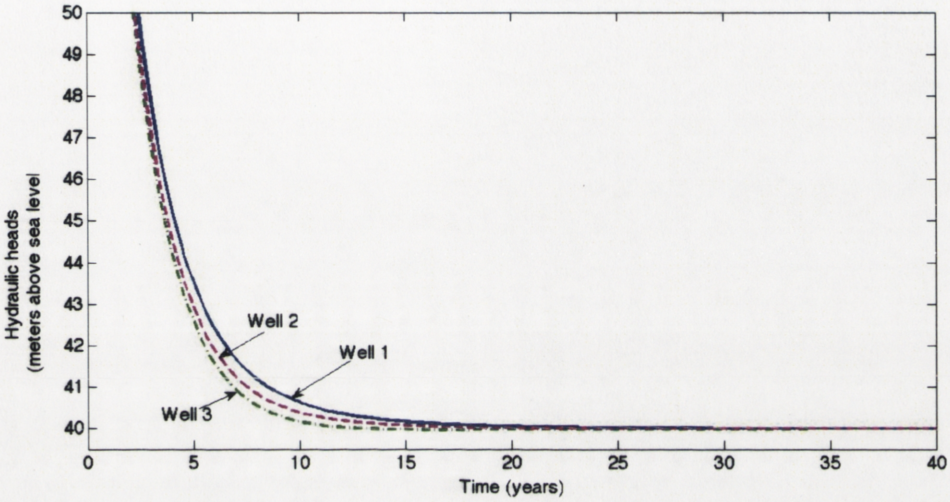
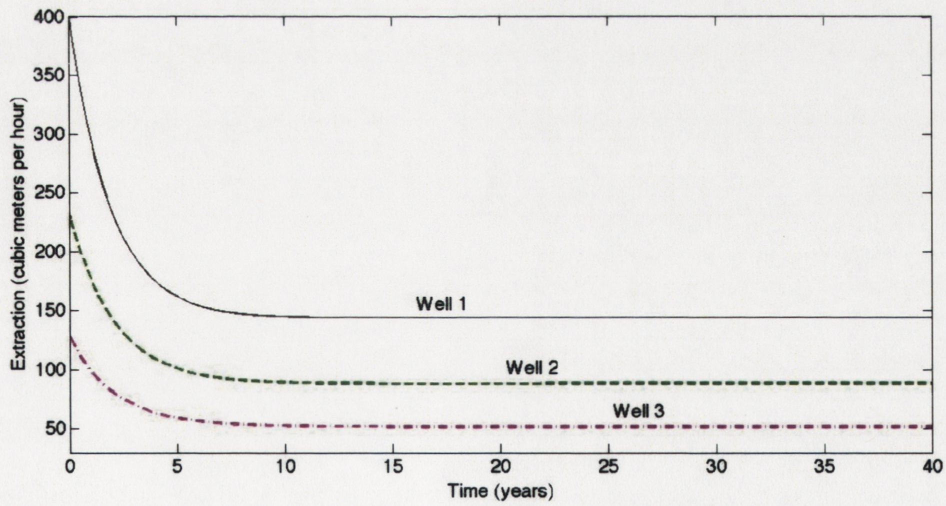


Figure 4.4 **Optimal extraction paths under certainty**



Uncertainty: multiple instruments are optimal

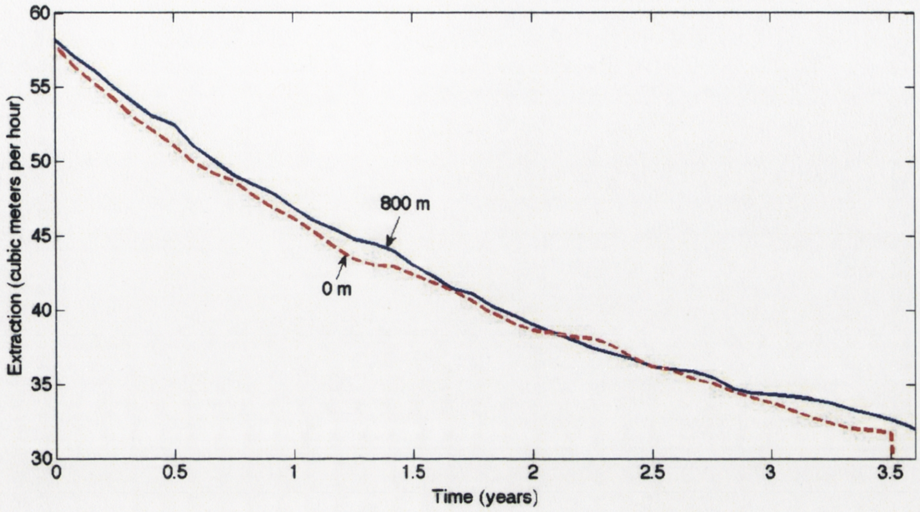
In the presence of stochastic environmental conditions, the difference between the value function under certainty and uncertainty decreases at greater distances to the interface, as deeper wells are more vulnerable to saltwater intrusion. Figure 4.2 shows that a lower proximity of pumping to the interface is economically beneficial. The value function increases with the distance limit until it reaches a maximum at 800 metres.

Even if extraction rates are optimally chosen under formed probabilities of threshold location and environmental variability, economic benefits increase when a second regulatory instrument is used simultaneously with extraction control. Thus, in an uncertain scenario, a management scheme with multiple instruments generates a higher economic payoff than using a single instrument.

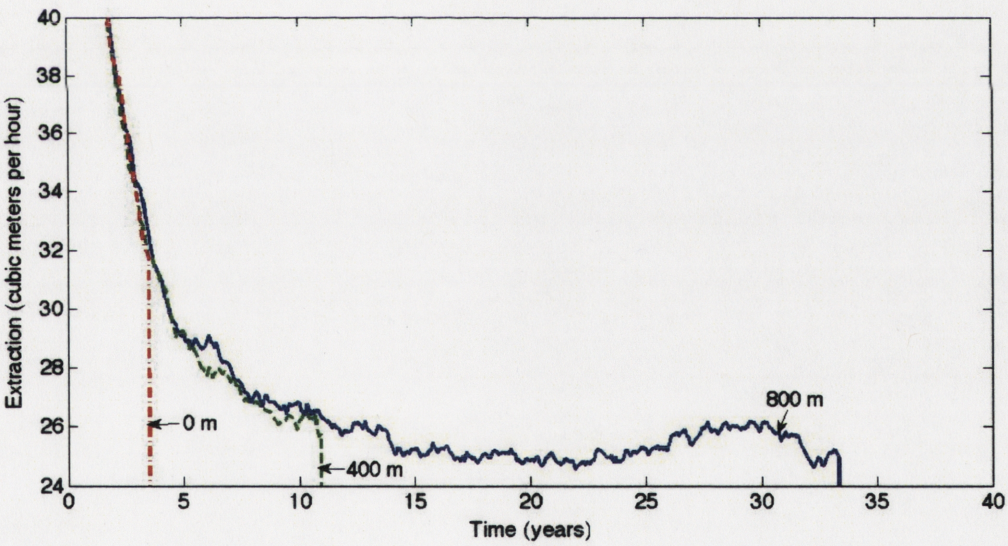
A 'resilience effect' explains the benefits of greater distances with environmental uncertainty. I define this effect as the time the hydrological system persists until it crosses an undesirable threshold given by irreversible saltwater intrusion. This resembles the definition used by Hertzler and Harris (2010) of 'economic resilience', which combines how fast the system is moving towards the threshold with how far the system is from a threshold.

Contrary to conventional wisdom on irreversible environmental damage, the use of a more 'conservationist' single instrument actually increases the risk of a catastrophic shift with respect to the use of multiple instruments. Figure 4.5 graphs the optimal extraction paths for one of the wells under three alternative management options: (1) only extraction control; (2) extraction control and a distance limit of 400m; (3) extraction control and a distance limit of 800m. As panel (A) shows, the 'only extraction control' alternative results in lower optimal extraction paths before saltwater intrudes (extraction is on average 2 per cent lower than alternative (3) during that period). Even though using a single instrument represents the most 'conservative' approach, Panel (B) shows that saltwater intrudes into the aquifer at an earlier time. This is because under a single-instrument scheme the aquifer is less resilient to uncertain shocks, persisting for a shorter period of time.

Figure 4.5 **Optimal extraction paths for well 1 at different distances to the interface.**



(A)



(B)

Although these resilience benefits (later saltwater intrusion time) increase with the limit on distance to the interface, the costs of a greater distance are reduced benefits from water of a lower quality from shallow wells. Table 4.2 shows that adding a distance limit of 200 metres to optimal extraction control increases the value function by 2 per cent, while the probability of saltwater intrusion falls by 5 per cent. Using multiple instruments delivers greater economic and 'resilience benefits' as the distance limit is tightened to 800 metres. At this point, the marginal benefit from a greater distance will equal the marginal cost from benefits foregone from higher water quality at deeper wells. The increase in economic benefits from using multiple instruments is maximised at 4.27 per cent (US$4.12 million) and the probability of saltwater intrusion is 74 per cent lower.

Table 4.2 **Resilience and economic efficiency under a multiple instrument policy**

Distance limit (m)	**0**	**200**	**400**	**600**	**800**	**1000**
Value function (billion US$)	0.0967	0.0990	0.0998	0.1005	0.1008	0.1006
Average probability of saltwater intrusion	0.9111	0.8637	0.7279	0.6981	0.1690	0
Aquifer's persistence (years)	3.5	5.5	11	12	33.5	40+

This 'win-win' situation does not hold for distances above the optimum. There are no economic benefits of increasing the distance limit over 800 metres. The additional expected gains from a longer persistence of the aquifer ('resilience benefits') are lower than the costs of extracting water of lower quality.

What are the direct policy implications of using multiple instruments under uncertainty? These results provide key insights for resource management in practice by quantifying the trade-off involved in the choice of a certain instrument mix. Figure 4.6 illustrates this trade-off by graphing the percentage increase in the value function and decrease in the probability of saltwater intrusion (average during the period) from using two instruments (optimal extraction control and distance limit) instead of one (optimal extraction control).

Figure 4.6 **Trade-off between efficiency and risk of multiple instruments**

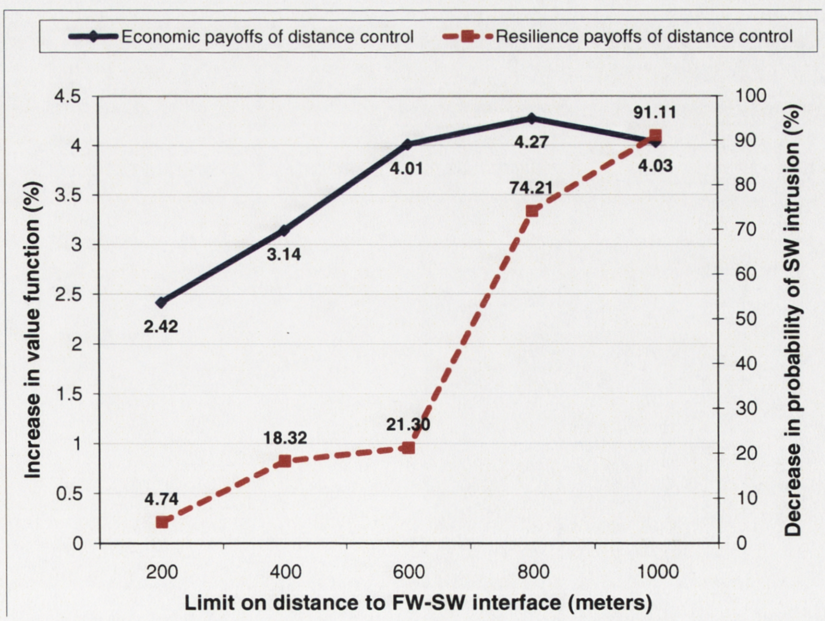


Figure 4.6 provides a powerful tool to policymakers by presenting the trade-off between economic efficiency and resilience of different instrument choices. For instance, relaxing the distance limit from 800 to 600 metres reduces benefits slightly (0.26 per cent), but the risk of saltwater intrusion is more than doubled. This information is crucially valuable for the design of environmental policies in second-best settings.

Sensitivity analysis

The sensitivity of saltwater intrusion risk to freshwater stock depletion (kc) affects optimal policy design. Table 4.3 shows that the higher the dependence of saltwater risk on head losses, the greater the optimal distance limit to the interface. The use of a single instrument becomes optimal if the hazard rate increases very slowly with stock declines. The reason is that the value of the distance limit to act as a buffer against stochastic fluctuations in the resource stock is less significant if the catastrophic risk is practically unrelated to the stock.

Table 4.3 **The value function (billion of US$) for different head-dependent catastrophic risks.**

	Distance limit (m)					
kc	**0**	**200**	**400**	**600**	**800**	**1000**
3	0.0945	0.0975	0.0988	0.1000	0.1005	**0.1006**
3.25 (Base)	0.0967	0.0990	0.0998	0.1005	**0.1008**	0.1006
3.75	0.0998	0.1012	0.1013	**0.1014**	0.1012	0.1006
4	0.1009	**0.1020**	0.1018	0.1017	0.1013	0.1006
5	0.1036	**0.1039**	0.1031	0.1025	0.1016	0.1006
6	**0.1048**	0.1047	0.1036	0.1028	0.1018	0.1006

Notes: (1) kc is the sensitivity of saltwater intrusion risk to freshwater stock depletion. (2) The cells in bold represent the highest payoffs for a given head-dependent risk.

The resilience of the freshwater aquifer is also partly determined by the recharge rate (β). The higher the recharge rate, the quicker the aquifer recovers from external shocks and the lower the optimal distance limit. Table 4.4 shows that for considerably high recharge rates, a single instrument becomes optimal.

Table 4.4 **The value function (billion of US$) for different recharge rates.**

	Distance limit (m)					
β	**0**	**200**	**400**	**600**	**800**	**1000**
0.3	0.0654	0.0693	0.0723	0.0746	0.0763	**0.0773**
0.4	0.0801	0.0878	0.0851	0.0870	0.0876	**0.0881**
0.5 (Base)	0.0967	0.0990	0.0998	0.1005	**0.1008**	0.1006
0.6	0.1135	0.1144	**0.1148**	0.1147	0.1141	0.1131
0.7	**0.1276**	0.1274	0.1268	0.1258	0.1244	0.1225

Notes: (1) β is the recharge rate. (2) The cells in bold represent the highest payoffs for a given recharge rate.

Finally, Table 4.5 shows that an increase in the discount rate (ρ) reduces the optimal depth limit. The smaller the value of future returns, the smaller the buffer value of depth control. However, a depth limit is still optimal at a discount rate of 97.5 per cent $(\rho = 0.975)$. Thus, as long as the aquifer has any future value, multiple instruments dominate a single instrument policy.

Table 4.5 **The value function (billion of US$) for different discount rates.**

	Distance limit (m)					
ρ	**0**	**200**	**400**	**600**	**800**	**1000**
0.01	0.43830	0.44813	0.45490	0.45917	**0.46107**	0.46068
0.05 (Base)	0.09666	0.09900	0.09980	0.10054	**0.10079**	0.10056
0.1	0.05396	0.05491	0.05541	0.05572	**0.05576**	0.05555
0.2	0.03262	0.03307	0.03323	**0.03331**	0.03325	0.03305
0.5	0.01983	**0.01998**	0.01993	0.01988	0.01976	0.01957
0.975	0.01569	**0.01574**	0.01562	0.01553	0.01539	0.01520

Notes: (1) ρ is the discount rate. (2) The cells in bold represent the highest payoffs for a given discount rate.

4.5 Conclusions

Real-world policymakers are usually uncertain about the response of their target to any given policy action. In particular, environmental problems typically involve uncertainties that are crucial to policy design and evaluation. This chapter explores how uncertain environmental irreversibilities can affect the optimal choice of policy when multiple instruments are available.

This chapter examines optimal instrument mixes for groundwater extraction under the uncertain threat of irreversible saltwater intrusion. The results suggest that, under uncertainty, the use of multiple policy instruments can be more efficient than the use of a single instrument. A 'resilience effect' explains the benefits of a second instrument with environmental uncertainty. The distance limit acts as a buffer against the volatility of stochastic fluctuations, thus allowing for higher extraction rates and increasing economic returns.

Evidence is provided against the common view that the presence of environmental irreversibilities under uncertainty makes optimal resource extraction policies more 'conservative'. The results suggest that this is not the case when multiple instruments are available. Although the use of a single instrument leads to more conservative extraction paths, the risk of crossing the threshold is actually higher than when multiple instruments are used because the stochastic evolution of the resource stock is not only determined by extraction rates, but also by the distance to the freshwater-saltwater interface.

The findings of this chapter have direct policy implications for the design and evaluation of optimal instrument mixes in an uncertain world. Although policymakers frequently use multiple instruments to address environmental and resource problems, there is little research that evaluates the efficiency of the actual mix of instruments employed in practice. The modeling results provide key information to understand and quantify the trade-offs between economic efficiency and ecological resilience involved in different policy choices. For instance, while there may be no significant difference between the economic efficiency of two instrument mixes, the risk of a catastrophic event may differ substantially.

Further research is needed on the nature and extent of severe or catastrophic outcomes and their implications for optimal policy design under uncertainty. Finally, uncertainty can also affect the optimal timing of implementation of different instruments. While a number of studies addresses this issue in the context of climate change, more work is needed on resource extraction problems.

Appendix: Asymptotic approximation of the solution

Certainty

Perturbation procedures have shown a superior mix of accuracy, speed and programming burden relative to traditional linear approaches, value function iteration and recent alternative procedures such as projection or discretisation methods (Aruoba et al. 2006). I use a perturbation method that builds a Taylor series expansion of the extraction and value functions as deviations from the steady state (Judd & Guu 1997).

I express the extraction and value functions as $U^{\alpha}(y)$ and $V^{c}(y)$ as the expansions

$$(4.24)\ V^{c}(y)=V^{c}(y^{SS})+V_{i}^{c}(y^{SS})(y-y^{SS})^{i}+\frac{1}{2}V_{ij}^{c}(y-y^{SS})^{i}(y-y^{SS})^{j}$$
$$+\frac{1}{3!}V_{ijl}^{c}(y-y^{SS})^{i}(y-y^{SS})^{j}(y-y^{SS})^{l}+\ldots$$

$$(4.25)\ U^{\alpha,c}(y)=U^{\alpha,c}(y^{SS})+U_{i}^{\alpha,c}(y^{SS})(y-y^{SS})^{i}+\frac{1}{2}U_{ij}^{\alpha,c}(y-y^{SS})^{i}(y-y^{SS})^{j}$$
$$+\frac{1}{3!}U_{ijl}^{\alpha,c}(y-y^{SS})^{i}(y-y^{SS})^{j}(y-y^{SS})^{l}+\ldots$$

Since problem (4.9) is autonomous, optimal heads evolve monotonically over time (Tsur & Zemel 2004). These paths are also bounded by the threshold, so they must approach a steady state. With $y_c > y_i^{ne}$, no internal steady state in the range $\left[y_c, \overline{y}\right]$ can be optimal. Thus, when the critical level corresponding to an irreversible event is known and lies above y_i^{ne}, the optimal head levels converge to a steady state at y_c.

The steady state values for y, u and V_i are determined by conditions (4.13), (4.16) and

(4.26) $0 = h^i(y,u)$

(4.27) $y^i = y_c$

which also yield $V^c\left(y^{SS}\right)$ and $U^c\left(y^{SS}\right)$. To determine the rest of the coefficients in (4.24) and (4.25), I just compute high-order derivatives of the system (4.13)-(4.16) and (4.26)-(4.27) with respect to the y^i's. I assume that the benefits and law of motion functions are C^∞ so that these derivatives exist. Continued differentiation will show that computing higher-order terms is easy because it reduces to linear systems.

I start by differentiating (4.13) with respect to y^j to find

(4.28) $0 = G_{\alpha j} + G_{\alpha j} U_j^\gamma + V_{ij} h_\alpha^i + V_i \left(h_{\alpha j}^i + h_{\alpha\gamma}^i U_j^\gamma\right)$

I differentiate (4.16) with respect to y^l and re-write (4.28) by expressing it in terms of the derivatives of V:

(4.29) $\rho V_{jl} = G_{jl} + G_{j\gamma}U_l^{\gamma} + V_{ijl}h^i + V_{ij}\left(h_l^i + h_\gamma^i U_l^{\gamma}\right) + V_{il}h_j^i + V_i\left(h_{jl}^i + h_{j\gamma}^i U_l^{\gamma}\right)$

(4.30) $U_j^{\gamma} = -\left(G_{\alpha\gamma} + V_i h_{\alpha\gamma}^i\right)^{-1}\left(G_{\alpha j} + V_{ij}h_\alpha^i + V_i h_{\alpha j}^i\right)$

Substituting (4.30) into (4.29) and imposing the deterministic steady state conditions $h^i = 0$, gives us the following system of equations

(4.31)

$$\rho V_{jl} = G_{jl} + V_{ijl}h_l^i + V_{ij}h_l^i + V_{il}h_j^i + V_i h_{jl}^i - \left(G_{j\gamma} + V_{ij}h_\gamma^i + V_i h_{j\gamma}^i\right)\left(G_{\alpha\gamma} + V_i h_{\alpha\gamma}^i\right)^{-1}\left(G_{\alpha l} + V_{il}h_\alpha^i + V_i h_{\alpha l}^i\right)$$

Solving (4.31) gives the steady state values of V_{jl} and through (4.30), the steady state values of U_l^{γ}. To compute higher-order terms I differentiate (4.28) and (4.29) with respect to y^m. Imposing again the steady state condition $h^i = 0$, yields the following equations for the steady state values of V_{ilm} and U_{lm}^{β}

(4.32)

$$0 = \left(G_{\alpha\beta} + V_i h_{\alpha\beta}^i\right)U_{lm}^{\beta} + \left(G_{\alpha\beta\gamma}U_m^{\gamma} + G_{\alpha\beta m} + V_{im}h_{\alpha\beta}^i + V_i h_{\alpha\beta m}^i + V_i h_{\alpha\beta\gamma}^i U_m^{\gamma}\right)U_l^{\beta} + G_{\alpha l m} + G_{\alpha l\gamma}U_m^{\gamma}$$
$$+ V_{ilm}h_\alpha^i + V_{il}\left(h_{\alpha m}^i + h_{\alpha\gamma}^i U_m^{\gamma}\right) + V_{im}h_{\alpha l}^i + V_i\left(h_{\alpha l m}^i + h_{\alpha l\gamma}^i U_m^{\gamma}\right)$$

(4.33)

$$\rho V_{jlm} = G_{jlm} + G_{jl\gamma}U_m^\gamma + G_{j\gamma m}U_l^\gamma + G_{j\gamma\delta}U_m^\delta U_l^\gamma + G_{j\gamma}U_{lm}^\gamma + V_{ijl}\left(h_m^i + f_\gamma^i U_m^\gamma\right) + V_{ijm}\left(h_l^i + h_\gamma^i U_l^\gamma\right)$$

$$+V_{ij}\left(h_{lm}^i + h_{l\gamma}^i U_m^\gamma + h_{\gamma m}^i U_l^\gamma + h_{\gamma\delta}^i U_l^\gamma U_m^\delta + h_\gamma^i U_{lm}^\gamma\right) + V_{ilm}h_j^i + V_{il}\left(h_{j\gamma}^i U_m^\gamma + h_{jm}^i\right) + V_{im}\left(h_{jl}^i + h_{j\gamma}^i U_l^\gamma\right)$$

$$+V_i\left(h_{jlm}^i + h_{jl\gamma}^i U_m^\gamma + h_{j\gamma m}^i U_l^\gamma + h_{j\gamma\delta}^i U_l^\gamma U_m^\delta + h_{j\gamma}^i U_{lm}^\gamma\right)$$

The steady state values of V_{ilm} and U_{lm}^β are easy to compute because they appear *linearly* in (4.32)-(4.33) and they are the only unknowns.

Uncertainty

I express the extraction and value functions as $U^\alpha(y,\varepsilon,\eta)$ and $V^u(y,\varepsilon,\eta)$. The expansions are

$$(4.34)\quad V^u(y,\varepsilon,\eta) = V(y^{SS},0,0) + V_i^u(y^{SS},0,0)(y-y^{SS})^i + V_\varepsilon^u(y^{SS},0,0)\varepsilon + V_\eta^u(y^{SS},0,0)\eta$$

$$+V_{i\varepsilon}^u(y^{SS},0,0)(y-y^{SS})^i\varepsilon + V_{i\eta}^u(y^{SS},0,0)(y-y^{SS})^i\eta + \frac{1}{2}V_{ij}^u(y^{SS},0,0)(y-y^{SS})^i(y-y^{SS})^j$$

$$+\frac{1}{2}V_{\varepsilon\varepsilon}^u(y^{SS},0,0)\varepsilon^2 + \frac{1}{2}V_{\eta\eta}^u(y^{SS},0,0)\eta^2 + \ldots$$

(4.35)

$$U^{\alpha,u}(y,\varepsilon,\eta)=U^{\alpha,u}(y^{SS},0,0)+U_i^{\alpha,u}(y^{SS},0,0)(y-y^{SS})^i+U_\varepsilon^{\alpha,u}(y^{SS},0,0)\varepsilon+U_\eta^{\alpha,u}(y^{SS},0,0)\eta$$
$$+U_{i\varepsilon}^{\alpha,u}(y^{SS},0,0)(y-y^{SS})^i\varepsilon+U_{i\eta}^{\alpha,u}(y^{SS},0,0)(y-y^{SS})^i\eta+\frac{1}{2}U_{ij}^{\alpha,u}(y^{SS},0,0)(y-y^{SS})^i(y-y^{SS})^j$$
$$+\frac{1}{2}U_{\varepsilon\varepsilon}^{\alpha,u}(y^{SS},0,0)\varepsilon^2+\frac{1}{2}U_{\eta\eta}^{\alpha,u}(y^{SS},0,0)\eta^2+\ldots$$

The steady state values for y, u and V_i were determined in the certainty case, as well as all the derivatives $\frac{\partial^i U}{\partial y^i}$ and $\frac{\partial^i V}{\partial y^i}$ $\forall i$. To determine the rest of the coefficients in (4.34) and (4.35) containing the auxiliary variables ($V_\varepsilon, V_\eta, V_{i\varepsilon}, V_{i\eta}, V_{\varepsilon\varepsilon}, V_{\eta\eta}, U_\varepsilon^\alpha, U_\eta^\alpha, U_{i\varepsilon}^\alpha, U_{i\eta}^\alpha, U_{\varepsilon\varepsilon}^\alpha$ and $U_{\eta\eta}^\alpha$), I again compute high-order derivatives with respect to ε and η.

Differentiating (4.23) with respect to ε and η and applying the maximum condition (4.22) yields

(4.36) $0=V_{i\varepsilon}h^i+\sigma_1(V_{ii}+\varepsilon V_{ii\varepsilon}^u)+\lambda(V_\varepsilon-V_\varepsilon)-\rho V_\varepsilon$

(4.37) $0=V_{i\eta}h^i+\sigma_1\varepsilon V_{ii\eta}+\lambda(V_\eta-V_\eta+V_i y^i)-\rho V_\eta$

At the steady state ($h^i=0$, $\varepsilon=0$ and $\eta=0$), (4.36) and (4.37) reduce to

(4.38) $0=\sigma_1 V_{ii}-\rho V_\varepsilon$

(4.39) $0 = +\lambda V_i y^i - \rho V_\eta$

which give us V_ε and V_η. Differentiating (4.36) and (4.37) with respect to y^j and evaluating at the steady state implies

(4.40) $0 = V_{i\varepsilon} h^i_j + V_{i\varepsilon} h^i_\alpha U^\alpha_j + \left(\sigma_1 V_{iij}\right) - \rho V_{j\varepsilon}$

(4.41) $0 = V_{i\eta} h^i_j + V_{i\eta} h^i_\alpha U^\alpha_j + \lambda V_{i\eta} y^i - \rho V_{j\eta}$

which yields the $V^u_{i\varepsilon}$ and $V^u_{i\eta}$ unknowns. Continued differentiation to compute higher-order expansion terms results in linear systems.

The burden of the perturbation method presented is taking all the required derivatives. The problem was coded in *Mathematica* which can easily handle higher derivatives of abstract functions (Judd and Guu 1997).

Table A.4.1: Estimation of coefficients in Taylor expansions

Estimated coefficients	Well depth (meters)					
	1000	1200	1400	1600	1800	2000
$V(y^{SS},0,0)$	90030600	91177100	92150500	92996800	94148400	94417300
$V_1(y^{SS},0,0)$	57459.8	57997.2	58453.5	58850.3	59390.1	59516.2
$V_2(y^{SS},0,0)$	-19319.4	-18441.8	-17696.7	-17048.9	-16167.4	-15961.6
$V_3(y^{SS},0,0)$	57672.2	58326.1	58881.3	59363.9	60020.7	60174.1
$V_4(y^{SS},0,0)$	180896	181798	182564	183230	184136	184348
$V_5(y^{SS},0,0)$	55338.9	56158.5	56854.3	57459.3	58282.5	58474.7
$V_6(y^{SS},0,0)$	37670.6	38739.7	39647.4	40436.6	41510.4	41761.2
$V_7(y^{SS},0,0)$	-15551.6	-14047.5	-12770.5	-11660.3	-10149.5	-9796.74
$V_{11}(y^{SS},0,0)$	-70.3565411	-71.1396849	-71.8065245	-72.3877703	-72.9030386	-73.3661688
$V_{12}(y^{SS},0,0)$	-0.12525004	-0.12698392	-0.12843221	-0.12967420	-0.13075973	-0.13172285
$V_{13}(y^{SS},0,0)$	29.5849175	29.70743355	29.81134588	29.90160016	29.98135429	30.05290716
$V_{14}(y^{SS},0,0)$	-16.8093756	-16.7823589	-16.7590354	-16.7384659	-16.7200064	-16.7033361
$V_{15}(y^{SS},0,0)$	3.08781276	3.113269574	3.134899801	3.153719411	3.170373732	3.185324663
$V_{16}(y^{SS},0,0)$	3.615550885	3.641816847	3.664140841	3.683569258	3.700764645	3.716206985
$V_{17}(y^{SS},0,0)$	6.061546355	6.106030594	6.143834087	6.176730827	6.205845167	6.231986903

$V_{21}(y^{ss},0,0)$	-0.12525004	-0.12698392	-0.12843221	-0.12967420	-0.13075973	-0.13172285
$V_{22}(y^{ss},0,0)$	6.735205265	5.991338617	5.356021551	4.800881701	4.307514058	3.863281131
$V_{23}(y^{ss},0,0)$	27.81905684	27.9792202	28.11534445	28.23376945	28.33862095	28.43278353
$V_{24}(y^{ss},0,0)$	-6.95807857	-6.84167402	-6.74245806	-6.65591961	-6.57911201	-6.51007252
$V_{25}(y^{ss},0,0)$	-39.0907246	-39.5997455	-40.0464186	-40.4187840	-40.7333910	-41.0415709
$V_{26}(y^{ss},0,0)$	0.6522866	0.697306254	0.735704415	0.769219052	0.798966749	0.825737108
$V_{27}(y^{ss},0,0)$	-1.91723774	-1.87105597	-1.83158285	-1.79706915	-1.76637849	-1.73872906
$V_{31}(y^{ss},0,0)$	29.5849175	29.70743355	29.81134588	29.90160016	29.98135429	30.05290716
$V_{32}(y^{ss},0,0)$	27.81905684	27.9792202	28.11534445	28.23376945	28.33862095	28.43278353
$V_{33}(y^{ss},0,0)$	-237.415110	-238.640013	-239.680436	-240.585121	-241.385574	-242.104347
$V_{34}(y^{ss},0,0)$	234.4922067	235.2399585	235.8725512	236.4207404	236.9039446	237.3371642
$V_{35}(y^{ss},0,0)$	-11.6823797	-11.6959520	-11.7072663	-11.7169457	-11.7253552	-11.7328529
$V_{36}(y^{ss},0,0)$	-57.9667441	-58.5574552	-59.0458258	-59.4873942	-59.8935531	-60.2325293
$V_{37}(y^{ss},0,0)$	-25.4103795	-25.4557167	-25.4938016	-25.5266037	-25.5553279	-25.5810024
$V_{41}(y^{ss},0,0)$	-16.8093756	-16.7823589	-16.7590354	-16.7384659	-16.7200064	-16.7033361
$V_{42}(y^{ss},0,0)$	-6.95807857	-6.84167402	-6.74245806	-6.65591961	-6.57911201	-6.51007252
$V_{43}(y^{ss},0,0)$	234.4922067	235.2399585	235.8725512	236.4207404	236.9039446	237.3371642
$V_{44}(y^{ss},0,0)$	-489.233191	-491.979223	-494.311240	-496.338841	-498.132105	-499.742584

$V_{45}(y^{SS},0,0)$	23.95008213	24.06745643	24.16701159	24.25348074	24.32987901	24.39844403
$V_{46}(y^{SS},0,0)$	31.43575958	31.58651811	31.71437715	31.82541846	31.92351641	32.01155551
$V_{47}(y^{SS},0,0)$	46.21288228	46.4249246	46.604701	46.76078613	46.89864109	47.02233944
$V_{51}(y^{SS},0,0)$	3.08781276	3.113269574	3.134899801	3.15371941	3.170373731	3.185324663
$V_{52}(y^{SS},0,0)$	42.91595725	43.50430073	44.01855318	44.44985803	44.81674878	45.1719312
$V_{53}(y^{SS},0,0)$	-11.6823797	-11.6959520	-11.7072663	-11.7169457	-11.7253552	-11.7328529
$V_{54}(y^{SS},0,0)$	23.95008213	24.06745643	24.16701159	24.25348074	24.32987901	24.39844403
$V_{55}(y^{SS},0,0)$	-57.7962702	-58.8051154	-59.6647772	-60.4145972	-61.0798608	-61.6779990
$V_{56}(y^{SS},0,0)$	7.353837432	7.521721028	7.664606574	7.78910558	7.89946271	7.998606411
$V_{57}(y^{SS},0,0)$	2.664518259	2.769612116	2.859154317	2.93724817	3.006538151	3.06881902
$V_{61}(y^{SS},0,0)$	3.615550885	3.641816848	3.664140841	3.683569258	3.700764646	3.716206986
$V_{62}(y^{SS},0,0)$	0.652286599	0.697306254	0.735704416	0.769219052	0.79896675	0.825737108
$V_{63}(y^{SS},0,0)$	24.05920313	24.56773352	24.98681169	25.36850149	25.72204659	26.0139169
$V_{64}(y^{SS},0,0)$	31.43575958	31.58651811	31.71437715	31.82541846	31.92351641	32.01155551
$V_{65}(y^{SS},0,0)$	7.353837432	7.521721028	7.664606574	7.78910558	7.89946271	7.998606411
$V_{66}(y^{SS},0,0)$	-35.8820036	-36.9360955	-37.8352018	-38.6200034	-39.3167040	-39.9436473
$V_{67}(y^{SS},0,0)$	-1.64073691	-1.50676508	-1.39246935	-1.29269035	-1.20408828	-1.12436390
$V_{71}(y^{SS},0,0)$	6.061546354	6.106030595	6.143834087	6.176730828	6.205845168	6.231986904

$V_{72}\left(y^{SS},0,0\right)$	-1.91723774	-1.87105597	-1.83158285	-1.79706915	-1.76637849	-1.73872906
$V_{73}\left(y^{SS},0,0\right)$	-25.4103795	-25.4557167	-25.4938016	-25.5266037	-25.5553279	-25.5810024
$V_{74}\left(y^{SS},0,0\right)$	46.21288228	46.4249246	46.604701	46.76078613	46.89864109	47.02233944
$V_{75}\left(y^{SS},0,0\right)$	2.664518259	2.769612116	2.859154317	2.93724817	3.006538151	3.06881902
$V_{76}\left(y^{SS},0,0\right)$	-1.64073691	-1.50676508	-1.39246935	-1.29269035	-1.20408829	-1.12436390
$V_{77}\left(y^{SS},0,0\right)$	3.295017451	2.269818864	1.394003234	0.628560112	-0.05186536	-0.66466881
$V_{8}\left(y^{SS},0,0\right)$	-41.192233	-42.0349240	-42.7539570	-43.3817346	-43.9392048	-44.4409593
$V_{9}\left(y^{SS},0,0\right)$	2.12E-16	-1.11E+06	-2.49E+06	-4.22E+06	-6.36E+06	-9.01E+06

Chapter 5 Conclusions

5.1 Spatial dynamics in groundwater economic models

Groundwater overextraction has features like the familiar commons game, but, in addition, it has a structure such that the choices of users in time and space matter for the system outcome. The task of management in this spatial-dynamic system is thus one that jointly manages both well-specific profit differences and the flows of groundwater among wells in order to maximise basin-wide returns. Thus, the typical common pool problem adopts two distinctive features which are critical for policy design. The first one has been widely recognised and is that the externalities of extraction are heterogeneous over space and time. Resource economics has lagged behind in investigating the second feature: spatially-variant choices beyond extraction are key to achieve optimal outcomes. The spatial-dynamic pattern of externalities depends not only on the level and location of current wells' extraction but also on the characteristics of new wells such as their location and depth. This feature is particularly relevant given increasing demand for groundwater (and thus, increasing number of wells).

The heterogeneity of externalities means that aggregate rents are maximised only when the economic and hydrological gradients are perfectly aligned. That is, extraction rates must vary across time and space to completely mitigate spatial-dynamic externalities.

However, a first-best spatially differentiated allocation was found to have some disadvantages. Firstly, it increases the inequality of private profits and leads to higher water drawdown at certain locations. Secondly, the information requirements of spatially and temporally variable external costs are high.

Most groundwater depletion problems unfold over landscapes with partially or totally unpredictable spatial dynamics. Since the spatial-dynamic pattern of externalities may also depend on stochastic natural processes, information is not only costly but sometimes impossible to obtain. Even if the distribution of shocks is correctly predicted, optimal extraction paths will result in a lower aggregate welfare than in a perfect information scenario. For instance, under the uncertain threat of irreversible saltwater intrusion, the first-best allocation consists of more conservative extraction paths, but saltwater still intrudes earlier in time than if externalities were certain.

Although analysing extraction externalities as a spatial-dynamic process poses significant regulatory challenges, it also broadens the choice variable set available for the dynamic optimisation of extraction benefits. The dispersal process of groundwater is dependent upon extraction and spatial choices which are available at different stages of an aquifer's development. Hence, optimally setting these multiple variables achieves higher levels of hydrological and economic objectives while increasing the resilience of the groundwater system to uncertain shocks. That is, if only one variable is set optimally, returns are not maximised and the aquifer may be more vulnerable to polluting sources.

5.2 Policy implications of groundwater spatial dynamics

The purpose of modeling spatial-dynamic processes, estimating parameters, constructing simulation models, and subjecting these to various optimisation techniques is not only to understand the nature of the human/groundwater interactions, but also to suggest policies that might be used to control such systems. In an ideal world in which transactions and information costs are zero, it would be economically optimal to design management policies that account for spatial interconnections among wells by utilising dynamic and spatially differentiated extraction controls. However, our results suggest that this first-best policy faces a number of constraints that make it inapplicable in practice. Firstly, the implementation and monitoring costs of finely-tuned policies are usually large. Secondly, the welfare and hydrological gains from implementing this policy may be unequally distributed among users. Thirdly, given the complexity and hidden nature of groundwater systems, information is usually far from perfect.

Although a first-best differentiated policy may be too costly to implement, it is still possible to take into account hydrological information about spatial interconnections and design second-best policies that maximise rents given the necessity of undifferentiated instruments. An important question is what the efficiency loss of a second-best policy is, and how it depends upon the structural nature of the diffusion system. For instance, a spatially uniform tax results in important welfare losses if the spatial variation in externalities is high. However, this policy is easier and less costly to implement. Furthermore, the efficiency loss must be contrasted to a lower user opposition, as a uniform tax is perceived as fairer and the distribution of private profits post-tax is more equal.

Even in the absence of constraints, a first-best spatially differentiated extraction policy may not be efficient in certain contexts. As part of an integrated groundwater management approach, additional instruments complement extraction controls and raise overall welfare. One example is optimal groundwater management under the uncertain threat of irreversible salt water intrusion. In this context, an additional regulation on well depths is found to simultaneously increase the resilience of the system and the economic returns of users, relative to a single instrument policy.

The use of multiple instruments is also optimal when the demand for groundwater is increasing. In this case, an optimal policy would also have to account for interconnections among new users. Even if extraction rates are optimally controlled, welfare is not maximised unless the locations of new users are also optimally chosen. Moreover, during the early stages of an aquifer's development, when hydrological stresses are incipient, a simple and easy to enforce location tool may recover most of the potential gains from management.

5.3 Policy feedbacks into groundwater economics

As discussed in the previous section, the inferences obtained from this research aim to inform policymaking. However, all three groundwater management models developed in this thesis incorporated elements from observed policy practices. On the theoretical side, policy may inform research by presenting additional choice variables that are frequently used to address groundwater depletion problems (for example, spatial regulations or decentralised profit-sharing systems).

On the empirical side, real-world policy proposals provide material that can be compared with empirical estimates of spatial-dynamic processes. Consider the interim minimum well separation adopted in the case study analysed in this thesis. Although this policy represents an important advance, it is not the result of an understanding of the underlying spatial dynamics. In fact, we find that not only the distance among wells but also the direction of groundwater flow should inform policymaking to maximise welfare gains from regulation.

Finally, the practical application of integrated groundwater management approaches motivates the expansion of collaborative multidisciplinary research efforts. Groundwater policy design requires tractable and easy to understand tools, where complexity is not simplified (like in 'bath-tub' models), but translated into insightful practical information. Policymakers are often not interested in implementing 'the optimal policy', but rather seek to understand the trade-offs involved in their decisions.

This thesis has quantified key policy trade-offs throughout the management issues analysed. For instance, the last essay (Chapter 4) examines the implications of uncertainty for optimal management by illustrating the relationship between risk and economic gains of alternative instrument mixes.

5.4 The way forward

The objective of this thesis was to demonstrate novel ways to deal with important groundwater economic issues emanating from its complexity. There remains to be accomplished large amounts of research on efficient groundwater resource management. In this last section, I propose a few interesting topics for further research endeavours.

Firstly, more studies are needed that quantify the transaction costs of first- and second-best groundwater policies and unitisation schemes. The efficiency payoffs of each alternative instrument do not provide enough information for the policy evaluation process. A remaining question is how costly different policies are to implement and monitor, and how these costs depend on the spatial dynamics of the aquifer.

Secondly, few studies can be found on decentralised spatially based approaches to self-regulate groundwater extraction. Since a wide variety of community-led groundwater management initiatives are in place, it would be informative to assess which factors condition whether coordination-based gains exceed internal transaction costs. Chief among these factors may be the mechanisms available to manage inequities and perverse incentives.

Finally, the effects of other types of uncertainty on optimal groundwater management designs also represent a fertile research space. Given the expansion of climate change-induced alterations in soil, land cover and rising sea levels, risk management studies are needed to quantify the trade-offs among conflicting objectives. Alternative stochastic optimisation techniques could be examined to analyse different shock structures to the groundwater system.

Glossary of Economic Terms

Aquifer: Wet underground layer of water-bearing permeable rock or unconsolidated materials (gravel, sand, or silt) from which groundwater can be extracted using a water well.

Aquifer recharge (infiltration): Seepage of water into an aquifer as precipitation through the soil, or as surface water through the beds of streams, wetlands, and lakes.

Autonomous (hazard rate): Independent of time.

Coefficient of variation: Normalized measure of dispersion of a probability distribution defined as the ratio of the standard deviation to the mean.

Common-pool resource: A natural resource such as an aquifer where use is rivalrous and it is costly to exclude users from undertaking withdrawals from the resource.

Competitive extraction: Extraction of natural resource which is unregulated such that there are no institutional limits placed on the rate of withdrawal by an individual resource user.

Cone of depression: When a well is pumped, the water level in the well is lowered. As the water flows into the well, the water levels or pressure in the aquifer around the well decrease. The amount of this decline becomes less with distance from the well, resulting in a cone-shaped depression radiating away from the well. This conical-shaped feature is the cone of depression.

Confined aquifer: An aquifer whose water-saturated zone is directly overlain by an impermeable layer, so that water in a well will rise above the top of the aquifer.

Drawdown: The difference between a well's static (non-pumping) and pumping water levels.

First best (optimal) regulation: The application of tools and policies to achieve the optimal utilisation of a resource system by changing user behavior.

Freshwater-saltwater interface: This interface delimits the salinity intrusion at the boundary between freshwater and brackish water.

Gini coefficient: Coefficient defined mathematically based on the Lorenz curve, which plots the proportion of the total income of the population that is cumulatively earned by the bottom x% of the population. The line at 45 degrees thus represents perfect equality of incomes. The Gini coefficient can then be thought of as the ratio of the area that lies between the line of equality and the Lorenz over the total area under the line of equality.

GIS: A geographic information system (GIS), geographical information system, or geospatial information system is a system that captures, stores, analyzes, manages and presents data with reference to geographic location data

Gisser-Sanchez Effect (GSE): The view that is little difference between the optimal rate of groundwater extraction when it is undertaken optimally and when it occurs under competitive extraction.

Hydraulic head: A specific measurement of water pressure above a geodetic datum. It is usually measured as a water surface elevation, expressed in units of length, at the entrance (or bottom) of a piezometer.

Hydraulic interference: Lowering of the water in one well due to pumping of another well, so that its usefulness is decreased.

Hydrogeothermal: That employs water heated geothermally.

Inelastic: Water demand that is fixed, independent of price changes.

Land subsidence: The lowering of the land-surface elevation from changes that take place underground. Common causes of land subsidence from human activity are pumping water, oil, and gas from underground reservoirs; dissolution of limestone aquifers (sinkholes); collapse of underground mines; drainage of organic soils; and initial wetting of dry soils (hydrocompaction).

Myopic: With no consideration of the effect of present decisions on future costs and benefits.

Opportunity cost: Cost of undertaking a specific action in terms of the costs associated with the next best alternative action. For example, the opportunity cost of extracting a volume of water from an aquifer might be the value of that same volume of water if it were extracted sometime in the future.

Property right: Whenever a recognizable entity is able to exclude others from using an asset or enjoying a flow of benefits from its use.

Pumping cost externality: Additional costs imposed on other extractors from a given decision by an extractor to pump water from a well and that are not accounting for in the pumping decision of an individual.

Random utility model (RUM): Probabilistic representation of the Neo-Classical microeconomic theory of individual choice. The probabilistic content of RUM arises from the propensity for an individual, when faced with the repetition of the same choice task, to exhibit variability in his or her preference ordering.

Remote sensing: The use of aerial sensor technologies to detect and classify objects on Earth (both on the surface, and in the atmosphere and oceans) by means of propagated signals (e.g. electromagnetic radiation emitted from aircraft or satellites).

Saltwater intrusion: Movement of saline water into freshwater aquifers.

Saltwater upconing: Saltwater intrusion can be manifested in two ways, by local upconing and by regional intrusion. Saltwater upconing, which occurs only in basal areas, is the movement of a cone of brackish water or saltwater from the interface toward a well screen.

Scarcity rent: The economic surplus that arises from the use of a resource when it is constrained or fixed in supply.

Stock externality: Reduction in the water available for use by others from a given extractor's decision to pump water from a well and that are not accounting for in the pumping decision of an individual.

Storativity: The volume of water released from storage per unit decline in hydraulic head in the aquifer, per unit area of the aquifer.

Subgame perfect Nash equilibrium: A refinement of a Nash equilibrium used in dynamic games. A strategy profile is a subgame perfect equilibrium if it represents a Nash equilibrium of every subgame of the original game.

Territorial User Rights Fisheries (TURFs): Usufructuary right to fish in a single area is given to a single entity, which can be an individual, a company, or a cooperative.

Transaction costs: Cost incurred in making an economic exchange. These include search and information costs, bargaining costs and policing and enforcement costs.

Transient mode: Simulation of a groundwater model where the magnitude and direction of flow are allowed to vary with time.

Transmissivity: Measure of how much water can be transmitted horizontally in an aquifer, such as to a pumping well.

Ubiquity: Property of being present everywhere.

Unconfined aquifer: An aquifer in which the water-saturated zone is directly overlain by a permeable but unsaturated material. The water-saturated aquifer is in direct contact with the air-filled aquifer.

Unitisation: Unit based operation of a common pool resource by consolidating or merging the entire field or a substantial part of it as a single entity and designating one or more of the parties as operator.

Volumetric tax: Fee to be paid by quantity used/extracted.

Water table: The upper surface of ground water. Below this surface, all the pore spaces and cracks in sediments and rocks are completely filled (saturated) with water.

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