Three approaches to measuring natural resource scarcity: theory and application to groundwater

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THREE APPROACHES TO MEASURING NATURAL RESOURCE SCARCITY:

THEORY AND APPLICATION TO GROUNDWATER

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Summary

Efficient pricing of a resource incorporates both marginal cost of extraction and scarcity rents. Since groundwater resources exhibit natural supply constraints, scarcity rents must be imposed on current users. Given the difficulty of establishing clear groundwater ownership rights, scarcity value frequently goes unrecognized and is difficult to estimate. This results in inefficient pricing and misallocation of the resource. This thesis builds on three different methods to develop appropriate theoretical and empirical models relevant for indirect estimation of these shadow scarcity rents, which we consider as the initial and most challenging step towards efficient groundwater management. Empirical analyses are based on economic and hydrological data from the island of Cyprus, representative of semi-arid regions.

Chapter 2 critically assesses previous theoretical and empirical attempts to derive the increase in social benefits from efficient pricing of groundwater and examines the potential for groundwater management. This potential is seriously challenged by Gisser-Sanchez's Effect ($\mathcal{GSE}$): i.e. net benefits from optimally managing groundwater are insignificant for all practical purposes. Chapter 3 attempts a re-examination of $\mathcal{GSE}$ by developing a dynamic model of adaptation to increasing groundwater scarcity, when backstop technology is available. Both groundwater scarcity rents and management benefits are derived by simulating the optimal and competitive-commonality solutions. Results point to the absence of $\mathcal{GSE}$ in aquifers facing complete exhaustion in the near future.

Chapter 4 proposes a refinement of revealed preference methods of valuation, by combining the hedonic and travel cost methods, and applies the refined model to derive the willingness to pay for groundwater quality. It is claimed that hedonic valuation of quality attributes can be misleading when the exogeneity assumption, with respect to these attributes, to sample selection is violated. Hence, the simultaneity between hedonic valuation and sample selection is modelled in the context of producer behaviour and investigated empirically in the case of land demanded for use as an input either in agricultural production or touristic development. The empirical analysis suggests that failing to correct for sample selection results in a biased valuation of groundwater quality. In chapter 5 duality theory is employed to develop the distance function methodology of deriving shadow groundwater scarcity rents. The empirical application of the model involves estimating a stochastic input distance function from which the *in situ* shadow price of groundwater is derived. Chapter 6 concludes the thesis by comparing and contrasting the magnitude of groundwater scarcity rents and willingness to pay for scarce groundwater quality, derived from the models put forward in this research.

To my parents who taught me who I am.

To my teachers who taught me what I know.

To Nikitas who taught me to believe in myself when I needed it the most.

Contents

Chapter 1

Introduction: The Potential for Groundwater Scarcity.

Water is essential to human life. It is also a thread which inextricably links economic and natural systems. Water resources are key to the survival of both systems and both the quantity and quality of water resources are impacted upon by economic and natural systems. The earth's renewable supply of water is governed by the hydrologic cycle, a system of continuous water circulation (figure 1.1). Enormous quantities of water are cycled through this system, though only a fraction of circulated water is available each year for human use. Available supplies are derived from two rather different sources: surface water and groundwater. This thesis focuses on groundwater resources.

Groundwater constitutes about 89 percent of the freshwater on our planet, discounting that in the polar ice caps[1], and is accumulated in underground aquifers that lie between layers of rock. Groundwater systems are dynamic with groundwater continuously in slow motion from zones of recharge to areas of discharge. Tens, hundreds, or even thousands of years may elapse in the passage of water through this subterranean part of the hydrological cycle, since flow rates do not normally exceed a few meters per day and can be as low as one meter per year[2]. Groundwater is primarily a depletable resource stock, although as a small proportion (less than

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[1] Global hydrogeological information reported in this chapter are derived from *Mays (1996)* and *Spulber and Sabbaghi (1998).*

[2] These groundwater velocities compare to rates of up to one meter per second for river flow.

5 percent) can be withdrawn each year and renewed by seepage of rainwater or snow melting into the aquifer. If the rate of groundwater use is less than or equal to the rate of recharge, water use from aquifers can be sustained indefinitely. If, however, withdrawals exceed the natural rate of recharge, groundwater is a nonrenewable resource. Hence groundwater can be regarded as a *“replenishable but depletable”* resource.

Figure 1.1: The Hydrologic Cycle.

Source: Cyprus Water Development Department (1999).

In certain parts of the world groundwater supplies are being depleted to the potential detriment of future users. Supplies, which for all practical purposes will never be naturally replenished, are being “mined” to satisfy current needs. Moreover, quantity is not the only problem. Quality is also a problem, as much of the available groundwater is polluted with chemicals, radioactive materials, salt or bacteria. Thus it is important to keep in mind that groundwater scarcity has an important qualitative dimension that further limits the supply of usable water.

Abundant surface water in proximity to the location of the groundwater could serve as a substitute for groundwater, effectively setting an upper bound on the marginal cost of extraction. The user would not pay more to extract a unit of groundwater than it would cost to acquire surface water. Unfortunately, while on a global scale the amount of available water (surface and groundwater) exceeds current aggregate rates of demand, in many parts of the world where groundwater overdrafts are particularly severe, the competition for surface water is already keen because of climatic conditions, geography, patterns of use, and water pricing policies.

Is this described allocation of groundwater efficient or are there demonstrable sources of inefficiency? Answering this question requires us to be quite clear about what is meant by an efficient allocation of groundwater resources.

1.1 The Efficient Allocation of Scarce Groundwater.

When groundwater withdrawals exceed recharge, the resource will be mined over time until either supplies are exhausted or the marginal cost of pumping additional water becomes prohibitive. The similarity of this case to the increasing-cost, depletable-resource model allows us to learn something about the efficient allocation of groundwater over time. The first transferable implication is that a marginal user cost is associated with mining groundwater, reflecting the opportunity cost associated with the unavailability in the future of any unit of water used in the present. An efficient allocation considers this user cost, which effectively signals the *in situ* scarcity of the resource, which is alternatively defined as the resource's scarcity rent. Thus efficient pricing of groundwater entails a unit price equal to the sum of marginal extraction cost plus this scarcity rent. The efficient extraction path for constant demand involves declining use of groundwater over time. Marginal extraction cost (the cost of pumping the last unit to the surface) would rise over time as the water table fell. Pumping would stop either when the water table ran dry or when the marginal cost of pumping was either greater than the marginal benefit of water use or greater than the marginal cost of acquiring water from some other backstop source. The difference between the efficiency price of the water and the marginal extraction cost, which equals groundwater scarcity rents, would decline over time, reaching zero at the switch point (if a substitute were available) or the point of exhaustion (if were not).

Is the efficient allocation of groundwater likely to be achieved in real world economies? If groundwater could be purchased in a perfectly functioning market, efficient pricing and allocation of the resource would be achieved through Adam Smith's "invisible hand" and groundwater management would not be an important policy matter. However, the difficulty of establishing clear ownership rights in groundwater exploitation makes it improbable or even impossible for markets for this resource to function competitively. For common property resources, the neoclassical economic paradigm suggests that scarcity rents are ignored, which has several direct consequences for groundwater allocation: pumping costs would rise too rapidly, initial price would be too low, and too much water would be consumed by the earliest users.

The discussion above can be graphically summarized in terms of figure 1.1.1[3]. The time path of marginal extraction costs from existing conventional groundwater sources, such as irrigation wells, is given by the marginal extraction cost curve. However the availability of a "backstop" technology provides groundwater users with an alternative source of water, other than irrigation wells. Unlimited quantities of water can be produced from this alternative source at the high (assumed time invariant in the figure) unit cost P_1. The efficiency price path shows the social cost of water, incorporating extraction costs as well as *in situ* value (scarcity rents). Suppose that, contrary to the common situation, a competitive market for buying and selling groundwater existed; that is, all rights to *in situ* groundwater could be owned and sold independently of overlying land. The question would then be how much must a new groundwater user pay to gain access to groundwater now used by another user. This payment will be bounded at the high end by what prospective buyers are willing to pay, and at the low end by what sellers are willing to accept as payment for the marginal unit of groundwater. Consider a potential buyer contemplating a capacity addition to the level Q_2. Under the supply conditions just outlined, the buyer can either purchase water rights covering an existing source,

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[3] A somewhat similar exposition can be found in *Bowen et al. (1991)*.

with extraction cost AQ_3, or use the available backstop at cost CQ_2. Thus for the incremental source at capacity Q_2, the buyer's maximum willingness to pay, over and above extraction costs, for existing rights is represented by the distance CA[4].

Figure 1.1.1: Efficient Allocation for Scarce Groundwater.

The owner's willingness to accept compensation in exchange for rights to a well is also affected by the scarcity situation. If today's rate of use increases by one unit, the aquifer's water table will fall (assuming negligible aquifer recharge) and the buyer will incur sooner higher costs of extraction. Thus the instantaneous cost of water pumping currently equals the

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[4] If the backstop technology was not available then the buyer's maximum willingness to pay for existing rights would not be bounded by the backstop unit cost; instead the maximum willingness to pay would be bounded by the marginal benefit derived from consuming Q_3. Net benefits for an individual would be derived by plotting the vertical distance between the marginal benefit curve and the marginal cost of acquiring groundwater at a given point in time. This distance depicts the maximum willingness to pay for existing groundwater rights over and above extraction costs, in the absence of a backstop source for water. This distance becomes zero when extraction costs become prohibitively large.

increase in present value of future extraction costs, and identifies the scarcity value attached to the marginal well. Adding marginal extraction costs to scarcity value yields the efficiency price of extracted water depicted in the figure. The owners' reservation price at Q_2, is determined by their (assumed) awareness that any prospective buyer will have to pay more, and sooner, for even the next-least-costly well if they refuse to sell. At (marginal) capacity Q_2, potential scarcity rent is the distance BA and represents the seller's minimum willingness to accept payment, over and above marginal costs. The shaded area represents total scarcity value of the resource for the time period during which the aquifer is used as the source of water; that is before the adoption of the backstop technology.

If groundwater was available in unlimited quantities at constant cost of extraction, no scarcity value would be generated for *in situ* groundwater. However, since groundwater resources exhibit natural supply constraints, the scarcity rent of that water must be imposed on current users. Only in this way will the proper incentive for conservation be created and the interests of future generations of water users be preserved. Under appropriate market conditions, the efficiency price would also be the market price of extracted water, and if marginal extraction cost was known, one could easily determine scarcity rent as a residual. But in the absence of clear ownership rights and viable efficient markets, including the scarcity value in groundwater prices is rather difficult because there are no price and quantity data from which the benefit of foregoing water usage currently as a means of reducing future costs of acquiring water, can be estimated. In this thesis, we propose and apply three different methods which aim to an indirect estimation of the *in situ* groundwater scarcity value: dynamic optimal control, hedonic pricing and the distance function approach. The empirical analyses are based on economic and hydrological data from the island of Cyprus, representative of semi-arid regions.

1.2 Measuring Groundwater Scarcity: Plan of the Thesis.

Chapter 2 focuses on a paradoxical empirical result that persists in the groundwater literature since 1980, when it was first identified by Gisser and Sanchez. In essence, Gisser-Sanchez's effect ($\mathcal{GSE}$) states that although serious depletion of aquifers is a major threat to many freshwater ecosystems all over the world, the numerical magnitude of benefits of optimally managing groundwater is insignificant. That is, the empirical difference between social benefits derived from groundwater use when current users incur the full social cost of their extraction, and those derived under competitive-commonality conditions where scarcity rents are not fully accounted for, is small. This result can be obtained if at least one of the following is true: (a) the hydrogeological physical structure of aquifers is such that eliminates the pre-mentioned externality effects, (b) the marginal benefit curve derived from groundwater use is very steep and as a result not significantly sensitive to the increase in the price of the resource implied by adding marginal scarcity rents to marginal extraction costs, (c) the marginal value of *in situ* scarcity of the resource is insignificantly small and as such its addition on marginal extraction cost does not cause significant behavioural changes in the market for water, (d) another positive externality is involved in groundwater extraction that reduces the effect of common property externalities, and/or (e) there is a major fault in the way the literature attempts to measure management benefits.

Chapter 2 critically reviews both the theoretical and empirical attempts to address the $\mathcal{GSE}$. It highlights the fact that in the theoretical literature the single most important cause for the presence of the $\mathcal{GSE}$ is the prevalence of very steep marginal groundwater use benefit curves, which imply that groundwater usage is not very sensitive to price. This cause amounts to point (b) mentioned above; however there exist circumstances that its effects can be eliminated. Thus the case for different theoretical investigations is put forward. In the same chapter we also point at various misconceptions, inaccuracies and omissions of the current state of the literature that could potentially resolve part of the existing puzzle.

Chapter 3 assesses the $\mathcal{GSE}$ theoretically and empirically via simulations, in a dynamic model with backstop technology availability. The empirical illustration of the model indicates that in the absence of a backstop technology, the $\mathcal{GSE}$ is eliminated when the assumption of infinite hydraulic conductivity -commonly adopted in the groundwater literature- is not imposed on the relevant dynamic model and natural recharge of the aquifer is sustained in the indefinite future. Intuitively, this result implies that when complete depletion of the aquifer is probable, it is welfare increasing to manage extraction. The model developed in chapter 3 is richer and more realistic than ones already available, because it explicitly incorporates the four main features of aquifers' exploitation, features which have previously been studied independently but have never before - to the best of our knowledge - been put together in a single model. These features are, quantity and quality externalities in a common-pool aquifer, demand for groundwater which is changing over time through endogenous adaptations to increasing resource scarcity, and availability of a backstop technology. The solution technique used is that of multi-stage optimal control. Simulation results from the Kiti aquifer in the island of Cyprus, suggest that situations where the competitive solution of the model leads to complete extinction of water in the aquifer, are likely in such semi-arid regions. Therefore the social benefits from managing the aquifer and achieving a steady-state of positive groundwater extraction to the indefinite future by sustaining aquifer recharge, are empirically significant. This result is sharper where groundwater scarcity is very acute and depletion of the resource is due in the near future. We suggest that this constitutes an important element in the resolution of the $\mathcal{GSE}$.

As argued in the introduction of this chapter, groundwater scarcity has an important qualitative dimension that further limits the supply of usable water. Chapter 4 attempts to derive the willingness to pay (WTP) for improvements in the *in situ* groundwater quality, which arises from the scarcity of this environmental attribute together with its contribution to enchancing individuals' well-being. Groundwater quality may affect the productivity of land as an input in production. Where this is so, the structure of land rents and prices will reflect these environmentally determined productivity differentials. Hence, by using data on land rent or land value for different properties we can in principle identify the contribution which the attribute in question, fresh groundwater quality, makes to the price of the traded good, land. This identifies an implicit or shadow price for the attribute fresh groundwater quality. Commonly used to implement this approach, are the hedonic technique and the travel cost valuation methods. Chapter 4 reviews these approaches and proposes that the hedonic approach with sample selection bias elements from the travel cost valuation method, is the most appropriate in the case of groundwater as a land attribute, where the exogeneity assumptions would otherwise seriously bias the results.

More specifically, chapter 4 of the thesis models hedonic valuation and sample selection simultaneity in the context of producer behaviour, and investigates empirically the case where land is demanded for use as an input either in agricultural production or in touristic development. The quantifiable water quality attribute is salinity. Salinity is ceteris paribus increasing with sea proximity, which is an attribute itself valued in tourist development but not agricultural production. This is the source for sample selectivity bias. The empirical econometric analysis, based on data collected from surveying 282 owners of land parcels, uses Heckman's two step estimation procedure and validates the hypothesis that failing to correct for sample selection results in a biased valuation of groundwater salinity. The estimated marginal (WTP) for fresh groundwater derived from the applied econometric analysis when correcting for sample bias is statistically not different from zero, whereas without this correction this value appears to have a significant positive effect on the value of land. This result indicates that ignoring selectivity correction ignores the fact that the cost of lower groundwater quality can be offset by an increasing probability of switching to the more lucrative tourism industry. It is also worth mentioning that arguments raised in this part of the thesis have implications for hedonic price analysis applied to housing and other goods whose quality characteristics can affect sample selection.

Moreover, the estimated WTP for groundwater quality derived from the hedonic model corrected for sample selection, is not only statistically insignificant but also low in magnitude. It is argued that the low private marginal WTP for improvements in groundwater quality derived from the hedonic valuation method with sample selection, is indicative of the significance of the dynamic commonality effect of groundwater resources in contrast to the $\mathcal{GSE}$. That is, it constitutes evidence that extraction behaviour is myopic; hence extracting agents are not willing to pay for marginal improvements in groundwater quality today because other free-riding agents might use the preserved groundwater quality in the future, or because they are thinking of switching to other productive activities that use other water sources (e.g. tourism).

Chapter 5 employs duality theory to derive the *in situ* shadow price of unextracted groundwater, through modelling the technology of vertically integrated agricultural firms that both extract and use groundwater as an input in their production. The key extension of this model on existing literature is the use of methods that do away with the need for behavioural assumptions, such as conventional cost minimization, which maybe violated in inefficiently managed or regulated industries, such as agriculture. In these cases the estimation of traditional cost, profit or revenue functions could be misleading. The method put forward uses the distance function approach, which allows production units to operate below the production frontier, i.e. to be inefficient. By using Shephard's input distance function to represent technology rather than a cost function, we can employ a dual Shephard's lemma to retrieve natural resource input specific shadow prices. Another useful advantage of distance functions in empirical applications is that they do not require price data to compute the parameters; only quantity data, which is often more readily available in natural resource industries, is needed.

The empirical application of chapter 5 involves estimating a stochastic input distance function by using panel microeconomic data on agricultural production in the region of Kiti, and deriving an estimate of the individual producer's valuation of the marginal unit of groundwater in the aquifer. Estimation results confirm the existence of significant technical inefficiencies in production, and thus provides support for the use of the distance function in estimating natural resource shadow prices. The estimated unit shadow scarcity rent of groundwater for year 1999, is again much lower than the optimal shadow price of the resource derived by simulating the optimization model of chapter 3, thus confirming previously derived evidence of myopic groundwater extraction by the agricultural sector.

The concluding chapter of the thesis attempts a brief summary comparison of the magnitude of *in situ* groundwater scarcity values and shadow price of *in situ* scarce groundwater quality, derived from the three different models proposed and applied in our research. Moreover, empirical results are used to derive inferences on extracting behaviour and assess the need for managing the resource under consideration. The main conclusion of the work presented in this thesis amounts to the following statement:

> When groundwater scarcity is very acute and complete depletion of the aquifer is due in the near future, the $\mathcal{GSE}$ disappears; thus evidence of the empirical prevalence of myopic groundwater extraction should constitute a signal for the need for managing groundwater resources. Implementing optimal extraction is going to be neither easy, nor costless, hence future work should be directed towards deriving cost and benefits

of different regulatory regimes of groundwater extraction[5].

1.3 Scarcity of Groundwater Resources in Cyprus.

The empirical analyses of the thesis are based on economic and hydrological data from the island of Cyprus. Cyprus is representative of arid and semi-arid regions in general, typified by lack of rain, spatial separation of supply and demand, irrigation-based agriculture, and overuse of groundwater sources. Annual precipitation ranges from 290 millimeters (mm) in the west to 1190 (mm) in the central Troodos mountains[6]. The mean annual long term precipitation is 515 (mm), which corresponds to 4650 million cubic meters (MCM) of water per year[7]. More than 80 percent of this returns to the atmosphere as loss through evapotranspiration and less than 20 percent, i.e. about 900 MCM, can be considered as the actual water available for use. From this 600 MCM is surface water and the rest 300 MCM flows into the aquifers. From the latter, about 70 MCM is lost in the form of sub-surface flow into the sea, leaving about 230 MCM for exploitation through wells, boreholes and springs.

Groundwater in Cyprus has not only been a freely accessed resource, but also a reliable and clean one. As such, it was the first targeted water source for exploitation in the island. The result is that all aquifers in the island have been pumped for thousands of years and exploited beyond their safe yield. Recent archeological findings show that Cyprus was one of the first countries where boreholes were possibly dug as long ago, as 6000 years. This long term exploitation of groundwater has caused sea intrusion into most of the coastal aquifers. However, the extraction of groundwater continues to be a very important element of water supply, both through official boreholes undertaken by the government, but also legally and illegally, through private boreholes with no control of the quantities of water extracted.

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[5] Additional directions for future research that emerge from this thesis, are discussed in the concluding sections of each of the consecutive chapters.

[6] Hydrogeological information for the island of Cyprus reported in this thesis are gathered from *Hydrological Year Books of Cyprus (Water Resources Division)* for the period 1964-1999, as well as from personal interviews with officials of the Cyprus Water Development Department.

[7] The island covers an area of 9250 square kilometers (km^2). The south of the island is governed by the Government of Cyprus (5727 km^2) and the north is administered by the Government of Turkey (3423 km^2).

Thus the notion of common property characterizes ownership of groundwater reserves, as the doctrine of *"absolute ownership"* governs the island's land law [8]. Although the doctrine conditions ownership of groundwater on ownership of land overlying the aquifer (thereby limiting access), in all other respects owners of land, own groundwater as a common property resource subject to the rule of capture[9]. As argued in section 1.1, this creates a pumping cost externality among groundwater users, thereby causing a traditional market failure. The existence of this market failure makes the scarcity rent of groundwater resources implicit; however this rent exists as it is apparent from the fact that current extractions exceed replenishable supplies, which implies that aquifers are being irreversibly drained. Ignoring scarcity rents in groundwater pricing means that prices are too low, thereby inducing excessive extraction, capacity investment and consumption. Even if water users were aware of the concept and importance of scarcity rent, the absence of market-determined groundwater prices makes the valuation of scarcity rents very difficult. As already argued, the main aim of this thesis is to investigate the importance of these scarcity rents and propose different approaches to measuring them.

1.4 Acknowledgments.

This brief survey of evidence suggests that water scarcity is not merely a problem to be faced at some distant time in the future. In Cyprus, as well as in many parts of the world, it is already a serious problem and unless preventive measures are taken, it will get worse. Moreover, given Cyprus accession to the European Union it is worth mentioning that a thorough restructuring process concerning European Water Policy is on the way, and a new Water Framework Directive

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[8] As far as water-related legislation in Cyprus is concerned, it has tended to develop on an *ad hoc* basis. There is no umbrella law covering water; most water related laws were enacted before 1960, and there have been only minor modifications since. These laws remain in force under Article 158 of the Constitution of the Republic, and form the basis of resource development, interaction between the government and users, and establishment of local water bodies. They state that all surface water, groundwater and wastewater is vested to the government which has power to construct waterworks and undertake their management. However, private individuals have the right to apply for permits to sink boreholes or dig wells, and it is further stated that "all springs and several surface and groundwater sources constitute *private property* in the form of registered water rights". At the same time, the Government has the power to declare some groundwater aquifers to be under "Special Measures" and impose restrictions on borehole drilling and water abstraction. *(Information gathered from the General Attorney's Office of the Republic of Cyprus).*

[9] In section 2.2.2 of chapter 2, we provide the exact definition of this property rights regime and discuss its effects on the magnitude of commonality externalities in an aquifer.

will be the operational tool, setting the objectives for water protection well into the next century. What is arguably one of this Directive's most important innovations is the introduction of "full cost recovery" pricing. That is, by 2010 Member States will be required to ensure that the price charged to water consumers - such as for the abstraction and distribution of freshwater and the collection and treatment of waste water - integrates the true costs, which include scarcity rents[10]. The problem of identifying and imposing these costs is not insoluble, though to date the steps necessary to solve it have not been taken. I consider this thesis as a step towards this direction and special thanks are due to those that made its completion possible. Since ideas can be understood only in relation to pre-established knowledge I owe an immense, if implicit, debt to earlier natural resource and environmental economists, as well as economists in general: the references are partial acknowledgment of that debt.

I am also indebted to my advisor, Dr. Paul Seabright for his excellent supervision. He has always been most generous with his time and help. He has provided me with the support, assistance and stimulation necessary to complete this thesis. I can record with pleasure his invaluable encouragement and assistance in helping to set straight the analyses presented in this thesis. I am also grateful to Prof. Bob Rowthorn who had the patience to go through the mathematical models of this thesis. I would also like to thank Prof. Richard Green and Prof. Timothy Swanson, for helpful comments and suggestions during the time they individually supervised this thesis. Prof. David Newbery and Prof. David Pearce examined an earlier version of this thesis and provided me with the appropriate guidance towards revising my work. I am especially in Prof. Newbery's debt for his examination comments on this previous version of the thesis. They had a substantial, beneficial effect on the final product. Moreover, a number of people read parts of earlier drafts of this thesis and gave me helpful comments. They include Prof. Panos Pashardes, Prof. Anastasios Xepapadeas, Prof. David Ulph, Prof. Louis Christophides, Dr. Elena Antoniadou and Dr. Christina Christou. Many thanks to them. I am also grateful to seminar participants, at the University of Crete, the University of Cyprus and University College London, for their helpful comments and suggestions.

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[10] As set out in the directive, this is a mandatory goal, but effort has been made to take into account the cases where such an approach is not possible, and provide criteria for the key cases.

I would also like to thank Peterhouse of the University of Cambridge, for being so generous as to select me among applicants from all over the world and award me with the Friend's of Peterhouse Bursary of 1994-1995. This bursary financed my one year course towards the M.Phil. in Economics in the Faculty of Economics and Politics of the University of Cambridge. The senior tutor of Peterhouse, Dr. Phillip Pattendent and the economics fellow of Peterhouse, Dr. Solomos Solomou, have supported me during my years of study in Cambridge. Moreover, financial support from Cambridge Commonwealth Trust and the Overseas Research Students' Awards (ORS) for my MSc and first year of my study towards a Ph.D. in Economics, is thankfully acknowledged. In addition, financial support from the Smuts Memorial Fund of Peterhouse and help from the Water Development Department of Cyprus, made the completion of the field work of this thesis possible.

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Finally I want to thank the European Commission represented by the Director General for DG XII Science, Research and Development, for financially supporting the last two years of my study towards the Ph.D. in Economics, through funding of the following project: "Integrated Water Management in Cyprus: Economic and Institutional Foundations". I am also in debt to the people who responded with enthusiasm to my suggestion of putting this project together. They include Prof. Timothy Swanson, Prof. Panos Pashardes, Prof. Michael Faure, Dr. Andreas Christodoulides, Prof. Werner Balderer, Prof. Anastasios Xepapadeas and Dr. Paul Herrington. I am also thankful to participants in the academic workshop on "Integrated Water

Management", Nicosia, July 1999, for their helpful comments on presented parts of my work.

The material in chapter 3 has been accepted for presentation in the Tenth Annual Conference of the European Association of Environmental and Resource Economists, Rethymnon, June 2000. The material in chapter 5 has been accepted for presentation in the 70th Seminar of European Association of Agricultural Economics, Thessaloniki, July 2000. The material in chapters 3, 4, and 5, will be presented in the International Symposium on Integrated Water Management, Nicosia, September 2000, organised by the University College London and the University of Cyprus. Finally, parts of chapters 2 and 4 will be published in a special issue of the journal *Environmental and Resource Economics*, on 'Optimal Freshwater Management'.

Chapter 2

The Potential for Groundwater Management: The Gisser-Sanchez Effect Reconsidered.

The Gisser-Sanchez effect ($\mathcal{GSE}$) refers to a paradoxical empirical result, present and persisting in the dynamic solutions of groundwater exploitation under different extraction regimes, since 1980. Namely, although serious depletion of aquifers is a major threat to many freshwater ecosystems all over the world, the benefits from managing groundwater extraction are numerically insignificant. Clearly, if the $\mathcal{GSE}$ extends to a general rule then the role and scope of water management are severely limited. This is even more evident when we take into consideration that implementing optimal extraction is not going to be costless. As argued in chapter 1, section 1.1, allocating groundwater efficiently implies a unit price equal to the sum of marginal extraction cost plus the marginal user cost (scarcity rent) of groundwater extraction, reflecting the opportunity cost associated with the unavailability in the future of any unit of water used in the present. Absence of management of this common-pool resource, or alternatively presence of a competitive extraction regime, refers to a situation where current users incur only the extraction costs of their groundwater use. That is, they free-ride on the relevant scarcity rent and as a result they impose an externality on future users. How then can it be that the no-management (competitive) solution of groundwater exploitation is almost identical to the efficient management (optimal control) solution, which imposes both extraction costs and scarcity rents on current users?

The identification of this effect can be rationalized in a number of alternative ways: (a) the hydrogeological physical structure of aquifers is such that eliminates the pre-mentioned externality effects, (b) the marginal benefit curve derived from groundwater use is very steep and as a result not significantly sensitive to the increase in the price of the resource implied by adding marginal scarcity rents to marginal extraction costs, (c) the marginal value of *in situ* scarcity of the resource is insignificantly small and as such it does not cause significant behavioural changes in the market for water, (d) another positive externality is involved in groundwater extraction that reduces the effect of common property externalities, and/or (e) there is a major fault in the way the literature attempts to measure management benefits. The main aim of this chapter is to investigate which of the above reasons can be put forward as possible explanations of the $\mathcal{GSE}$ and identify additional possible factors that could potentially reduce or eliminate this effect.

Moreover, the scope of this chapter is broader than an attempt to rationalize the $\mathcal{GSE}$. It also aims to investigate the broader potential for managing groundwater, given that in chapter 1 we have established that an efficient allocation of groundwater is not likely to be achieved in real world economies. Section 2.1 focuses on factors that reduce the likelihood that voluntary agreements will be initially sought, then negotiated and finally enforced, in order to achieve an efficient groundwater allocation. Hence some form of intervention may be needed to correct the workings of the free market. The first step towards this goal is to understand the resource's behaviour and the behaviour of the agents involved in its exploitation. Section 2.2 identifies a number of factors that increase the complexity of this initial step. More specifically, it identifies the diversity of externalities, the diversity of groundwater property rights structures, the diversity of behaviour models for extracting agents, as well as the heterogeneity of aquifer's hydrogeological characteristics.

Given the inherent difficulty and complexity of managing groundwater, it is important to establish whether there is indeed scope for managing this resource? As already argued, this question was confronted by the economics profession in 1980's and the result was the so-called Gisser-Sanchez effect, which essentially states that there may be negligible numerical difference between competitive and socially optimal rates of water pumping. This implies that the numerical magnitude of the various pumping costs and common property externalities is insignificant and that marginal cost pricing of the resource is approximately efficient. Section 2.3 presents Gisser-Sanchez's model and discusses its caveats and robustness, while section 2.4 examines the model's long-run robustness. Section 2.5 examines the robustness of this effect when groundwater is modelled as a differential game and section 2.6 re-examines the effect's robustness for tributary aquifers and for the case of conjunctive use of groundwater and stochastic surface supplies. Section 2.7 concludes the chapter and motivates the remaining research in the thesis.

2.1 The Difficulty of Managing Groundwater.

As indicated in the introductory chapter of this thesis, the issue of groundwater management is a practical concern in arid and semi-arid regions throughout the world and water managers continue to grapple with the question of how to manage this resource. The extensive use of groundwater in many parts of the world and related environmental harm (i.e. water level drawdown[1], aquifer mining[2], saltwater intrusion[3], stream baseflow reduction[4] and land surface subsidence[5]) implies the difficulty of efficiently and equitably defining, allocating and

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[1] As groundwater is pumped, the water table (i.e. the top edge of the saturated medium) will typically decline. If pumpage greatly exceeds recharge (flow into the aquifer), drawdown can be significant. Drawdown is a concern for two reasons: first, lift costs increase, and second, if the water table drops below the screened depth of the well, the well may have to be reworked or even abandoned and replaced.

[2] Aquifer mining refers to the withdrawal of groundwater from confined aquifers (aquifer's bounded above and below by impervious layers) and aquifers with minimal recharge rates, resulting in aquifer storage decreases. When such aquifers are used, groundwater miners face continually higher lift costs as water levels decline, and ultimately, turn to alternative surface water sources, reuse schemes, conservation plans, or abandonment of the water-intensive use.

[3] Saltwater intrusion results as fresh groundwater is drawn down and saline water flows in to replace it. Costly osmosis or catalysis methods have to be applied in order to treat brackish water and make it once again usable.

[4] Surface streams can include artesian springflow from underlying aquifers. However, if the aquifers are pumped in excess of their recharge rates, the springflow, or stream baseflow, can be reduced. Pumpage by upland or upriver well owners can seriously interfere with use by those who hold rights to downstream surface water flows. Moreover, reduced springflow or stream baseflow may threatened populations of rare species that live in artesian pools.

[5] As groundwater is pumped and withdrawn from the pore spaces of aquifer clays, sands, and other media, these spaces often collapse. When they collapse, overlying strata, and ultimately the land surface as well, drop. Land surface subsidence in coastal areas can cause inundation, and in inland regions, it can damage building and

protecting rights to a common, fluid resource through market mechanisms without guidance from publicly agreed and enforced rules. It is doubtful that groundwater pumpers are unusually irrational or perverse. Why then well owners continue to pursue heavy groundwater use, despite attendant to the environmetal problems mentioned above? Why do pumpers appear to ignore these problems and fail to take steps to reduce the damage or compensate those harmed? Why have efficient well supply schemes, such as coordinated spacing arrangements, not been more widely adopted? Why have more efficient water use policies and conservation devices not been employed? Failing these measures, why haven't those responsible for the harm faced injunctions or damage judgments?

A norms-based answer to some of these questions may simply be that the problems are just not severe enough to merit concern or response. This argument and related research will be critically reviewed in sections 2.3, 2.4, 2.5 and 2.6 of this chapter. Alternatively, it may be the case that the problems and feasible solutions are seen, but cannot be agreed upon. We now turn to a number of factors that reduce the likelihood that voluntary agreements will be initially sought, then negotiated, and finally enforced and obeyed.

For many years, there was *little understanding of groundwater sources, quantities, and behaviour*. Pumpers were unaware of the effects of groundwater use and unlikely to consider, much less enter in on agreements to coordinate their use with affected parties[6]. As time has passed, understanding of groundwater dynamics has improved greatly, and ignorance has become less of an excuse for groundwater abuse. Still, though, knowledge is somewhat restricted to theoretical generalities and aggregate supply and use figures; that is, key factors in groundwater availability and flow often turn on site-specific and widely varying parameters such as storativity[7] and conductivity[8]. Although not precise, knowledge about groundwater and consequently knowledge about benefits derived from groundwater management, remains costly to acquire.

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road foundations.

[6] As a nineteenth century United States court decision laments: "...the existence, origin, movement and course of such waters, and the causes which govern and direct their movements,...are secret, occult, and concealed", *Frazier v. Brown, 12 Ohio St. 294, 311, (1861).*

[7] Storativity is a function of the pore space volume in an aquifer and a good indicator of the amount of water held in the aquifer, and can vary by a factor close to 3,000.

[8] Hydraulic conductivity is an expression of the ease with which water will flow through an aquifer, which can fluctuate by a factor of over 5,000,000.

The costs include technical expenses such as well monitoring, aquifer computer modelling, legal costs for negotiating and drawing contracts for surface canal and allocation of yield shares may also arise.

Secondly, the classical *prisoner's dilemma* can be used to frame the options facing one pumper considering whether to cooperate with a second pumper. The prisoner's dilemma is a typical game of strategy in which individual incentives lead to a non-optimal (non-cooperative) outcome. If a bargain for coordinating or reducing pumpage can be reached, this dilemma can be used to describe the choices available to each pumper, considering whether to comply with the deal he has made or not. In such a case the benefits of defection are tempting (i.e. a prompt supply of water at an individually convenient flow rate and location can be developed immediately) and the risks of defection are quite slight (i.e. monitoring compliance with a well pumpage scheme would be difficult, given the great number, wide spacing and private location of wells). Conversely, the benefits of cooperation are difficult to show given that they rely on site-specific aspects of an aquifer and on data-intensive monitoring of pump flow rates, well sites and screen depths, and they will only be evident in comparison with the lone-ranger pumping scheme which the contracting pumpers have supposedly abandoned.

A third factor, related to prisoner's dilemma, is introduced by the *limits of self-help and enforcing agreement.* That is, if a pumper suspects that his neighbour is not complying with a supply or use agreement, he has few effective ways to enforce that agreement. First, it is difficult to identify who is defecting from the agreement. Second, even if a pumper knew who the culprit was, he would have limited means of forcing his cooperation. In *Coase's (1960)* words:

> "...In order to carry out a market transaction, it is necessary to discover who it is that one wishes to deal with, to inform people that one wishes to deal and on what terms, to conduct negotiations leading up to a bargain, to draw up the contract, to undertake the inspection needed to make sure that terms of the contract are being observed, and so on. These operations are often extremely costly[9]."

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[9] Transactions in groundwater markets (if they exist) are also costly (or even impossible if no relevant market

Coase, 1960, p. 15.

Moreover, the difficulties of negotiating a cooperative agreement with another pumper and subsequently complying with that agreement are compounded if other, third-party pumpers are considered. The individual harms of shunning agreements or subsequently defecting from agreements will seem small relative to the cumulative aquifer effect and the pumper's foregone wellwater. Here the pumper faces a situation similar to the paradigm posed by *Hardin (1968)*, referred to as the *"tragedy of the commons"*. In his words:

> "...Therein is the tragedy. Each man is locked into a system that compels him to increase his herd[10] without limitation - in a word that is limited. Ruin is the destination toward which all men rush, each pursuing his own best interest in a society that believes in freedom of the commons."

Hardin, 1968, p. 1247.

Finally, the *effects of racing* (rule of capture) also limit the likelihood of successful voluntary agreements for the exploitation of groundwater resources. If a pumper shares his groundwater supply with others, he can no longer be sure that unused groundwater will remain for his use tomorrow: another pumper may have already pumped it. His opportunity cost quickly becomes uncertain, and more so as the number of competing pumpers grows and the size of the aquifer diminishes. Other, more general factors may also reduce the opportunity cost: high interest rates and dubious survival of the groundwater-dependent business may contribute. Ultimately, there may remain little reason to forestall today's pumping to allow future withdrawals.

Viable alternative management options outside groundwater use and agreements might relieve the pressure to compete with individual, group, and future pumpers. Possible options include: (1) reducing consumption needs through conservation measures, (2) restoring the quantity and quality of groundwater to allow future use, and (3) turning to surface sources

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exists). Thus, groundwater cannot be efficiently allocated through the workings of the "Coase Theorem", which states that if transaction costs are zero then location of ownership makes no difference to resource use and income can be redistributed without affecting resource use.

[10] *Hardin (1960)* used the famous example of cattle-grazing to illustrate his point.

or in the absence of abundant surface water, producing water by adopting available backstop technologies. Each, however, has significant costs which could make these options unattractive.

2.2 The Inherent Complexity in Modelling Groundwater Exploitation.

As it is obvious from the above brief discussion, groundwater management is an inherently interesting resource issue, and thinking about it in broad terms provides insights to larger questions of resource management. However, the first step towards managing a resource is to achieve a realistic modelling of its flow. Groundwater is analytically similar to biological resources such as fish because the water is rechargeable as the fish are reproducible. But unlike fish, the recharge rate of the water is not biological; that is, not stock dependent[11]. In this sense, the water is like minerals or gas in the ground. But unlike these, the natural growth (recharge) rate is not zero.

The theory of the intertemporal allocation of groundwater has been developed and studied extensively during the last forty five yeas[12] *(Milliman, 1956; Kelso, 1961; Renshaw, 1963; Scott, 1967; Smith, 1968; Burt, 1964, 1967, 1970; Burt and Stauber, 1971; Brown and Deacon, 1972; Cummings and McFarland, 1974; Gisser and Sanchez 1980 a, b; Feinerman and Knapp, 1983; Allen and Gisser, 1984; Nieswiadomy, 1985; Worthington, Burt, and Brustkern, 1985; Kim et. al., 1989; Burness and Brill, 1992; Provencher and Burt, 1993; Brill and Burness, 1994; Knapp and Olson, 1995; etc.).* In most of the dynamic mathematical models employed in this literature, groundwater is modelled as a resource to be depleted in a mining era before moving to a stationary-state era. Moreover, in these models the mobility of groundwater leads to interdependence among users; one user's withdrawals influence the conditions of production experienced by neighboring pumpers in the future. As argued in section 1.1 of chapter 1, in

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[11]

- However, the recharge rate can be stock dependent if the aquifer becomes nearly full and develops leaks to the surface. This possibility however is not relevant for aquifers in arid and semi-arid regions that face the threat of depletion. We further discuss this point in chapter 3, section 3.4.

[12] At its current state this theory is the twin sister of the fisheries models, introduced by *Gordon (1954)*.

the absence of restraining property institutions the individual user tends to ignore the effects of his present pumping on the future stock of groundwater, in his private calculations of gains and losses from groundwater use. Hence he does not incur the total social cost of his pumpage and as a result an inefficient allocation of the resource emerges.

2.2.1 Diversity of Externalities Involved in Groundwater Exploitation.

The type of externality that emerges in commonly owned aquifers has been discussed extensively in the literature of groundwater economics and, as suggested by *Gisser and Sanchez (1980 a, b)* one could consider the case of pumping an aquifer as lying between fishery harvesting at one extreme and the cutting of privately owned timber at the other. The nonexclusiveness of the fishing grounds leads to dissipation of rent as well as a possibly inefficient distribution of effort over time (*Cheung, 1970)*, whereas in the case of privately owned timber owners maximize the present value of all future income streams. In an aquifer, exclusiveness is present to a very large extent when only farmers who own land overlying the aquifer can pump water and as a result other farmers are excluded from the resource. But exclusiveness is not as complete as in the case of privately owned timber. As a result "...the individual farmer cannot expect to have more water in storage for him next year if he pumps less this year. Consequently, instead of maximizing present value, farmers simply pump water each year, satisfying the condition that the marginal cost of pumping equals the marginal physical product of water" *(Gisser and Sanchez, 1980(b), p.638).*

This kind of externality has been discussed in the literature before the appearance of Gisser and Sanchez's seminal paper (*Burt, 1964, 1967, 1970; Burt and Stauber, 1971; Brown and Deacon, 1972; Cummings and McFarland, 1974*) and thereafter was implicitly adopted by most researchers in the field (*Feinerman and Knapp, 1983; Allen and Gisser, 1984; Sloggett and Mapp, 1984; Nieswiadomy, 1985; Worthington, Burt, and Brustkern, 1985; Caswell and Zilberman, 1986; Kim et. al., 1989; Burness and Brill, 1992; Brill and Burness, 1994*). Clearly their description uses the "rule of capture" argument. However, Gisser and Sanchez's mathematical model considers another type of externality, namely the pumping cost externality[13].

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[13] See below for the exact definition of the pumping cost externality and section 2.3.2 for Gisser and Sanchez's

Such inconsistencies between the theoretical and mathematical representations of these externalities were the rule rather than the exception in the reviewed literature, until *Provencher and Burt (1993)* achieved a clarification of the different externalities relevant in groundwater extraction.

In particular, they point to three externalities that prevent efficient allocation of groundwater resources: the *stock externality*, the *pumping cost externality*[14] and the *risk externality*[15]. The *stock externality*, is identical to the externality described in *Gisser and Sanchez (1980)* by employing the "rule of capture" argument. This externality arises because the pumping decision of each firm using the groundwater resource is constrained by the total groundwater stock. By pumping the marginal unit of groundwater stock in period (t), a firm reduces the set of pumping alternatives available to other users in period $(t+1)$. Attempts by a firm to increase its welfare by storing groundwater are futile because other firms may gain access to the stock; that is, a firm may lay claim to a unit of groundwater stock only by pumping it. The *pumping cost externality*, is the externality described by the mathematical representation in *Gisser and Sanchez (1980 a, b)* which arises because the cost of pumping groundwater depends on the groundwater stock. By pumping the marginal unit of groundwater stock in period (t), a firm affects the cost at which other users may pump groundwater in period $(t+1)$. Firms withdraw water too quickly because, while a firm's decision to reduce its rate of pumping lowers the future pumping costs of all firms, it is not compensated for its conservation.

The *risk externality* was completely overlooked by the literature until the early 1990s, when groundwater was first treated as a contingent source of water[16]; i.e. as a buffer to seasonal and annual revenues against the vicissitudes of surface water supply. This externality ulti-

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mathematical model.

[14] Actually *Bredehoeft and Young (1970)* were the first to identify the distinction between the stock and the pumping cost externalities in groundwater extraction, without calling them that. However, their treatment of these externalities was only descriptive.

[15] Before the taxonomy introduced by *Provencher and Burt (1993)*, *Negri (1989)* discussed the *strategic externality*. This refers to pumping more water because of the understanding that leaving it in the ground stimulates the pumping of one's neighbours, whereas the stock externality arises due to the finiteness of the groundwater stock. This strategic behaviour arises even when the groundwater stock is infinite. Provencher and Burt treat this strategic externality as an outcome aggravating already existing inefficiencies, rather than as the source of a distinct externality.

[16] See section 2.5 of this survey, on models on the allocation of groundwater when stochastic surface water inflows are the primary source of water.

mately arises because the income risk of all water using firms is affected by the total amount of groundwater stock available for pumping. Each additional unit of groundwater stock available for future consumption lowers income risk of all firms by increasing the buffer against risk, provided by the total amount of groundwater stock available for future pumping. But of course, in its decision-making a firm considers only the private benefit of risk reduction, and consequently fails to extract groundwater at the socially optimal rate.

In the taxonomy of *Smith (1969)*, these three externalities are all stock externalities, because they ultimately arise due to the effect of the resource stock on the pumping decisions of the firms. However, as it became obvious from the latest developments in the groundwater literature, their distinction is quite informative when the efficiency of alternative management regimes is considered[17]. The sum of these external effects reflects the scarcity value of groundwater, which should be imposed on its current users if an efficient dynamic allocation of the resource is to be achieved.

2.2.2 Diversity of Possible Structures of Groundwater Property Rights.

The literature on intertemporal allocation of groundwater focuses on the efficiency effects of one or more of the externalities identified above, which are assumed to arise because of the 'common-property nature' of the resource. As argued by *Schlager and Ostrom (1992)* however,

> "The term 'common property resource' is a glaring example of a term that is repeatedly used by political economists to refer to varying empirical situations including: (1) property owned by a government, (2) property owned by no one, and (3) property owned and defended by a community of resource users. The term is also used to refer to any common-pool resource used by multiple individuals regardless of the type of property rights involved."
>
> Schlager and Ostrom, 1992, p. 249.

The confusion in the use of the term 'common property' has been addressed frequently (*Ciriacy-Wantrup and Bishop, 1975; Runge, 1981; Bromley 1982, 1986, 1989*) without much impact,

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[17] We return to this point in section 2.5.2 of this survey, when the efficiency of a private property rights regime in managing extraction from an aquifer, is considered.

however, on its careless use. Groundwater is a characteristic example of a common-pool resource used by multiple individuals for which economists use the term common property to characterize its ownership structure, regardless of the exact form of property rights involved. Indeed, a number of ownership structures can arise which lead to different degrees of exclusiveness in groundwater exploitation. Different degrees of exclusiveness give rise to varying external effects. The magnitude of these external effects is important because it affects the scarcity value of the resource.

Exclusiveness may be vague, or it may be tightly and clearly defined, depending on the common-law doctrine governing the allocation of groundwater. *Gisser (1983)* argues that groundwater rights should clearly specify the right to (a) use, (b) exclude, and (c) transfer. Measurement (quantification) and enforcement are required in order to render this definition meaningful (*Cheung, 1970).* Do the three most frequently used common-law doctrines of groundwater ownership, satisfy Gisser's three-dimensional definition of a water right? The *absolute ownership (English)* doctrine gives the land owner the right to pump any amount of water from an aquifer that underlies his land and transport it elsewhere. This implies that the element of quantification is missing from this doctrine. The *reasonable use* doctrine modifies the absolute use doctrine by constraining an overlying landowner to pump groundwater for a reasonable use only. The courts' interpretation of the term 'reasonable use' is that landowners cannot transport water away from the land from which it was taken if other landowners overlying the same common aquifer were thereby injured[18]. Quantification is also missing from this doctrine.

Gisser argues for the superiority of the *prior appropriation* doctrine: "The main strength of the prior appropriation doctrine is its intrinsic economic logic and its internal consistency; it is capable of providing a stable framework for a viable groundwater market, no matter what technology and the economy may bring in the future" *(Gisser, 1983, p. 1026-27).* In its general form, the appropriation doctrine establishes priority by time of application from the

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[18] A further refinement of the reasonable use doctrine gave rise to the so-called *correlative rights* doctrine. Water rights to an allowed amount are distributed in proportion to the ownership share of the overlying land. When there is a water shortage due to drought, the landowners share the burden by proportionately reducing their use. When there is excess supply, allocation to non-overlying areas is permitted.

appropriate state agency ("first in time, first in right"). Permits are granted if the new use is "beneficial" (has economic value), and if it does not conflict with the rights of higher priority users or the public interest. This doctrine establishes groundwater rights exclusively owned and quantified based on "consumptive use". "Consumptive use" equals pumpage minus water inflows (i.e. return flow plus natural and/or artificial recharge) in the aquifer. Specifically, a groundwater user may not pump water for the purpose of transporting unlimited amounts to a distant location; instead, he may sell his limited "consumptive use" rights in whole, or in part, to such a user. This implies that while ownership of consumptive use may change hands, total depletion per unit of time may not exceed a certain upper limit. The economic efficiency of the prior appropriation regime is discussed in some detail in section 2.5.2 of this survey, where we describe the private property rights regime as it applies to groundwater extraction.

The vast majority of papers modelling groundwater extraction assumes that only farmers who own land over the aquifer are allowed to exploit the aquifer's groundwater, whereas other agents are excluded from pumping water from the aquifer. That is, the term "common property" in the groundwater literature refers to a resource exploited by a well-defined, finite set of firms, each of which freely chooses its rate of exploitation, hence assuming absolute ownership property rights. However, the possibility implied by both the absolute and reasonable use common law doctrines, of land not overlying the aquifer being irrigated from aquifer's water, is rarely examined in this literature. This possibility can easily reduce the extent of excludability in the exploitation of an aquifer and give open access characteristics to the system. The distinguishing feature of open-access resources from common-property resources is the appearance of *congestion externalities* in the former. By allowing entry in a model of groundwater exploitation, rivalry between different farmers increases with congestion and as a result one farmer's pumping further detracts from others pumping possibilities. Hence, the *congestion externality* is an additional externality present in groundwater aquifers that have open access characteristics, which can potentially make groundwater aquifers similar to fishing grounds.

Naturally, together with the limited attention to the open access characteristics of aquifers, the theme of the optimal level of aggregate groundwater rights associated with *potential users* has also been neglected by the groundwater literature. The common practice is to tacitly assign the role of fixing the aggregate demand curve for groundwater to Plato's philosopher-king. A notable exception to the neglect of congestion externalities by the groundwater literature is *Brown (1974)*, who recognized the issue of congestion externality and recommended a tax to induce the correct level of aggregate activity. *Gisser (1983),* a second attempt to discuss the open access characteristics of aquifers, argues that for a Pareto-optimal allocation a criterion function is needed, that takes into consideration the area under the demand curve of both incumbent *and* potential users. A version of water law that would allow potential users to bargain with incumbent users over a compensation in exchange for fresh groundwater rights would be Pareto optimal. This possibility is actually provided by the prior appropriation doctrine.

2.2.3 Variety of Behavioural Models for Extracting Agents.

In addition to the diversity of possible types of property rights and corresponding external effects, the groundwater literature exhibits a number of alternative behavioural models that describe different configurations of extracting agents' actions in a common-pool aquifer. By far the most popular behavioural model is the one in which the firms using groundwater execute myopic pumping decisions; that is, the state equation does not enter the firm's decision problem (see, for instance, *Gisser and Sanchez, 1980; Feinerman and Knapp, 1983; Llop and Howitt, 1983; Allen and Gisser, 1984; Nieswiadomy, 1985; Worthington et al., 1985*[19]). At first glance this assumption seems rather peculiar. One could argue that a rational firm will eventually learn that its pumping decisions do affect the stock of groundwater and will bring this information to bear in its pumping decision. On the other hand, one might expect this model of behaviour to perform reasonably well when the groundwater resource is exploited by a large number of small firms, just as the assumption of competitive "price taking" behaviour no doubt accurately depicts the situation in many input and output markets. In other words, each firm is too small a part of the whole to give serious consideration to how its pumping decision affects future water supplies. Support for this model comes from a survey of farmers in Kern County, California, conducted by *Dixon (1989).* He found that, in the absence of government control, farmers

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[19] See section 2.3 of this survey, for further discussion on these papers.

are apparently unconcerned with how their groundwater pumping affects the future availability of the resource; hence groundwater scarcity value is completely ignored. As it will become apparent in the consecutive chapters, the same behaviour implications are derived from the empirical work in this thesis.

Although myopic groundwater pumping may be a good approximation of behaviour when the groundwater resource is exploited by a large number of small firms, and although this may be the typical case, the appropriate characterization of pumping behaviour when the number of firms is small remains an interesting theoretical question which is empirically relevant in aquifers of small storage capacity. *Dixon (1989), Negri (1989), and Provencher and Burt (1992)* all discuss the open and closed loop models of pumping behaviour under the common property arrangement. In both of these models that have emerged in the literature, firm behaviour is "memoryless", in the sense that each firm's pumping behaviour depends only on the current state of nature. Firms pursuing open loop (path) strategies take the extraction paths of their rivals as given. On the other hand, firms pursuing closed loop (feedback) strategies take the state-dependent extraction rules of their rivals as given, where an extraction rule expresses the groundwater pumping decision as a function of the observed groundwater stock. The closed loop model appears to be the more realistic of the two because usually firms do not commit to particular paths of groundwater extraction, instead they base their extraction decisions on the observed state of nature[20].

Other models of behaviour are also possible. For instance, a small number of firms or individuals may overcome the difficulties mentioned in section 2.1 and cooperate to achieve the economically efficient allocation of a groundwater resource over time. *Bromley (1991)* for example, points out that a finite set of users may ultimately exploit a resource at the efficient rate by developing rules governing the use of the resource. Likewise, *Schlager and Ostrom (1992)* discuss the prevalence of cooperative behaviour to allocate the commons. Moreover, *Dixon (1989)* discusses non-cooperative behaviour involving the use of "trigger" or "punishment" strategies, where the credible threat of retaliation keeps all firms pumping groundwater at the efficient rate. This section intended to discuss the diversity of behavioural models relevant

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[20] See section 2.5 of this survey for further discussion on game theoretic models of groundwater extraction.

to the common property arrangement, and to emphasize that myopic behaviour, favoured by the literature, represents the "worst case scenario" under the common property arrangement. That is, the myopic firm internalizes none of the social marginal user cost in its groundwater extraction decision, while in other behavioural models the firm internalizes at least part of this cost (for instance, the part which is private).

2.2.4 Heterogeneity and Diversity of Aquifers' Hydrogeological Characteristics.

Another prevalent characteristic of the reviewed literature is that it employs what hydrologists often call "lumped parameter" models, as contrasted to detailed modeling of the aquifer using many small sub-areas among which hydrologic interdependencies are taken into account. "Lumped parameter" models assume that groundwater quickly adjusts to a common depth above sea level after a local perturbation, such as caused by pumping from a well. However, true hydraulic equilibrating flows are often slow and subject to great variability among and within aquifers. Moreover, a basic hydrology law *("Dracy's Law")* suggests that the amount of lateral movement of groundwater from beneath one landowner's property to another's should be rather modest if they are pumping at about the same rate per hectare and the local region of the aquifer is homogeneous. Hence, when lateral groundwater movement is slow, externality effects are insignificant and private decisions of firms approximately maximize social welfare.

If aquifers are heterogeneous and water demands among users variable (which is often the case), water in the future might have to be pumped from a greater depth and thus at greater cost, or it may prove physically unavailable at any depth, because of losses through lateral movement. Neighbours over deeper parts of the aquifer could rapidly pump the water from beneath their own property, creating a large differential hydraulic head and an associate lateral movement of the groundwater. These physical and economic circumstances create considerable risk for the individual firm in an uncontrolled pumping situation because involuntary losses of groundwater from beneath its land can cause greater pumping costs in the future, as well as the possibility of water becoming physically unavailable. Unfortunately such realistic hydrological features have not been considered in economic models of groundwater extraction, perhaps due to the need for an interdisciplinary approach towards their construction and solution[21].

What is apparent from section 2.2 as a whole, is that the task of modelling groundwater exploitation is a complex one, facing a diversity of property rights structures and corresponding externalities, a diversity of behavioural models possible under different ownership structures, and a diversity of hydrogeological features possible for different aquifers[22]. The inherent diversity and complexity of this resource problem increases the difficulty of deriving its true *in situ* scarcity. However, derivation of an exact measure of this value is needed if intervention in the market is deemed necessary for achieving a dynamically efficient allocation of groundwater extraction. That is, scarcity rents have to be imposed on current users of the resource, over and above extraction costs, so that they pay the full social cost of their extraction.

Sections 2.1 and 2.2 establish the difficulty and diversity of efficiently managing groundwater, respectively. However, an even more important question has to be answered first before we establish the usefulness of the discussion in these two sections of this chapter. Is there scope for managing this resource, or is it the case that all the identified difficulties are irrelevant? This would be the case if the free market allocation of the resource was approximately efficient in empirical investigations. As already argued in the introduction of this chapter, this question was first confronted by the economics profession in 1980 and the result was the so-called Gisser-Sanchez effect ($\mathcal{GSE}$), which essentially states that there may be negligible numerical difference between competitive (myopic) and socially optimal rates of water pumping and hence little scope for managing this resource. In section 2.3, we concentrate on the findings and consecutive research resulting from the seminal paper of *Gisser and Sanchez (1980, a, b),* which identified this effect and effectively dominates the relevant literature. Section 2.4 examines the long-run robustness of $\mathcal{GSE}$. Section 2.5 reviews the research initiated by *Dixon (1989), Negri (1989),* and *Provencher and Burt (1992),* and examines the robustness of $\mathcal{GSE}$ in a game theoretic

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[21] A brief section on possible costs of using "lumped parameter" models can be found in *Provencher and Burt (1994).*

[22] However, as already argued to date most of relevant models in the literature assume that access to the resource is limited (either institutionally or by virtue of the high cost of pumping and moving groundwater around) to those individuals or firms with land overlying the resource. Usually left implicit is the myopic extraction behaviour of firms under the common property arrangement. Moreover, the term "common property" refers to a finite number of firms that exploit the resource without any of them holding exclusive rights to any portion of it, and each and everyone of them free-riding on the scarcity value of the resource.

framework, i.e. when the interaction between extracting agents is explicitly taken into account. Section 2.6 reviews studies that examine the presence of $\mathcal{GSE}$ when the interlink between surface and groundwater is recognized or the stochastic nature of groundwater recharge is acknowledged. Finally, section 2.7 concludes the survey.

2.3 Gisser-Sanchez's Model, Caveats and Robustness.

The $\mathcal{GSE}$ essentially states that there is little scope for groundwater management because the increase in social benefits derived from optimally managing the resource is insignificantly small, if compared to benefits derived under no intervention in the resource's market. As argued in chapter 1, optimal management of groundwater means that current users incur both the marginal extraction cost and the user cost (scarcity rent) of their groundwater extraction. At first glance, economic principles point to a number of reasons that could provide a justification of the presence of the $\mathcal{GSE}$: (a) the marginal benefit curve derived from groundwater use is steep; (b) the marginal scarcity value of *in situ* groundwater is insignificantly small and as a result its addition to marginal costs of groundwater extraction cannot cause significant behavioural changes in the market for water; (c) there is a major fault in the way the literature attempts to measure these benefits; (d) another positive externality is involved in groundwater extraction that reduces the effects of negative commonality externalities in a groundwater basin; (e) there is a major fault in the way the literature attempts to measure management benefits. Before an attempt to identify the cause of the $\mathcal{GSE}$ we first review the work that cumulated to Gisser and Sanchez's seminal article. Then we take a closer look at the actual model and thereafter we discuss the model's robustness.

2.3.1 Groundwater Models Before Identification of the Gisser-Sanchez Effect.

Historically, economists have taken it for granted that the divergence between the temporal allocation of groundwater yielded by optimal control and the free market, is practically significant for social welfare because of the absence of well defined groundwater property rights and related resulting externalities, which lead current resource users to ignore or free-ride on groundwater scarcity rents. As a result they acknowledged the need for the study of optimal control (or equivalently, dynamic programming) of temporal groundwater allocation. *Scott (1967)*, *Smith (1968)* and *Quirk and Smith (1969),* suggested that the economic theory of mining extractive natural resources can be applied to the problem of the temporal allocation of groundwater. Problems of groundwater allocation have been studied in the context of the theory of mine by a number of economists including *Milliman (1956)*, *Renshaw (1963)* and *Kelso (1961)*. Then, *Burt (1964, 1966, 1967, 1970)* in a notable series of papers has drawn on principles of inventory management to derive decision rules for the optimal temporal allocation in a dynamic programming format[23].

Extending Burt's work, *Bredehoeft and Young (1970)* have incorporated a complex groundwater model, taking account of the heterogeneity of a hypothetical aquifer[24], into a simulation program representing a groundwater basin system, and studied the effects of different policy instruments that might correct the misallocation of commonly owned groundwater. They found that net benefits from groundwater management, could amount to over $100 per acre but noted that these benefits would decline with increases in the interest rate or increases in the specific yield coefficient[25] of the aquifer[26]. They also studied the efficiency of a use tax (or extraction fee) and a quota (or pumping rights). Their conclusions indicated that the quota policy yields results similar to those from simulating a tax policy. However, they argued for the superiority of a system of pumping rights, on the grounds of administrative simplicity and because it directly removes an essential difficulty of common pool usage, i.e. the fact that property rights in the

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[23] The case dealt with by Burt can be regarded as somewhat more complex than those cases studied in the theory of the mine, in that groundwater stocks were treated as partially renewed by a stochastic process and the value of the resource was imputed by reference to its role as an intermediate product (for production of irrigated crops) by an industry composed of multi-product firms.

[24] Previous attempts to consider the problem of the optimal rate of pumping over time from a groundwater basin have used simplified models of groundwater systems, which assumed uniformly distributed drawdowns (in response to withdrawals) through the basin. However, as argued in section 2.2.4 of this survey, large differences in drawdown commonly occur in developing groundwater systems, which lead to great variations in water costs and perhaps to localized economic and hydrologic failure.

[25] The specific yield (or alternatively, storativity coefficient) of an aquifer indicates the storage capacity of a particular aquifer.

[26] In a second paper, *Young and Bredehoeft (1972)* applied a simulation model to a stretch of the South Platte River in Colorado. With an infinite time horizon and a real interest rate of 5%, their results suggested benefits approximately $102 per acre of irrigated cropland net of administrative costs.

pool are ambiguous[27]. Building on Burt's work as well, *Brown and Deacon (1972)* derived a formula for a tax that should be imposed on groundwater (pumped) in order to yield the optimal control solution. Then, as mentioned in section 2.2.2, *Brown (1974)* recognized the issue of congestion externality in aquifers with open access characteristics, and suggested a charging tax for the use of a unit of the variable factor to accommodate this externality.

At the same time other economists studied competitive solutions to the problem of temporal allocation of groundwater, where scarcity rents are completely dissipated by resource's users. *Gisser and Mercado (1972, 1973)* in an extension of the work of *Kelso (1961)* and the model discussed by *Cummings and McFarland (1973),* developed a competitive model for farmers pumping water out of an aquifer by integrating the demand function for water with hydrologic theory. They showed that in a free market, farmers will pump until the aquifer reaches an unacceptable water level. When this point is reached farmers will either import supplemental water or be restricted to use a smaller amount of water by being assigned water rights. Assuming however, that at some future time farmers might reach the bottom of the aquifer anyway, they might want to consider optimal regulation of pumping at times earlier than the actual time of reaching the bottom. This argument poses an optimal control problem and warrants a solution that should be compared with the case of no control. This was the departure point for Gisser and Sanchez's work in 1980.

2.3.2 The Gisser-Sanchez Effect.

Indeed, it was not until *Gisser and Sanchez (1980, a ,b)* that the profession paused to compare the temporal allocation of groundwater yielded by optimal control with the free market. The basic model analyzed by Gisser and Sanchez is a simplified representation of the economic, hydrologic and agronomic facts that must be considered relative to the irrigator's choice of water pumping. The irrigators benefit function is represented by,

$$\pi(t) = V[w(t)] - C[H(t)]w(t) \tag{2.1}$$

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[27] A previous study by *Hirshleifer et al. (1960, p.66)* also reached this conclusion.

where $\pi(t)$ denotes profits at time (t). Net farm revenues from water use $w(t)$ (neglecting pumping costs) is denoted by $V(w) = \int_0^w p(x)dx$, where $p(w)$ is the inverse demand function for water. $C(H)$ is the average and marginal pumping costs per acre-foot of water, where $H(t)$ is the height of water table above some arbitrary reference point at time (t). The change in the height of the water table is given by the following differential equation, which represents the hydrologic state of the aquifer (or equivalently, the environmental constraint of the problem),

$$\dot{H} = \frac{1}{AS}[R + (a-1)w], \qquad H(0) = H_o \tag{2.2}$$

where (R) is constant recharge measured in acre feet per year, (a) is the constant return flow coefficient which is a pure number, (H_o) is the initial level of the water table measured in feet above sea level, (A) is the surface area of the aquifer (uniform at all depths) measured in acres per year, and (S) is the specific yield of the aquifer which is a pure number. Figure 2.3.1 illustrates aquifer's inflows and outflows modelled by Gisser and Sanchez's model, where (S_L) indicates the elevation of the irrigation surface measured in feet above sea level.

More precisely, the aquifer in Gisser and Sanchez's work is modelled as a "bathtub"[28], unconfined aquifer[29], with infinite hydraulic conductivity[30]. Moreover, while the assumption of constant return flow is not inappropriate, it is not innocuous in the presence of fixed irrigation technology. In particular, it suggests constant rate of water application[31]. As already mentioned, recharge is also assumed deterministic and constant, which is a reasonable assumption

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[28] A "bathtub" model describes a "single-cell" aquifer, in which all users are assumed to pump from the same aquifer and the return flow of water finds its way back into the same aquifer. Thus, implicit in a "bathtub" model is the assumption of zero natural discharge. (*Gisser and Mercado (1973)* considered nonzero natural discharge.)

[29] In an unconfined aquifer the water table is free to fluctuate as the aquifer is not bounded from above by an impervious layer. If water from precipitation flows into the aquifer, the water level will rise. If water is withdrawn from the aquifer, the water level will fall. The upper part of the aquifer, above the water table, is unsaturated while the lower part is saturated.

[30] Infinite hydraulic conductivity implies that the aquifer will never dry up, irrespective of groundwater extraction rates. This assumption is equivalent to the assumption of a bottomless aquifer. Following *Brown and Deacon (1972)*, Gisser and Sanchez justified their adoption of the bottomless aquifer assumption by arguing that it is implied by the standard assumption in the literature that time goes to infinity. However, if this is not the case a steady-state solution might not be reached and as suggested by Gisser and Sanchez, either junior rights must be called, or alternatively, if all water rights are of the same vintage, water rights should be restricted. Moreover, *Zimmerman (1990)* showed that the optimal pumping rate can be substantially lower when the hydraulic conductivity is small enough to result in a significant cone of depression around the well, where the water height in the well is less than the height in the rest of the aquifer.

[31] *English (1990)* addresses this complex engineering issue.

given that recharge is very small in the Pecos Basin[32], the aquifer chosen for the application of their model. In conjunction with the assumption of constant return flow, this implies constant types of land use (i.e., no introduction of municipal and industrial uses), independence of surface water and groundwater systems, and constant average rainfall. Moreover, sunk costs, replacement costs, and capital costs in general are ignored, and it is implicitly assumed that energy costs are constant. It is also implicitly assumed that the well pump capacity constraint is nonbinding. As already mentioned, exclusiveness in Gisser and Sanchez's model is achieved by assuming that only land overlying the aquifer can be irrigated, i.e., the demand curve does not shift to the right over time. We believe that explicit recognition of these assumptions is sufficient to make the point that Gisser and Sanchez's results should be used with caution on real aquifer systems.

Figure 2.3.1: A model of an aquifer.

Source: Adapted from Gisser (1983).

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[32] The Pecos Basin, located in the semi-arid region of New Mexico, is neither interconnected with surface water nor benefited by substantial natural recharge.

Given the above hydro-economic model, Gisser and Sanchez used the results from Gisser and Mercado's (1972) parametric linear programming to estimate empirically the linear demand function for water in the Pecos Basin. They also used hydrologic parameters that were considered realistic in the 1960s but have been revised since then. Assuming a discount rate of 10 percent, they simulated the intertemporal water pumpage once under the assumption of no control and once under the assumption of optimal control. The results of their simulations were as follows:

No Control:

$$H(t) = 1,525 + 1,875 \cdot \exp(-0.000617)t$$

$$W(t) = 237,000 + 213,825 \cdot \exp(-0.000617)t$$

Optimal Control:

$$H(t) = 1,538 + 1,862 \cdot \exp(-0.000613)t$$

$$W(t) = 237,000 + 211,056 \cdot \exp(-0.000613)t$$

where (H) and (W) represent the water table (measured in feet above sea level) and pumping (measured in acre feet per annum), respectively. Notice that the trajectories under the two regimes are almost identical. The wealth (present value of future income streams) was estimated at ($\$309,990,007$) under no control and at ($\$310,002,484$) under optimal control. The two figures are practically identical, implying that imposing on current groundwater users the scarcity rents of their resource use over and above extraction costs, does not significantly increase welfare.

This result led them to conclude that there is no substantive quantitative difference between socially optimal (planning) rules for pumping water, wherein common property effects are considered, and the so-called "competitive" rates, where common property effects are ignored; hence the welfare loss due to the intertemporal misallocation of pumping effort is negligible. This conclusion amounts to the well-known Gisser-Sanchez Effect ($\mathcal{GSE}$). More specifically, Gisser and Sanchez's comparison of the analytical solutions of the optimal control and competitive strategies of groundwater extraction, showed that if equation (2.3) is true, then the difference between the two strategies is so small that it can be ignored for practical consideration.

$$\left[\frac{kC_1(a-1)}{AS}\right]^2 \simeq 0 \tag{2.3}$$

In the equation above (k) is the decrease in demand for water per \$1 increase in price (i.e., the slope of the uncompensated demand curve for groundwater), (C_1) is the increase in pumping cost per acre foot per 1 foot decline in the water table, and (a) and (AS) as given in equation (2.2). Gisser and Sanchez's argument was that if (2.3) is true, then the rate of discount will practically vanish from the exponents of the optimal control formulation of the problem. Thus the exponents of the optimal control result will be practically identical with the exponents of the competition result. As can be inferred from equation (2.3), this analytical derivation implies that as long as the slope of the (uncompensated) demand curve for groundwater use (or alternatively, the slope of the relevant marginal benefit curve) is small relative to the aquifer's area times it's storativity, then the Gisser Sanchez effect will persist.

The upshot of this result is obvious: if there is no quantitative difference between optimal and competitive rates of water pumping, then policy considerations can be limited to those which ensure that the market operates in a competitive fashion and concerns relative to rectifying common property effects are obviated. This is even more evident when we take into consideration that implementing optimal extraction is not going to be costless. In other words, the $\mathcal{GSE}$ establishes that the inefficiency of private exploitation is not a sufficient condition for public intervention since regulation of the resource would have to be based on an accurate cost-benefit analysis. This suggests that there is little or no role for water policy in the form of pumping limitations, a conclusion which seems to contradict apparent common consensus opinion that groundwater is becoming increasingly scarce with many aquifers facing depletion in the foreseeable future[33]. At issue, of course, is whether such depletion is "premature" in any sense. To the extent that it is, then these observations are clearly dichotomous.

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[33] See chapter 1.

2.3.3 Testing the Robustness of the $\mathcal{GSE}$.

The policy implications of the $\mathcal{GSE}$ arose considerable concerns that led to a number of investigations which, at least in part considered the robustness of the effect. Almost simultaneously to the appearance of Gisser and Sanchez paper, *Noel et al. (1980)* found that control increases the value of groundwater in the Yolo basin in California by 10%, and *Lee et al. (1981)* found that control raised the net benefit of groundwater in the Ogallala basin by only 0.3%. Moreover, both *Feinerman and Knapp (1983)* and *Nieswiadomy (1985),* compared the two solutions by considering a wide range of parameter values in sensitivity analyses. In particular, Feinerman and Knapp derived empirical estimates of benefits from groundwater management for Kern County in California[34] with heavy reliance on groundwater supplies. Their sensitivity analysis showed that these benefits are quite sensitive to the water demand schedule and interest rate[35]. However, in all cases considered the increase in welfare from groundwater management was at most ten percent. *Nieswiadomy (1985),* utilized empirically the difference equation (2.2) given in section 2.3.2, in order to calculate annual water pumpage at the county level from primary data. Then, using these water pumpage calculations, he estimated a water demand equation and tested the $\mathcal{GSE}$. Although his results indicated that groundwater management in the Texas High Plains[36] would be unwarranted, he proceeded with a sensitivity analysis on present value profits using different slope and intercept values for the groundwater demand curve. This analysis showed that benefits from groundwater management do not increase monotonically as the absolute value of the slope increases.

A basic assumption in Gisser and Sanchez's model is the linearity of the demand curve for irrigation water. To study the effect of this assumption on Gisser and Sanchez's conclusions, *Allen and Gisser (1984)* compared optimal control and no-control strategies using a non-linear

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[34] The Kern County in California is a major agricultural area with approximately 0.9 million acres of farmland, which rely on both groundwater and highly variable surface supplies for irrigation water. The basin in this area is not interconnected with surface water, but benefits from substantial natural recharge.

[35] *Bredehoeft and Young (1970)* were the first to discuss the sensitivity of the economic yield of a groundwater basin to the interest rate and the sensitivity of the optimal temporal allocation of groundwater to the postulated properties of the demand. They also mentioned the sensitivity of pumping costs and therefore the economic yield, to the storage capacity (specific yield) of the aquifer, which is also one of the contributing factors to the persistence of the $\mathcal{GSE}$ (see equation 2.3).

[36] The Basin in Texas High Plains is neither interconnected with surface water nor benefited by substantial natural recharge. Groundwater supplies approximately 80% of all irrigation water in this region.

demand curve and the same data. This comparison confirmed for the case of the nonlinear demand function what had been demonstrated by the $\mathcal{GSE}$ for the case of a linear demand function: namely, if the storage capacity of the aquifer is relatively large, the difference between a strategy of no control and a strategy of optimal control is small and thus can be ignored for practical policy considerations. Furthermore, Allen and Gisser argued that optimal control may be impossible in the real world because the true demand curve is not really known. In particular, they demonstrated that even if simulated optimal control yields slightly better results than no control, a strategy of no control is likely to yield better results than optimal control, unless one can be sure that the estimated demand for groundwater is very close to the true demand. To illustrate this point they used figure 2.3.2.

Figure 2.3.2: Simulated Optimal Control Versus No Control

Source: Allen and Gisser (1984)

Suppose that the true and estimated demand curves for groundwater are the ones depicted in this figure. MC_{oc} and MC_{nc} are the marginal extraction costs under the assumption of optimal control and no control at a moment of time[37], respectively. An optimal control management imposes on current groundwater users both the marginal extraction cost denoted by $\overline{AB}$, plus the estimated marginal user cost (marginal scarcity value) denoted by $\overline{BC}$. The sum of these two marginal costs is then equated with the estimated value of the marginal benefit of groundwater measured by $\overline{AC}$; hence, an optimal control regime would dictate constraining users to $\overline{OA}$ acre feet per unit of time.

However, for the same marginal scarcity value of the resource, the true optimal level of pumping ought to be $\overline{OE}$ acre feet per unit of time, which is consistent with equating the marginal cost $\overline{EF}$ plus $\overline{FG}$ with the true value of marginal benefit $\overline{EG}$. A strategy of no control would induce users to extract $\overline{OH}$ acre feet per unit of time, which is consistent with equating the marginal cost of pumping under no control with the value of the marginal physical product of water, marked by point K. Now, if the area times the storativity coefficient of an aquifer is large relative to natural recharge and the slope of the linear estimated demand function is relatively small, then the likelihood that the distance between points E and H will be smaller than the distance between points A and E is indeed high. Hence Allen and Gisser concluded that even if simulated optimal control strategy yields a slightly greater wealth than the simulated strategy of no control, since the true demand for water is unknown, no control strategy has a good chance of yielding the highest wealth to users. This also implies that the shadow user cost per unit of time, derived by the optimal control solution of the model has no good chance of being an accurate estimate of the scarcity value of the resource under consideration, unless the researcher is confident for the accuracy of his groundwater demand curve estimation.

Moreover, not only a realistic estimate of the demand curve for groundwater, but also a good approximation of the true cost curve of groundwater extraction are needed to make the comparison of welfare benefits derived under different strategies of extraction reliable. *Worthington*

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[37] MC_{oc} is lower than MC_{nc} because of the assumption that optimal control management will restrict farmers to a smaller aggregate pumping, thus resulting in a higher water table trajectory than the one resulting under a regime of no control.

et al. (1985) applied dynamic programming[38] to a model of a confined aquifer underlying the Crow Creek Valley in southwestern Montana, to determine an optimal interseasonal allocation of groundwater extraction from the aquifer. Firstly, their simulation results suggested that the difference between the two regimes may not be trivial if the relationship between the average extraction cost and the water table level is not linear. In particular, they argued that although in most groundwater studies a linear marginal pumping cost relationship is assumed, when an aquifer is confined, the associated artesian pressure introduces an interval of sharp curvature in the marginal cost function which contains groundwater stocks as the argument. Thus the relationship between unit pumping cost and groundwater storage can hardly be linear. In this study it was found to be highly nonlinear, having considerable impact on the shape of the derived decision rule.

Secondly, their simulation results suggest that the difference between the two regimes may not be trivial if there are significant differences in land productivity. When land is assumed to be homogeneous, the gross returns function with respect to water use tends to be nearly linear. But with greater heterogeneity in productivity, the returns function is more concave, and differences in the optimal use policy under a common property setting are more pronounced. This holds regardless of whether an aquifer is confined or unconfined. From our point of view this result points to the need of more theoretical work to resolve an asymmetric groundwater pumping differential game where the differences in land productivity are taken into account.

The empirical evidence on the robustness of $\mathcal{GSE}$ until the mid-80s are summarized in table 2.3.1. The first column in part (A) of the table reports the authors and publication dates of each relevant research. The second column indicates whether the assumptions used in each particular research, were significantly different from those adopted in Gisser and Sanchez's formulation. If not, then the model is called the "baseline model". The third column presents the difference between the present value of returns from optimal allocation and the common pool allocation, when the costs of optimal basin management are completely ignored. The interest rate (r)

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[38] Dynamic programming represents the solution of the problem as an optimal decision rule where the rate of water use per year is expressed as a function of the volume in storage each year. As such Worthington et al. argued, that the dynamic programming solution of the problem provides much more information about the decision process. By contrast, the "time path" solution derived from applying optimal control implies a time path for a given initial state.

adopted by each study is given in brackets. As already discussed, *Gisser and Sanchez (1980)* found that control of the Pecos Basin of New Mexico would yield virtually the same level of aggregate welfare as the "no-control" case. The follow-up study by *Allen and Gisser (1984)* using a nonlinear specification for demand reached the same result. Moreover, in a study of the southern part of the Ogallala aquifer in Texas, *Lee et al. (1981)* found that control raised the net benefit of groundwater by only 0.3 percent. Likewise *Nieswiadomy (1985)* in a study of the Texas High Plains found that controlling groundwater pumpage would only increase profits by 0.28 percent.

However, not all studies have found such modest returns to groundwater management. Among those studies to find that control increases the value of groundwater by at least 10 percent are *Noel et al. (1980), Feinerman and Knapp (1983), and Worthington et al. (1985).* While different basins (see column four of table 2.3.1) with different hydrologic characteristics (see column five of table 2.3.1) and economic parameters (see column two of table 2.3.1) were employed in these studies, several general conclusions emerge. That is, under optimal control management the possibility of negligible benefits from groundwater management exists. This implies that under specific circumstances, marginal extraction cost pricing of the resource leads to an approximately efficient allocation of groundwater over time. It also seems clear that management benefits may differ from one basin to the next depending on the economic, hydrologic and agronomic parameters. However, there are converging lines of evidence as to the sensitivity of management benefits, irrespective of the magnitude of these parameters. As indicated in part (B) of table 2.3.1, management benefits are quite sensitive to the slope of the demand function and interest rate, moderately sensitive to aquifer storativity and size, and relatively insensitive to other parameters. Taken together, the issues raised above suggest that a water planner would be ill-prepared to determine the optimal allocation of groundwater over time. However, a number of important and possibly enlightening issues, such as the long-run robustness of $\mathcal{GSE}$, alternative behaviour models of groundwater extraction and conjunctive use of surface and ground water, have not been discussed yet. These are the issues we focus on in the remaining sections of this survey.

Table 2.3.1: Testing the Robustness of GSE (1980-1985).

PART A

Authors	Model	Welfare Gains[1]	Basi
Gisser and Sanchez (1980)	Baseline Model	0.01% (r=10%)	Peco
Noel et al. (1980)	Baseline Model	10.00% (r=10%)	Yolo
Lee et al. (1981)	Baseline Model	0.30% (r=10%)	Oga
Feinerman and Knapp (1983)	Baseline Model	10.00% (r=5%)	Ker
Allen and Gisser (1984)	Non-Linear Demand	0.01% (r=10%)	Peco
Nieswiadomy (1985)	Baseline Model	0.28% (r=10%)	Higl
Worthington et al. (1985)	Variable Productivity, Non-Linear Extraction Cost	28.98% (r=6%)	Crov

[1] Welfare gains = net returns (optimal allocation) − net returns (common pool). Does not consider costs of optimal basin mar

PART B

Sensitivity Analyses	Effects on Welfare Gains	Sensitivity Analyses (cont.)	Effe
Increase in Aquifer Area[2]	Negative & Moderate	Increase in Energy Costs[6]	Pos
Increase in Aquifer Storativity[3]	Negative & Moderate	Increase in Interest Rate[7]	Neg
Increase in Surface Inflow[4]	Positive & Small	Increase in Demand Intercept[8]	Pos
Increase in Initial Lifts[5]	Negative & Small	Increase in Demand Slope[9]	Pos

[2, 3, 4, 5, 6, 7] See for example, Feinerman and Knapp (1983).

[8, 9] See for example, Nieswiadomy (19

2.4 Long-Run Robustness of $\mathcal{GSE}$.

2.4.1 Allowing Variable Economic Relations and Endogenous Rates of Change.

As mentioned in section 2.3.2, implicit in Gisser and Sanchez's model and in follow up research, are the assumptions of fixed economic relations (e.g. time-independent demand) and/or exogenous and constant rates of change (e.g. constant and fixed exogenous crop mix, constant crop requirements, fixed irrigation technology[39], constant energy costs[40], constant exogenous types of land use, and constant hydrologic conditions). As in any long-run study however, projected results become more tenuous as the steady-state is approached. Thus, the estimated benefit and cost functions used to derive the $\mathcal{GSE}$ that were based on current observations, may bear little relation to the actual benefit and cost functions when economic, hydrologic and agronomic conditions are much different. More complex representations of increasing resource scarcity incorporate opportunities for adaptation to the rising resource prices that signal increasing scarcity. That is, in the long-run, adoption of new techniques, substitution of alternative inputs, and production of a different mix of products offer rational responses to increasing scarcity.

Kim et al. (1989) developed an optimal control model formulated in n discrete stages, that incorporated the opportunity for adaptation to resource depletion[41]. In particular, the paper disaggregated agricultural demand for groundwater into crop-specific linear demand curves, and as the intertemporal shadow price of groundwater increased in a mining era, the number of irrigated crops diminished in stages. The model suggested two supplementary traits to a conventional intertemporal depletion path: the relative allocation of groundwater among

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[39] *Burness and Brill (1992)* considered endogenous irrigation technology choice. Moreover, *Shah et al. (1995)* integrated technology diffusion within Hotelling's exhaustible resource model, where the modern technology was drip irrigation (conservation technology) used with groundwater. In their model, resource quality heterogeneity and rising water prices were responsible for the gradual adoption of the modern technology, and under reasonable conditions the diffusion curve turned out to be an S-shaped function of time. Their results indicated that without intervention, the diffusion process will be slower than is socially optimal, and optimal resource use tax will accelerate the diffusion of the conservation technology and slow down excessive resource depletion caused by market failure due to commonality conditions.

[40] *Sloggett and Mapp (1984)* discussed the implications of rising energy prices; however, they did not proceed to an empirical investigation.

[41] This model is an extension of the work of *Kamien and Schwartz (1981), Rossana (1985)* and *Tomiyama (1985),* who developed two-stage theoretical optimal control models that accounted for sequential changes through time.

irrigated crops and endogenous switch times describing an intertemporal cropping pattern. Both planning and common property equilibria were derived and compared empirically. Their results from an application to the Texas High Plains indicated that transition away from irrigation of sorghum to dryland agriculture occurs twice as fast when done optimally. However, benefits from groundwater management were as small as \$0.36 to \$4.16 million (1-3.7 percent) as the interest rate varied from 5-2 percent. Thus the $\mathcal{GSE}$ persists even when the opportunity of adaptation to resource depletion is incorporated in the model under empirical investigation. However, Kim et al. adopted the assumption of infinite hydraulic conductivity and did not allow for adoption of a backstop technology, which is realistic reaction to increasing resource scarcity. In chapter 3 we extend this model towards these directions and re-examine the robustness of the $\mathcal{GSE}$.

Brill and Burness (1994) further explored the robustness of $\mathcal{GSE}$ under alternative hydrologic/economic hypotheses, and noted scenarios under which divergence of competitive and optimal rates of water pumping was significant. They found that a 2 percent annual demand growth, laid to significant difference (16.85 percent) in socially optimal versus competitive rates of groundwater pumping in the Ogallala aquifer[42]. They also found that considering declining well yield laid to 2.95 percent divergence in net present value of benefits between optimal and competitive rates of groundwater extraction in the same aquifer. In addition, high social discount rates diminished the importance of user costs and (future) pumping cost externalities in their model, causing a convergence of competitive and planning pumping rates; conversely, low social discount rates laid to marked divergence in these pumping rates.

2.4.2 The Issue of Discounting and Intergenerational Models of Resource Exploitation.

As indicated above and in table 2.3.1, management benefits are very sensitive to the choice of the discount rate used in the optimal control model of groundwater extraction. Present-value calculations and the broader issue of discounting, are central in understanding the long-

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[42] More specifically, they consider a case study of the "five county" area in eastern New Mexico, consisting of Curry, Roosevelt, Quay, Union, and Harding Counties, all of which overlie the Ogallala Aquifer.

run limitations of $\mathcal{GSE}$. Moreover, these issues are central in understanding the limitations of the broader literature on the dynamic allocation of natural resources, which is handicapped by assumptions that abstract from the realities of human demographics and the institutional forces that guide economic development. This abstraction is not just an artifact of the historic evolution of economic and environmental thought[43]. One might argue that this weakness has its roots in the structure of the ethical framework that underpins conventional environmental economics, i.e. utilitarianism.

Broad sense utilitarianism[44] asserts that the welfare of a society at some point in time is a function of the levels of utility of the members of that society. However, the issues with which natural resource management in general and groundwater management in particular, are concerned, involve choices which affect different generations of people over time, so one needs to understand utilitarianism in an intertemporal framework. The dynamic device used in the groundwater literature, is to assume the existence of a "representative agent" whose life

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[43] Although the management of natural resources has been viewed as a dynamic problem amenable to solution by the calculous of variation since early 1960s, it was not until *Colin Clark's "Mathematical Bioeconomics: The Optimal Management of Renewable Resources" (1st ed., 1976)* that a mathematically consistent framework for the dynamic solution of these problems emerged. During the formulation of this framework, however, environmental economists agreed that resource scarcity and environmental degradation posed no significant threat to the welfare of future generations. See for instance, *Harold Hotelling's* seminal article of 1931, where he offered his well-known counter-argument to *Malthus' (1798)* and *Ricardo's (1821)* concerns over the capacity of natural resources to support sustained improvements in human well-being. According to Hotelling, competitive firms would manage exhaustible resource stocks to maximize present-value profits. Competitive extraction paths would therefore match those chosen by a social planner seeking to maximize intertemporal social surplus. In particular, Hotelling noted that *social* and *private* discount rates must be the same for this result to hold. Subject to this caveat, the equivalence between competitive markets and the work of a rational planner ostensibly meant that the invisible hand was sufficient and policy intervention inappropriate. Moreover, *Solow (1974),* by introducing an exhaustible resource to a standard model of intertemporal development, established that a sustainable consumption level could be achieved, in principle, given sufficient substitutability between resource and capital inputs. Given these results which suggest that resource scarcity and environmental degradation pose no significant threat to the welfare of future generations, environmental economists believed that they could safely abstract from questions of intergenerational fairness. As a result, the profession focused on the efficiency of intertemporal resource allocation, without paying attention to intergenerational issues.

[44] Utilitarianism originated in the writings of *David Hume (1711-1776)* and *Jeremy Bentham (1748-1832)*, and found its most complete expression in the work of *John Stuart Mill (1806-1873)*, particularly in his *"Utilitarianism" (1863)*. Classical utilitarianism possesses three main components: (1) an assertion that outcomes can be assessed only in terms of the extent to which they contribute to the social good, (2) a criterion as to what contributes to the social good and (3) the principle that individual good or well-being is ordinally measurable and comparable over persons and time. This framework has been criticized for the strength and restrictiveness of its assumptions. Within orthodox microeconomics, the problem associated with the assertion that utility is cardinally measurable have led economists to search for a theoretical structure that does not require one to make such an assertion. A large part of modern economics does not require that utility be cardinally measurable. *Kneese and Schulze (1985)* use the term neoclassical utilitarianism to describe such a weaker form of utilitarian theory.

spans from the present to the indefinite future. This agent is characterized by preferences that are additively separable in time with a positive rate of pure time preference. If c_t is taken as the individual's consumption level at dates $t = 0, 1, ...$, then individual's preferences are expressed by the mathematical form $\sum_{t=0}^{\infty} u(c_t)/(1+r)^t$ where $r > 0$ and $u(c_t)$ represents the agent's instantaneous utility at each date. Although this specification is useful in the analysis of certain problems given its simplicity and mathematical tractability, it is only one of many possible alternatives and it is an analytical abstraction with nontrivial implications for economic modelling *(Koopmans, 1977)*. Yet, as far as the literature we survey is concerned, it is adopted as a criterion for "optimal" groundwater allocation without much attention to its links to ethical theory.

Intergenerational issues did not concern the researchers in the groundwater literature, with the exception of a short paragraph in *Gisser (1983)*:

> "Unfortunately previous researchers, when they rushed to provide optimal-control quidelines for groundwater management, assumed that aggregate demand for groundwater is fixed by some Platonic philosopher-king...There is the philosophical problem of the inappropriateness of welfare maximization over an infinite horizon. This is the difficult question of whether the current generation necessarily does a good job of representing future generations."
>
> Gisser, 1983, p. 1002.

Gisser also adopted *Ferejohn and Page's (1978)* argument that the use of the discounted present value welfare function is inappropriate when dealing with welfare maximization over an infinite horizon, because it implies stationarity of the underlying social preference ranking. He concluded however, that the only way out of this problem is to assume that the present generation feels altruistic towards its descendants and thus represents the interests of future generations.

According to *Howarth and Norgaard (1990)* however, an adequate model for addressing this problem must consider a sequence of generations with endowments of assets transferred from each generation to the next. These generations must overlap, permitting the competitive exchange of goods and services between them. Although overlapping generations models have become a standard tool in macroeconomic analysis, their use in natural resource and environmental economics is a relatively recent development[45] not yet adopted by the groundwater literature. Given sufficient intergenerational transfers, cost-benefit analysis may be used to improve the efficiency of groundwater allocation to the benefit of both present and future persons. An augmentation of transfers from present to future generations would probably drive down the rate at which future returns from a basin are reduced to present value terms, and raise the benefits from groundwater management.

Concern over the effects of current policy decisions of groundwater management on future generations is intensified by the presence of suspected irreversibilities. For example, suppose a particular aquifer is threatened by contamination. Remediation of the aquifer would be extremely costly and natural bioremediation may take decades or longer. Also suppose that the aquifer is not currently a significant source of water for human use. There is a chance, because of population growth, that the aquifer nevertheless may become a major source of water for humans in the future. The uncertainty of future population growth combined with the discounting process may result in very low weights being placed on the possible future benefits of protecting the aquifer from contamination, if the sustainability constraint[46] is not incorporated in the solution of this management problem. Consequently, a management policy to protect the aquifer from contamination may not pass a standard cost-benefit analysis, which is the device employed by the literature for making policy decisions.

Moreover, *Tsur and Zemel (1995)* developed a theoretical model of optimal exploitation of renewable groundwater resources when extraction affects the probability of occurrence of an

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[45] Using an overlapping generations framework, *Kemp and Long (1980)* illustrated the problem of dynamic inefficiency for an economy constrained by an exhaustible resource. *Cropper (1990)* examined social willingness to pay to reduce risks to life. *Hultkrantz (1991)* and *Lofgren (1991)* considered the problem of optimal forest management using closely similar models. Finally *Burton (1993)* illustrated the relationship between intertemporal and intergenerational preferences in natural resource allocation.

[46] The principle of sustainable development is central in understanding the importance of using the analytical framework of overlapping generations models when dealing with the dynamics of groundwater resources. Sustainable development has emerged as a unified approach to environmental and development policy. While various interpretations of this criterion have appeared in the literature, a common theme is that current decisions should ensure that members of future generations have access to the resources required to enjoy life opportunities no less satisfactory than our own *(World Commission on Environment and Development, 1987)*. Given the asymmetries of birth and time, the "endowments" of future generations are effectively specified by their immediate predecessors. Hence sustainability is largely a question of ensuring adequate transfers of assets from present to future generations.

irreversible event, where the term irreversible signifies that the event occurrence renders the resource obsolete. They found that uncertainty concerning the event occurrence has a profound effect. The expected loss due to the event occurrence is so high that it does not pay to extract in excess of recharge, even though under certainty (i.e. when the stock level below which the event occurs is known in advance) doing so would be beneficial. Thus uncertainty about the future availability of the resource does eliminate the $\mathcal{GSE}$. This issue is further discussed in the following section of this survey.

2.4.3 Total Economic Value of an Aquifer.

Krutilla (1967) argues that the various categories of value utilized in the determination of *total economic value* are: (a) direct use value, (b) indirect use value, (c) option value, and (d) existence value. All of these values relate to a particular decision making framework, usually whether to conserve or convert some particular natural resource. Direct use values are those which are comparable to those obtained from non-environmental goods and services; these flow from individualized benefits from consumption and production in the non-converted environment. The optimization models employed by the reviewed literature derive only these direct use value of groundwater for the agricultural sector, although these are not the only values relevant for deriving the *"total shadow price of the resource"*. Indirect use value relates to individually received benefits derived from systems remaining intact by reason of non-conversion, e.g. the maintenance of the benefits of a watershed. In chapter 4 of this thesis, we concentrate on methods that aim to derive both direct and indirect use values for groundwater quality, in an effort to investigate whether the indirect component of use value increases significantly the social value of groundwater.

These first two categories of value concern flows of services received by the current generation from the natural asset. As argued in section 2.4.2 however, current user of the resource are not the only relevant agents whose welfare should in principle be considered in deriving the total social value of a resource. In 1964 Burton Weisbrod introduced the concept of option value (OV), which refers to an additional value, over and above the expected value of a good's consumption, that is attached to maintaining a good's future availability when faced with uncertainty about its future demand or supply. As argued by *Freeman (1993, p. 264)* however, "...it is time to expunge option value from the list of possible benefits associated with environmental protection"[47].

In 1974 Arrow and Fisher forwarded a different approach to option value, which represents the value of retaining a given range of options while information is still arriving that may render one of those options important in the future decision making. In particular they demonstrated that relative to a situation in which the decision-maker ignores opportunities for learning, an extra value is attached to preservation when it is realized that one may learn the true benefits of preservation. This extra value they called "quasi-option value". Whether quasi-option value exists or whether it is positive or negative for preservation depends on the nature of the uncertainty[48], the opportunities for gaining information, and the structure of the decision problem. Quasi-option value is not a component of the values individuals attach to resource changes; even if individual's utility functions were known, quasi-option value could not be estimated separately and added into a cost-benefit calculation. Quasi-option value is a benefit of adopting better decision-making procedures. Its magnitude can only be revealed by comparing two strategies where one of the strategies involves optimal sequential decision making to take advantage of information obtained by delaying irreversible resource commitments. Hence optimal groundwater management, should be guided by not only the more traditional evaluation meth-

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[47] Research on OV has shown that it derives from risk aversion (see for example *Graham, 1981; Bishop, 1982; Smith, 1983; Graham-Tomasi and Myers, 1990*). Weisbrod apparently viewed the existence of positive option value as being intuitively obvious. However, *Schmalensee (1972), Anderson (1981),* and *Bishop (1982),* showed that even for a risk-averse individual, option value could be greater than, equal to, or less than zero depending upon particular circumstances. Because of the theoretical contributions of authors such as *Schmalensee (1972), Graham (1981), Bishop (1982) and Smith (1987a, 1987b)*, we can now see that what has been called an option value is the algebraic difference between the expected value of the consumer surplus and the state-independent willingness to pay (option price). Since these two points represent alternatives ways of measuring the same welfare change, the difference between their expected value cannot be a separate component of value. Furthermore, option value cannot be measured separately; it can only be calculated if we have enough information on preferences to calculate both option price and expected surplus. Finally, neither of these points on the willingness-to-pay locus have any particular claim as a superior welfare measure.

[48] The type of uncertainty faced in a hydrogeological environment has been classified as either geological uncertainty or parameter uncertainty *(Freeze et al., 1990)*. Geological uncertainty refers to the uncertainty associated with the location of boundaries between geological units, layers, or zones (i.e. there is an infinite number of potential geological environments). Parameter uncertainty refers to uncertainty in the parameter values that are assigned to each of the blocks that make up the idealized representation of a hydrogeological environment (see section 2.1 of this survey). The degree of uncertainty about either geological or parameter uncertainty can be reduced through field measurements and advancements in the science of hydrology. Moreover, uncertainty arises with respect to the effects of hydrogeological changes on the broader freshwater system an aquifer belongs to, and those affected by it.

ods (such as cost-benefit and environmental impact analysis) but by a pre-posterior analysis of how future information and technology could alter the desired level of development.

"Existence value", often referred to as "nonuse value", is the residual category of value, corresponding to a very wide range of motivations for which individuals might value a stock of the resource. The majority of economists working in the field of environmental and resource economics accept the hypothesis of nonuse values, at least in principle, and many believe that existence values can be large in the aggregate, at least in some circumstances[49]. If they are large, ignoring them in natural resource policymaking could lead to serious errors and resource misallocations. Beyond this, however, there is very little agreement among economists as to terminology, definitions, what motivates people to hold these values and how to measure them empirically. The relevant literature emphasizes the uniqueness or specialness of the resource and the irreversibility of the loss. But there are problems in giving operational meaning to the idea of uniqueness. In economic terms, uniqueness would be reflected in the absence of substitutes and a low price elasticity of demand. But there is no threshold on price elasticity that distinguishes between the presence or absence of close substitutes. Similarly, long-term injury with slow recovery could give rise to nonuse values that are of the same order of magnitude as those associated with irreversible injury. Our understanding is that at the present time there is no general method for determining whether groundwater is sufficiently unique or hydrogeological change due to aquifer economic exploitation is of sufficient duration to generate important nonuse values.

2.5 Groundwater Extraction as a Differential Game.

2.5.1 Open-Loop and Feedback Nash Strategies.

During the last twenty years, environmental and resource economists have recognized that the theory of dynamic games[50] provides an extremely powerful framework for studying many

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[49] Reviews of the evidence bearing on the hypothesis of existence values are *Randall (1991)* and *Freeman (1993)*.

[50] Dynamic game theory models are developed in both discrete and continuous time. The first category encompasses both "repeated games" and "difference games", while the term "differential games" applies to the second

of the classic questions in resource extraction, by providing economists with the possibility to model the dynamic interactions involved in the allocation of scarce natural resources[51]. As argued in section 2.2.3, this development has also attracted the interest of groundwater economics and was employed in order to characterize pumping behaviour when the number of firms is small. Moreover, interesting inference can be derived in comparing the steady-state groundwater level under (a) optimal control, (b) uncontrolled strategic interaction and (c) uncontrolled non-strategic interaction.

Dixon(1989), Negri (1989), and *Provencher and Burt (1993)*, discuss open and closed loop models of pumping behaviour under common property arrangements. In these papers, a firm's strategy is the groundwater extraction plan defining its behaviour in each period of its planning horizon. An equilibrium in Nash strategies is a set of (M) admissible groundwater extraction plans, the jth element of which maximizes the value of groundwater to the jth firm, given the other $(M-1)$ groundwater extraction plans in the set. The precise nature of the equilibrium depends on whether firms pursue path or decision rule strategies. Nash equilibria in path strategies reflect the inclination of firms to take the extraction *paths* of the other firms exploiting the resource as given. Nash equilibria in decision rule strategies reflect the inclination of firms to take the *decision rules* of the other firms exploiting the resource as given. In essence, path and

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case. One of the big advantages of difference and differential games is that they can take into account the fact that most externalities exhibit some form of structural time dependence. That is, not only the flow of external effects is important for the level of environmental damage and depletion, but also the stock or concentration of external effects. To model the dynamic features of these games an analytical framework which can handle intertemporal objective functionals with dynamical constraints (like optimal control theory) is needed. In essence, a differential game results from the combination of an optimal control problem and a game. To be able to solve general differential games, one has to resort to solution techniques developed for optimal control problems with only one decision maker. The two main solution techniques are Pontryagin's minimum (maximum) principle and Bellman's dynamic programming. For an optimal control problem these two methods yield the same solution because of the principle of optimality, but for a differential game the outcomes are generally different. In fact Pontryagin's minimum (maximum) principle (which amounts to a set of necessary conditions that hold only on optimal paths, thus satisfying the Hamiltonian equation) assumes an open-loop information structure, whereas Bellman's dynamic programming by construction leads to a feedback Nash equilibrium. In particular, the central concept in Bellman's dynamic programming is the value function that denotes the costs-to-go for a player at time (t) starting at time (t), given that from time (t) onwards the equilibrium strategies will be played. In continuous time the value functions have to satisfy the so-called Hamiltonian-Jacobi-Bellman equations.

[51] By the early eighties, in the analysis of private exploitation of common property resources the hypothesis of myopic behaviour had already been replaced by the hypothesis of rationality by authors such as *Levhari and Mirman (1980)* in their analysis of restricted access fishery, and *Eswaran and Lewis (1984)* in their study of a common property nonrenewable resource. *Hartwick (1980), Berck and Perloff (1984), Clemhout and Wan (1985) and Van der Ploeg, (1987)* are other examples in the fishery literature, and *McMillan and Sinn (1984), Reinganum and Stokey (1985)* and *Bolle (1986)* in the nonrenewable resource literature.

decision rule formulations of players' strategy spaces correspond to extreme assumptions about players' abilities to make commitments about their future actions. The use of path strategies corresponds to the assumption that commitments extend over the entire future horizon; the use of decision rule strategies corresponds to the assumption that no commitment at all is possible[52].

However, it is becoming apparent in this literature that Nash equilibria in path strategies are not good approximations of extracting behaviour, because it is doubtful that under the common property regime the firms exploiting the groundwater resource will jointly commit to a set of path strategies, especially in light of the stochastic processes which place a premium on flexibility in decision making. The alternative equilibrium concept is a type of *Markov-Nash equilibria*, in which the decision rules of firms at time (t) are a function of only the current values of the state variables[53]. Given that firms usually base their extraction decisions on the observed state of nature, feedback equilibria seem to be a more realistic description of actual behaviour and as a result appear more prominently in the groundwater literature. Moreover, as shown in Negri's groundwater pumping differential game where open-loop and feedback equilibria are theoretically compared, the open-loop solution captures only the pumping cost externality whereas the feedback solution captures both, the pumping cost externality and the strategic externality[54], and exacerbates the inefficient exploitation of the aquifer compared to open-loop solution. Although the existence and uniqueness of the feedback solution are assumed rather than proven by Negri, his result allows us to distinguish between cost and strategic externalities.

In *Provencher and Burt (1993)* optimal and feedback equilibria, computed using discrete-

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[52] Both approaches have been used in the industrial organization literature. For example, path strategies have been used to study investment in a new market *(Spence, 1979)*, the learning curve *(Spence, 1981; Fudenberg and Tirole, 1982)*, the extraction of nonrenewable resources *(Crawford et al., 1980; Dasgupta and Heal, 1979; Lewis and Schmalensee, 1980; Loury, 1980; and Salant, 1979)*, limit pricing *(Flaherty, 1980)*, and cost-reducing investment *(Flaherty, 1979)*. Decision rule strategies have been used to study the arms race *(Simaan and Cruz, 1975)*, the extraction of renewable resources *(Levhari and Mirman, 1982)* and nonrenewable resources *(Stokey, 1981; Eswaran and Lewis, 1984)*, oligopoly theory *(Clemhout et al., 1973)*, and research and development *(Reinganum, 1981, 1982)*. The last four papers describe situations in which the path and decision rule equilibria coincide (in general, open-loop Nash equilibria and linear feedback Nash equilibria differ, unless players do not influence each other's state, so that the game aspect from a differential game disappears). The two types of strategies were first compared and contrasted in *Kydland (1975)*.

[53] *Karp (1990)* refers to such Markov-Nash equilibria as "memoryless feedback" equilibria, because the decisions of firms do not depend on the past behaviour of other firms.

[54] See section 2.2.3 of this survey for the exact definition of these externalities.

time dynamic programming, are compared. The authors explore dynamic inefficiencies via Kuhn-Tucker conditions[55]. They conclude that if the value function is concave[56] then strategic behaviour increases the inefficiency of private groundwater exploitation. They further conclude that the steady-state groundwater reserves attained when firms use decision rules strategies are bounded from below by the steady-state arising when firms are myopic and from above by the steady-state arising from optimal exploitation.

Moreover, *Dixon (1989)*, examined other equilibria involving decision rule strategies known as *punishment strategy (trigger strategy) equilibria.* In the context of groundwater exploitation, these equilibria are typically (though not necessarily) characterized by the result that aggregate welfare is maximized by the credible threat of *all* firms to pump groundwater at sub-optimal rates if *any* firm defects from the optimal rate of groundwater pumping. These equilibria are not memory-less because in a stochastic environment the decision rules of firms in period (t) depend on more than just the state of nature in period (t); they also depend on past behaviour of firms, or equivalently, on the state of nature in period $(t-1)$. However, as economic intuition suggests, *Dixon* found evidence from a survey of farmers in Kern County, California, that when the number of firms using the groundwater resource is large, trigger strategy equilibria are unlikely to evolve.

It has been usual in the differential game literature to resort to *linear* strategies to obtain feedback equilibria (see for instance, *Levhari and Mirman (1980), Eswaran and Lewis (1984)* and *Reynolds (1987)*)[57]. However, since the publication of *Tsutsui and Mino's (1990)* paper,

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[55] Kuhn-Tucker conditions are the first-order conditions necessary for the solution of a concave programming problem, i.e. a problem where function constraints are set as weak inequalities and these constraints as well as objective functions are all concave.

[56] The concavity of the value function (which represents the present value of net returns over an infinite planning horizon under an optimal policy) is intuitively appealing for models of groundwater extraction, because it implies diminishing returns to the resource stock. Nonetheless, the properties of the value function must be derived, not assumed. *Beckmann (1968)* presents the conditions for the concavity of the value function as: (a) a concave criterion function, and (b) a convex constraint set, or as suggested by *Kennedy (1986),* a negative or equal to zero second derivative of resource stock in period $t+1$ with respect to resource stock in period t. In Provencher and Burt's dynamic game, although it is easy enough to assert that the criterion function is concave, the relevant constraint includes the equilibrium solution of the game so it cannot be assumed that a convex constraint set exists. This impasse is broken only when the number of identical extracting firms falls to one, in which case the equilibrium solution is eliminated from the constraint of their maximization problem.

[57] Much research in game theory has focused on the question of whether, in a dynamic context, cooperative outcomes can be made self-enforcing, so that the prisoner's dilemma disappears. The main result in repeated

calculation of *nonlinear* strategies has become more frequent. Tsutsui and Mino examine, for a differential game taking place in a duopolistic competitive environment with sticky prices, whether it is possible to construct a more efficient feedback equilibrium using nonlinear strategies. They conclude that it is not possible to construct a feedback equilibrium which supports the cooperative or collusive price, in other words, it is not possible to get a result equivalent to the Folk theorem in repeated games. Nevertheless, they find that there exist feedback equilibria which approach the cooperative solution more than the open-loop equilibrium. In the context of environmental economics literature *Dockner and Long (1993)* have obtained results identical to the ones shown by Tsutsui and Mino for a symmetric differential game of international pollution control with two countries, and *Wirl and Dockner (1995)* have proved that cooperation between an energy cartel and a consumers' government is not necessary to reach the efficient long-run concentration of CO_2 in the atmosphere. These precedents point to possibilities of future research as far as the groundwater differential game is concerned. That is one could compute the feedback equilibria of the groundwater pumping differential game resorting to nonlinear strategies, with the aim of examining whether strategic behaviour plays *against* the efficiency of the solution and increases the probability of elimination of the $\mathcal{GSE}$, as has been established by Negri and Provencher and Burt; or whether strategic behaviour plays *for* the efficiency of the solution and further increases the probability of persistence of the $\mathcal{GSE}$, as seems to happen in Tsutsui and Mino, Docker and Long and Wirl's papers.

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games is the well-known "folk theorem"; that is, playing trigger strategies any feasible, individually rational payoff can be sustained in a (subgame-perfect) Nash equilibrium as long as each player has a payoff at least as large as what that player can guarantee for him/herself and as long as the players are sufficiently patient *(Fudenberg and Maskin, 1986)*. However, a similar result has not yet been developed for differential games. Some research has been done on closed-loop memory equilibria in which the players can condition their actions not only on the current state but also on the past states. In this framework equilibria exist which are a Pareto improvement over the linear feedback Nash equilibrium, but this line of research was not pursued any further. The most promising development has been the discovery of non-quadratic value functions that satisfy the Hamilton-Jacobi-Bellman equations of a symmetric linear-quadratic differential game with one state variable and an infinite horizon. These value functions lead to non-linear feedback Nash equilibria that can almost sustain the cooperative outcome *(Tsutsui and Mino, 1990)*. To be precise Tsutsui and Mino showed that, as the discount rate approaches zero there exists a steady-state feedback equilibrium that asymptotically approaches the steady-state cooperative or collusive price. A drawback of this approach, is that equilibrium strategies become very complex and it is questionable whether they have any practical relevance. *Ceşar (1994)*, however, showed how simpler trigger strategies can be used to make cooperation sustainable in a differential game. By considering outcomes on the Pareto frontier only, he proves that the folk theorem holds for a particular type of differential games. Theses game theoretic developments could provide us with interesting ways to secure cooperation in groundwater extraction models.

Furthermore, the combination of the literature of dynamic game theory with the literature on uncertainty/irreversibility, can give interesting insights to the problem of how to secure cooperation to reduce groundwater depletion and how to respond to the considerable uncertainty about the extent of resulting damages of groundwater depletion on the various users interlinked through wetland ecosystems. *Ulph (1998)* shows that by combining the two literatures, some of the results from the separate literatures are not robust. Specifically, the conclusions about the differences in resource depletion rates between cooperative and non-cooperative equilibria carry over to a world of uncertainty and learning, as do the conclusions about the benefits from cooperation. However, the conclusions from the literature on uncertainty, irreversibility and learning for a single decision maker do not generalize to a world of many players acting non-cooperatively: in a non-cooperative equilibrium better information could make all players worse off. This possibility of information having a negative value arises when externalities have very different implications in terms of costs and benefits for different players, which, as argued in section (2.2.4), is a plausible configuration in the extraction of groundwater from a heterogeneous aquifer. Once again we point to the need for more theoretical work to resolve an asymmetric groundwater pumping differential game under uncertainty and establish whether irreversibility and learning plays against the efficiency of the non-cooperative solution of the extracting game; a result that could eliminate or reduce the significance of the $\mathcal{GSE}$.

2.5.2 Private Property Rights Regime in a Commons Aquifer.

The remedy usually prescribed by the literature for the inefficiencies arising in common property groundwater extraction, is central (optimal) control by a regulator, who uses taxes or quotas to obtain the efficient allocation of resource over time. When differential games are used in the general environmental literature, the instrument considered to implement the full-cooperative outcome is, apart from side payments, a tax or a tradable permit scheme[58]. In the context of groundwater depletion *Young and Bredehoeft (1972), Smith (1977)*[59], *Gisser*

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[58] For example, *Hoel (1993)* studied the impact of imposing a carbon tax and showed that a tradable permit scheme can achieve the same result as a tax.

[59] *Smith (1977)* was the first to suggest privatizing the groundwater resource.

(1983), *Anderson et al. (1983)*[60], *Provencher (1993)*[61] and *Provencher and Burt (1993, 1994)*, suggested a similar institutional arrangement in which private shares to the groundwater stock are established. In these works privatization does not mean that groundwater users are assigned particular units of groundwater stock - say for instance, those units directly beneath their land. Such a scheme would be impossible to operationalize, due to the fugitive nature of the resource. Nor did they mean that firms hold permits assigned each year by a regulator controlling the annual aggregate level of groundwater pumping[62]. In their framework, firms are granted an endowment of tradeable permits to the *in situ* groundwater stock, which they control over time[63]. Each firm's bundle of permits represents its private stock of groundwater. This private stock declines due to groundwater pumping and increases to reflect the firm's share of periodic recharge. It also changes in response to the firm's activity in the market for groundwater stock permits, increasing when permits are purchased and decreasing when permits are sold. As a practical matter, the market price for permits serves to allocate groundwater over time.

This particular regime is economically inefficient; both the pumping cost externality and the risk externality (present in stochastic frameworks, where groundwater is treated as a buffer to surface water drought) persist after the allocation of permits[64]. Moreover, this regime is time-inconsistent[65]. However, attempts to quantify the value of groundwater resource under

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[60] *Anderson et al. (1983)* were the first to informally analyze groundwater privatization. In particular, they pointed out that privatizing the groundwater stock eliminates the stock externality, but not the pumping cost externality. In this light, the relative merit of the privatization scheme rests with the relative importance of the stock and pumping cost externalities; where the stock externality is a significant source of overpumping, and the pumping cost externality is unimportant, the privatization scheme could prove to be a practical alternative to central control. Moreover, they suggested that a private property rights regime may provide firms with risk benefits not available under central control. The next section of this survey elaborates on the treatment of risk externality in the context of groundwater extraction.

[61] In particular, *Provencher (1993)* examined in a deterministic setting the applicability of the tradable permit scheme for the case where the groundwater resource is already pumped "too deep," that is, beyond the optimal steady-state, and the task of the regulator is to return the water table to its optimal steady-state.

[62] *Gisser (1983)* refers to such permits as "groundwater pumping rights," but clearly such a permit system is simply a way to operationalize a depletion path guided by central control.

[63] *Dudley (1988)* examines this arrangement in the context of reservoir management, and refers to it as "capacity sharing".

[64] The inefficiency of the private property rights regime let economists to generally overlook this regime as a means to manage resources like groundwater. For instance, *Dasgupta and Heal (1979),* discuss the futility of privatizing fugitive resources like groundwater and oil. Their argument concerned regimes granting firms entitlements to particular units of the resource. As argued above however, in the private property rights regime proposed in the groundwater literature, a firm is entitled to a particular number of units of the resource, via its endowment of permits, but is not entitled to particular units of the resource.

[65] As argued by *Provencher (1993)*, "... the most problematic aspect of the private property rights regime

both central (optimal) control and the private property rights regime indicate that groundwater privatization recovers most of the potential gain from management. In particular, in *Provencher's (1993)* programming model of Madera County California this regime recovered 95% of the potential gain from management[66]; likewise, in a somewhat more complicated stochastic dynamic programming model of the same region, *Provencher and Burt (1994)* found that the private property rights regime recovers about 80% of the expected welfare gain from groundwater management. Given that under a private property rights regime both the pumping cost and the risk externalities persist, these findings may be attributed to the fact that this regime is more capable than others to exploit the private information held by firms. They may also suggest that the risk and pumping stock externalities are not important factors contributing to the inefficiency of unconstrained groundwater extraction. In the next section of this thesis we review research that investigates whether the elimination of the risk externality, contributes to the elimination of the $\mathcal{GSE}$ in stochastic frameworks of groundwater extraction.

Significantly, although the private property rights regime recovers a relatively large proportion of the potential gain from groundwater management, this gain is relatively small, in agreement with $\mathcal{GSE}$. In particular, *Dixon (1989)* found that control raised the net benefit of

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is not its economic inefficiency ... but rather its *time-inconsistency".* Time inconsistency is the conundrum faced by regulators whose optimal policy depends on the initial state of nature. In general, there are two versions of dynamic consistency: the weak and the strong version. *Weak time-consistency* requires that along the equilibrium path, the continuation of a Nash equilibrium strategy remains a Nash equilibrium. *Strong time-consistency* implies subgame perfection, requiring that this property holds at every subgame, not just those along the equilibrium path. For example, the path strategy Nash equilibrium is dynamically consistent, but not subgame perfect for $K \geq 2$, where K is the number of periods in a path strategy game. Dynamic inconsistency is frequently a feature of games with leader / follower structure. There is a sizable macro-economic literature on this topic, while *Newbery (1981)* provides an analysis of dynamic inconsistency in a resource extraction context. As far as the private property rights regime is concerned, the positive price of groundwater stock permits is derived not from the regulator's initial allocation of groundwater stock permits, but rather from the regulator's initial allocation of stock permits implied by the first binding minimum. Typically the minimum water table that maximizes welfare given the current state of the resource is not the same one that would maximize welfare given the state of the groundwater resource in the future. This conundrum reflects the time inconsistency of policy instruments *(Kydland and Prescott, 1977).* In the context of the implementation of the private groundwater property rights regime, a credible solution to the time inconsistency problem, suggested by *Provencher and Burt (1994)*, is to set the minimum water table at its steady-state level, as determined from the regulator's optimization problem, and to deny the regulator the discretionary power to change this minimum. In a strict sense this approach is usually suboptimal, but it nonetheless goes a long way to ensuring the viability of the private property rights regime.

[66] Although *Provencher's (1993)* theoretical model was formulated in a deterministic framework, he used a stochastic dynamic programming model for his empirical analysis. The only source of uncertainty that he introduced in his empirical model is the stochastic delivery of the Central Valley Project to one of the groundwater basins he considered in his three-cell aquifer model.

groundwater in the Kern County California by 0.3 percent, *Provencher (1993)* found that control raised the value of groundwater resource of Madera County California by 2-3 percent and *Provencher and Burt (1994)* by 4-5 percent for the same basin[67]. In this regard, the simulated value of groundwater stock of the Central Valley under the private property rights regime, is the latest contribution to the recent literature finding low returns to groundwater management.

Still, the conclusion that there is no need to manage the Central Valley's groundwater resource would be premature. The low returns to groundwater management in Kern and Madera Counties reflect the large surface water delivery to the county. In areas where surface water deliveries are not so large, or where future surface water supplies dwindle as water is redirected to urban uses, groundwater management could yield large welfare gains. Moreover, when firms are risk averse the private property rights regime offers potential benefits from risk management not available under the common property arrangement[68]. As already argued in this section of the thesis, the theoretical models developed by *Provencher (1993)* and *Provencher and Burt (1994)* do not acknowledge the stochastic nature of groundwater recharge, whereas their empirical models are developed in a stochastic framework where firms are assumed to be risk neutral. The next section reviews recent developments in the groundwater literature that not only acknowledge the stochastic nature of groundwater recharge in their theoretical representations, but they also take into account the hydrologic link between surface water and groundwater resources.

2.6 Models of Tributary Aquifers and Stochastic Surface Supplies.

In *Gisser's (1983)* taxonomy aquifers are categorized in the following three major natural forms: (a) aquifers that are neither interconnected with surface water nor benefited by substantial natural recharge [e.g. the Ogallala basin (which underlines part of Texas, New Mexico, Oklahoma, Colorado, Nebraska, and Kansas) and the Tucson basin in Arizona]; (b)

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[67] Table 2.6.1 in section 2.6 of this chapter, summarizes the results of empirical investigations conducted from the mid eighties until today.

[68] We further discuss this issue in section 2.6.2.

aquifers that are not interconnected with surface water but benefited by substantial natural recharge [e.g. the Kern County aquifer in California]; and (c) aquifers that are interconnected with surface water and are either benefited by substantial natural recharge or not benefited by considerable recharge [e.g. the aquifer of the Rio Grande, which is interconnected with the Rio Grande]. A *tributary* aquifer is characterized by a groundwater stock that is hydrologically connected to a body of surface water and as such falls under category (c) of Gisser's taxonomy. In a tributary aquifer, surface water may recharge the underground aquifer, or groundwater may supplement surface flows depending upon hydrological conditions.

2.6.1 Tributary Aquifers with "River Effects".

As mentioned in section 2.3.1, the first and most extensive studies of conjunctive use of surface water and groundwater is found in *Burt (1964, 1966, 1967, 1970)*, where groundwater stocks were modelled as partially renewed by a stochastic process. Burt's analysis, however, modelled surface water and groundwater as substitute goods, abstracting from the problems associated with the lagged hydrologic effect present in a tributary aquifer. Subsequently, *Nieswand and Granstran (1971)* attempted to incorporate the so called "river effects" into a model of conjunctive use water management. These are the effects of connection between a groundwater stock and a body of surface water. However, their focus was more on the relationship between uncertain river flows and the availability of water than on the link between pumping and surface water supply. Moreover, *Young et al. (1986)* considered the case of the farmers in Colorado relying on the South Platte River for irrigation water, which were found to be adversely affected by pumping from a groundwater deposit associated with the river.

Burness and Martin (1988) were the first to develop an analytical economic model which focused primarily on the hydrologic link between surface and groundwater, by modelling the instantaneous rate of aquifer recharge caused by groundwater pumping, through river effects. They modelled such river effects as externalities which reinforced groundwater overpumping present due to the usual common property effects. Their conclusion was that optimal policy requires compensation to be paid for both river effects and aquifer depletion net of river effects. This work points to an additional externality created by groundwater pumping that can be corrected with the appropriate management, and potentially increase the significance of groundwater management benefits to the society. However, Burness and Martin did not proceed to an empirical estimation of these benefits.

2.6.2 Conjunctive Use of Groundwater with Stochastic Surface Water Supplies.

Unfortunately, there exists no literature on models focusing primarily on the hydrologic link between ground and surface water and at the same time acknowledging the stochastic nature of surface water supplies. Instead, the literature on stochastic surface supplies adopted *Burt's (1964)* analysis, where surface water and groundwater are modelled as substitute goods and aquifers are not interconnected with surface water, but are benefited by substantial natural recharge; that is, aquifers that fall under category (b) in *Gisser's (1983)* taxonomy. One of the interesting issues that arises in this context, is whether a groundwater resource is more valuable in a stochastic setting than in a deterministic[69] one.

Feinerman and Knapp (1983) were the first to investigate the case of stochastic surface supplies which they assumed to be independently and identically distributed normal random variables. They found that the probability distribution of the lift converged to a steady-state distribution with constant variance and a mean equal to the deterministic steady-state. Moreover, expected benefits from groundwater management in Kern County in California under uncertainty, were found to be similar to expected benefits under certainty. As a result the authors did not pursue the uncertainty case any further. *Tsur (1990)* and *Tsur and Graham-Tomasi (1991)* however, argued that economic intuition suggests that groundwater is undervalued in a deterministic setting, because such a setting fails to consider the role of the resource as a buffer against surface water drought. This intuition was supported by simulations for the Negev Desert in Israel reported in Tsur and Graham-Tomasi. The authors found that the buffer value of groundwater ranged from 5% to 84% of the total value of the resource, depending on extraction costs, the variability of surface water inflows, and aquifer size.

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[69] The typical approach of removing uncertainty from a model is to fix random variable at their means.

Interestingly however, the positive sign on the buffer value is an empirical result, not a theoretical one. That is, one cannot rely solely on microeconomic “first principles” to prove that groundwater is undervalued in a deterministic analysis; additional assumptions are necessary. Under central (optimal) control the buffer value is positive if the firm-level *unconditional* expected present value of net revenues from groundwater consumption, is greater than the firm-level *conditional* (i.e. conditional on random surface water supplies being fixed at their means) expected present value of net revenues, for all feasible values of the groundwater stock. By *Jensen’s inequality*[70], this relationship holds if the value function is convex in surface water supplies for all feasible values of groundwater stock. In *Tsur and Graham-Tomasi’s (1991)* model, such is the case if (a) net revenues are *concave* in groundwater at time (t) and the total volume of water consumed at time (t), and (b) the third derivative of the water revenue function is not negative over the economically relevant range of consumed water volume. Condition (b) is not sustained by “first principles” alone. Recalling that the derived demand for water is the inverse of the revenue function, this condition requires that the demand for water is convex. Although this is certainly plausible, and perhaps empirically prevalent, its violation does not violate the standard assumptions of the neoclassical paradigm. Generally, if we accept that in the real world the buffer value of groundwater is usually positive, then deterministic analyses usually underestimate the scarcity value of the resource, and the benefits derived from managing this resource.

Moreover, *Provencher and Burt (1993, 1994)* argued that managing groundwater by adopting the regime of private tradeable water permits[71], may generate considerable welfare in a stochastic framework by providing opportunities for risk management[72]. Figure (3.6.1) provides an illustrative example of how the groundwater stock affects income risk. As drawn, this

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[70] *Jensen Inequality Theorem:* Let ξ be a random variable from a probability space $(\Omega, \mathcal{B}, P)$ into a finite closed interval on R and let q be a convex function on R. Then for any sub-σ-algebra $\mathcal{B}_o$ of $\mathcal{B}$,

$$q[E^{\mathcal{B}_o}(\xi)] \leq E^{\mathcal{B}_o} q(\xi) \tag{i}$$

Particularly

$$q[E(\xi)] \leq E q(\xi) \tag{ii}$$

Corollary: (i) and (ii) hold for any random variable ξ into any closed subset of R provided that the conditional expectations $E^{\mathcal{B}_o}(\xi)$ and $E^{\mathcal{B}_o}[q(\xi)]$ exist. *(Source: Bergström, 1982, p. 73-6).*

[71] See section 2.5.2 for the exact description of this regime.

[72] See section 2.2.1 for the exact definition of risk externality.

figure reflects the simplifying assumptions that surface water is delivered to firms at no cost, and groundwater pumping is costless. Under these assumptions surface water and groundwater are perfect substitutes; thus there is no economical reason to distinguish among them in the production process. Hence, production income in period 2 (of a two-period model) may be expressed as a function of only the firm's total water consumption, denoted by (w_2). Moreover, production income is a drawn by assumption as a monotonically increasing and concave function of water consumption.

Figure 3.6.1: The effect of the total groundwater stock on income risk.
Source: Provencher and Burt (1994).

Given the situation described by this figure, each of the (M) identical firms consumes $(w_2 = q_2 + x_2/M)$ units of water in the terminal period, where (q_2) is each firm's random exogenous water allocation in period 2 and (x_2) is the basin-wide stock of groundwater in period 2. Hence, the magnitude of the total groundwater stock has a mean-shifting effect on the distribution of the firm's water consumption, shown in the figure by presenting two particular density functions of water consumption $(f_w \mid \widetilde{x}_2)$ and $(f_w \mid \widehat{x}_2)$, that have the same shape but are positioned differently. In particular, the former density function is characterized by a high level of total carryover stock, $(\widetilde{x}_2)$, while the latter density function is characterized by a low level of total carryover stock, $(\widehat{x}_2)$[73]. The density functions of production income are identified by the notation $(f_h \mid x_2)$, and are obtained graphically by using the income curve $(h(w_2))$ to map the density function of water consumption into the probability space of production income. The figure shows that, insofar as production income is concave in water consumption, the distribution of a firm's income from productive activities is more compact - that is, less risky - at relatively high levels of total groundwater stock than at relatively low levels. As stated by *Provencher and Burt (1994),* the intuition behind this result is straightforward: when the stock of available groundwater is large, water is not scarce, and so productive activities are insensitive to the vicissitudes of surface water supply.

Furthermore, *Provencher and Burt (1994)* argue that the negative correlation between production income and income from groundwater stock permits (that is, water scarcity reduces production income but increases the price of groundwater stock permits, thereby increasing stock trade income) provides a means of risk management not available under central control. Additional means of managing the riskiness of water consumption include among others, the construction of surface reservoirs, the use artificial recharge[74] and the production of desalination water. That is, surface water inflows are not necessarily purely exogenous; water managers can exert some control over inflows. By Jensen's inequality, because the water revenue function is concave in water consumption, surface water inflows are more valuable when fixed at their mean value, than when drawn from the natural distribution of inflows. This result suggests the potential for welfare gains from "smoothing" surface water inflows. Note, however, that this rationale is diminished by the presence of groundwater, which is itself a source of water consumption "smoothing". In this context, the buffer value of groundwater is the welfare gain from

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[73] All density functions in the figure are associated with density axes that are suppressed for the sake of clarity.

[74] The variability of net revenues can be further reduced by using "excess" inflows in wet periods to recharge the groundwater resource, thereby reducing groundwater pumping costs in dry periods. *Reichard and Bredehoeft (1984), Danskin and Gorelick (1985), Pyle (1988), Danskin (1990), Pyle and Iger (1990)* have studied the practice of diverting surface water to groundwater.

postponing (perhaps indefinitely) those inflow-smoothing surface water projects which would prove economical to undertake immediately in the absence of groundwater. In other words, because groundwater is available, costly projects to smooth surface water flows - projects which would otherwise pass a benefit-cost test - are optimally postponed.

The question that remains to be answered, however, is whether the buffer value of groundwater is significant enough to make the return to groundwater management practically significant. The answer to this question turns on the relative magnitude of the buffer values under central (optimal) control and the common property arrangement. If the buffer value of the groundwater resource is about the same under the common property arrangement as under central control, the common practice in groundwater literature, of calculating the return to groundwater management in a deterministic setting provides a good estimate of the "true" return to management. Still, this is once again an empirical question. A relevant study[75] is the one by *Knapp and Olson (1995).*

Knapp and Olson's (1995) analytical solutions for optimal management and common property regimes were characterized using lattice programming methods[76]. In particular, they considered joint operation of a surface reservoir and groundwater aquifer, where reservoir inflows are stochastic and outflows can be used for irrigation or for recharge to the aquifer[77]. By contrasting efficient groundwater use to common property use they find that common property withdrawals are larger than efficient withdrawals for similar values of the state variables, resulting in significantly greater pumping depths in the steady state. Despite this however, they

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[75] As indicated in section 2.5.2, *Provencher (1991)* and *Provencher and Burt (1994)* used stochastic dynamic programming models in their empirical analyses, but their theoretical treatment of the optimization problem was deterministic.

[76] For a state of the art analysis of lattice programming methods see *Milgrom and Shannon (1994).* Although these methods have received relatively little attention in resource and environmental economics (variations of these methods have been used in the literature on renewable resources by *Sobel (1975)* and *Mendelsohn and Sobel (1980)*) they appear quite promising as they allow analysis where stock effects on extraction costs imply nonconcave objective functions. For renewable resources in general, the annual net benefit function may be nonconcave due to stock effects on costs. Such nonconcavities create two difficulties: optimal policies may not be unique-valued functions of the state variables, and the analysis of optimal policies cannot be based on the concavity of the value function. Lattice programming methods developed by *Topkis (1978),* provide a direct and convenient way to characterize the behaviour of optimal policies in such settings: if the objective function in an optimization problem exhibits a specific form of complementarity, then *optimal* decisions vary monotonically with the underlying states or parameters.

[77] In their analysis groundwater is treated as a renewable resource (see section 2.2 of this chapter for a brief discussion on the intuition of this treatment).

found that the benefits from groundwater management are relatively small. In particular, the expected present value of net benefits under common property operation was found to be equal to 5.04 billion dollars in contrast to 5.17 billion dollars under efficiency. In their framework, this implied annualized benefits from groundwater management in Kern County of roughly 7 dollars per acre of farmland per year. Based on these results, it seems that the $\mathcal{GSR}$ prevails in stochastic frameworks as well. Interestingly however, the mean and standard deviation for annual net benefits in the limiting distribution were \$209 and \$25, respectively, under optimal management, and \$192 and \$30, respectively, under common property. Hence, optimal management does reduce the variability of returns, so benefits may be larger under risk aversion; an indication that empirical work in this literature should aim towards constructing empirical models with risk aversion[78].

Table 2.6.1 summarizes the empirical evidence on the robustness of the $\mathcal{GRE}$ from mid eighties onwards. The main conclusion that can be derived from this table is that the $\mathcal{GRE}$ persists in economic frameworks characterized by time-varying economic relations, as well as in stochastic frameworks. However, as already argued, optimal management does reduce the variability of returns, an empirical result that suggests that benefits may be larger in models that depart from risk-neutrality and explicitly take account of risk aversion. Moreover, in section 2.6.1 we argued that in tributary aquifers optimal management may produce significant benefits by eliminating not only the cost, stock and risk externalities, but also by internalizing the so called "river effects" that can be significant (although this argument has not yet been tested empirically). Furthermore, in section 2.5.1 we argued that incorporation of uncertainty, irreversibility and learning in a groundwater extraction game may increase the inefficiency of uncontrolled water pumping and further increase the benefits from management. In addition, in

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[78] Risk is pervasive in agriculture and as a result agricultural economists have frequently incorporated risk preferences into their analysis. Farmers with dynamic decision problems typically confront intra-year risk because profits are not deterministic in given decision-state combinations, and inter-year risk because state transition processes are stochastic. However due to the inherent complexity of the problem of incorporating risk in the framework of dynamic programming, most researchers applying this technique have assumed that farmers are risk neutral. The handful of stochastic dynamic programming applications that have incorporated intra-year risk aversion *(Karp and Pope, 1984; Young and van Kooten, 1988)* encounter two main theoretical objections. They violate the independence axiom of expected utility theory and they assume risk neutrality toward inter-year risk *(Krautkraemer et al., 1992)*. How important are these theoretical problems in applied research remains to be investigated. On the whole more theoretical and empirical research is needed to properly reflect the influence of risk aversion on optimal dynamic programming solutions.

section 2.4.3 we argued that there are other components to the total economic value of water in an aquifer, over and above the direct use value of the resource which is captured by the reviewed models; thus the possibility of significant management benefits derived from preserving these values. Finally, in section 2.4.2 we argue that it is economically intuitive to decrease the discount rate used in empirical comparisons of optimal and no control of groundwater extraction, which as established in section 2.3.3 increases management benefits. All these are suggestions for future research that can potentially resolve the $\mathcal{GSE}$ paradox. However, there already exists empirical work that constitutes an exception to the persistence of the $\mathcal{GRE}$. In section 2.4.1 and in the table below, we mention the empirical results derived by *Brill and Burness (1994)*, where a significant increase in management benefits is observed when demand for groundwater is non-stationary. This empirical result reinforces the conclusion derived from table 2.3.1. of this survey, which emphasizes the sensitivity of the $\mathcal{GRE}$ to the shape and properties of groundwater demand function.

Table 2.6.1: Testing the Robustness of GSE (1986 - today).

Authors	Model	Welfare Gains[1]	Basin and Location	Recharge
Kim et al. (1989)	Adaptation to Depletion	1-3.7% (r=5-2%)	High Plains, Texas	Moderate
Dixon (1989)	Stochastic DP	0.3% (r=5%)	Kern, California	Substantial
Provencher (1991)	Stochastic DP	2-3% (r=5%)	Madera, California	Substantial
Brill & Burness (1994)	Demand Growth (2% p.a.)	16.85% (r=1%)	Ogallala, California	Negligible
Provencher & Burt (1994)	Stochastic DP	4% (r=5%)	Kern, California	Substantial
Knapp & Olson (1995)	Stochastic OC	2.6% (r=5%)	Kern, California	Substantial

[1] Welfare gains = net returns (OC) − net returns (NC). Does not consider costs of optimal basin management.

2.7 Conclusion.

2.7.1 Summarizing Possible Rationalizations of $\mathcal{GSE}$.

Indeed, the sensitivity of the $\mathcal{GSE}$ to the demand function is the central result of this chapter. As established in section 2.3.2 the $\mathcal{GSE}$ effectively states that if the slope of the demand equation is small relative to the storage of the aquifer, then the difference between the socially optimal and the private exploitation of the aquifer, represented by the myopic competitive-commonality equilibrium, is insignificant for all practical purposes. Even before the identification of the $\mathcal{GSE}$, a well-established view that *Kelso (1967)* has characterized as the "the water-is-different syndrome" maintains that the derived demand for irrigation water is price inelastic (the price elasticity of demand is defined as the percentage change in quantity demanded resulting from 1% change in price, that is $n = -\left(\frac{\Delta Q}{\Delta P}\right)\left(\frac{P}{Q}\right)$, where (P) is price and (Q) is quantity) and thus changes in prices will redistribute income to or from farmers but not alter significantly water usage in agriculture. Thus the accuracy of estimates of price elasticities of demand for irrigation water is extremely important in predicting producer reactions to future changes in relative water prices and inferring whether managing groundwater will have a significant positive effect on total welfare.

However, a significant problem exists in empirically testing this hypothesis. The absence of observations over a wide range of prices has necessitated the use of programming approaches to estimate the elasticities of the derived demand for water. Linear programming studies by *Moore and Hedges (1963), Gisser and Mercado (1972), Heady et al. (1973)* and *Hedges (1977),* have tended to support the contentions that the demand for irrigation water is inelastic. However, *Shumway (1973)*, also using linear programming found that the demand for irrigation water was elastic in the price range of $9-16 per acre-foot in 1965 relative prices. On the whole, however the indication from previous research into the impacts of water demand generally shows a relatively inelastic demand relationship though admittedly the evidence is not conclusive.

Another related point worth making, is that groundwater demand for irrigation purposes is not the only relevant one. Aquifers have historically been a clean source of water for domestic, industrial and commercial purposes as well. Studies of the demand for water carried out in the past for different parts of the world and at different times, show that the price elasticity of various classes of water demand as well as total water demand, is significantly different from zero. These studies have invariably attempted to regress demand for water against such variables as price, income, wealth, climate, etc. A summary of the findings of a number of these studies is provided by *Herrington (1987)*, where it is argued that price elasticity of demand for water lies somewhere in the range of (0.0) to (-0.3), again indicating inelastic demand schedules. Hence one could conclude that the shape of real world demand curves for this resource, is probably one of the main causes of the $\mathcal{GSE}$.

Moreover, in section 2.2.4 of this chapter we argued that when the lateral groundwater movement is slow, externality effects are insignificant and private decisions of firms maximize social welfare. However, slow lateral water movement is a characteristic of homogeneous aquifers only and not a general aquifer characteristic. Furthermore, in section 2.5.1 we indicated that the steady-state groundwater stock in an uncontrolled game theoretic environment is higher than the steady-state groundwater stock in an uncontrolled competitive environment. This result suggests that if real world groundwater extraction is strategic, then management benefits will be even smaller than benefits from managing competitive, non-strategic extraction. Finally, as argued in section 2.6.2, the buffer value of groundwater in a stochastic framework is not always positive, a result one cannot guarantee the increase in management benefits when the stochastic nature of surface water supplies, that are used conjunctively with groundwater, is acknowledged.

However, this is not to say that there exist no need for groundwater management. On the contrary, in this chapter we have identified a number of circumstances that have or may potentially render groundwater management significantly welfare increasing. Firstly, *Worthington et al. (1985)* have pointed out in an empirical work, that the difference between the optimal control and competitive regimes may not be trivial in confined aquifers if the relationship between the average extraction cost and the water table level is not linear and there are significant differences in land productivity (see section 2.3.3). This result points to the need to develop more empirical work to derive a good approximation of the shape of marginal cost of extraction curve, and more theoretical work to resolve an asymmetric groundwater pumping differential game where the differences in land productivity are taken into account. Secondly, *Brill and Burness (1994)* derive the same empirical result with non-stationary groundwater demand (see section 2.4.1), which points to the importance of allowing time-varying economic parameters in infinite horizon optimal control models.

Thirdly, in section 2.4.2 we argue that driving interest rates down, in the light of suspected irreversibilities and uncertainty about future water demand and supply, would raise groundwater management benefits. Moreover, in section 2.5.1 we argue that incorporation of uncertainty, irreversibility and learning in a groundwater extraction game may increase the inefficiency of uncontrolled water pumping and further increase management benefits. Fourthly, in section 2.4.3 we argue that there might exist additional components of value in groundwater preservation, over and above "direct use values" that are considered in the literature under investigation. Taking account of "indirect use", "quasi-option" and "existence values" of groundwater, could increase the benefits from management if the sum of these values is significant. Fifthly, in section 2.6.1 we argue that in tributary aquifers it is possible that additional negative externalities are involved in groundwater extraction, over and above the three groundwater stock externalities identified in section 2.2.1, such as presence of the so called "river effects". Correcting for these externalities as well as the stock externalities, could potentially increase management benefits and reduce the relevance of the $\mathcal{GSE}$. Finally, in section 2.6.2 we argue that already existing stochastic differential games and optimal control models in the groundwater literature, assume risk neutrality and are not able to estimate possible management benefits from reduction in the variability of returns that could arise in a risk averse environment.

2.7.2 Motivation of Consecutive Research.

The $\mathcal{GSE}$ in essence states that in *certain circumstances* there may be a negligible numerical difference between competitive and socially optimal rates of water pumping from an underground aquifer; i.e. the numerical magnitude of the various pumping cost and common property externalities is insignificant. This result implies that marginal cost pricing of the resource is approximately efficient and that the *in situ* scarcity value of the resource is negligible. Clearly, if this result extends to a general rule then the role and scope of water management policy are severely limited. That is, a corollary of the $\mathcal{GSE}$ is that the potential benefits associated with the regulation of the resource are relatively small, so that from an economic point of view (i.e. using cost-benefit analysis), regulation of the resource could not be advised. However, the evolution of economic thought indicates that such simplified models as the one introduced by *Gisser and Sanchez (1980 a, b)* often lead to strong theorems and clear-cut results; the danger is that abstraction from reality may often bias results in directions inconsistent with real world behaviour.

This result motivated consecutive research in this thesis. More specifically, the research in chapters 3 and 5, builds on two different economic methodologies to develop appropriate theoretical and empirical models relevant for measuring the scarcity value of *in situ* groundwater; these measures are used in the derivation of inferences on the potential of managing this resource. As already argued, if social groundwater scarcity rents are significant but not incurred by current resource users, then groundwater extraction is dynamically inefficient and some form of management is needed (not necessarily price management). If the scarcity rents of the resource are insignificant then marginal cost pricing of groundwater extraction is approximately optimal, and groundwater management is not needed. Moreover, chapter 4 combines and builds on two existing economic literatures in order to provide a methodology for deriving an accurate measure of willingness to pay for improved groundwater quality, which arises from the scarcity of this attribute of groundwater and its role in enchancing individuals' well-being. Once again, inferences on the appropriate management of the resource under consideration are derived.

Consecutive models are deterministic because, as argued in section 1.3, empirical research is based on data from a semi-arid region where natural recharge of the resource is insignificant. In particular, the empirical application of the three models developed in this thesis concern the Kiti aquifer, situated in a coastal region in the island of Cyprus. This aquifer suffers from serious depletion and quality deterioration and faces the danger of complete exhaustion of its water in the near future. Thus, the assumption of infinite hydraulic conductivity (that implies that the aquifer will never dry up irrespective of groundwater extraction rates) adopted by all models reviewed in this chapter[79], should not and does not characterize our theoretical and empirical investigations. Moreover, the Kiti aquifer is a small aquifer as far as storage

The material in chapter 3 is a direct extension of the reviewed literature. The key contribution of this chapter is the explicit recognition of the potential for infinite production of water through the existence of a backstop technology. In particular, we develope a model that derives groundwater scarcity rents and management benefits under the assumption of endogenous adaptation to a backstop technology that allows infinite production of water to the indefinite future. The availability of a backstop technology is a realistic aspect of groundwater management that has been ignored by the relevant literature and can potentially contribute to the elimination of the $\mathcal{GSE}$. The derived solutions of this model under optimal and no-control of groundwater extraction, provide the benchmarks for inferences on extraction behaviour implied by the econometric estimates of scarcity rents derived in the two consecutive chapters of the thesis. Chapter 4 combines the hedonic and travel cost methods, in order to develop a hedonic model consistent with endogenous selectivity, for indirect estimation of the marginal willingness to pay for scarce groundwater quality, from data on land prices and land characteristics. Chapter 5 derives the shadow price of groundwater by employing a method prevalent in the literature of productivity theory, but not yet used -to the best of our knowledge- for valuing *in situ* natural resources. Chapter 6 contrasts and compares derived results, and concludes the thesis by inferring the form of extraction behaviour relevant for the aquifer under consideration, and by discussing the potential for its management.

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[79] See section 2.3.2 of this survey.

Chapter 3

Dynamic Sectoral Adaptation to Increasing Resource Scarcity, when Backstop Technology is Available: Theory and Application to Groundwater Allocation.

3.1 Introduction.

As can be inferred from the critical assessment of the Gisser-Sanchez literature presented in chapter 2, consecutive modifications and refinements of the basic Gisser-Sanchez model did not change the essence of the result. The main rationalization of $\mathcal{GSE}$ we offered in the previous chapter of the thesis, is the non-responsiveness of the demand for water, to price changes imposed on current users after a regime switch from no-control to optimal control. However, all refinements of the basic Gisser-Sanchez model ignore one of the most realistic aspects of groundwater management and treat the resource as an exhaustible flow. It is not obvious however, why one should treat groundwater resources, or water resources in general, as exhaustible. Water resources are effectively available in unlimited quantities, but under a range of different supply conditions. Deposits of groundwater stored in aquifers may be cheaper than water produced by desalination of seawater for example, but they are also exhaustible. Estimates of the amounts available from the latter source are subject to great error, but suggest that if society is prepared to pay the price, supplies will be available into the indefinite future. In this sense a backstop technology is available for groundwater - to use a phrase given prominence by *Nordhaus (1973)*.

This chapter assesses the $\mathcal{GSE}$ theoretically and empirically via simulations, in a dynamic model with backstop technology availability. The empirical application of the model indicates that in the absence of a backstop technology, the $\mathcal{GSE}$ is eliminated when the assumption of infinite hydraulic conductivity (adopted -sometimes implicitly- by almost all researchers in the groundwater literature) is not imposed on the relevant dynamic models and when natural recharge of the aquifer is sustained in the indefinite future under an optimal control regime of extraction. This is in sharp contrast to a competitive regime of groundwater extraction with myopia, where current users of the resource incur only the marginal extraction cost (and free-ride on the relevant scarcity rents), when this results in complete depletion of the aquifer without sustaining aquifer recharge. Sustaining aquifer recharge to the indefinite future after depletion of the aquifer through managing groundwater extraction results in significant welfare gains and eliminates the $\mathcal{GSE}$. Intuitively, our empirical results imply that when complete depletion of the aquifer is probable, it is welfare increasing to manage extraction.

Given that we want to assume away infinite hydraulic conductivity, the aquifer used for the empirical application of the model developed in this chapter, is seriously depleted and faces the threat of complete exhaustion in the near future. Hence the assumption of infinite hydraulic conductivity, which implies that the aquifer will never dry up irrespective of groundwater extraction rates, is not relevant for the hydrological system under investigation. Aquifers that face the threat of complete depletion are common in arid and semi-arid regions, which are apparently the regions with serious water shortage and immediate need of optimal groundwater management. Moreover, the chosen aquifer has a smaller storage capacity than any other aquifer used to empirically test the magnitude of the $\mathcal{GSE}$ that we are aware of. As already argued in chapter 2, the $\mathcal{GSE}$ will persist as long as the slope of the demand function relative to aquifer's storage is small. Hence the magnitude of the effect could be reduced when simulating optimal and uncontrolled extractions from a small aquifer.

Moreover, we are dealing with a *coastal* aquifer. As argued by *Krulce et al. (1997),* coastal aquifers have a distinguishing feature which calls for a somewhat different model. This feature amounts to the possibility of seawater desalination, which provides a natural "backstop" water source situated next to the aquifer. The proximity to the backstop technology allows departure from issues of cost of transferring desalinated water to the location of its consumption. Moreover, because we are interested in aquifers located in semi-arid regions, we model groundwater as a potentially exhaustible resource. That is, aquifers in semi-arid regions do not benefit from substantial natural recharge and as a result the groundwater growth rate is not stock depended through leakages[1]. Thus in the context of our model, groundwater is mined until its efficiency price[2] rises to the backstop price. When this equality is satisfied groundwater is replaced by the backstop as the primary water source; thereafter the resource's price remains constant at the unit cost of the backstop technology.

Similar applications of the non-renewable resource model to groundwater management are *Moncur and Pollock (1998)* and *Bowen et al. (1991).* A major weakness of these studies however, is that they do not model the demand-side of the problem and cannot explain changes in the willingness to pay for groundwater that might occur over time, and affect the optimal time of adopting the available backstop technology. In our model, demand for groundwater is assumed to be changing over time through endogenous adaptations to resource depletion. As will become apparent from the analysis of this chapter, these changes are potentially significant for the derivation of the correct scarcity value of groundwater. In addition this particular representation of groundwater demand allows instantaneous estimation of the relative allocation of water between different users, which can be an important information for reforming policy institutions that concern the exploitation of the resource. The solution of the model uses

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[1] Krulce et al., modelled groundwater as a renewable resource; that is, the natural growth rate (recharge) of groundwater was assumed to be stock dependent, with a growth rate equal to the difference between inflow and aquifer leakages, which (the aquifer leakages) were represented as a function of the groundwater stock in the aquifer.

[2] Efficient pricing of a natural resource is graphically derived in section 1.1 of the introductory chapter of the thesis. Also, see the analysis in section 3.3 of this chapter.

the mathematical technique of multi-stage optimal control to derive the social benefit from groundwater use under an optimal management regime and compare it with the social benefit derived under the competitive-commonality situation. As already argued, the difference between the two solutions emerges because competitive groundwater extraction ignores one component of the social cost of groundwater, namely the social benefit of foregoing water usage currently as a means of reducing future costs of acquiring groundwater. This equals the social *user* cost of groundwater, which represents the *in situ* scarcity value of the resource.

In addition to providing a natural backstop technology, seawater may become a source of environmental harm for coastal aquifers. Coastal fresh groundwater systems are in contact with saline water, which if drawn into the aquifer, can diminish the water's potability as well as its usefulness for other purposes (such as irrigation purposes). As argued in chapter 1, groundwater scarcity has an important qualitative dimension that further limits the supply of usable water; this exact dimension is explicitly modelled in the analysis of this chapter. Saltwater intrusion can result as fresh groundwater is drawn down and saline water flows in to replace it, in an "attempt of nature" to restore the hydrological balance of a freshwater ecosystem. Although the dynamics of saltwater intrusion developed by hydrologists are in a relatively advanced stage[3], this phenomenon has not attracted the interest of economists. A notable exception is the optimization model of exploitation of groundwater reserves with saltwater intrusion, developed by *Cummings (1971).*

Summing up, this chapter aims to analyze the optimal strategy of consuming a resource (groundwater) whose total availability is potentially infinite through availability of a backstop technology, its cost of extraction is an increasing function of the total already extracted, and is bounded from above by the price of the backstop technology. This seems to describe with tolerable realism the situation of water resources, where a number of different sources of supply exist, the cheaper ones being exhaustible but the most expensive ones (typically desalination or possibly large-scale recycling of past consumption) providing unlimited amounts of the input in question. This chapter is organized as follows. In section 3.2, we provide a graphical illus-

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[3] See *Reilly and Goodman (1985)* for a survey on the quantitative hydrological analysis of saltwater-freshwater relationships in groundwater systems.

tration of the advantages of achieving a disaggregated modelling of the demand for a natural resource, which describes the demand-side of our model. In section 3.3, we provide a graphical representation of the supply-side of our model that illustrates the role of scarcity rents in an optimization model with backstop technology availability. In section 3.4, we formulate the multistage optimal control model of groundwater depletion, where endogenous adaptation to rising resource scarcity defines the intertemporal pattern of economic sectors that use groundwater and the endogenous time of introducing the backstop technology. The solution of the problem, presented in section 3.5, involves sequentially solving a series of free endpoint problems, each of which defines the date when an economic sector's demand for groundwater reaches zero. The terminal endogenous switch is defined by the adoption of the backstop technology. The adoption of the backstop technology characterizes the steady-state conditions of the problem and the multi-stage solution allows efficient choice of the quantity of water to be produced by the backstop technology. Section 3.6 provides an illustrative empirical application of the model, where the optimal control and competitive-commonality solutions of the system are numerically derived and compared in order to establish whether the Gisser-Sanchez effect is present. Section 3.7 concludes the chapter.

3.2 Comparison of Simple Aggregate Demand Versus Multiple-Sectoral Demand: The Demand-Side of the Model.

Optimal allocation of groundwater is a multistage decision process. At each stage, e.g. each year, a decision must be made regarding the level of groundwater use which will maximize the present value of economic returns to the basin. The intial conditions for each stage may be different due to changes in either the economic or hydrologic parameters of the basin under consideration. However, in most of the dynamic mathematical models employed in the literature reviewed in chapter 2 [see for example, *Burt, 1964; Bredehoeft and Young, 1970; Gisser and Mercado, 1973; Gisser and Sanchez, 1980 (a, b); Noel, 1980; Feinerman and Knapp, Allen and Gisser 1984; Nieswiadomy, 1985; Worthington et al., 1985; Zimmerman, 1990, Knapp and Olson; 1995]* groundwater is modelled as a stock to be depleted in a mining era before moving to a stationary-state era. As already argued in section 2.4.1 of chapter 2, implicit in this literature are the assumptions of fixed economic relations and/or exogenous rates of change through time[4]. However, as indicated in the second part of table 2.3.1 of chapter 2, converging lines of evidence from sensitivity analyses show that benefits from groundwater management are highly sensitive to the functional form and price elasticity of the relevant demand function used in the optimal control model. Hence, paying attention to temporal changes in the benefit functions that govern depletion modelling, is potentially important.

More complex and realistic representations of increasing resource scarcity incorporate opportunities for adaptation to rising resource prices. That is, in the long-run perspective, shift away from water intensive production activities, adoption of new techniques or backstop technologies, substitution of alternative inputs, and production of a different mix of products offer rational responses to increasing scarcity. *Kamien and Schwartz (1981)*, *Rossana (1985)* and *Tomiyama (1985)*, developed theoretical two-stage optimal control models that accounted for sequential changes through time. *Kim et al. (1989)* generalized these models to (n) stages. In particular, Kim et al. developed the technique of *multistage optimal control* in the context of groundwater mining for agricultural production. Rather than directly stating aggregate demand, their model states disaggregate categories of demand curves for different crops, with the intertemporal relative allocation of the resource among categories of products being defined as groundwater prices increase through time. Their approach provides the possibility of a more detailed description of natural resource depletion, where allocation across products of resource use can be portrayed in an intertemporal context. In the present chapter, we employ this technique to describe the chronological pattern of groundwater use by different economic sectors in order to define optimally the quantity of the resource that should be produced when the available backstop technology is adopted at some endogenously defined time. Including in a control model the opportunity for this type of adaptation strengthens its ability to describe economic processes associated with natural resource depletion. The additional detail, further can inform public policy decisions concerning natural resource allocation among economic sectors, optimal timing of adoption of an available backstop technology and definition of optimal quantity of

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[4] As already mentioned in footnote 38 of chapter 2, two notable exceptions exist in the literature. *Burness and Brill (1992)* considered endogenous irrigation technology choice, and *Shah et al. (1995)* integrated conservation technology diffusion within the exhaustible groundwater model. Their results indicated that without intervention the gradual adoption process of the conservation technology will be slower than is socially optimal.

the resource to be produced by this technology for each of the different users.

The essence of the above arguments that call for an endogenous formulation of the benefit function in an optimal control model, is the following. Projected results from optimal control models become more tenuous the further one moves into the future. In particular, one of the difficulties of using long-run optimal control is the need to provide the mathematical model with estimates of willingness to pay (WTP) not only relevant for the present but also relevant for some time in the future. However as time passes by, WTP for the resource in question may change as the scarcity and hence the relevant price for the resource changes. (Price equals marginal extraction cost in a competitive-commonality situation where rights are not exclusively assigned, and marginal extraction costs plus scarcity rents if extraction is optimally controlled).

Two approaches exist towards estimation of the relevant demand functions. The first is the traditional approach, where a functional form is chosen and used in the estimation of the demand function based on past and/or current observations. This demand function is assumed to be relevant for the entire time span over which the problem is solved. However, discontinuities may occur because the WTP of various demanders/users of the resource may be bounded from above at different shadow prices. With groundwater shadow prices increasing through time as the resource's scarcity increases, some users of the resource may exit the market and their WTP for the resource be driven down to zero. That is, there is a choke price for the resource (which varies among different resource users) above which demand for groundwater becomes zero. Thus, the estimated benefit functions based on current observations, may bear little relation to the actual benefit function when future economic, hydraulic and agronomic conditions are much different. The piecewise approach adopted in our analysis, takes account of some foreseeable discontinuities in the derivatives of the demand functions. Both of these approaches are extrapolations into the future, but the piecewise approach offers some advantages over the traditional approach because it uses more of the available information. If the incorporated foreseeable changes do take place, results from the piecewise approach will be more relevant in a long-run perspective.

More specifically, the use of the piecewise demand approach enables us to establish optimal intertemporal mining paths for different economic sectors, model the possibility of demand adaptation to resource depletion and derive accurate benefits from groundwater management at steady-state conditions. Below we briefly discuss these strengths of the piecewise approach if compared with the traditional approach based on aggregate water demand. Equations (3.1) and (3.2) represent the demand for water by the agricultural and the domestic economic sector, respectively,

$$W_A = a_1 - b_1 P \tag{3.1}$$

$$W_D = a_2 - b_2 P \tag{3.2}$$

where (W_A) , (W_D) are groundwater quantities demanded by the agricultural and domestic sectors respectively, (P) is groundwater price. Optimality dictates that the price of groundwater should equal the marginal benefit derived from groundwater use. However, in the absence of clear property rights price equals marginal extraction costs. Parameters (a_1), (a_2), (b_1) and (b_2) are coefficients of the ordinary (uncompensated) sector specific demand curves for water.

Figure 3.2.1: Aggregate Versus Disaggregate Demand Curves.

Figure 3.2.1 presents these demand curves as AA' and DD', respectively. Horizontal summation of the two demand curves gives the kinked demand curve DBC, which represents the multiple-sector piecewise aggregate water demand. Several strengths of the approach based on multiple-sector aggregate demand become evident from this figure. In the descriptive mode, two opportunities for a more detailed analysis exist. First, differentiating by economic sector permits estimation of the instantaneous relative allocation of groundwater between the agricultural and the domestic sectors during the groundwater depletion era. In particular, the model generates an endogenous switch time, the year at which groundwater is used only by the domestic sector rather than the agricultural and domestic sectors, simultaneously. For example, when the price of groundwater at some time (or the marginal cost of water extraction in the absence of a groundwater market) increases to (P_1) in figure 3.2.1, as a consequence of greater pumping lifts, agricultural use of groundwater becomes zero and remains zero thereafter. The shift exclusively to the domestic sector provides an example of a sectoral pattern that occurs through time. The pattern is one of a shrinking number of existing economic sectors in a region's economy as the price of groundwater pumping increases secularly with mining.

Second, prices that are higher than (P_1) result in distinct extraction volumes depending on which notion of aggregate demand is used; this proves to be crucial in choosing the exact volume of water to be produced by the backstop technology at steady-state conditions. For example, if the unit price of desalination is (P_2), the multiple sector notion results in an accurate prediction of (W_2) rather than an underestimate of (W_2'). Thus, water prices above (P_1) generate different estimates of social benefits. These affect both descriptive and normative analyses. In particular, the kinked representation of aggregate demand provides a larger, and more accurate estimate of the surplus from the economy-wide groundwater use relative to the traditional approach. This additional information may prove crucial as groundwater mining becomes pervasive and policy makers attempt to reform groundwater institutions or decide when it is optimal to adopt an expensive backstop source of water. For example, if the unit price of desalination is (P_3) then the adoption of the available backstop technology is feasible only if the multi-sector notion of the aggregate demand curve is used. Hence, accurate estimates of the value of social benefits derived from groundwater use for the economy as a whole, may help to balance equitably and efficiently any future reforms. When data is available, an approach based on a multiple-sector piecewise aggregate demand for groundwater offers a superior alternative to the approach commonly adopted in the literature based on undifferentiated aggregate demand.

3.3 Representation of Scarcity Rents in an Optimization Model: The Supply-Side of the Model.

Given that optimal pricing in groundwater market dictates that price equals marginal benefits from groundwater use, if the marginal extraction cost of water is lower than the corresponding marginal benefit, then this implies that water sales should involve a positive marginal scarcity rent. Assuming that these conditions apply for the situation depicted in figure 3.2.1, then for prices below (P_1), the marginal net benefit is positive for both sector-users. Could we draw the diagram so that marginal net benefit (and, hence, marginal scarcity rent) would be zero? Marginal scarcity rent would be zero if water were not scarce. If the availability of water as depicted by the groundwater supply curve, was greater than the amount represented by the point where the aggregate marginal benefit minus extraction costs intersects the horizontal axis (indicating quantity of water demanded), water would not be scarce. Both sectors would get all they wanted and their demands would not be competing with each other. Their marginal net benefits would both be equal to zero.

Natural resource scarcity rents can be motivated from either a utility maximization perspective *(Heal, 1976, p. 373-74)* as done in the previous paragraph, or in terms of profit maximizing producers *(Hotelling, 1931)* as described in section 1.1 of the introductory chapter. In our model we adopt *Howe's (1979)* rationalization of the existence of scarcity rents for a natural resource, i.e. these rents reflect purely the scarcity of groundwater itself, given present sources and the prospect that desalination, which is relatively more expensive, will have to be used in the foreseeable future[5]. In figure 3.3.2, the dotted line depicts marginal extraction costs at a moment of time for existing, conventional water sources, such as irrigation wells. If these sources were not available, the alternative would be a "backstop" source such as desalination,

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[5] More specifically, *Howe (1979)* states that anticipated higher costs for a resource imply a scarcity rent on use of existing cheaper sources today.

which we assume to be available in unlimited quantities though at the high (and constant) cost ($\overline{p}$). The efficiency price line[6] shows the efficient price for water, incorporating extraction costs as well as *in situ* value. Suppose that, contrary to the common situation, all rights to *in situ* groundwater could be owned and sold independently of the overlying land. The question would then be how much must a new groundwater user pay to gain access to groundwater now used by landowners[7]. Consider a potential buyer contemplating a capacity addition to the level (q_{Gt}). Under the conditions just outlined, the buyer can either purchase water rights covering an existing source, with extraction cost ($q_{Gt}c$), or develop the backstop at cost ($q_{Gt}\overline{p}$). Thus for the incremental source at capacity (q_{Gt}), the buyer's maximum willingness to pay for existing rights is represented by the distance ($c\overline{p}$).

Figure 3.3.1: Extraction Cost, Scarcity Value, and Efficiency Price of Groundwater.

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[6] Note that constant extraction costs generate rising scarcity values up to the time that desalination is introduced, in contrast to the steadily declining values generated by linearly or exponentially increasing cost structures. For further discussion on this issue see *Moncur and Pollock (1988).*

[7] Because of the indeterminacy of small number bargaining situations and market related imperfections, a point estimate of these payments is not possible. However, this payment will be bounded at the high end by what prospective buyers are willing to pay, and at the low end by what sellers are willing to accept.

The owner's willingness to accept compensation in exchange for rights to a well is also affected by the scarcity situation. If today's rate of use increases by one unit, the buyer will incur sooner the higher costs of supra-marginal wells. The resulting increase in the present value of future costs is the scarcity value attached to the marginal well. Adding marginal extraction cost to marginal scarcity value yields the efficiency price of extracted water referred to above. Moreover, we assume that owners of the marginal source are fully aware that any prospective buyer will have to pay more, and sooner, for even the next-least-costly well if they (owners) refuse to sell. This awareness is the basis for determining the owner's reservation price. At (marginal) capacity (q_{Gt}), potential scarcity rent is the distance ($c\lambda$) and represents the seller's minimum willingness to accept payment. In the solution of the optimal control model to be developed in this chapter the adjoint variables ($\lambda_j(t)$) represent the distance between marginal extraction costs and efficiency price at time (t) for each (j) stage of the system of differential equations. That is, ($\lambda_j(t)'s$) represent groundwater scarcity rents.

At this point, it is worth noting and explaining the difference between figure 1.1.1 presented in the introductory chapter of the thesis, and figure 3.3.1 introduced in this chapter. Both figures aim to describe the time path of scarcity rents, extraction costs and efficiency price of *in situ* groundwater, in the presence of an available backstop technology at a known price. In chapter 1, groundwater is treated as a fixed resource stock to be mined until supplies are exhausted, or marginal extraction cost becomes prohibitive. In this chapter however, groundwater is treated as a partly renewable resource, which implies a stock effect on the *in situ* value of the resource. This stock effect allows for the possibility of a positive *in situ* value of groundwater at the endogenously defined time of adopting the backstop technology, which defines steady-state conditions. That is, at steady-state a positive level of extraction is sustained at lower private marginal extraction cost than the cost of the backstop technology, because of the exogenously given rate of water inflow in the aquifer (through recharge from rainfall and percolation of used water back into the aquifer). As a result, at steady-state the social marginal cost of water that becomes equal to the unit cost of the backstop technology, is composed of marginal extraction cost and scarcity value of net inflows. This equality defines the timing of the last endogenous switch in the model developed in the following section of this chapter, which as already indicated, is characterized by the adoption of the backstop technology.

Ignoring *in situ* values overlooks a real element of total opportunity cost of groundwater. After all, this is the essence of the literature reviewed in chapter 2, which aims to derive an accurate value of the effect of imposing these scarcity rents on groundwater users, and to provide the economic intuition behind the magnitude of this effect. As argued in section 1.1 of the introductory chapter, in the presence of clear ownership, no externalities, and the existence of viable markets, competitive market processes will establish the efficient level of scarcity rent of a resource and, thus, the efficient time path of extraction and consumption. In the absence of clear ownership rights and markets however, scarcity value frequently goes unrecognized. Groundwater resources provide an important example of this phenomenon, given the growing apparent depletion of water in aquifers. Ignoring scarcity rents in groundwater pricing means that the price of groundwater (which equals the marginal cost of extraction in the absence of a market for groundwater) is too low, thereby increasing excessive extraction. Thus efficient groundwater prices call for: (a) use of marginal extraction costs and (b) incorporation of the scarcity value of *in situ* groundwater. Empirical determination of marginal extraction cost for groundwater is - at least conceptually - straightforward, using cost data kept by the relevant agency. Scarcity rent is another matter. If marginal extraction cost and price is known, one can easily determine scarcity rent as a residual. But without a market-determined price, one needs an indirect estimation of scarcity rent[8]. The model developed and solved in the consecutive sections of this chapter enables us to derive the total optimal scarcity value of groundwater in a particular basin. Moreover in Appendix B3 we derive the common property solution of the model and in section 3.6 we empirically estimate the magnitude of the difference in the net present value of benefits derived under optimal and competitive solutions of the model, in order to investigate whether the $\mathcal{GSE}$ persists.

3.4 The Model.

We assume that farmers sell their production in competitive markets so that the price of water is equal to the value of its marginal product. Moreover, the agricultural production

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[8] See appendix B5, chapter 5 for a brief literature review of different approaches to specifying the time paths of derived *in situ* (scarcity) value of various natural resources.

function is assumed to be constant returns to scale and factors other than water and land are optimized conditional on the rate of water extraction. Access to the aquifer is restricted by land ownership and consequently the number of farmers is fixed and finite over time. Moreover, following *Kim et al. (1989)*, model construction begins by stating disaggregate categories of sector-specific demand curves. Analysis of the opportunity of adaptation to resource depletion develops as a consequence of the disaggregate representation: with the efficiency price of water increasing through time, the intertemporal relative allocation of the resource among economic sectors follows naturally. Equation (3.3) represents the inverse demand function for water for the *ith* sector,

$$P = \frac{a_i}{b_i} - \frac{1}{b_i}(W_i), \quad i = 1, 2, ..., n \tag{3.3}$$

where, (P) is the price (or marginal extraction cost in the absence of water markets and optimal control) of water and (W_i) measures quantity of water demanded by sector i. The parameters (a_i) and (b_i) are sector-specific time-invariant demand parameters, with (b_i) assumed to be greater than zero. As proposed by *Kim at al. (1989)*, the sector-specific inverse demand curves are ordered so that $\frac{a_1}{b_1} < \frac{a_2}{b_2} < ... < \frac{a_n}{b_n}$. This ordering implies that as (P) increases over time due to increasing groundwater scarcity, water demand for each of the n economic sectors reaches zero sequentially. In the absence of backstop technology and given that there exist (n) economic sectors demanding water, $(n-1)$ endogenous switching times should result from this series of choke prices. Thus, aggregate water demand, in this representation, appears as a piecewise linear function.

Groundwater extraction costs and desalination costs, together with hydrology, represent the supply-side of the model. The marginal pumping cost function (MC) is,

$$MC_G = c[h(t)] \tag{3.4}$$

where (h) represents the head of the aquifer above sea level. At lower head levels, it is more costly to extract water because more and/or deeper wells must be drilled and the water must be pumped farther distances. As the aquifer nears exhaustion $(h = 0)$ extraction cost rises rapidly. Thus we model the average cost of extracting water from the aquifer as a positive, decreasing, convex function of the head[9]; i.e. $c(h) \geq 0$, $c'(h) < 0$, $c''(h) \geq 0$ and $\lim_{h \to 0} c(h) = \infty$.

A second important feature of this research is that we are dealing with a coastal aquifer. As indicated in the introductory section of this chapter, a distinguishing feature of such aquifers is the possibility of seawater desalination, which provides a natural "backstop" water source. Thus the aquifer is not the only possible source of water. Following *Nordhaus (1973, 1979)* and *Heal (1976)*, we consider a super-abundant resource to flow from a backstop technology with constant unit cost ($\overline{p}$). As indicated in section 3.1, we model groundwater supplies as exhaustible stocks to be depleted over time, so that at a particular point in time the efficiency price of groundwater will reach the desalination price and eventually groundwater will be replaced by the backstop as the primary water source. Thereafter the price of water will remain constant at the unit cost of the backstop resource. The behaviour of economic sectors whose demand for water is driven to zero before the efficiency price of groundwater reaches the desalination price, is not affected by the existence of the backstop technology. The economic sectors that will be demanding water from the aquifer at the time at which desalination starts, will continue to use water at the desalination price. This defines behaviour at the steady-state[10].

With this particular formulation for the backstop technology we abstract from both economies of scale and technical change. As argued by *Krulce et al. (1997)*, assuming constant returns to scale is unlikely to be an important source of error for empirical work, because economies of scale are quickly exhausted once desalination begins *(Leitner, 1992)* and the primary input (saltwater) does not become more scarce as the desalinized quantity increases. Technological change however, should ideally be incorporated in this model as it affects the price of the back-

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[9] More generally, the extraction cost could be a function of the rate of extraction as well, $c(h, q)$. Our formulation, however, assumes constant returns to scale in extraction technology.

[10] As a related matter, we briefly comment on the issue of optimal sequencing of resource extraction with rising unit extraction costs. *Solow and Wan (1976)* considered a simple two-period, two deposit model of an exhaustible resource and showed that it is preferable to fully exploit the low cost deposit before extracting from the high cost deposit in period one, while deferring some extraction program. Subsequently, *Kemp and Long (1980)* developed a more general model wherein it may be preferable to exploit high and low cost resource deposits simultaneously for the purpose of smoothing consumption over time. Commenting on the work by Kemp and Long, *Lewis (1982)* derived sufficient conditions under which strict sequencing of extraction (from low cost to high cost) becomes optimal, consistent with the model of Solow and Wan: extracted resources can be converted into productive capital. A different problem arises in the case of physical mining constraints which prevent optimal sequencing of resource extraction per *Solow and Wan (1976).* Moreover, *Hartwick (1978)* and *Cairns (1986)* examined situations where sources of varying quality must be exploited at a single time. We adhere to the simpler model of extraction costs rising with increased resource depletion.

stop technology and as a result the time of adopting this technology. In this model we do not allow for technological change, hence the cost of producing water from desalination at a rate (q_{Di}) is equal to ($\overline{p} \cdot q_{Di}$). The present methodology, however, can be used to incorporate expected technological change by specifying what the backstop price is expected to be at that time in the future when it is expected to be used. Sensitivity analysis can then be applied to explore how the extraction and efficiency price paths respond to changes in the expected backstop price.

The hydrological equation of motion given in equation (3.5), represents the change in the level of the head of the aquifer through time and defines the constraint of the system,

$$\dot{h}(t) = \frac{R + (f - 1 - s) \sum_{i=1}^{n} q_{Gi}(t)}{A \cdot S} \tag{3.5}$$

where ($\dot{h}$) is the time derivative of $h(t)$ and $h(t) \leq h(t)^e$, where $h(t)^e$ is the natural hydrologic equilibrium. The aquifer's recharge rate is represented by (R) and f ($0 \leq f \leq 1$) is the return-flow coefficient of percolation back into the aquifer. As argued in the introductory section, another special feature of coastal aquifers is that they are vulnerable to sea water intrusion; that is, as the aquifer is emptied, saltwater intrudes in the aquifer in order to replace the hydrological balance[11], eventually making water unusable. The salinity coefficient is represented by s ($0 \leq s \leq 1$)[12] which indicates the loss of effective quantity of groundwater available in the aquifer, due to poor quality. The size of the aquifer is measured by (A), and (S) is the storativity coefficient (the average saturation of water in the aquifer). The formulation in equation (3.5) implicitly assumes that changes in the water level are transmitted instantaneously to all users. As argued in section 2.2.4 of chapter 2, this assumption clearly exaggerates the degree of

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[11] See appendix (A3) for a schematic hydrological description of the physical system of saltwater-freshwater interaction.

[12] The modelling of saltwater intrusion is oversimplified in this chapter. A more accurate description of this phenomenon should take into account not only the decrease in freshwater potential caused by groundwater extraction, but also the dependence of seawater intrusion on freshwater stock; i.e. the greater the freshwater stock the less the intrusion. Moreover, the quality of water appropriate for consumption in the residential sector is higher than the relevant quality appropriate for consumption in the agricultural sector, and different crops cultivated by the agricultural sector have different levels of salt tolerance. However our model makes the simplifying assumption of a uniform salt tolerance for all relevant sectors and crops. Finally, there is a spatial element to the movement of seawater in an aquifer, which is also ignored. A detail description and static economic analysis of this spatial aspect of the phenomenon can be found in chapter 4.

common property.

In equation (3.5), (R) is assumed constant and deterministic. A constant recharge rate is a reasonable assumption for a confined basin, which is isolated from adjacent groundwater reservoirs, except for very high levels of water table. When an aquifer becomes nearly full, it develops leaks to the surface through springs and augments streams and rivers, making (R) a decreasing function of (h) as storage capacity is approached. The aquifer finally reaches its natural hydrologic equilibrium defined by (h^e). For this reason the differential equation (3.5) has been admitted in the literature as a good approximation of the dynamics of a confined aquifer within the economically relevant range of groundwater reserves, given that when extracting agents are mining the aquifer the water table will probably be below the critical value for which the recharge begins to be a decreasing function of the water table.

The goal of the planning equilibrium is to maximize the present value of generated economic surplus (net social benefits) from intertemporal water use and the production of water from desalination, subject to the hydrological constraint of the system. Economic surplus generated from activity in an input market measures scarcity rents to producers plus consumer's surplus in the product market under general equilibrium, competitive conditions *(Just and Hueth, 1979)*[13]. Social benefits from water use are given by,

$$SB = \sum_{i=1}^{n} \int_{0}^{q_{Gi}(t)+q_{Di}(t)} \left[\frac{a_i}{b_i} - \frac{1}{b_i} W_i \right] dW_i$$

or

$$SB = \sum_{i=1}^{n} \left[\frac{a_i}{b_i} W_i - \frac{1}{2b_i} W_i^2 \right] \tag{3.6}$$

where (W_i) represents the total quantity of water used by the *ith* economic sector, and is equal to the sum of sector $ith's$ consumption of groundwater $(q_{Gi}(t))$ and water produced from

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[13] The water demand curve used in both the empirical and theoretical analysis of this chapter is assumed to be the general equilibrium input demand. See appendix B3 for a brief discussion of welfare measures in an input market.

desalination ($q_{Di}(t)$). Total pumping costs (TC) are,

$$TC(t) = \sum_{i=1}^{n} [c[h(t)]q_{Gi}(t) + \overline{p}q_{Di}(t)] \tag{3.7}$$

Thus net social benefits (NSB) at a given time are,

$$NSB = \sum_{i=1}^{n} \left[\frac{a_i}{b_i} W_i - \frac{1}{2b_i} W_i^2 \right] - \sum_{i=1}^{n} [c[h(t)] \cdot q_{Gi}(t) + \overline{p} \cdot q_{Di}(t)] \tag{3.8}$$

In sections 3.5 and 3.6 we employ the technique of multi-stage optimal control, introduced by *Kim et al. (1989),* in order to derive the optimal path of water use over consecutive time periods, during which endogenous adaptation to water depletion and backstop technology is allowed; this requires the imposition of a user cost that reflects the value of leaving water in the ground to reduce future costs of acquiring water, which represents scarcity rents of the resource.

3.5 Multi-Stage Optimal Control Formulation.

The ordering of groundwater sector-specific demands according to their price intercept ($\frac{a_1}{b_1} < \frac{a_2}{b_2} < ... < \frac{a_n}{b_n}$) together with the existence of the backstop technology, results in a natural partitioning of the problem into stages, with successive stages representing a smaller number of economic sectors demanding water. This assures an intertemporal depletion path that moves along the multiple-sector, piecewise linear aggregate demand curve. This dynamic adaptation to groundwater depletion stops as soon as the efficiency price of water reaches the price of desalination (we assume that both groundwater reserves in the aquifer under consideration and the price of desalination, are high enough so that the economy starts with using water from the aquifer). At this price the economic sectors that derive a marginal benefit from water usage at least as high as the desalination price, will continue to demand a constant amount of water, the one indicated by the parameters of their demand curves at the cost (price) of desalination. Given a discount rate $r > 0$, the mathematical representation of this dynamic optimization problem of the model developed in section 3.4 is,

$$\begin{aligned} MaxP &= J_1 + J_2 + ... + J_k \\ &= \int_0^{T_1} e^{-rt} \left[\sum_{i=1}^{n} \int_0^{q_{Gi}(t)+q_{Di}(t)} \left(\frac{a_i}{b_i} - \frac{1}{b_i} W_i \right) dW_i - \sum_{i=1}^{n} \left(c[h(t)] q_{Gi}(t) + \bar{p} q_{Di}(t) \right) \right] dt \\ &+ \int_{T_1}^{T_2} e^{-rt} \left[\sum_{i=2}^{n} \int_0^{q_{Gi}(t)+q_{Di}(t)} \left(\frac{a_i}{b_i} - \frac{1}{b_i} W_i \right) dW_i - \sum_{i=2}^{n} \left(c[h(t)] q_{Gi}(t) + \bar{p} q_{Di}(t) \right) \right] dt \\ &\vdots \\ &+ \int_{T_{k-1}}^{\infty} e^{-rt} \left[\sum_{i=k}^{n} \int_0^{q_{Gn}(t)+q_{Dn}(t)} \left(\frac{a_i}{b_i} - \frac{1}{b_i} W_i \right) dW_i - \sum_{i=k}^{n} \left(c[h(t)] q_{Gi}(t) + \bar{p} q_{Di}(t) \right) \right] dt \end{aligned} \tag{3.9}$$

Equation (3.9) can also be written in summary form as,

$$\begin{aligned} Max \sum_{j=1}^{k} P_j &= \sum_{j=1}^{k} \left\{ \int_{T_{j-1}}^{T_j} e^{-rt} \left[SB_i(t) - TC_i(t) \right] dt \right\} \\ T(t &= 0) = T_o \\ T(t &= k) = \infty \\ j &= 1, 2, ..., k \qquad \text{and} \qquad k - 1 \leq n - 1 \end{aligned} \tag{3.10}$$

The above maximization is solved subject to the following constraints as defined by each stage's hydrological equation of motion,

$$\begin{aligned} \dot{h}(t) &= \frac{R + (f - 1 - s) \sum\limits_{i=1}^{n} q_{Gi}(t)}{A \cdot S}, \;\; 0 \leq t \leq T_1, \\ \dot{h}(t) &= \frac{R + (f - 1 - s) \sum\limits_{i=2}^{n} q_{Gi}(t)}{A \cdot S}, \;\; T_1 \leq t \leq T_2, \\ &\vdots \\ \dot{h}(t) &= \frac{R + (f - 1 - s) \sum\limits_{i=k}^{n} q_{Gn}(t)}{A \cdot S}, \;\; T_{k-1} \leq t \leq \infty. \end{aligned} \tag{3.11}$$

Constraint (3.11) can be summarized as,

$$\dot{h}_j(t) = \frac{R + (f - 1 - s)\sum_{i=j}^{n} q_{Gi}(t)}{A \cdot S}, \quad T_{j-1} \leq t \leq T_j \tag{3.12}$$

The initial conditions of the maximization problem are,

$$h(t = 0) = h_o \tag{3.13}$$

$$q_{Di}(t = 0) = 0, \quad i = 1, 2, ..., n. \tag{3.14}$$

The time of adoption of the backstop technology is $(k - 1)$, e is the exponential function, $T_j (j = 1, 2, ..., k - 1)$ is the jth switch time, J_j represents social benefits for the jth depletion stage $(j = 1, 2, ..., k)$. Note that the maximum number of endogenous switches possible as this problem runs to infinity, is $(n-1)$. Assuming that the efficiency price of water is lower than the price of water produced from desalination, initial condition (3.14) indicates that desalination is not used at time period $t = 0$. The stages are defined by sequential shifting away from the economic sector that produces the lowest marginal benefit from its water consumption, until the time period in which the efficiency price of water reaches the price of water produced from desalination. At this particular period switching stops and the economic sectors that derive a marginal benefit from water use at least as high as the price of desalination $(\overline{p})$, will continue demanding water and be provided with water from both water sources (i.e. the aquifer and the backstop technology) at a uniform price equal to $\overline{p}$. From this point onwards $q_{Di}(t) > 0$.

The current value Hamiltonian functions, which represent the above j-stage optimal control problem are given in equation (3.15),

$$\begin{aligned} \mathcal{H}_j[q_{Gi}(t), q_{Di}(t), h(t), \lambda_j(t), t] &= \sum_{i=j}^{n} \int_0^{q_{Gi}(t)+q_{Di}(t)} \left(\frac{a_i}{b_i} - \frac{1}{b_i} W_i \right) dW_i \\ &- \sum_{i=j}^{n} \left[c[h(t)] \cdot q_{Gi}(t) + \overline{p} \cdot q_{Di}(t) \right] + \lambda_j(t) \left[\frac{R + (f - 1 - s)\sum_{i=j}^{n} q_{Gi}(t)}{A \cdot S} \right] \\ j &= 1, 2, ..., n \end{aligned} \tag{3.15}$$

where $q_{Gi}(t)$, $q_{Di}(t)$ are the control variables guiding inter-sector water allocation over time, $h_j(t)$ are the state variables representing the hydrological motion of water over time for the j stages, and $\lambda_j(t)$ are the adjoint variables for the j stages. The scarcity rents are represented by $\lambda_j(t)$, which are the conventional user costs (i.e. the benefit of foregoing groundwater usage currently as a means of reducing future costs of acquiring water).

Necessary conditions for optimality[14], which hold for all t are derived by using the Pontryagin principle,

$$\dot{h}_j(t) = \frac{R + (f - 1 - s) \sum\limits_{i=j}^{n} q_{Gi}(t)}{A \cdot S} \quad j = 1, ..., k \tag{3.16}$$

$$\dot{\lambda}_j(t) = r \cdot \lambda_j(t) - \frac{\partial \mathcal{H}_{\not j}}{\partial h_j(t)} = r \cdot \lambda_j(t) + c'[h(t)] \sum_{i=j}^{n} q_{Gi}(t) \;\; j = 1, ..., k \tag{3.17}$$

$$\begin{aligned}
\frac{\partial \mathcal{H}_{\not j}}{\partial q_{Gi}(t)} &= \frac{a_i}{b_i} - \frac{1}{b_i}\left(q_{Gi}(t) + q_{Di}(t)\right) - c[h(t)] - \lambda_j(t)\left(\frac{s + 1 - f}{AS}\right) \leq 0, \\
\text{for } i &= 1, ..., n; \; j = 1, ..., k; \; k \leq n \\
&= 0 \text{ if } \; q_{Gi}(t) > 0 \\
q_{Di}(t) &= 0 \text{ for } \; j = 1, 2, ..., k
\end{aligned} \tag{3.18}$$

---

[14] The necessary conditions stated in equations (3.16-3.25) are also sufficient for the maximization of P of equation (3.10) at each stage j, if the following conditions are satisfied:
(1) The net social benefits function in equation (3.8), is differentiable and jointly concave in q_{Gi}, q_{Di} and h.
(2) One of the following is true:
(i) Equations (3.12) are linear in (q_{Gi}, h);
(ii) Equations (3.12) are concave in (q_{Gi}, h) and $\lambda(t) \geq 0$ for $t \in (0, T)$; or
(iii) Equations (3.12) are convex in (q_{Gi}, h) and $\lambda(t) \leq 0$ for $t \in (0, T)$.
When the above conditions are not satisfied, e.g. when the annual net benefit function is nonconcave due to stock effects on costs, two difficulties are created: optimal policies may not be unique-valued functions of the state variables, and the analysis of optimal policies cannot be based on the concavity of the value function. As argued in section 2.5.2 of chapter 2, lattice programming methods provide a direct and convenient way to characterize the behavior of optimal policies in such settings. In essence, *Topkis (1978)* shows that if the objective function in an optimization problem exhibits a form of specific complementarity, then optimal decisions vary monotonically with the underlying states or parameters.

$$
\begin{aligned}
\frac{\partial \mathcal{H}_{\cancel{j}}}{\partial q_{Di}(t)} &= \frac{a_i}{b_i} - \frac{1}{b_i}\left(q_{Gi}(t) + q_{Di}(t)\right) - \overline{p} \leq 0, \\
\text{for all } i &= 1, ..., n;\ j = 1, ..., k;\ k \leq n \\
&= 0\ if\ q_{Di}(t) > 0 \qquad (3.19)
\end{aligned}
$$

$$\lim_{t\to\infty} \lambda(t) = 0 \qquad (3.20)$$

$$\lim_{t\to\infty} p(t) = \overline{p} \qquad (3.21)$$

$$\lambda_j(T_j-) = \lambda_j(T_j+) \qquad (3.22)$$

$$\lambda_j(T_{j-1}) = -\left(\frac{\partial J_j^*}{\partial h(T_{j-1})}\right) \qquad (3.23)$$

where J^* represents the optimal value function at the $jth - 1$ switching time. Each of the j stages represents a control problem and has an adjoint variable $\lambda_j(t)$ associated with it, which represents the scarcity value of groundwater at each solution stage. Equations of (3.16) are the stages' equations of motion. The adjoint equations are represented by (3.17). These equations demonstrate that groundwater pumping costs $\left(c'[h(t)]\sum_{i=j}^{n} q_{Gi}(t)\right)$ create the value associated with user cost. The equations of (3.18) assure that water use for a particular sector equates marginal benefit to marginal pumping cost plus marginal user cost (scarcity value), and guide water allocation among the economic sectors to equate their marginal value products. They are necessary for allocative efficiency of groundwater over time and across sectors. The incorporation of marginal user cost in the equations ensures representation of the scarcity value of groundwater (i.e. the opportunity cost of current pumping).

Once desalination is introduced, equation (3.19) guides inter-sectoral allocation of water by equating their marginal value products. At this time the opportunity cost of current pumping becomes zero. Equation (3.20) and (3.21) are the conventional transversality conditions, which must hold in the limit as time approaches infinity. The remaining two equations have been introduced by Kim et al. for the solution of a multi-stage optimal control problem. Equations of (3.22) state that the adjoint variable, which represents user cost, must be continuous at each switch time. Equations of (3.23) give an additional set of transversality conditions for the $(k-1)$ stages prior to the final stage of desalination. These transversality conditions, simply represent a marginal condition that equates the benefit of marginal accretions to the groundwater stock between stages by setting equal the user cost of one stage and the derivative of the optimal value function of the next stage with respect to (h), both evaluated at the switching time.

3.5.1 Solution of the Multi-Stage System: the Mining Era.

To solve the system of equations (3.16)-(3.23) given the initial conditions in equation (3.13) and (3.14), it is useful to think in terms of the optimal price path in each stage of the system. The inverse demand curve for water for *ith* agent is given by,

$$\begin{aligned} D_j^{-1}\left(q_{Gi}(t)+q_{Di}(t)\right) &\equiv \frac{a_i}{b_i}-\frac{1}{b_i}\left(q_{Gij}(t)+q_{Dij}(t)\right)=p_{ij}(t) \\ \text{for } i &= 1,2...n \text{ and } j=1,2,...,k \end{aligned} \tag{3.24}$$

We assume that both the cost of desalination and groundwater reserves are high enough so that water is always extracted from the aquifer. Then condition (3.18) holds with equality. As mentioned in section 3.4, this condition guides water allocation among sectors for each stage of the system to equate their marginal value product. Hence the price of water for the different sectors is equal at each stage (i.e., $p_{1jt}=p_{2jt}=...=p_{njt}=p_{jt}$ for $j=1,...,k$). This gives,

$$\lambda_j(t)\left(\frac{s+1-f}{A\cdot S}\right)=p_j(t)-c[h_j(t)] \tag{3.25}$$

Thus the *in situ* shadow price of water is equal to the royalty (i.e., price less unit extraction cost). Rearranging equation (3.17) yields,

$$r\cdot\lambda_j(t)=\dot{\lambda}_j(t)-c'[h(t)]\sum_{i=j}^{n}q_{Gi}(t) \tag{3.26}$$

Equation (3.26) is a general optimal condition that must hold for all t, for all j, whether or not desalination is being used and can be interpreted as an arbitrage condition. The left-hand side is the foregone marginal benefit of extracting water in terms of pounds realized after one period. The right-hand side is the marginal benefit of conservation, that is the interest on the resource royalty. The first term on the right is the foregone increase in value that would have been realized by conserving the marginal unit. The second term is the increase in future extraction cost due to extracting the marginal unit now instead of later. Thus equation (3.26) says that at the margin, the benefit of extracting water must equal the efficiency cost of extracting water.

Substituting equation (3.24) into (3.19) gives,

$$\begin{aligned} p_j(t) - \overline{p} &\leq 0 \\ &< \quad if\ q_{Dij}(t) = 0 \end{aligned} \tag{3.27}$$

which says that if price is below the cost of desalination at any of the j stages, desalination is not used. The initial condition of the system given in equation (3.14), indicates that we assume that at first desalination is not used $[q_{Di}(t = 0) = 0]$, hence $p_j(t) < \overline{p}$. From condition (3.25) and its time derivative we get,

$$\lambda_j(t) = \frac{A \cdot S}{(s + 1 - f)} \left[p_j(t) - c[h_j(t)]\right] \tag{3.28}$$

$$\dot{\lambda}_j(t) = \frac{A \cdot S}{(s + 1 - f)} \left[\dot{p}_j(t) - \Big(c'[h_j(t)] \cdot \dot{h}_j(t)\Big)\right] \tag{3.29}$$

Combining equations (3.16), (3.17), (3.28) and (3.29) gives,

$$\dot{p}_j(t) = \frac{r\left[p_j(t) - c[h_j(t)]\right]}{A \cdot S} + \frac{c'[h(t)] \cdot R}{A \cdot S} \tag{3.30}$$

The solution to the optimal control problem for each of the (j) stages of the mining era (during which $p_j(t) < \overline{p}$) is governed by the system of differential equations composed of equation (3.30) and equation (3.31) given below. Equation (3.31) is the same as equation (3.10) and gives the hydrological equations of motion for each of the j stages,

$$\dot{h}_j(t) = \frac{R + (f - 1 - s) \sum\limits_{i=j}^{n} q_{Git}}{A \cdot S} \tag{3.31}$$

where $q_{Gij}(t) = a_i - b_i p_j(t)$. Equation (3.30) and (3.31) define the optimal trajectory of water price and the optimal trajectory of aquifer head, respectively. The switching times (T_j) are defined by the following two conditions,

$$q_{Gij}(t) = 0 \tag{3.32}$$

$$p_j(t) = \frac{a_i}{b_i} \tag{3.33}$$

Thus, to derive optimal switching times we need a differential equation showing the time path of groundwater extraction by each economic sector. Given that equation (3.18) holds with equality when desalination is not used, we take the time derivative of this equation for $q_{Dij}(t) = 0$. This gives,

$$\dot{\lambda}_{jt} = \left(\frac{AS}{s + 1 - f}\right)\left(-\frac{1}{b_i}\dot{q}_{Gij}(t) - \left(c'[h_j(t)]\dot{h}_j(t)\right)\right) \tag{3.34}$$

Combining equations (3.16), (3.17), (3.18) with $q_{Dij}(t) = 0$, and equation (3.34), gives a differential equation for the quantity of groundwater demanded by each sector,

$$\dot{q}_{Gij}(t) = r\left[q_{Gi}(t) + b_i c[h_j(t)] - a_i\right] - \frac{c'[h(t)] b_i R}{A \cdot S} \tag{3.35}$$

The system of differential equations that needs to be solved for the derivation of endogenous switches is given by equation (3.35) and equation (3.31) above. The jth switch time is derived by setting $q_{Gij}(t) = 0$. A numerical solution of the system of differential equations and derivation of optimal switching times are provided in section 3.6.

3.5.2 Steady-State Conditions: the Desalination Era.

As already argued once desalination begins, $p_j(t) = \overline{p}$ and $\dot{p}_j(t) = 0$. Moreover, the head of the aquifer is maintained at h^*, that is $h_j(t) = h^*$ and $\dot{h}_j(t) = 0$. These conditions imply that the system reaches a steady-state, at which desalination continues to be used, price is fixed at $\overline{p}$, and the aquifer head is maintained at h^*. Substituting $\overline{p}$ into equation (3.25) we get,

$$\lambda_j(t) = (\overline{p} - c[h(t)]) \left(\frac{A \cdot S}{s + 1 - f} \right) \tag{3.36}$$

The time derivative of (3.36) gives,

$$\dot{\lambda}_j(t) = 0 \tag{3.37}$$

Combining equations (3.16), (3.17), (3.36) and (3.37) we get,

$$\bar{p} - c[h_j(t)] = -c'[h_j(t)] \frac{R}{r(A \cdot S)} \tag{3.38}$$

which gives the optimal level of the head of the aquifer, which is maintained in the steady-state.

Because $c'[h(t)] < 0$, $R > 0$, $r > 0$ and $AS > 0$, equation (3.38) says that $c[h_j(t)] < \bar{p}$ whenever desalination is being used; the cost of extracting water from the aquifer is less than the cost of desalinated water. This contradicts the intuitively reasonable proposition to use the aquifer as long as the cost of extraction is lower than the cost of desalination. However, the true cost of extracting water from the aquifer is not only the cost of current extraction but also the cost of future extraction. As water is drawn from the aquifer, the cost of extracting future water is increased, which may increase overall costs. The cost of extracting future water must be balanced with the lost benefits of leaving water in the ground. The optimal amount of water to leave in the aquifer is h^*. It is also worth noting that desalination may never come into play. This would occur if demand were completely satisfied by water from the aquifer without ever drawing the aquifer down to h^*. However, in the numerical solution of model provided in section 3.6 aquifer depletion is high enough so that desalination is eventually used.

3.5.3 Summary of Solution Stages.

Solving the optimal control problem requires finding the initial shadow price for *in situ* groundwater (λ_0), that will cause the efficiency price path to rise to the desalination price at exactly the same time that the aquifer head reaches (h^*). The solution of the model entails the following solution stages:

Solution Stage 1: Initial Conditions of the System - No Desalination.

Initially the efficiency price of water is below the cost of desalination, which is constant at price ($\overline{p}$). Moreover, the efficiency price of water is below the marginal benefit of water use for each of the *ith* sectors in the economy. Each sector i optimally chooses the quantity of groundwater it consumes, given the costs of acquiring groundwater and the hydro-technical constrains imposed by the equation of motion of the head of the aquifer. At this stage no water is produced by desalination, (i.e. $q_{D_i}(t = 0) = 0$) and total demand of water in the economy is satisfied by groundwater supplies.

Solution Stage 2: Endogenous Adaptation Era - No Desalination.

The efficiency price of groundwater is still below the price of desalination, hence the backstop technology does not enter the picture yet. During this period the model exhibits an intertemporal depletion path that moves along the multiple-sector, piecewise linear aggregate demand curve. As depletion of groundwater continues, the efficiency price of water increases, and as a result we observe sequential shifting away from economic sectors with lower marginal benefit from groundwater usage. Put otherwise, the economic sectors that are characterized by elastic water demand curves, are soon faced with a situation where the shadow price of water is higher than their marginal benefit from water use and as a result their willingness to pay for groundwater becomes zero. That is, during this era we observe sequential exits of economic sectors from the groundwater market. Our model allows identification of the sector specific optimal exit times.

Solution Stage 3: Edogenous Adaptation of Backstop Technology - Desalination Begins.

The efficiency price of water reaches the cost of desalination and desalination begins. At this point, the head of the aquifer is exactly h^* (i.e. the economy reaches a steady-state where water inflows are exactly equal to water outflows and as a result equation (3.5) balances at h^*). This causes price changes to cease. Price is set at exactly the cost of desalination ($\overline{p}$), $\dot{p}_{ij} = 0$, and groundwater is extracted from the aquifer at exactly the rate of net inflow to the aquifer (as given by equation (3.5), the hydro-technical equation of motion of the system). Thus $\dot{h}(t) = 0$, and the aquifer's water head is maintained at h^*. The balance of quantity demanded is supplied by desalination such that $q_{Dk}(t) = a_k - \bar{p}b_k - q_{Gk}(t)$. Moreover, disaggregated representation of groundwater demand adopted by our model, allows identification of the intersectoral allocation of both desalinated and extracted water.

3.6 Application of the Model.

The focus of this study is the Kiti coastal region, located in the southern part of the semi-arid island of Cyprus[15]. The aquifer in this region is neither benefited by substantial natural recharge, not interconnected with surface water. Moreover, in Kiti the notion of common property characterizes ownership of groundwater reserves. As argued in section 1.3 of the introductory chapter of the thesis, the doctrine of absolute ownership governs groundwater property law in the island. Although the doctrine conditions ownership of groundwater on ownership of land overlying the aquifer (thereby limiting access), in all other respects owners of land, own groundwater as a common property resource subject to the rule of capture. This creates a pumping cost externality among groundwater users, thereby causing a traditional market failure.

The empirical application of the dynamic model uses economic and hydrologic parameters for the Kiti region supplied by the Water Development Department of Cyprus[16]. Table (3.6.1) summarizes these parameters.

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[15] The interested reader can find a geographical map indicating the location of the Kiti region, in sections D of the appendix of the questionnaire used in the *Survey of Production (1999).* The relevant questionnaire is attached at the end of the thesis.

[16] Given the absence of observations over a wide range of prices, researchers at the Water Development Department of Cyprus have used linear programming for the estimation of the derived sector specific demands for groundwater.

Table 3.6.1: Economic and Hydrologic Parameters Pertaining to the Kiti Area.

Symbol	Description	Parameter Value
b_a	Absolute value of the slope of agricultural water demand	6,118,500 $\mathrm{m}^3/£^*$
b_d	Absolute value of the slope of domestic water demand	1,270,000 $\mathrm{m}^3/£$
a_a	The intercept of agricultural water demand	9,436,500 m^3
a_d	The intercept of domestic water demand	4,048,000 m^3
ϵ_a	Price elasticity of agricultural water demand for relevant range	0.48
ϵ_d	Price elasticity of domestic water demand for relevant range	0.18
k_1	Cost of pumping one cubic meter of water per meter of lift	0.02 £/m^3
k_2	The intercept of the pumping cost equation	0.3672 £/m^3
f	Return flow coefficient	0.05 pure number
A	Area of the aquifer	12,000,000 m^2
S	Storativity coefficient	0.7 pure number
s	Salinity Coefficient	0.3 pure number
R	Rechrage rate	4,000,000 m^3 p.a.
h_o	Initial elevation of water table above sea level	3.45 masl**
$\overline{p}$	Unit price of desalination	0.5 £/m^3
* In 1999 £1 Cyprus is worth £1.14 UK.		
** Meters above sea level.		

In order to find the steady-state hydraulic head, switching times during the mining era, as well as the terminal endogenous switching time defined by the adoption of the desalination, we have attempted a numerical solution of the problem formulated in sections 3.3 and 3.4. Our empirical application involves groundwater demand by the two existing sectors of the economy of Kiti: the domestic sector and the agricultural sector. As explained in section 3.4, sequential exits from the groundwater market are defined by the relative magnitude of the parameter ratio $\left(\frac{a_i}{b_i}\right)$ of sector specific demand curves. In the present application these equal $1.5422£/m^3$ for the agricultural sector and $3.1874£/m^3$ for the domestic sector. These are the prices per m^3 of water at which the quantity demanded by the agricultural and domestic sectors become zero, respectively; hence the agricultural sector should exit the market first. This result is in agreement with the empirical regularity identified by e.g. *Gibbons*[17] *(1986)*, which indicates that the marginal net benefits from agricultural uses are lower than the marginal net benefits of water use by the domestic sector.

The explicit marginal cost function used in the solution of the system is,

$$c[h(t)] = k_1 \cdot [SL - h(t)] = k_2 - k_1 \cdot h(t)$$

The difference $(SL-h)$ measures pumping lift, the distance from the water table to the irrigation surface. This is the pumping cost function traditionally adopted in the groundwater literature (see for example, *Gisser and Sanchez (1980 a, b)* and *Kim et al. (1989)*), which represents a specific form of a general cost function. The derivatives of this cost function have the desirable properties; i.e. a positive partial derivative with respect to (q_G) and a negative cross-partial derivative between (q_G) and pumping lift.

Using the data in table 3.6.1, we calculate optimal extraction rates and price paths for various initial shadow prices. The solution method involves first using the steady-state head equation (3.38) to calculate the final head, and solving for the end time (t_{k-1}), the time that desalination is introduced, such that the solution to the system of differential equations (3.30) and (3.31) with boundary conditions $h(t_{k-1}) = h^*$ and $p(t_{k-1}) = \overline{p}$, results in $h(t_0) = h_0$. Simultaneously we solve the system of differential equations that allows derivation of endogenous switches, given by equations (3.35) and (3.31). Substituting the relevant parameters from table 3.6.1 in equation (3.38) gives the optimal level of the head of the aquifer, which is maintained in the steady-state at $h^* = 2.88$ $(masl)$ meters above sea level. Our programming results[18] indicate that with interest rate equal to 5% *per annum* and desalination price $(\overline{p})$ at £$0.5m^3$, the initial per cubic meter scarcity value of groundwater in the aquifer is £$0.20176m^3$[19] and desalination is introduced instantaneously[20], before any of the two sectors leave the market. At steady-state,

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[17] Gibbons provides a detailed survey and synthesis of existing studies on the economic value of water in various uses.

[18] The programming package used for the solution of the model is *Mathematica 4.0 (1999),* by Stephen Wolfram.

[19] This corresponds to an average *in situ* value of the resource equal to £0.487105 per square meter of land, or equivalently £478.105 per 0.1 hectare of land.

[20] Desalination is to be introduced in the region under consideration in May 2000. The desalination plant under

the quantity of water demanded by the domestic and agricultural sectors are $3.413mm^3$ and $6.378mm^3$, respectively[21]. Of the total quantity of water demanded, $3.200mm^3$ will be extracted from the aquifer and the remaining $6.591mm^3$ will be provided from desalination. Of the total quantity of water produced, $2.298mm^3$ and $4.293mm^3$ will be consumed by the domestic and agricultural sectors respectively. Moreover, $1.116mm^3$ will be extracted by the domestic sector and $2.084mm^3$ by the agricultural sector. Hence although the empirical application of the model does not identify any endogenous sectoral exits from the groundwater market, the disaggregated representation of the groundwater demand curve allows estimation of the intersectoral allocation of water from both relevant sources. Steady-state conditions are summarized in the table below[22]:

Table 3.6.2: Steady-State Conditions Under Optimal Control (With Desalination)

Price of Water (Desalination Price)	£0.50	Per Cubic Meter of Groundwater
Unit Extraction Cost	£0.3100	Per Cubic Meter of Groundwater
Optimal Head (h^*)	2.8800	Meters Above Sea Level
Initial Marginal Scarcity Value (λ_0)	£0.2017	Per Cubic Meter of Groundwater
Initial Scarcity Value (λ_0)	£487.1050	Per (0.1) Hectare of Land
Last Endogenous Switch Time (t_{k-1})	1999	Year of Desalination Adoption
Quantity Demanded by Domestic	3.4130	Millions Cubic Meters of Water
Quantity Demanded by Agriculture	6.3780	Millions Cubic Meters of Water
Quantity Extracted from the Aquifer	3.2000	Millions Cubic Meters of Water
Quantity Produced by Desalination	6.5910	Millions Cubic Meter of Water

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construction aims to cover only domestic water demand. However, there exists major opposition with reference to the location of the desalination plan, because the salt resulting from the desalination causes environmental harm if discharged in not deep enough areas of the sea. This is another aspect of the problem, and possibly an interesting future extension of the model.

[21] (mm^3) stands for millions of cubic meters.

[22] In their supply-side study of oil prices, *Roumasset et al. (1983)* conducted a sensitivity analysis showing that the assumption of an unlimited backstop technology does not introduce a substantial inaccuracy in the estimation of efficiency prices if the backstop price is set sufficiently high and if total resources available at and below the backstop price are abundant. In particular, their test of this condition was that the efficiency prices in the present and projection period of interest (e.g., 50-100 years) were not sensitive to changes in the backstop price of the ultimate resource. However, in situations like the one we have considered in the current empirical application, where total resources available below the backstop price are scarce, efficiency prices are very sensitive to changes in the backstop price.

The components of annual welfare derived from these steady-state conditions are shown in table 3.6.3. These add up to $£170.36m$ (millions) of total annual welfare discounted indefinitely at 5% rate of interest.

Table 3.6.3: Welfare Under Optimal Control - With Desalination	
Consumer Surplus of the Agricultural Sector	£3.324 m
Consumer Surplus of the Domestic Sector	£4.586 m
Producer Surplus from Water Extracted from Aquifer	£0.608 m
Total Annual Welfare	£8.518 m
Total Annual Welfare discounted at 5% indefinitely	£170.360 m

Let us now calculate welfare under competitive (myopic) conditions of groundwater extraction[23]. Taking a discrete time approximation to our model yields the following table:

Table 3.6.4: Calculation of Welfare Under Myopic Extraction

Year	h_o	MC	P	Q_A	Q_D	Q_A+Q_D	h_c	W_A	W_D
	$masl$	$£/m^3$	$£/m^3$	mm^3	mm^3	mm^3	$masl$	$£m$	$£m$
1	3.45	.2982	.2982	7.612	3.669	11.281	2.247	4.735	5.299
2	2.247	.3223	.3223	7.465	3.638	11.103	1.071	4.554	5.211
3	1.071	.3458	.4180	6.879	3.517	10.396	0.000	3.867	4.870

The first column of the table above gives the year of groundwater extraction, the second column gives the opening head of the aquifer (measured in meters above sea level), and the third column gives the unit cost of groundwater extraction given the opening head for each specific year (measured in pounds per cubic meter). Column four gives the price of groundwater under myopic extraction, which is usually equal to the unit extraction cost (measured in pounds per cubic meter of water). Columns five and six give the quantities of groundwater demanded by the agricultural and domestic sectors (measured in millions of cubic meters), respectively.

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[23] See appendix B3 for the analytical derivation of extraction and water level time trajectories, as well as endogenous switch times, under common property conditions.

Column seven gives the total quantity of groundwater demanded by both sectors of the economy (measured in millions of cubic meters). Finally columns eight and nine indicate sector-specific consumer surpluses which give the annual welfare derived from agricultural and domestic use of groundwater respectively (measured in millions of pounds). Note that in the last year the total quantity demanded has been set so as to exactly exhaust the aquifer. This produces a small producer surplus in year 3 (because price is above pumping cost) equal to £$0.751m$ (or equal to £$0.681m$ if discounted at 5% rate of interest). However, we have ignored this in the calculation of overall welfare since this is just an artifact of the discrete approximation. As shown in table 3.6.4, under myopic groundwater extraction the aquifer is exhausted in three years. Adding up welfares and discounting at 5% yields a net present value (NPV) welfare equal to £$27.259m$.

The above calculation assumes that when the aquifer is completely exhausted, natural recharge disappears and as a result there are zero benefits after exhaustion of the aquifer. However, given the availability of a backstop technology in our model, after the aquifer is exhausted the price jumps to £$0.5/m^3$ and desalination will be introduced. Hence, in the presence of desalination the mining phase of myopic groundwater extraction will be identical to the one described in table 3.6.4 and the steady-state phase will be similar to the one described in table 3.6.3, except that there will be no producer surplus from the aquifer, that is all water will be provided from desalination. Hence, annual welfare in the desalination phase will be £$7.91m$, capitalized at 5% that is worth £$158.2m$, and discounted back to year 1, that is worth £$136.66m$. Adding this to the NPV from the mining phase as described in table 3.6.4, gives a total NPV for this case of £$163.919m$. Comparing this figure with total welfare under optimal control with desalination (given in table 3.6.3 at £$170.36m$), provides a welfare improvement of 3.8%. From this result we can conclude that in the presence of a backstop technology the $\mathcal{GSE}$ persists, even when the assumption of infinite hydraulic conductivity is not imposed on the relevant dynamic models. This is an intuitive result, as the availability of a backstop technology effectively reduces the scarcity of the resource and consequently the welfare improvement to be achieved if current users incur not only the unit extraction cost, but also the scarcity rents of the resource they consume.

The obvious question that arises at this point is how robust is the Gisser-Sanchez effect in the absence of backstop availability, when compelete depletion of the relevant aquifer is due in the near future (that is, assuming away infinite hydraulic conductivity). To calculate welfare under the optimal control regime in the absence of a backstop technology, we take a discrete time approximation to our model, which yields the following table:

Table 3.6.5: Calculation of Welfare Under Opitmal Control.

No Desalination⟶ Exhaustion of the Aquifer in Year 4.

Year	h_o	MC	P	Q_A	Q_D	h_c	CS_A	CS_D	PS_A	PS_D
	masl	$£/m^3$	$£/m^3$	mm^3	mm^3	*masl*	*£m*	*£m*	*£m*	*£m*
1	3.450	0.2982	.5000	6.378	3.413	2.469	3.324	4.586	1.287	0.689
2	2.469	0.3178	.5228	6.237	3.384	1.513	3.179	1.125	1.279	0.694
3	1.513	0.3369	.5456	6.098	3.355	0.582	3.039	1.077	1.273	0.700
4	0.582	0.3555	1.1634	2.318	2.570	0.000	0.439	0.031	0.493	0.707

As in table 3.6.4, the first column of the table above indicates the year of extraction, the second column gives the opening head (measured in meters above sea level), and the third column gives the unit cost of groundwater extraction given the opening head for each specific year (measured in pounds per cubic meter). Column four gives the optimal price of groundwater - which is equal to the sum of the unit extraction cost and the unit scarcity value of the resource- (measured in pounds per cubic meter of water). Columns five and six give the quantities of groundwater demanded by the agricultural and domestic sectors, respectively (measured in millions of cubic meters). Columns eight to eleven indicate sector-specific consumer and producer surpluses, which give the annual welfare derived from agricultural and domestic use of groundwater, respectively (measured in millions of pounds). Note that in the last year the total quantity demanded has been set so as to exactly exhaust the aquifer. Hence, under the regime of optimal control the aquifer is exhausted in four years[24]. Adding up consumer and producer welfares for both sectors of the economy, and discounting at 5% yields a net present

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[24] To limit water demand to $3.2mm^3$ (ignoring recharge) which is what is available from the aquifer at steady-state conditions (see table 3.6.2), we need a price of $£1.392/m^3$ at which consumption from agriculture and domestic sectors would be $0.9198mm^3$ and $2.2802mm^3$, respectively. For this to be an optimum we need to find a head that satisfies equation (3.38). It is straightforward to see that there is no positive value of the head of the aquifer that satisfies this equation. Hence, optimal control also involves exhausting the aquifer.

value (NPV) welfare equal to £$22.83m$.

However, the welfare benefits of keeping the natural recharge of the aquifer available, are substantial[25]. As indicated in table 3.6.1, the natural recharge of the aquifer under consideration is equal to $4.0mm^3$ and the steady-state quantity demanded of groundwater extracted from the aquifer under optimal control is equal to $3.2mm^3$ (see table 3.6.1). To limit demand to this level a price of £$1.392/m^3$ is needed, at which consumption from agriculture and domestic sectors would be $0.9198mm^3$ and $2.2802mm^3$, respectively. The annual consumer surplus from agriculture having its $0.9198mm^3$ is £$9.069m$. The annual consumer surplus from the domestic sector having its $2.2802mm^3$ is £$2.047m$. However, there is considerable producer surplus because pumping costs when the aquifer is empty are £0.3672 per m^3 while the selling price is £1.392 per m^3. Applying this surplus to $3.2mm^3$ is worth £$3.279m$ annually. Thus total annual benefits are £$5.395m$, and capitalizing at 5% makes that worth £$107.9m$. Assuming this regime did not start until year 4 after the aquifer is (almost) exhausted, gives a NPV of £$88.77m$. Adding this amount to £$22.83m$, which is the total welfare received the first four years of optimal groundwater extraction before the exhaustion of the aquifer, gives an overall NPV for optimal control with no desalination but continuous recharge of £$111.60m$. Comparing this welfare gain with the one derived under myopic conditions of groundwater extraction (£$27.259m$) gives a huge welfare improvement of 409.4% and the Gisser-Sanchez effect certainly disappears. Table 3.6.6 summarises welfare derived under different regimes with and without backstop availability.

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[25] Some hydrologists consider that a myopically managed aquifer subject to saline intrusion runs the risk of irreversible loss of recharge, which can be avoided at little or no cost with careful (optimal) management. This is a hydrological possibility for aquifers that consist of fine materials (e.g. silty sands), while it is less relevant for aquifers that consist of coarse materials (e.g. gravels). Coastal aquifers such as the one we are modelling in this chapter consist of fine materials. As indicated above, this makes the hydrological possibility of irreversible loss of recharge under myopic extraction that can be avoided at little or no cost with optimal management, very probable. For this reason in this chapter I am schematically modelling the simplified case in which irreversibility precludes the use of aquifer recharge, although admitting that reality may be more complex and site specific.

Table 3.6.6: Examining the robustness of the $\mathcal{GSE}$.

Regime	Backstop	Welfare	Welfare Improvement	$\mathcal{GSE}$
Optimal Control	Available	£170.36m		
Myopic	Available	£162.621m	3.8%	Persists
Optimal Control	Not Available	£110.51m		
Myopic	Not Available	£25.961m	409.4%	Disappears

Our results suggest that in the presence of a backstop technology the $\mathcal{GSE}$ persists. This is an intuitive result because it suggests that when the scarcity of the resource is reduced due to the presence of a backstop technology, welfare gains from controlling resource extraction are not significant for any practical purposes. However, our results suggest that in the absence of a backstop technology and continuous natural recharge the $\mathcal{GSE}$ disappears; that is, a huge welfare improvement is derived from controlling extraction as compared to myopic exploitation of the aquifer. This result constitutes a partial resolution of the Gisser Sanchez effect and applies to situations where extraction is likely to exhaust the water in the aquifer and social benefits from managing the aquifer and sustaining natural recharge to the indefinite future, are found to be significantly greater than benefits derived under myopic extraction which involves complete exhaustion of the aquifer. However, all relevant empirical applications that identify the existence of the $\mathcal{GSE}$ are characterized by model parameters that converge to a steady-state of positive groundwater extraction and aquifer head, under both competitive and optimally controlled solutions. As mentioned in the introduction of this chapter, this is an artifact of the commonly adopted assumption of infinite hydraulic conductivity, which implies that the aquifer will never dry up, irrespective of groundwater extraction rates. However, in situations where extraction is likely to exhaust the water in the aquifer under consideration, this assumption should not be adopted. In the present model this assumption was not adopted, and as a result social benefits from managing the aquifer and sustaining natural recharge of the aquifer, are found to be significant for all practical purposes. It is worth noting however, that this result holds only if sustaining natural recharge of the aquifer is possible under optimal control even if the aquifer is completely exhausted[26].

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[26] This throws some doubt on the wisdom of using linear demand and pumping cost functions, since behaviour

3.7 Conclusion.

Although motivated by the case of coastal aquifers, the model is an extension of the model of an exhaustible resource subject to a backstop technology *(Heal, 1976),* generalized to include the possibility of demand adaptation to increasing resource scarcity. Our empirical results indicate that when a bakstop technology is available the $\mathcal{GSE}$ persists, while in the absence of backstop availability it is possible that the $\mathcal{GSE}$ disappears. This provides a partial resolution of the Gisser-Sanchez paradox that dominates the relevant literature since 1980. The essence of our argument is that net groundwater management benefits are very significant in situations where no management of the resource leads to complete exhaustion of the water in the aquifer under consideration, while optimal management of the resource achieves to sustain positive rates of groundwater extraction through sustaining natural recharge in the indefinite future (although it also involves complete depletion of the aquifer).

While the notion of a backstop technology as a basis for resource management remains controversial, we submit that the existence *per se* of a backstop is not the critical issue. Virtually limitless and renewable resource substitutes do exists (e.g. seawater, solar power, etc.). The critical issue is at which unit costs can they be made effective substitutes for nonrenewables. Moreover, the concern of most relevance to policy is what happens in the interim on the way to the steady-state. In the final analysis it is the trajectory to the steady-state, rather than long-run sustainability, that captures concerns for the future. Our model, not only solves for the optimal time of adopting this technology which defines the steady-state conditions, but also models the optimal path of resource use towards this steady-state, by allowing endogenous demand adaptation to increasing resource scarcity. Other applications of the approach developed in this chapter, could disaggregate resource demand by technological efficiency of resource use and describe the chronological pattern of adopting more efficient irrigation technologies. Moreover, the optimal time of use of other sources of water, such as surface water from a dam or a reservoir, or artificial recharge, could be introduced in the model as additional backstops to groundwater depletion.

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close to zero is crucial. At the same time it indicates interesting lines of future research.

The model developed in this chapter does not take into account dynamic strategic interactions between extracting units within or among economic sectors, which is a realistic description of groundwater exploitation in situations with a small number of relevant extracting agents. As argued in section 2.4 of chapter 2, these external effects are independent of the pumping cost externality and if present and significant, they may affect the value the resource scarcity rents *(Negri, 1989; Dixon, 1989; Provencher and Burt, 1993).* The intrinsic logic of this model however, can easily accommodate game theoretic formulations, by reformulating the optimal control model into a differential game and employing closed-loop (feedback) solution techniques for the derivation of relevant trajectories.

A limitation of our model is that it uses the agents' benefits to characterize socially optimal exploitation, which is problematic when irreversible events or irreparable damage to nature are involved. Given that we are dealing with an aquifer that faces complete depletion in the near future, it would be more appropriate for the water management authority to incorporate the water table level into its objective function and postulate some kind of intervention to avoid 'extinction' or the occurrence of irreversible events[27], even if the backstop price is so high that renders its endogenous adoption non-optimal under a management regime. This could be another subject for further research.

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[27] See section 2.4.2 of chapter 2, where we discuss the work of *Tsur and Zemel (1995),* where optimal exploitation of groundwater when extraction affects the probability of irreversible event occurring is investigated.

Appendix A3.

Description of the Physical System of Saltwater-Freshwater Interaction.

The development of groundwater resources in mainland coastal areas is a delicate issue, and careful management is required if water quality degradation due to the encroachment of seawater is to be avoided. The general class of groundwater systems that our model attempts to describe, consists of a saturated porous medium containing a miscible fluid of variable density and salt concentration. In a porous media in a coastal area, a zone of mixing, known as the zone of diffusion or dispersion, forms between the two fluids, as shown in the hypothetical cross-section in figure *A.3.1.* At this zone of mixing, some of the saltwater mixes with the freshwater and moves seaward causing the saltwater to flow toward the area of mixing.

Figure A3.1: Hypothetical cross-section showing the zone of diffusion and flow patterns in homogeneous coastal aquifer *(modified from Cooper et al., 1964)*.

Appendix B3.

Welfare Measures in an Input Market.

Mishan (1968) demonstrated the well-known partial equilibrium result that the area behind a competitive supply curve conditioned on fixed-input prices (producer's surplus) measures returns or quasi rents on fixed-production factors. Likewise, it can also be shown that the area behind a derived demand for inputs (conditioned on fixity of other input and output prices) measures returns or quasi rents on fixed-production factors of the production process using the input. That is, a producer's surplus as consumer of any of his inputs is the same as his surplus as producer and supplier of his output in the fixed-price situation. In contrast to this extremely partial approach, a number of other authors *(Johnson, 1960 ; Krauss and Winch, 1971)* have attempted to approach welfare surplus from a general equilibrium standpoint where all other prices in the economy are allowed to vary. These works have culminated in the paper by *Anderson (1974)* which shows that welfare changes can be determined by comparing the change in income arising from production (the area behind the general equilibrium supply function) with the income effect of price changes in consumption.

Then, *Just and Hueth (1979)* argued that the area behind a general equilibrium demand curve in an input market does not measure benefits to buyers in that market alone, but rather measures the sum of rents to producers selling in all higher markets (assuming no intervening market has perfectly elastic demand) plus final consumer's surplus. These results hold given the usual conditions required for validity of consumer's surplus measures in the final goods market and producer's surplus in the initial resource market. If the final consumer's surplus is the Marshallian surplus calculated from an ordinary final goods demand, then the results of *Willig (1976)*[28] can be used to determine the closeness of approximation to the proper

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[28] Although the Marshallian consumer surplus, which is defined as the area behind the inverse uncompensated demand curve, has some intuitive appeal as a welfare indicator, it does not measure any of the theoretical definitions of welfare change. It is neither an index of utility change, expect under special conditions, nor a measure of gain or loss that can be employed in a potential compensation test. The Marshallian surplus does lie between compensating variation (the welfare change associated with a price decrease given by the reduction in income needed to hold the individual on the original indifference curve, which measures the area to the left of the Hicks-compensated demand curve that passes through the initial position) and equivalent variation (the additional expenditure (income) necessary for the individual to reach the original utility level, given the initial set of prices, which measures the area to the left of the Hicks-compensated demand curve that passes through the final position). This opens the question of whether it can be a useful approximation to either of these

Hicksian concept. If the demand curve used in calculating the change in consumer surplus and generating intermediate market demands is the proper compensated demand, then the change in consumer surplus is the proper Hicksian welfare measure. Moreover, if some other final good's price changes as a result of altering price in the market under consideration, then only the Hicksian version of the demand curve has the proper path independence of the line integral used to evaluate the change in the expenditure function[29]. However, as argued by Robert Willig "in most applications the error of approximation will be very small. in fact the error will often be overshadowed by the errors involved in estimating the demand curve" *(1976, p. 589).*

In the natural resource literature researchers have attempted to directly estimate compensating variation (CV) and equivalent variation (EV) welfare measures, using the concept of willingness to pay and willingness to sell, respectively. In contrast to Willig's proposition, heuristic arguments and empirical evidence have supported the belief that willingness to sell exceeds willingness to pay. *Bockstael and McConnell (1980)* draw attention to some difficulties in applying Willig's results in empirical work, and point out that economists should be careful about estimating the value of removing or providing access rights to natural resources. There is no strong evidence to show that unambiguous measures of welfare changes can be calculated when a resource is eliminated, as in the empirical application of the optimal control model of this chapter. This is unfortunate, because some of the most controversial questions faced by economists deal with the consequences of eliminating/depleting natural resources. Calculating the value of removing access to/or depleting a resource implies the equivalent of a price increase which reduces quantity to zero, and hence makes it difficult to use Willig's error bounds for compensating and equivalent variation. Moreover, for some functional forms (linear, double-

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other measures. *Willig (1976)* has offered rigorous derivations of expressions relating the Marshallian surplus, compensating variation and equivalent variation. These expressions provide a way of calculating the magnitude of the differences among the three measures for given prices, quantities, and income. Willig's bounds for the approximation errors are based on the fact that the differences between the three measures arise from an income effect on the quantity demanded; and the size of that effect depends on the change in real income brought about by the price change and on the income elasticity of demand for the good.

[29] When simultaneous changes in all prices take place, the Marshallian consumer surplus is defined as a line integral. This integral will be independent of the path of integration (that is, the order in which prices and/or incomes are assumed to change) only if the income elasticities of demand for all goods are equal. The income elasticities of all goods can be equal to each other only if they are all equal to one, in other words, if preferences are homothetic. Finally, if the prices of only a subset of all goods change, a unique Marshallian surplus exists if the marginal utility of income is constant with respect to only those prices that are changed *(Just, Hueth, and Schmitz; 1982).*

log), we cannot calculate the errors of approximating willingness to buy or sell by the area under the demand curve.

Appendix C3.

Common Property Solution of the Model.

In chapter 2 we argued that *Gisser and Sanchez (1980 a, b)* derived a result, which prophetically summarized the up to date empirical estimates of the difference in the net present value of benefits derived under socially optimal and competitive rates of water pumping. This result essentially states that in certain circumstances, the numerical magnitude of the various pumping cost and common property externalities is insignificant. In this appendix we derive analytically the competitive extraction and water table level equilibrium paths, as well as competitive switch times for sectoral exits from the groundwater market and for endogenous adoption of the desalination technology. The competitive-commonality solution of the model we develop, allows estimation of the magnitude of common property externalities, if compared with the optimal control solution of the model. The numerical solution of the model under both regimes allows identification of the presence or absence of the $\mathcal{GSE}$.

The common property equilibrium characterizing groundwater depletion differs from the planning equilibrium in the five intertemporal traits of the model: rate of groundwater mining, groundwater allocation between sectors, switch times representing a sector's demand for groundwater becoming equal to zero, the time of adoption of the backstop technology and the quantity of water produced by the backstop technology at steady-state conditions. To derive the common property equilibrium, we ignore groundwater's scarcity value and adopt the myopic condition of marginal benefit of groundwater use equals current marginal cost of groundwater pumping. As analyzed in chapter 2, the myopia of ignoring user cost stems from behavioral incentives that originate in common ownership of groundwater.

As suggested by *Kim et al. (1989)*, the characterization of the common property equilibrium of our model, follows from manipulating equations (3.3), (3.4) and (3.5). To derive this equilibrium we explicitly define the marginal cost equation (see section 3.6),

$$MC_G = c[h(t)] = k_1(SL - h) = k_2 - k_1 \cdot h(t) \qquad \text{for } q_{D_i} = 0 \tag{3.39}$$

$$MC_G = \overline{p} = \qquad \text{for } q_{D_i} > 0 \tag{3.40}$$

$$h(t=0) = h_o \tag{3.41}$$

$$q_{D_i}(t=0) = 0 \tag{3.42}$$

Equations (3.39) and (3.40) give the relevant marginal cost of extraction during the mining era and after the introduction of desalination, respectively. Equation (3.41) gives the initial condition for the head of the aquifer and equation (3.42) reveals the assumption that both the cost of desalination and groundwater reserves are high enough so that desalination is not used at the initial stage of the system. Given zero production of water from desalination, equating price (marginal benefit of groundwater extraction) in equation (3.24), with the current marginal cost of groundwater pumping and substituting this expression into the inverse demand equation (equation 3.3) gives,

$$q_{Gi}(t) = a_i - k_2 b_i + k_1 b_i h(t) \qquad i = 1, ..., n. \tag{3.43}$$

The equality in the equation (3.43) remains through time, thereby ignoring the value of groundwater left in the aquifer from reducing future pumping costs, i.e. ignoring the scarcity value of the resource. Moreover, equation (3.43) equates marginal benefits of water use across economic sectors and as a result it satisfies static inter-sectoral allocative efficiency, although it does not satisfy dynamic efficiency. Inserting equation (3.43) in the hydrological constraint of the system gives,

$$\begin{aligned} \dot{h}(t) &= \left[\frac{k_1(f-1-s)\sum\limits_{i=j}^{n} b_i}{AS} \right] \cdot h(t) \\ &\quad + \left[\frac{R + (f-1-s)\sum\limits_{i=j}^{n} a_i - k_2(f-1-s)\sum\limits_{i=j}^{n} b_i}{AS} \right] \\ for\ j &= 1 \end{aligned} \tag{3.44}$$

The solution to (3.43) is,

$$\begin{aligned}
h(t) \quad &= \quad -\left[\frac{R+(f-1-s)\sum\limits_{i=1}^{n}a_i-k_2(f-1-s)\sum\limits_{i=1}^{n}b_i}{k_1(f-1-s)\sum\limits_{i=1}^{n}b_i}\right] \\
&\quad + \left\{h_0+\left[\frac{R+(f-1-s)\sum\limits_{i=1}^{n}a_i-k_2(f-1-s)\sum\limits_{i=1}^{n}b_i}{k_1(f-1-s)\sum\limits_{i=1}^{n}b_i}\right]\right\} \\
&\quad \cdot \exp\left[\frac{\left(k_1(f-1-s)\sum\limits_{i=1}^{n}b_i\right)t}{AS}\right] \qquad (3.45)
\end{aligned}$$

Inserting $h(t)$ in equation (3.43) gives,

$$\begin{aligned}
q_{Gi}(t) \quad &= \quad \left[\frac{a_i-b_i\left[R+(f-1-s)\sum\limits_{i=1}^{n}a_i\right]}{(f-1-s)\sum\limits_{i=1}^{n}b_i}\right] \\
&\quad + \left[\frac{b_i\left[R-\left[k_1(SL-h(t=j-1))\right](f-1-s)\sum\limits_{i=1}^{n}b_i+(f-1-s)\sum\limits_{i=1}^{n}a_i\right]}{(f-1-s)\sum\limits_{i=1}^{n}b_i}\right] \\
&\quad \cdot \exp\left[\frac{\left(k_1(f-1-s)\sum\limits_{i=1}^{n}b_i\right)t}{AS}\right] \\
i \quad &= \quad 1,...,n. \qquad (3.46)
\end{aligned}$$

Equations (3.45) and (3.46) characterize depletion in the first stage of the system, with n sectors using water in their production activities.

Endogenous switch times are derived by using the numerical ordering of sectors by intercept, as defined in the main text of this chapter. Setting $q_{Gi}(t) = 0$ and solving equation (3.46) for (t), gives the first endogenous exit for the common property solution. With the first switch time established, the solution of the system of equations (3.45) and (3.46) represents common property equilibrium paths, for the first (j) stage. Characterizing the intertemporal paths for subsequent stages again develops into a routine, sequential procedure. In stage 2, the value of equation (3.45) at the first endogenous switch establishes the initial condition for $h(t)_{j=2}$. Using stage 2's initial condition the procedure followed for the derivation of equations (3.43-3.46) is repeated in order to define the time path of water allocation among the $(n-1)$ sectors, until equation (3.40) becomes binding. At this point the backstop technology is adopted, and the system reaches a steady-state at which desalination continues to be used and marginal benefit of water is fixed at the unit cost of the backstop technology $(\bar{p})$ (hence $\dot{p}_j(t) = 0$). In section 3.6, the numerical solution of the common property equilibrium characterized in this appendix is derived and compared with the optimal control solution of the problem.

Chapter 4

Hedonic Price Analysis and Selectivity: Theory and Application to Groundwater as a Productive Input.

4.1 Introduction.

In chapters 1 and 2, we have argued that the difficulty in establishing clear ownership rights in groundwater exploitation makes it improbable for markets for this resource to function well. In the absence of well-functioning markets there is no price or quantity data from which the benefit (willingness to pay) from having access to good quality groundwater, can be reliably estimated. Although, the marginal willingness-to-pay curves for nonmarketed, public goods cannot be estimated from direct observations of market transactions, they do exist. How then, can they be derived? Revealed preference approaches to environmental valuation aim to obtaining demand and benefits information for nonmarketed, public goods. They depend on the existence of observable behaviour within a market which is connected in some clearly defined way with the environmental non-marketed resource to be valued. Information derived from this observed behaviour are used to estimate willingness to pay for the resource. Two such methods, prevalent in the environmental literature, are the *hedonic* and the *travel cost* methods.

The hedonic method rests on the assumptions that (a) the price of some marketed good (e.g. land, house, car, wage rate, etc.) is a function of its different characteristics, (b) an implicit price exists for each of the characteristics, and (c) this price can be identified statistically. If one of the characteristics is a differing but measurable environmental or resource attribute (e.g. varying groundwater supplies or qualities), the hedonic technique enables derivation of the implicit marginal willingness to pay (price) for an incremental unit of that characteristic. Likewise, the principle being used in the travel cost technique, is that of inferring the value of a set of non-marketed attributes from expenditure in another market. However, this technique can be applied in somewhat different cases; i.e. it can be applied if (a) individuals are observed to incur costs in order to consume commodities related to the environmental or resource characteristics of interest, and (b) the consumed commodities are non-marketed. Intuitively, the extra time and money an individual is willing to spend to access a site with more desirable environmental or resource characteristics, yields useful information for valuation of those characteristics.

The hedonic price technique was developed by *Griliches (1971)* and others, initially for the purpose of estimating the value of quality change in consumer goods. The formal structure of hedonic models was first analyzed by *Rosen (1974)* who has used the hedonic price concept to analyze the supply and demand of the characteristics that differentiated products in competitive markets. *Freeman (1974)* was the first to provide the profession with an early discussion of the application of the concept to measuring the demand for environmental quality characteristics, while the first empirical study of housing prices and an environmental amenity was by *Ridker and Henning (1967).* The earliest examples of hedonic methods applied to irrigation water valuation were *Milliman (1959)* and *Hartman and Anderson (1962).* Their work anticipated most of the major developments of the hedonic method in the 1970's, but predated the coining of the term 'hedonic'. Moreover, the relationship among land prices and surface and groundwater access (both in quantity and quality terms) has been studied in a hedonic framework by *Miranowski and Hammes (1984), Gardner and Barrows (1985), Ervin and Mill (1985)* and *King* *and Sinden (1988)*[1]. A more recent example applied to irrigation water value is *Toell, Libbin and Miller (1990)*, who compared sales of irrigated and non-irrigated lands in order to measure the value of groundwater in the southern High Plains in the United States. The travel cost technique seems to have been first proposed by *Hotelling (1931)*, and subsequently developed by *Clawson (1959)* and *Clawson and Knetsch (1966).* Such models have also been employed to measure the welfare effects to changes in water quality of recreational sites (e.g. *Binkley, 1978; Freeman, 1979; Caulkins et al., 1986; Smith and Desvousges, 1986; Bockstael et al., 1987*).

This chapter considers the case where the quality characteristics of an input influence its usage and argues that this can cause sample selection problems giving rise to misleading parameter estimates corresponding to the hedonic shadow prices of the quality characteristics of the input. The input under consideration is land. The sample selection problem here is analogous to the one considered in the travel cost models, where the endogeneity of the decision to visit a recreational site is shown to result in estimated demand that exaggerates the consumer surplus associated with the trip[2] (*Miller and Hay, 1981; Vaughau and Russell, 1982; Hellerstein and Mendelsohn, 1992; Hausman et al., 1992*). The sample selection problem investigated here arises from the fact that the decision to pay for a particular input (i.e. a parcel of land) is not exogenous to the level of the price paid. This is because certain quality characteristics can be responsible for the parcel being included in or excluded from the sample. For example, in a hedonic analysis of residential housing, traffic noise can be found to have a positive valuation because houses in main roads have a high probability of being converted to business properties.

We demonstrate this argument in a model where land is demanded for use as an input either in agricultural production or in touristic development. In the context of this model the hedonic valuation of the quality characteristics of the land parcel is investigated together with

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[1] Moreover, *Caswell and Zilberman (1986)* considered alternative exogenous irrigation technologies in a static setting and argued that the introduction of modern land quality-augmenting irrigation technologies tends to increase the value of the lower quality land on which the new technologies are adopted, but it may reduce the value of prime lands, reducing the hedonic prices of land quality and water depth.

[2] Recent attention to limited dependent variable models in the econometrics literature has led to a wholesale departure from ordinary least squares estimation of travel cost models. When the data available to the researcher are collected "on-site", the sample will be conditioned on recreational participation at that site and is said to be "truncated". More interesting stories are possible when data include observations on non-participants as well. Such data are especially important if one wishes to use the results of the model to predict responses to policy changes where these changes might cause individuals to enter or leave the "market" for a recreational good.

this selection decision, in order to avoid the sample selection bias of the type described above. Proximity to the sea in particular, decreases the probability of land usage for farming due to salinization of groundwater supplies and increases the probability of tourism usage due to attractiveness to tourists. Land parcels closed to the seaside however, may be used in agriculture in spite of the poor quality of their groundwater supplies, because the marginal cost - marginal benefit calculation undertaken by prospective buyers, based on benefits achieved by agricultural or touristic development of each particular parcel of land, does not allow use of the parcel in touristic development. The relevant net marginal benefit is a function of the characteristics of the parcel (including the quality of groundwater supplies accessible to each particular parcel) but is not observable. The aim of this chapter is to investigate empirically how this selectivity problem affects the willingness to pay for improvements in groundwater quality; the form of quality degradation under consideration is seawater intrusion.

The structure of this chapter is as follows. Section 4.2 describes the decision environment in which the selectivity problem of interest arises. Section 4.3 develops a model of producer demand for package factors of production and discusses the behavioural effects of characteristics reflecting quality. Section 4.4 reports the results obtained from the empirical analysis and section 4.5 concludes the chapter.

4.2 Decision environment.

As argued in the introduction of this thesis, it is important to keep in mind that groundwater scarcity has an important qualitative dimension that further limits the supply of usable water. In chapter 3 we investigated the dynamics of one particular cause of quality deterioration of groundwater resources, namely seawater intrusion. This refers to coastal fresh groundwater systems that are in contact with saline water which, if drawn into the freshwater aquifer systems, can diminish the water's usefulness for various purposes. Figure 4.2.1 presents a simplified description of the movement of intruding seawater into an aquifer. Consider a coastal irrigation district. A reference boundary (R) is defined, where (R) may be the coastal perimeter of the irrigation district, the seaward limit of agricultural activity, or an arbitrarily defined line. The object of (R) is to provide a point of reference from which to measure the length of intrusion.

For an arbitrarily given depth (d) measured at (R), (L_s) is the length measure of saltwater intrusion. Note that the interface and the point of measuring the length of intrusion (L_s), is not between saltwater and freshwater. In as much as saltwater and freshwater are miscible fluids, a transition zone will exist between the two fluids. The maximum level of salt concentration for irrigation water is usually around 3000 TDS[3] mg/l (milligrams per litre). Hence as far as the agricultural sector is concerned interest lies in the interface between water with total salinity greater than 3000 and water with total salinity less than 3000, i.e. the interface between 'brackish water' and 'fresh-water', as shown in figure 4.2.1[4].

Figure 4.2.1: Representation of Seawater Intrusion.

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[3] Although the effects of particular ions on crop productivity vary, the usual approach is to lump all salinity into a macro measure called "total dissolved solids" (TDS).

[4] This figure is a stylized version of the figure in Appendix A3, where the zone of diffusion corresponds to the area of the aquifer filled with brackish water.

To understand the movement of saltwater intrusion imagine a district that is divided into (n) zones. The dimensions of each zone depend on the impact of saltwater intrusion on pumping activity. For example, starting at (R), an inland movement of the saltwater interface to a distance $\left(L_s^1\right)$ results in the loss of pumping activity in a given area. This arc would be zone 1. The impact of further movements of the interface is usually treated discretely, with each succeeding zone defined in terms of the impact of intrusion on pumping potential. Thus the location of a parcel of land with respect to its proximity to the sea, is defining for the quality of groundwater supplies accessible to owners of the parcel under consideration: the further away from the sea the parcel is, the lower the impact of seawater intrusion on its groundwater supplies. It is also worth noting that in terms of freshwater stock, instability in the interface between salt water and freshwater causes a widening of the transition (diffusion) zone. Thus as the aquifer is mined, saltwater not only replaces freshwater, but relatively larger quantities of freshwater become brackish. Instability of the interface is directly related to the rate of mining of the aquifer given a level of freshwater stock.

As it is obvious from figure 4.2.1, if the phenomenon of saltwater intrusion occurs in a particular aquifer, proximity of a parcel of land to the sea is a proxy for the existence and extent of saltwater intrusion in a parcel's groundwater supplies. As groundwater supplies are contaminated, if other sources for irrigation water are not readily available, new wells must be drilled, coastal injection wells installed, and/or brackish groundwater treated with costly osmosis or catalysis methods. All these imply additional costs for the farm owner (agricultural producer). Moreover, if salinated water is applied for irrigation, dissolved soils become concentrated in irrigated soils (as part of the applied water evaporates through plants) and adversely affect crop productivity. Crops vary in their sensitivity to salinity. Generally speaking however, the least sensitive crops are also the least valuable, so areas irrigated with highly saline waters tend to emphasize low-valued types of crops. Thus proximity to the sea decreases the benefits from agricultural use of a parcel of land (if other clean, but equally priced sources of water are not readily available). As a result, proximity to the sea decreases the probability of land usage for farming. That is, owners of land close to the sea substitute away from fresh groundwater as an input in their production because fresh groundwater becomes more expensive to access due to saltwater intrusion. Hence sea proximity does not only affect the value of agricultural land, but it also affects the decision to use a parcel of land as an input in agricultural production. If this endogeneity problem is ignored, hedonic results for agricultural land market will ignore the full effect of groundwater salinization on the price of agricultural land; thus giving wrong estimates of shadow prices of relevant environmental and resource characteristics. To correct for this problem we adopt a simple Heckman *(1976, 1979)* type process.

However, property value measures, have the capability of capturing the marginal value of all possible effects of environmental changes in a single number. In our model, proximity to the sea also increases the probability of land usage for tourism development due to attractiveness to tourism[5]. That is, owners of land who chose to use their land for agricultural production, value sea proximity because of the prospect of switching to the most lucrative tourism industry in the near future. Omitting this effect, will ignore the increase in the shadow price of land which is a prospective candidate for use in tourist development. Thus, on the whole proximity to the sea gives rise to two opposite effects on the price of land *already* used as an input in agricultural production: (a) the probability of land usage for farming decreases and (b) the probability of land usage for tourism development increases. To separate these two effects in our empirical analysis, we use two continuous index variables specifying the proximity of each parcel of land to the coast and the town center of the region under consideration, respectively. Given that the town of the region is located on the coast and touristic development is traditionally more intense closer to the town centre, this variable aims to serve as a proxy for the effect of sea proximity on the attractiveness of an agricultural parcel for tourism development.

To summarize the decision process put forward in this section, there is an endogenous selection on the use of land based on the quality of the land's groundwater supplies and other characteristics, and an additional positive effect on the shadow value of land after deciding to use it in agricultural production, emerging once again from the effect of sea proximity on prospective future tourism development of the land. The decision tree relevant for understanding the above argument is graphically presented in figure 4.2.2., where we provide a stylized exposition of the decision process we want to study both theoretically and empirically in this chapter[6]. We also

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[5] It is worth noting that the tourism industry in the region under consideration, does not use groundwater as an input in its production. Instead surface water is used.

[6] For the construction of this figure, we adopt two of the assumptions that will be employed in the theoretical

note that the first decision step shown in the figure, that is whether to purchase land or not, is ignored in this chapter due to absence of relevant data that would allow empirical investigation of the matter.

Figure 4.2.2: Endogenous Selection of a Packaged Input.

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model of this chapter, to be presented in the following section. Firstly, we assume that the cost function is weakly separable in land, so that prices of other goods can be excluded from the decision to buy a parcel of land (see *Deaton and Muellbauer, 1980, p. 122-137*, for an excellent discussion on the meaning and usefulness of the "separability assumption" and "two-stage budgeting"). Secondly, we assume that each individual purchases only one land bundle. We explain the need for this assumption in the following section.

4.3 Selectivity and Input Demand.

We assume that firm-specific production sets over packaged inputs[7] of agricultural production are described by the separable cost function,

$$C(p, Y_\ell) = G_\ell \left[c_1 \left(p_{11}, ..., p_{1K} \right), ..., c_I \left(p_{I1}, ..., p_{IK} \right), Y_\ell \right] \tag{4.1}$$

where Y_ℓ are the units of output produced by the ℓ^{th} producer (firm) from the use of all the packaged inputs of production, $c_i\left(.\right)$ is a sub-function reflecting the unit cost of the i^{th} package and p_{ik} is the price of the k^{th} input in this package. In this context, producer $\ell = 1, .., L$ obtains the $k = 1, ..., K$ input indirectly, through purchasing the package $i = 1, .., I$. Applying Shephard's lemma[8] to (4.1) we obtain the demand for the k^{th} input in the i^{th} package by the ℓ^{th} producer,

$$q_{ik\ell} = \frac{\partial C\left(p, Y_\ell\right)}{\partial p_{ik}} = \frac{\partial G_\ell\left[.\right]}{\partial c_i\left(.\right)} \frac{\partial c_i\left(.\right)}{\partial p_{ik}} \tag{4.2}$$

where $\partial G_\ell\left[.\right] / \partial c_i\left(.\right)$ represents the demand for the i^{th} package and $\partial c_i\left(.\right) / \partial p_{ik}$ the *conditional* demand for the individual k^{th} factor of production in this package, i.e. demand for k^{th} input subject to the expenditure of the i^{th} package being decided. Here we focus on the case where producers purchase only one input package at a time[9], i.e. the outcome of the above optimization problem is a 'corner solution'. We therefore drop the i^{th} subscript for convenience and incorporate the selection aspect in the analysis by writing expenditure on the selected package by the ℓ^{th} producer as,

$$\begin{aligned} y_\ell &\equiv \Sigma_k q_{\ell k} p_k = \Sigma_k \left[\frac{\partial G_\ell\left[.\right]}{\partial c\left(.\right)} \frac{\partial c\left(.\right)}{\partial p_k} \right] p_k \\ &= \frac{\partial G_\ell\left[.\right]}{\partial c\left(.\right)} \Sigma_k \frac{\partial c\left(.\right)}{\partial p_k} p_k = \frac{\partial G_\ell\left[.\right]}{\partial c\left(.\right)} c\left(.\right) \end{aligned} \tag{4.3}$$

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[7] A packaged input is an input which has several attributes that are recognized by purchasers, but the attributes cannot be unbundled when purchasing it.

[8] Shephard's lemma states that the partial derivatives of the cost function with respect to prices (if they exist) are the Hicksian demand functions.

[9] This assumption is convenient for modelling quality heterogeneity through a hedonic price function, that appears below. More specifically, if more than one land package were purchased, it would be necessary that the bundles be identical or that the hedonic price function be linear in all characteristics. This is because there can be only one marginal implicit price recorded for each individual for each characteristic.

where $\partial G_\ell\left[.\right]/\partial c\left(.\right)=1$ if the package is selected by the ℓ^{th} firm and $\partial G_\ell\left[.\right]/\partial c\left(.\right)=0$ otherwise.

We model the package selection decision using a simple Heckman *(1976, 1979)* type process,

$$I_\ell^* = g\left(x_\ell\right) + v_\ell \tag{4.4}$$

where $x_\ell = x_{1\ell}, x_{2\ell}, ...x_{M\ell}$ is a vector of variables affecting the package choice, including quality characteristics and other firm-specific production characteristics like farming skills etc.; v_ℓ is an error term. Each firm values a particular parcel according to it's characteristics. In particular each firm makes a marginal benefit - marginal cost calculation based on the benefit achieved by making the purchase and using the land for production in the agricultural sector, and by not making the purchase and using the money for something else (i.e. purchase land for touristic development). As I_ℓ^* increases (due to quality improvements, increases in firm efficiency etc.) so does the probability of selecting this package for agricultural production. Since marginal net benefit is obviously not observable, we model the difference between benefit and cost with the unobservable variable I_ℓ^*. However, we are able to observe whether a parcel of land is purchased and used in agriculture, or not. Hence, we can infer the sign of I_ℓ^*, but not its magnitude, from such information. Using the dummy variable $D_\ell = 1$ when the i^{th} package is selected by the ℓ^{th} firm and $D_\ell = 0$ otherwise, we can write,

$$\begin{aligned} D_\ell &= 1 \text{ if } I_\ell^* > 0 \\ \text{and } D_\ell &= 0 \text{ if } I_\ell^* \leq 0 \end{aligned} \tag{4.5}$$

Turning to the modelling of quality heterogeneity of agricultural land parcels used by different producers[10], recall that $c_i\left(.\right)$ in (4.1) is the unit cost of the i^{th} package and defines the quality augmented price of the k^{th} input in the package selected by the ℓ^{th} producer as $p_{k\ell}^* = \theta_{k\ell} p_k$, where $\theta_{k\ell} \geq 1$. Then quality heterogeneity is introduced in the analysis by writing

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[10] *Palmquist (1989)* has developed the analytical hedonic model for agricultural land. *Miranowski and Hammes (1984)* and *Palmquist and Danielson (1989)* present estimates of hedonic price functions and marginal implicit prices for agricultural land.

the unit cost of the package under consideration as,

$$c\left(p_{1\ell}^{*}, ..., p_{K\ell}^{*}\right) = c(\theta_{1\ell}p_1, ..., \theta_{K\ell}p_K) \tag{4.6}$$

At base period prices ($p_k = 1$, for all k), equation (4.6) obtains the form $c\left(.\right) = c(\theta_{1\ell}, ..., \theta_{K\ell})$. Then expenditure on the package by the ℓ^{th} producer incorporating the selection decision can be written as,

$$lny_\ell = lnc(\theta_{1\ell}, ..., \theta_{K\ell}) + u_\ell \quad \text{if } D_\ell = 1 \tag{4.7}$$

With (D_ℓ) and (x_ℓ) observed for a random sample, but (y_ℓ) observed only when $D_\ell = 1$, the expenditure variable in this equation is incidentally truncated[11] from below, on a non-positive net benefit from buying land for agricultural purposes (i.e. $I_\ell^* > 0$). Assuming that v_ℓ and u_ℓ have a bivariate normal distribution with zero means and correlation ρ, then we can insert these in Theorem 2 in Appendix A4 to obtain,

$$E\left[u\right]_{D_\ell=1} = \sigma\frac{\phi_\ell\left(.\right)}{1-\Phi_\ell\left(.\right)} \tag{4.8}$$

where $E\left[.\right]$ denotes expectations, $\phi_\ell\left(.\right)$ and $\Phi_\ell\left(.\right)$ are the values of the standard normal probability density (*pdf*) function and the standard normal cumulative function (*cdf*), truncated at $\left[-g\left(x_\ell\right)\right]^{12}$, respectively; $\sigma = cov(v_\ell, u_\ell)$ reflects simultaneity in the participation and hedonic equations[13]. Therefore, for $D_\ell = 1$ we may write (4.7) as,

$$lny_\ell = lnc(\theta_{1\ell}, ..., \theta_{K\ell}) + \sigma M_\ell + \eta_\ell \tag{4.9}$$

where M_ℓ is the Mill's ratio $\phi_\ell\left(.\right)/[1-\Phi_\ell\left(.\right)]$ and η_ℓ a *random* error term. This equation can be estimated by OLS methods by replacing the unknown M_ℓ values with those computed at

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[11] See appendix A4 for a brief description of the effects of incidental truncation on normal distribution.

[12] Given that $a = 0$ and $\sigma_\upsilon = 1$, the degree of truncation is equal to:

$$\alpha_\upsilon = \left(\frac{0-g(x_\varrho)}{\sigma_\upsilon}\right) = -g(x_\varrho)$$

[13] Covariance between (υ_ℓ) and (u_ℓ) in this econometric model is given by $\left(\sigma = \rho\sigma_\upsilon\sigma_u\right)$, where σ_υ and σ_u are the standard deviations of (υ_ℓ) and (u_ℓ), respectively.

$[-\widehat{g}\,(x_\ell)]$, the predictions obtained from the selection equation (4.4).

4.4 Empirical analysis.

The empirical analysis focuses on demand for land parcels by individual production units. The data is drawn from a *Survey of Production (1999)* in Kiti, a coastal region located in the island of Cyprus. In the area under investigation the phenomenon of seawater intrusion is pervasive. Data on usage (agriculture or tourism[14]) and price (y_ℓ, $\ell = 1, ..., L$) from actual sales are collected for 282 land parcels. The relevant transactions took place over the time period of 1994-1998 (including) and prices are corrected to 1998 constant prices. Also collected for these parcels are many characteristics ($\theta_{k\ell}$, $k = 1, ..., K$) reflecting the quality of land, such as the groundwater and soil quality, fragmentation, distance from the sea, distance from the town centre and other environmental and location characteristics. Moreover, using data on the distance (measured in kilometers) of a parcel of land from the coast and the town center, we constructed two separate indexes indicating proximity of each parcel in the sample to the coast and town center, respectively. These indexes equal one if the parcel is located on the seaside or on the reference point chosen for the town center, and equal zero if the parcel is located at the furthest distance point relevant for the sample of data under consideration. See appendix B4 for a more detailed description of the procedure followed for the construction of the questionnaire, collection of the data, and construction of the data-set used in the empirical analysis of this chapter. Moreover, see thesis attachment for the actual questionnaire used in the collection of this data, detail description of collected information and constructed variables, as well as their descriptive statistics.

Assuming that $lnc(\theta_{1\ell}, ..., \theta_{K\ell})$ has the Translog form, we write expenditure on the package by the ℓ^{th} producer at base period prices (4.9) as,

$$lny_\ell = a_o + \Sigma_k a_k ln\theta_{k\ell} + \tfrac{1}{2}\Sigma_k \Sigma_j \gamma_{kj} ln\theta_{j\ell} ln\theta_{k\ell} + \sigma \widehat{M}_\ell + \eta_\ell \tag{4.10}$$

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[14] The residential sector is not considered in this chapter.

where $\widehat{M_\ell} = \phi_\ell(.)/[1 - \Phi_\ell(.)]$ predicted from the following probit equation[15],

$$D_\ell = \lambda_o + \Sigma_s \lambda_s x_{s\ell} + v_\ell \tag{4.11}$$

where $D_\ell = 1$ when the i^{th} package is used for farming and $D_\ell = 0$ otherwise (i.e. used in tourist development), and $x_{s\ell}$ includes the $\theta_{k\ell}$ quality characteristics plus years of experience in farming (reflecting farm-specific production skills).

The package used for estimation is the *Time Series Processor (TSP) 4.4,* by Bronwyn H. Hall. Table 4.1 reports the results from the probit specification of equation (4.11). Table 4.2 reports the parameters obtained from applying (4.10) to the individual agricultural land parcel data described above. The probit model uses analytic first and second derivatives to obtain maximum likelihood estimates via the *Newton-Raphson* algorithm[16]. Zeros are used as starting values. The reported log likelihood is the log likelihood function as the program iterated to a solution[17]. Note that the value of the likelihood increases with each guess. In this context there is no precise analog to the R^2 used to indicate the goodness of fit of linear regression models, thus we use the *Kullback-Leibler* R^2, which is a generalized measure of explanatory power for a wide class of nonlinear models[18].

In the probit model, the derivative of the probability with respect to the independent variables varies with the level of these variables. As a result, it is not generally useful to report the coefficients from a probit, unless only the sign and significance of the coefficients are of interest. Both explanatory variables included in the estimated probit model of this application, have

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[15] The normal distribution has been used in regression models explaining binary (0/1) dependent variables, giving rise to the probit model,

$$\Pr ob(y=1) = \int_{-\infty}^{g(x_l)} \phi(t)dt = \Phi(g(x_l))$$

[16] The basis for *Newton's* method is a linear Taylor series approximation. The method converges very rapidly in many problems. If the criterion function is globally concave, it is probably the best algorithm available. This method is very well suited to maximum likelihood estimation.

[17] One feature of the probit is that the likelihood functions are *globally concave.* Therefore, an optimization package does not have to worry about discriminating between local maxima and global maxima when it tries to find parameter values that maximize the log-likelihood function; they will be the same.

[18] The *Kullback-Leibler* R^2 is computed as the ratio of one minus the log likelihood of the fitted model, to the log likelihood of the model with intercept only.

significant coefficients at 95% significance level and their signs conform to expectation. That is, more years of experience in farming (referring to the owner of the parcel) increase the probability of a parcel being used in agriculture. Proximity of the parcel to the coast, which serves as a proxy for increased salinization of farm's groundwater supplies, decreases this probability. One useful expedient is to calculate the value of the derivatives at the mean values of all the independent variables in the sample. The motivation is to display the derivative for a "typical" element of the sample. These derivatives are reported in the second half of table 4.1.

TABLE 4.1: PARAMETER ESTIMATES FROM PROBIT ESTIMATION.

Variable	**Parameter**	**t-ratio**
Intercept	-0.40220	-0.63748
Years of Experience in Farming	0.03942	1.7772
Proximity to Coast	-0.64487	-2.48901
Diagnostic Testing		
Number of Observations	282	
Log likelihood	-29.7400	
Kullback-Leibler R^2	0.31179	
Value of Derivatives at the Mean Values of all Independent Variables		
Use of Package	$D_l = 1$ *(agricultural)*	$D_l = 0$ *(tourism)*
Intercept	-0.02262	0.02262
Years of Experience in Farming	0.00222	-0.00222
Proximity to Coast	-0.03627	0.03627

In table 4.2, the results obtained from the unrestricted version of (4.10) are under the heading 'with selectivity correction' and the results obtained subject to the restriction $\sigma = 0$ are under the heading 'without selectivity correction'. The estimated equation is the hedonic function, which depicts the relationship between the price of the various parcels of land as a function of their characteristics. This hedonic function represents the equilibrium for the hedonic market, which is given by the double envelope of the bid curves of agricultural producers and the offer curves of landowners for the different land characteristics. The dependent variable of the estimated hedonic expenditure function is the natural logarithm of per (0.1) hectare price of land, measured in Cyprus Pounds (£)[19].

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[19] In 1999 £1 Cyprus is worth £1.14 UK.

Table 4.2: Parameter Estimates of Demand for Land

	No selectivity correction		Selectivity correction	
Variable	Parameter	t-ratio	Parameter	t-ratio
Intercept	9.11550	32.2472	8.23301	20.5839
Area (0.1 hectares) Per Parcel	-0.068666	-2.95819	-0.063782	-2.80292
Existence of House on Parcel (dummy)	0.49507	1.30937	0.50443	1.36423
Existence of Well on Parcel (dummy)	0.16357	1.10975	0.13066	0.90397
Expenditure (£) on Fertilizers Per Parcel p.a.	-0.00046881	-2.01384	-0.00047785	-2.09888
Expenses (£) on Investments in Parcel* p.a.	-0.000013402	0.89142	0.000016155	1.09674
Index of Proximity of Parcel to Town Center	0.0022397	6.86747	0.0023008	7.20007
Water Extraction (m^3) Per Parcel p.a.	0.000000312	1.04986	0.00000039	1.33806
Existence of Groundwater Toxicity (dummy)	-0.25685	-1.6409	-0.22692	-1.47939
Index of Proximity of Parcel to the Coast	0.14194	4.31643	-0.06633	-1.63431
Mill's ratio	-	-	3.00440	3.05280

* Total Expenses on construction works and other investments, excluding investments in machinery.

Diagnostic Testing for Model with Selectivity Correction

Number of observations	193
Mean of dependent variable	7.76669
Standard deviation of dep. var.	1.18107
Variance of residuals	0.75769
R-squared	0.48794
Adjusted R-squared	0.45682
Durbin-Watson	1.75224 [L = 1.55, U = 1.99]
Ramsey's RESET2	0.87576 [F-critical = 1.25]
F (zero slopes)	15.6797 [F-critical = 1.25]
LM het. test	0.16835 [χ^2-critical = 53.7]

In equilibrium the marginal implicit price of a productive characteristic of land can be derived by differentiating the hedonic expenditure function with respect to that characteristic. This gives the increase in expenditure that is required to obtain a parcel of land with one more unit of that characteristic, other things being equal. If the price of the model was a linear function of its characteristics, then this would imply constant implicit prices for the different farmers. But if the price is a nonlinear function of its characteristics, then the implicit price of a characteristic depends on the quantity of the characteristic being purchased. Linearity will occur only if farmers can "arbitrage" attributes by untying and repackaging bundles of attributes *(Rosen, 1974, p.37-38)*. As indicated in table 4.2, the area has a strongly significant effect on the value of the agricultural land, which is positive but diminishing. This result indicates the existence of fixed costs per transaction, which is what presumably prevents landowners from repackaging their plots into smaller sizes, thereby increasing their overall profit.

It may alternatively be argued that the failure of the hypothesis of costless repackaging of land is a reflection of mispecification of the estimated model. To test the validity of this argument we attempt a *Box and Cox (1962)* transformation on the model and we then turn to the results of the various diagnostic tests reported in the second half of table 4.2[20]. Using the Box-Cox transformation[21] we find that the log-linear model is most likely to have generated the observed data[22]. The Durbin-Watson test for the model with selectivity correction indicates that the null hypothesis of no first-order autocorrelation cannot be rejected, although the estimated statistic falls in the zone of indecision. Moreover, the regression specification error test (RESET) introduced by Ramsey, suggests correct specification of the estimated model. The reported F-test strongly suggests rejection of the null hypothesis of zero slope coefficients for the explanatory variables, indicating the overall significance of the included land characteristics in explaining its price. Finally, the LM-tests for heteroscedasticity suggests acceptance of the null hypothesis of no heteroscedastic residuals. The results from the above hypothesis tests suggest

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[20] All reported hypothesis tests are carried out at 95% confidence level.

[21] *Halvorsen and Pollakowski (1981)* suggested the use of the quadratic Box-Cox functional form, which is a flexible functional form that embodies many of the popular functional forms as special cases. Parameter restrictions on the quadratic Box-Cox may be tested to determine whether any of the simpler forms should be preferred in a particular application.

[22] This suggests that $\theta's$ in the Translog expenditure function (equation 4.10) are taken to be equal to the exponents of the regressors included in the estimated model.

that, costly repackaging rather than statistical mispecification is the relevant hypothesis for explaining the non-linearity of the estimated model.

Commending on the results reported in the first half of table 4.2, all variables in the regression model with selectivity correction have effects conforming to expectation. A more detail description of the estimated variables and their descriptive statistics can be found in the thesis attachment. Moreover it is worth noting that the results presented in table 4.2 are the outcome of a number of preliminary empirical estimations of the hedonic function. The final version of the empirical estimation was selected based on statistical considerations. We started our preliminary estimation of the hedonic price function by including two variables indicating (a) the percentage of the total area of each parcel of land that is irrigated and (b) the percentage of the total area of each parcel of land that is not irrigated. These two variables were included in order to investigate if the suitability of land for cultivation of irrigated agricultural products (which are higher valued crops compared to crops produced by arid-agriculture) affects the per (0.1) hectare price[23] of land. These variables turned out to be statistically insignificant at 95% confidence level. Moreover, we used dummies indicating the ownership structure of each parcel, that is the area of land of each parcel (measured in (0.1) hectares) that is owned, rented and government granted. These dummy variables also turned out to be statistically insignificant at 95% confidence level. Given these results, in the final version of the estimated hedonic equation we only included the area of land (measured in (0.1) hectares) covered by each parcel as well as its square, the latter capturing non-linear effects of the total area of a parcel on its price.

In addition to the above, a number of other variables were incorporated in the preliminary versions of the estimated hedonic function, but were excluded from the final version of the estimation due to their statistical insignificance. These include the grand total of production expenses measured in CY£ per parcel per annum (see attached questionnaire for a detail description of the composition of this variable), production expenses on water purchased measured in CY£ per parcel per annum, as well as receipts from sales of crops per parcel per annum. Moreover, three variables indicating the number of man-hours worked per week per parcel by

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[23] The units of price per (0.1) hectares of land are Cyprus pounds. As already mentioned in chapter 3, in 1999 £1 Cyprus appears to be worth £1.14 UK (British pound).

permanent, casual and administrative workers, were included in the preliminary estimations of the hedonic function. From our point of view, these variables could indicate the productive capacity of a particular parcel. Unfortunately, these variables did not have a statistically significant effect on the per (0.1) hectare price of land and where finally excluded from the final model. Furthermore, a number of dummy variables were constructed to take account of whether each particular parcel was connected to a water scheme, a dam or a reservoir, and whether it belongs to an irrigation division[24]. Once more, these dummy variables did not contribute significantly to the explanation of the variation in the dependent variable of the hedonic price function, possibly indicating the scarcity of other water sources in the area (e.g. water in dam and reservoirs) as well as groundwater. Moreover, the dummy variable indicating whether the quality of a parcel's soil belongs to classes I, II, II, IV or V (see appendix of the attached questionnaire, section A, for the detail description of these fives classes of soil quality) turned out to be statistically insignificant as well. Likewise, average rainfall (measured in millimeters per annum) relevant for the region of location of each parcel of land, turned out to be a statistically insignificant variable in our sample, perhaps due to the lack of significant variation of average annual rainfall among parcels of land in the data-set, given the smallness of the area under investigation.

Finally it is worth explaining why groundwater salinity was proxied by the index constructed to indicate coast proximity rather than directly using dummy variables indicating the quality of groundwater supplies beneath a parcel's land (i.e. generally suitable for irrigation, restricted for certain crops, generally unsuitable for irrigation, suitable for residential use, generally unsuitable for residential use[25]), or even hydrogeological information on salinity levels of a parcel's groundwater supplies (i.e. existence of upconing of saline groundwater[26], existence of saltwater intrusion[27]). Firstly, all these variable were included in the preliminary estimation of our model

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[24] Irrigation divisions have the responsibility for operation and maintenance of small non-government irrigation schemes. Irrigation divisions are established on the basis of the Irrigation Division Law. Irrigation divisions function well, with a high level of participation by users in making decisions for requesting new or extended schemes, and with responsibility for operation and maintenance.

[25] See appendix of attached questionnaire, section B, for the detail description of these variables.

[26] Where the regional saltwater-freshwater system is in equilibrium, a pumping well screened in the freshwater zone can cause a disturbance of this equilibrium. Under certain conditions, the well induces a greater upconing of saline water and the well discharge becomes saline to a degree governed by the discharge rate, the duration of pumping and local hydrological conditions. This is hydrological phenomenon is called "upconing".

[27] See appendix of attached questionnaire, section B, for the detail description of these variables.

as dummy variables and turned out to be statistically non-significant due to high multicollinearity among them. Moreover, the index variable we constructed indicating proximity to the coast is a continuous variable and as such is richer in information than any crude dummy variable that tries to proxy the effect of salt-water intrusion. In addition, this index variable accurately captures the spatial nature of this hydrogeological phenomenon. Finally this continuous index variable is readily comparable to the index variable indicating proximity to the coast, which proxies the suitability of each parcel of land for touristic development. The comparability of these two indexes allows intuitive comparisons on derived willingness to pay for groundwater quality given present and prospective uses of land, which is the essence of the argument developed in this chapter. At this point we also mention that a run of the relevant regressions in per hectare form did not produce more intuitive results for our empirical analysis, possibly because the dummy variables included in the estimation model (e.g. existence of a house on a parcel, existence of a well on the parcel, groundwater toxicity of a parcel's groundwater supplies) as well as other explanatory variables of interest (proximity to coast and the town center) are by construction in per parcel form.

From this point onwards we restrict our discussion to variables with significant coefficients at 95% confidence level. Unlike the dummy variables representing soil quality which turned out to be statistically insignificant, expenditure on fertilizers which can serve as a proxy for the quality of soil of the parcel, has a significant negative effect on per (0.1) hectare price of land, apparently indicating the effect of poor soil quality on the selling price of land. One possible rationalization of the statistical significance of this variable as opposed to the statistical insignificance of the dummies of soil quality, is that expenditure on fertilizers indicates the suitability of the soil of a parcel for the crops already cultivated in the specific parcel, and not soil suitability for cultivation in general. That is, soil suitability for cultivation as given by the soil dummies, considers all possible cultivations some of which may be irrelevant for the owner of the land in the region under consideration; hence their statistical insignificance in explaining willingness to pay for a parcel located in this region.

Proximity to the town centre has a strongly significant positive effect. As argued in section 4.2, this variable proxies the effect of sea proximity on the attractiveness of an agricultural parcel for future tourism development. Moreover proximity to the town reduces the transportation costs for firms, since the town center is the location where trading of agricultural products takes place. Hence the positive effect on the value of land. The variable of interest here, proximity to the coast[28], does not appear to be significant in the model where a correction for sample selection (farming versus tourism) is made by including the Mill's ratio in the explanatory variables. Without this correction, however, proximity to the coast appears to have a significant positive effect on the value of agricultural land, apparently indicating that ignoring selectivity correction ignores the fact that the costs of salinization can be offset by an increasing probability of switching to the more lucrative tourism industry. Although the estimated coefficient indicating the marginal shadow value of groundwater toxicity is not statistically significant at 95% confidence level, is worth noting that it has approximately the same effect in both models (with and without correction for selectivity bias). This result suggests that the cost of increased groundwater toxicity to agriculture cannot be offset by an increasing probability of switching to tourism because this characteristic is not relevant for tourism development, whereas proximity to the sea is.

As argued above, the marginal implicit price of a productive characteristic of land can be derived by differentiating the hedonic expenditure function with respect to that characteristic. This marginal implicit price of coast proximity, that serves as a proxy for increased salinization

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[28] The correlation coefficient between the variables proximity to the coast and proximity to the town centre is 0.068, which is low. The figure below explains why this is the case.

In the figure, dashed lines indicate distance from the town centre and black lines indicate distance from the coast. Take for example parcel number 3. This parcel is on the coast, but far away from the town centre.

of groundwater supplies, can be taken as a measure of the producer's equilibrium marginal willingness to pay (WTP) to avoid the marginal increase in the salinization of fresh groundwater supplies beneath his land. This leads us naturally to the question of whether producers' inverse demand functions for factor inputs can be identified from observations of marginal implicit prices and quantities[29]. The answer depends on the circumstances of the case. In the model estimated in this chapter the hedonic price function is nonlinear and as a result, different producers selecting different bundles of characteristics will have different marginal implicit prices for groundwater quality. There is one situation where the inverse demand function can be immediately identified - that is, if all producers have identical incomes (factor endowments) and profit functions. Then the marginal implicit price function is itself the inverse demand function for factor inputs. Since the marginal implicit price curve is the locus of equilibrium points on produces' inverse demand curves, with identical incomes and production functions, all producers have the same inverse demand curve for factor inputs. Since all the equilibrium points fall on the same inverse demand curve, they fully identify it.

In the more realistic case where differences in incomes, production functions, or other variables result in producers having different inverse factor demand functions, *Rosen (1974)* argued that implicit price and quantity data from a single market could be used to estimate the inverse demand function, provided that the standard identification problem of econometrics[30] could be solved. It is now clear in the literature that this analysis is incorrect. The problem is that the data from a single market are insufficient to identify how the same producers would respond to different implicit prices and income. There are at least two ways in which estimates of inverse

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[29] If the inverse demand function could be identified, it could be used to estimate the welfare change of a producer associated with change in groundwater quality, assuming that other things are held equal. Specifically, if the quantities of other characteristics and amenities do not change, the welfare change can be found by intergrating the inverse demand function over the relevant range of the change in the characteristic. However, a change in the quantity of one characteristic can result in changes in the quantities of other characteristics the producer chooses and in changes in the hedonic price function itself. Moreover, in the case where the improvement in the environmental characteristic leads to changes in output prices, there will be further changes in producer's surplus and compensated consumer's surplus. These must be taken into account in deriving a welfare measure.

[30] Unlike the standard market model in which an individual faces an exogenously determined price and chooses a quantity, and unlike a quantity-rationed market in which an individual faces an exogenously determined quantity and reveals a marginal willingness to pay, the individual chooses both a point on the hedonic price schedule *and* its associated quantity. The choice of that point simultaneously determines the marginal willingness to pay and the quantity of the characteristic. This makes it very difficult to separate out the effects of demand-shifters from the price-quantity relationship itself.

demand functions for fresh groundwater can be obtained from hedonic analysis. The first is to increase the quantity of information obtained from marginal implicit prices by estimating hedonic price functions for several separate markets, and then pooling the cross-sectional data on the assumption that the underlying structure of demand is the same in all markets *(Freeman, 1974; Palmquist, 1984).* The second approach is to impose additional structure on the problem by invoking a priori assumptions about the form of the underlying cost function.

We restrict our conclusions to information derived from the marginal implicit price for groundwater quality (i.e. less salinity), that is considered to be the producer's equilibrium marginal willingness to pay (WTP) per (0.1) hectare of land in order to avoid marginally higher salinization of its groundwater supplies (measured as increased sea proximity). In interpreting the empirical results reported in table 4.1, recall that in the environmental valuation literature the marginal implicit price of a productive characteristic of land can be derived by differenting the hedonic expenditure function with respect to that characteristic. This marginal implicit price is the marginal WTP for that productive characteristic. Given that the model we estimate in this chapter has a log-linear functional form, the marginal WTP per (0.1) hectare of land in order to avoid marginally higher salinization of its groundwater supplies (measured as increased sea proximity), is equal to the exponent of the estimated coefficient of the indexed variable indicating proximity of a parcel of land to the coast, in the estimated hedonic regression. In the regression model with selectivity correction this marginal WTP for avoiding coast proximity is equal to £1.07 (Cyprus Pounds) per (0.1) hectare of land (i.e. it is equal to exponential of 0.06633, which is the value of the estimated coefficient of sea proximity in the hedonic model with selectivity correction). It is also interesting to note that the model without selectivity correction indicates that the agricultural producer has a marginal WTP of £1.15 per (0.1) hectare of land to *gain* a marginal increase in groundwater salinization (i.e. this figure is derived by taking the exponential of 0.14194, which is the value of the estimated coefficient of sea proximity in the hedonic regression without selectivity correction). Of course, the latter result is counter intuitive and is explained by the fact that the model without selectivity correction estimates the marginal WTP for sea proximity which increases the value of land for prospective touristic uses.

The estimated coefficient of sea proximity in the hedonic regression with selectivity correction is not statistically significant at 95% confidence level, in explaining the variation in the dependent variable of the regression which is the natural logarithm of per (0.1) hectare price of land, measured in Cyprus pounds. This conclusion is derived by performing a t-test on the relevant coefficient. At 95% confidence level and 182 degrees of freedom, the null hypothesis that the relevant coefficient is zero is rejected only if the calculated t-statistic [calculated t-statistic $= \frac{estimated\ coefficient\ -\ 0}{standard\ error\ of\ coefficient}$] is larger than 1.96. Since the calculated t-statistic reported in table 4.2 is equal to 1.634, the null hypothesis cannot be rejected. As already mentioned above, the marginal implicit price of a productive characteristic of land can be derived by differenting the hedonic expenditure function with respect to that characteristic. This marginal implicit price is the marginal WTP for that productive characteristic, which in our model is derived by taking the exponent of the statistically insignificant coefficient of sea proximity. Hence, the coefficient from which we derive the marginal WTP per (0.1) hectare of land in order to avoid marginally higher salinization of groundwater supplies does not affect significantly (i.e. does not explain significantly the variation in) the per (0.1) hectare price of land, which is the dependent variable of the hedonic regression. On the other hand, the estimated coefficient of sea proximity in the hedonic regression without selectivity correction is statistically significant at 95% confidence level. This result is again derived by performing a t-test on the relevant estimated coefficient. This result indicates that the coefficient from which we derived the marginal WTP for marginally increased sea proximity given prospective touristic uses of the land, is statistically significant in explaining the variation in the per (0.1) hectare price of land.

The statistical insignificance of the coefficient from which we derive the marginal WTP per (0.1) hectare of land in order to avoid marginally higher salinization of groundwater supplies can be rationalized in a number of ways. Theoretical reasons that could undermine the validity of this result point to the presence of non-convexities in repackaging of land and fixed costs of switching from one use of land to another. The presence of such non-convexities is indicated by the non-linearity of the estimated hedonic price function and constitutes a standard reason for the failure of first best general equilibrium solution. Hence the marginal WTP for avoiding groundwater quality deterioration is derived from a distorted general equilibrium water demand, instead of the first-best general equilibrium input demand. On the other hand, the insignificance of WTP for groundwater quality per (0.1) hectares of land could imply that agricultural producers that use groundwater as an input in their production are myopic and not willing to pay a significant amount of money for preserving groundwater quality in the aquifer because they do not consider future use of groundwater in their production activities. As argued in previous chapters of this thesis, this result is an artifact of the absence of clearly allocated property rights for water in the aquifer, which implies that groundwater quality conserved today by one producer, might be extracted tomorrow by another producer. Hence the need for optimal management of this aquifer emerges, so that current users of the resource pay the social cost of their groundwater extraction which in principle includes the cost of deterioration of groundwater quality, caused by overpumping of extracting agents.

The estimated marginal WTP for avoiding groundwater salinization is not directly comparable to the scarcity value of the resource derived from the optimization model of chapter 3, or the one to be estimated by the use of the stochastic distance function in chapter 5. However, the marginal WTP for improvements in groundwater quality as far as less salinity is concerned, also arises from a scarcity situation: the scarcity of salt-free groundwater. This scarcity situation refers to the qualitative dimension of groundwater scarcity, which as argued in chapter 1, is as important as the quantity dimension of this particular resource problem (studied in chapter 3 and 5 of this thesis). In a broader sense, values assigned to environmental and resource service flows are determined by their roles in enchancing individuals' well-being[31] and arise from their scarcity or limited availability. If the services of the environment could be purchased in a perfectly functioning market, estimating the marginal willingness-to-pay curves would be a fairly straightforward econometric problem. But environmental and resource service flows typically have characteristics such as nonexcludability and nonrivalry, which make it difficult

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[31] Economic values can only be defined in terms of some underlying criterion that identifies what is to be considered good. In neoclassical welfare economics good is defined in terms of the well-being of individuals. An individual's well-being can be represented by an ordinal utility function. An allocation of resources, good and services in an economy is Pareto optimal if there is no feasible reallocation hat can increase any one person's utility without decreasing someone else's utility. Of course, there is an infinite number of Pareto optimum allocations for an economy, each with a different distribution of utilities across individuals. In order to rank the allocations it is necessary to have a social welfare function that aggregates the utilities of the individuals, perhaps by assigning social welfare weights. If such a social welfare function exists, pareto optimality is a necessary but not sufficient condition for maximizing that function. Hence, pareto optimality is the solution to a constrained maximization problem in which some of the constraints are the exogenously determined environmental and resource service flows. The shadow prices on these constraints are the economic values of these service flows.

or impossible for markets for these services to function well. Often individuals are not free to vary independently the level of the services that they consume. The public good character of environmental services then leads to market failure. And without a market, there are no price and quantity data from which the demand relationships can be estimated. This chapter aimed to provide a method of deriving an accurate measure of the marginal willingness to pay for an environmental and/or resource quality when selectivity issues are involved.

4.5 Conclusion.

The argument put forward in this chapter is that hedonic valuations can be misleading when the quality characteristics intended for valuation have sample selection implications. We consider this argument in the case of land close to the seaside that can be used either as an input in agricultural production or for touristic development. In this case, proximity to the sea can reduce the quality of land as an input in agricultural production, due to salinization of groundwater supplies, but increases the probability of switching the land usage from agriculture to the lucrative tourism market. Deterioration of the groundwater supplies can then appear to have a positive effect on the price of agricultural land. The empirical analysis of this chapter confirms this argument. Furthermore, it shows that in a model where the selection and hedonic valuation aspects of agricultural land are modelled simultaneously, low quality groundwater supplies do not have a positive effect on the price of agricultural land.

The overall conclusion of this chapter is that researchers and policy makers in environmental valuation must be careful when employing hedonic techniques to derive willingness to pay for environmental an/or resource quality; it is possible for these techniques to give rise to misleading conclusions about the effect of an environmental attribute on producers (or consumers) welfare if potential biases from inappropriate sample selection criteria are ignored. Moreover, the arguments raised in the chapter have implications for hedonic price analysis applied to other goods whose quality characteristics can affect sample selection. For example, the approach followed in this paper may be used to correct for traffic noise appearing to have a potentially positive valuation effect on residential housing because houses in main roads have a high probability of being converted to business properties.

The analysis described in this chapter results in a measure of the implicit price of and the marginal willingness to pay in order to avoid the loss of fresh (salt-free) groundwater, which is found to be insignificantly small. However, a limitation of property value models in general, is that they are based on observing behaviour responses to differences in amenity levels across properties and as a result they only capture marginal willingness to pay for *perceived* differences in amenities and their consequences. For example, if there are subtle, long-term effects associated with reduced environmental quality at some property sites but people are unaware of their casual link to the property site, their marginal willingness to pay to avoid these effects will not be reflected in property price differences[32].

Moreover, in the model described in this chapter, it makes intuitive sense to speak of the individual producers as *using* the environmental or resource service of fresh groundwater. Thus the values estimated are direct or indirect use values. However, it is also possible for individuals to value environmental and resource services independently of any use they might make of those services. *Freeman (1993)* has shown that if the assumption of weak complementarity holds, then market demand information can reveal everything there is to know about the value of the resource; that is, value measures derived from market data reflect total value. If conditions of weak complementarity do not hold, then the existence component of the total economic value of fresh groundwater is not reflected in indirectly derived market demands[33]. This challenge does not rule out the application of this chapter provided that results are properly interpreted as representing use values alone. However, the indirect valuation method described in this chapter can shed no light on the possible magnitude of the existence value of the resource in question. Where existence values are potentially significant, most researchers argue that the only method to estimate total values for environmental amenities is contingent valuation[34].

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[32] See *Freeman (1993, p. 33-36)* for a discussion of the noneconomic foundations of resource valuation and the importance of the need for a second understanding of the underlying biological and physical processes by which environmental and resource service flows are generated.

[33] Though it is convenient to pretend that existence values can be totally separated from the use values of market goods this is probably not completely true *(Larson, 1991)*. That people could care about the preservation of an aquifer and yet not alter their behavior in any way seems unlikely. In more complex models that include time allocation, surely amenities that affect welfare would influence time devoted to information gathering. Still such preference-revealing behavior is likely to be difficult to trace and use in valuation.

[34] Contingent valuation is a method of non-market valuation which asks individuals their values (in money terms) for specified changes in quantities or qualities of goods or services. See *Bishop and Heberlein (1990)* for a survey of this method.

APPENDIX A4.

INCIDENTAL TRUNCATION OF NORMAL DISTRIBUTION.

The topic of *sample selection* (or *incidental truncation)* has been the subject of an enormous literature, both theoretical and applied. Four fairly extensive, though far from exhaustive surveys of this topic are *Dhrymes (1984)*, *Maddala (1983, 1984)*, and *Amemiya (1984)*[35]. More recent studies on this issue are *Heckman (1990)*, *Manski (1989, 1990)*, and *Newey et al. (1990)*. The effect of truncation occurs when sample data are drawn from a subset of a larger population of interest. The *sample selection problem* is a form of truncation. A truncated distribution is the part of an untruncated distribution that is above or below some specified value.

If (x) is a continuous random variable normally distributed with mean (μ) and standard deviation (σ),

$$\text{Prob}(x > a) = 1 - \Phi(\frac{a-\mu}{\sigma}) = 1 - \Phi(\alpha)$$

where $\alpha = \left(\frac{a-\mu}{\sigma}\right)$ and $\Phi(.)$ is the standard normal cumulative density function (*cdf*). The truncated normal distribution is, then,

$$\begin{aligned} f(x \quad | \quad x > a) &= \frac{f(x)}{1-\Phi(\alpha)} \\ &= \frac{(2\pi\sigma^2)^{-1/2}e^{-(x-\mu)^2/(2\sigma^2)}}{1-\Phi(\alpha)} \\ &= \frac{(1/\sigma)\phi((x-\mu)/\sigma)}{1-\Phi(\alpha)} \end{aligned}$$

where $\phi(.)$ is the standard normal probability density function (*pdf*). It is also worth noting that if the truncation is from below, as it is the case in the model developed in the main text of chapter 4, the mean of the truncated variable is greater than the mean of the original one. (If truncation is from above, the mean of the truncated variable is smaller than the mean of the

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[35] The last is part of a symposium on censored and truncated regression models.

original one). Truncation reduces the variance compared to the variance in the untruncated distribution.

For the moments of the truncated normal distribution, we have the following theorem[36]:

Theorem 1 *: **Moments of the Truncated Normal Distribution:** if* $x \sim N[\mu, \sigma^2]$ *and* (a) *is a constant*

$$E[x \quad | \quad truncation] = \mu + \sigma\lambda(\alpha)$$
$$Var[x \quad | \quad truncation] = \sigma^2(1 - \delta(\alpha))$$

where $\alpha = (a - \mu)/\sigma$ *and*

$$\lambda(\alpha) = \frac{\phi(\alpha)}{1 - \Phi(\alpha)} \qquad if\ truncation\ is\ x > a$$

$$\lambda(\alpha) = \frac{-\phi(\alpha)}{\Phi(\alpha)} \qquad if\ truncation\ is\ x < a$$

$$\delta(\alpha) = \lambda(\alpha)(\lambda(\alpha) - \alpha)$$

An important result is that $0 < \delta(\alpha) < 1$, for all values of α, and $d\phi(\alpha)/d\alpha = -\alpha\phi(\alpha)$. The function $\lambda(\alpha)$ is called the *inverse Mills ratio* or the *hazard function* for the distribution. A useful way to view truncation is in terms of the probability that (x) is less than (a), which indicates the *degree of truncation*. This is an increasing function of (a). As this probability rises, a greater proportion of the distribution is being discarded, and the mean rises accordingly.

In the theoretical and empirical model developed in chapter 4, we use the incidentally truncated bivariate normal distibution. Suppose that (ζ) and (z), have a bivariate distribution with correlation (ρ). We are interested in the distribution (ζ) given that (z) exceeds a particular value. Intuition suggests that if (ζ) and (z) are positively correlated , the truncation of (z)

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[36] Details may be found in *Johnson and Kotz (1970*, p.81).

should push the distribution of (ζ) to the right. The truncated joint density of (ζ) and (z) is given by,

$$f(\zeta, z \mid z > a) = \frac{f(\zeta, z)}{\Pr ob(z > a)}$$

The moments of the incidentally truncated bivariate normal distribution are given in Theorem 2[37].

Theorem 2 *: **Moments of the Incidentally Truncated Bivariate Normal Distribution:** If (ζ) and (z) have a bivariate normal distribution with means (μ_ζ) and (μ_z), standard deviations (σ_ζ) and (σ_z), and correlation (ρ), then*

$$\begin{aligned} E[\zeta \quad \mid \quad z > a] &= \mu_\zeta + \rho\sigma_\zeta\lambda(\alpha_z) \\ Var[\zeta \quad \mid \quad z > a] &= \sigma_\zeta^2(1 - \rho^2\delta(\alpha_z)) \end{aligned}$$

where

$$\begin{aligned} \alpha_z &= \frac{a - \mu_z}{\sigma_z} \\ \lambda(\alpha_z) &= \frac{\phi(\alpha_z)}{1 - \Phi(\alpha_z)} \\ \delta(\alpha_z) &= \lambda(\alpha_z)(\lambda(\alpha_z) - \alpha_z) \end{aligned}$$

If the truncation is $z < a$, we make the replacement

$$\lambda(\alpha_z) = \frac{-\phi(\alpha_z)}{\Phi(\alpha_z)}$$

The truncated mean is pushed in the direction of the correlation if the truncation is from below and in the opposite direction if it is from above.

As already indicated the model developed in the main text of this chapter, motivates a regression model that corresponds to the results in Theorem 2. The problem of truncation

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[37] Much more general forms of the result that apply to multivariate distributions are given in *Johnson and Kotz (1974)*. See also *Maddala (1983, 266-267)*.

surfaces when we account for the fact that the expenditure equation (section 4.3, equation 4.7) describes expenditure on land purchases, but an actual figure is observed only if land is purchased and used for agricultural production (instead for tourism development). Occurrence of agricultural use of land, allows us to infer that the benefit from using the parcel for agricultural production exceeds the reservation shadow value (in terms of net profits or other net benefits derived from agricultural use of land) necessary to make the purchaser participate in the agricultural sector of the region under consideration. Thus, the expenditure variable in the hedonic equation is incidentally truncated.

As argued in *Greene (1997)*, recent research has cast some skepticism on the selection model based on the normal distribution[38]. Among the findings are that the parameter estimates are surprisingly sensitive to the distributional assumption that underlies the model. Of course, this in itself does not invalidate the normality assumption, but it does call its generality into question. On the other hand, there exists compelling evidence that sample selection, in the abstract, raises serious problems, distributional questions aside. The most recent literature, for example *Duncan (1986), Manski (1989, 1990),* and *Heckman (1990),* has suggested some promising approaches based on robust and nonparametric estimators. These obviously have the virtue of greater generality. Unfortunately, the cost is that these approaches generally are quite limited in the breadth of the models they can accommodate. That is, one might gain the robustness of a nonparametric estimator at the cost of being unable to make use of the rich set of accompanying variables usually present in the panels to which selectivity models are often applied. For example, the nonparametric bounds of *Manski (1990)* is defined for two regressors. Other methods (e.g. *Duncan, 1986)* allow more elaborate specification. The upshot is that the issue remains unsettled. For better or worse, the empirical literature on the subject continues to be dominated by Heckman's original model built around the joint normal distribution, which is the model adopted in the theoretical and empirical analysis of chapter 4.

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[38] See *Goldberger (1983)* for an early survey of this literature.

APPENDIX B4.

SURVEY OF PRODUCTION (1999).

The data used in the empirical analysis of chapter 4 is drawn from a Survey of Production (1999) in Kiti, a coastal region located in the island of Cyprus. For the interested reader the questionnaire used in the survey is attached at the end of this thesis, together with the description of the collected information and constructed variables, as well as their descriptive statistics. The construction of the questionnaire is based on our preference for data on actual market transactions[39]. For rental land parcels there is a regular monthly "market transaction" from which fairly accurate data on rents could be gathered. However, the majority of land parcels is owner-used. The relevant transactions took place over the period of 1994-1998 (including) and prices are corrected to 1998 constant prices.

Data on usage (agriculture or tourism) and price is collected for 282 parcels of land. Also collected for these parcels are many of their characteristics such as: area of holding, land use and tenure, area planted, production of temporary and permanent crops, production expenses, administrative costs, hydrogeological characteristics, personal characteristics of buyers and sellers, employment of holders and family members, labour costs, value of construction works and other investments, indirect taxes and other expenses. The constructed data-set is readily available from the author.

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[39] There is agreement in the hedonic literature that the most preferred source of data is systematically collected information on actual sales prices of individual dwellings or land parcels along with relevant characteristics. The presumed superiority of individual transaction data over non-market estimates provided by experts, is based on the assumption that the housing market is in an equilibrium in which all opportunities for possible gains from further trade at the revealed set of prices have been exhausted. This is a heroic assumption. The divergence from full equilibrium of the land market however, will only introduce random errors into the estimates of marginal willingness to pay (see *Freeman, 1993, p. 382-83*).

Chapter 5

On the Use of a Stochastic Distance Function to Retrieving Natural Resource Shadow Prices: Theory and Application to Groundwater as a Productive Input.

5.1 Introduction.

The aim of this chapter is to derive the *in situ* shadow price of unextracted groundwater in an aquifer, through modelling and empirically analyzing the technology of vertically integrated agricultural firms that both extract and use groundwater as an input in their production. As mentioned repeatedly in this thesis, this shadow price, also referred to as the resource's scarcity rent or royalty, represents the marginal valuation of the individual agricultural producer for the resource left *in situ,* and is not directly observable. In addition, the effect of cumulative extraction on the marginal cost of extraction, which is one of the major theoretical factors determining the time path of natural resource prices is also not directly observable. In the model developed in this chapter, the non-observability of the *in situ* shadow price of groundwater is caused by the fact that market transactions in vertically integrated agricultural firms occur only after groundwater has been extracted and used in the production of agricultural products; that is there is no market for groundwater.

This chapter uses duality theory in order to derive information on the *in situ* shadow price of the resource and the effects of cumulative extraction on the marginal cost of extraction. Firstly, we solve the "restricted" version of the dual cost minimization problem of the vertically integrated agricultural firm. The solution of this problem presented in section 5.2 gives *lemma 1,* that establishes the relationship between the current (unobserved) *in situ* shadow price of groundwater in the unrestricted solution of the problem, with the derivatives of the observable and estimable restricted cost function. This exact same method has been employed in theoretical and applied work, for the derivation of the time path of *in situ* shadow prices of unextracted ore, to be used as a production input in the vertically integrated Canadian metal mining industry *(Halvorsen and Smith, 1984, 1991).*

Secondly, we propose another method that allows derivation of the unobservable shadow price of *in situ* resources through the use of an input distance function. In empirical applications, distance functions have a number of virtues that make their use attractive when the environment under which firms operate is regulated and/or when firms are inefficient due to lack of incentives faced by their operators. In particular, the first virtue of distance functions is that they do not necessarily require price data to compute the parameters; only quantity data is needed. Secondly, distance functions do not impose any behavioural hypothesis (such as profit maximization or cost minimization). That is, they allow production units to operate below the production frontier (i.e. to be inefficient) and they also allow derivation of firm-specific inefficiencies. Thirdly, the duality result between the distance functions and the more conventional cost, profit and revenue functions provide flexibility for empirical applications *(Färe and Primont, 1995).* In section 5.3 of this chapter we derive *lemma 2*, which establishes the relationship between the derivatives of the estimable input distance function with the unobserved shadow price of *in situ* groundwater. The derivation of this lemma is possible by the use of the pre-mentioned duality between Shephard's input distance function and the cost function.

The key extension of this chapter on the existing literature is that it establishes that when cost, profit or revenue function representations are precluded[1], the restricted distance function provides an excellent analytical tool for estimating unobservable shadow prices of *in situ* natural resources produced and used as inputs in production processes of vertically integrated firms. Section 5.3.1 briefly reviews relevant concepts concerning distance functions and related efficiency measures. Section 5.3.2 solves the restricted production problem of vertically integrated agricultural firms that both extract and process groundwater, by using the distance function approach, and derives *lemma 2*. In section 5.3.3 we briefly review alternative methods of estimating distance function frontiers and argue for the superiority of the stochastic frontier model, adopted in the empirical analysis to follow. The stochastic frontier model exhibits two major advantages over alternative estimation methods: (a) it acknowledges that observed costs may deviate from an efficient cost frontier due to events that are both within and outside a firm's control, and (b) it allows firm-specific derivation of shadow prices, whereas other methods allow derivation of shadow prices for efficient firms only.

The empirical application of the restricted distance function methodology to deriving the current *in situ* groundwater shadow price is presented in section 5.3.3. It involves estimating a restricted input distance function stochastic frontier and employing *lemma 2* to derive an estimate of the individual produce's valuation of the marginal unit of groundwater in the aquifer. We also provide a brief discussion on estimated firm-specific technical inefficiencies. That is, our empirical analysis suggests that cost minimizing behaviour is not achieved (or not pursued) by relevant firms and as a result, estimation of resource scarcity rents through estimation of a restricted cost function as suggested by *Halvorsen and Smith (1984, 1991),* will give biased estimates. The identification of these inefficiencies provides strong support for the use of the distance function approach, because as already mentioned this approach does not impose any behavioural hypothesis. The procedure is illustrated with data for groundwater use by the agricultural sector in the Kiti region of the island of Cyprus. One advantage of this data-set is that it enables us to test for inefficiency using truly microeconomic data. Although most previous empirical analyses in the literature have been conducted on data that have been aggregated to some degree, evidence on technical inefficiency may be lost in the aggregation

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[1] That is, profit maximization or cost minimization are violated, resulting in distortions in the shadow prices of resources that are both produced and used as inputs in the production processes of vertically integrated firms.

process. If this conjecture is correct, then we should expect to find clearer evidence of inefficiency using microeconomic data.

5.2 The Use of the Restricted Cost Function to Deriving Groundwater Scarcity Rents.

In this section, we model the behaviour of the individual agricultural firm[2], in order to derive its marginal valuation for unextracted groundwater. Following the methodology proposed by *Halvorsen and Smith (1984, 1991)* we derive the restricted cost function of vertically integrated agricultural firms, dual to the production function for final agricultural output, in order to achieve analytical derivation of an estimable shadow price of *in situ* groundwater. Agricultural firms are vertically integrated, because they engage both in the extraction and use of groundwater resources as an input in their production process. The firm is assumed to maximize the wealth obtainable from its stock of the natural resource given input and output prices, the technological conditions governing extraction and production, and the resource transition equation. We assume that groundwater recharge is significantly lower and slower than withdrawals, so the groundwater stock is treated as an exhaustible resource. The following differential equation describes the environmental constraint of the firm's maximization problem,

$$\dot{H}(t) = \frac{R - (1 + s - f) \cdot W(t)}{AS} \tag{5.1}$$

where (H) is the aquifer head, representing the yearly effects of cumulative groundwater extraction on the total stock of groundwater available to agricultural firms owning land above the relevant aquifer[3]. The stock of the resource is reduced by extraction (W) at each (t), implying that the change of the aquifer's hydraulic head $(\dot{H})$ depends on $[W(t)]$. Moreover, (R), (s) and (f) are constant hydrological parameters representing deterministic groundwater recharge, the

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[2] The model can allow for more than one producers, which exhibit either price taking or strategically interacting behaviour. Strategic interaction can be modelled through the equation of motion of the model, representing the effect of cumulative extraction on the level of aquifer head $(\dot{H})$. See equation (5.1).

[3] As in previous chapters of the thesis, we assume that access to groundwater is restricted to firms owning land above the aquifer.

salinity coefficient and the return flow of percolation back to the aquifer, respectively. The area and storativity of the aquifer are represented by (A) and (S), respectively[4].

Assuming that the quantities of inputs used in groundwater extraction are separable from those used in agricultural production, output of the vertically integrated agricultural industry is produced according to the following production function[5],

$$Q = Q\left(X^{p}, T, W\left(X^{w}, H, T\right)\right) \tag{5.2}$$

where (Q) is the quantity of final output, (X^{p}) is a vector of agricultural inputs other than groundwater, (T) is time which indexes the effects of technological change, and $[W(.)]$ is the output of the extraction sub-production function; that is, the quantity of groundwater extracted. The extraction sub-production depends on inputs used in the extraction process (X^{w}), the head of the aquifer (H) and technological change (T). With a positive market rate of interest (r), the relevant wealth maximization problem for the vertically integrated agricultural firm is given by equation (5.3) below. Note that the profit maximization problem is consistent with the intertemporal control problem, since the Hamiltonian essentially summarizes an infinite series of static optimization problems.

$$\max_{X^{p}, W} \int_{0}^{\infty} e^{-rt}\left[P_{Q}Q - P_{p}X^{p} - C^{w}\left(W, P_{w}, H, T\right)\right] dt$$

subject to,

$$\begin{aligned} \dot{H}(t) &= \frac{R - (1+s-f)W(t)}{AS} \\ H(0) &= H_{o} \end{aligned} \tag{5.3}$$

where (P_{Q}) is the price of output, (P_{p}) is the vector of agricultural input prices, (P_{w}) is the vector of groundwater extraction input prices, and (C^{w}) is the minimal total cost function dual

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[4] See chapter 3, section 3.4, for precise definitions of these hydrological parameters.

[5] From this point onwards, time (t) is suppressed in the mathematical exposition of this chapter.

to the groundwater extraction sub-production function given by,

$$C^w\left(W, P_w, H, T\right) = \min_{x^w}\left\{P_w X^w : W = W\left(X^w, H, T\right)\right\} \tag{5.4}$$

If a competitive market existed for clean (salt-free) *in situ* groundwater, its market price in period (t) would be equal to the marginal opportunity cost to the firm of one unit of groundwater stock left in the aquifer. We denote this price by (μ_t). Thus the current value Hamiltonian for the maximization problem of equation (5.3) is,

$$\mathcal{H} = P_Q Q - P_p X^p - C^w\left(W, P_w, H, T\right) + \mu\left[\frac{R - (1 + s - f)W}{AS}\right] \tag{5.5}$$

where (X^p) and (W) are control variables, and (μ) is the costate variable, representing user cost of groundwater. The first-order conditions for an interior solution include,

$$\begin{aligned}
\frac{\partial \mathcal{H}}{\partial X^p} &= 0 \Rightarrow P_Q \frac{\partial Q}{\partial X^p} = P_p & (5.6)\\
\frac{\partial \mathcal{H}}{\partial W} &= 0 \Rightarrow P_Q \frac{\partial Q}{\partial W} = \frac{\partial C^w}{\partial W} - \mu\left(\frac{f - s - 1}{AS}\right) & (5.7)\\
\dot{\mu} - r\mu &= -\frac{\partial \mathcal{H}}{\partial H} \Rightarrow \dot{\mu} - r\mu = \frac{\partial C^w}{\partial H} & (5.8)
\end{aligned}$$

Equations (5.6) and (5.7) are the static optimality conditions for agricultural input and the natural resource input, respectively. For agricultural inputs, the value of the marginal product is equated to the price of the input, whereas for the natural resource, the value of the marginal product is greater than the marginal extraction cost by an amount equal to the unobserved shadow price of fresh groundwater *in situ*. Moreover, equations (5.8) is the dynamic optimality condition for the natural resource.

Equations (5.6), (5.7) and (5.8) cannot help in the empirical derivation of the producer's valuation of *in situ* groundwater given the non-existence of data on (μ) and $\left(\frac{\partial C^w}{\partial W}\right)$. However, duality theory suggests that the above maximization problem corresponds to a cost minimization problem. Below we solve the "unrestricted" cost minimization problem of the vertically integrated agricultural firm, given by,

$$\min_{X^p, X^w} \; P_p X^p + \mu W\left(X^w, H, T\right)$$

$$s.t.\; Q(X^p, W, T) \geq Q \tag{5.9}$$

The Lagrangian for the unrestricted cost minimization problem is,

$$L^U = P_p X^p + P_w X^w + \mu W\left(X^w, H, T\right) + \theta^U \left[Q - Q\left(X^p, T, W\left(X^w, H, T\right)\right)\right] \tag{5.10}$$

where (μ) is again the (unobserved) shadow price of groundwater in the aquifer. The first-order conditions for agricultural inputs are,

$$\begin{aligned} \frac{\partial L^U}{\partial X^p} &= P_p - \theta^U \frac{\partial Q}{\partial X^p} = 0 && (5.11) \\ \frac{\partial L^U}{\partial X^w} &= P_w - \left(-\mu + \theta^U \frac{\partial Q}{\partial W}\right) \frac{\partial W}{\partial X^w} = 0 && (5.12) \end{aligned}$$

Once again the solution of the unrestricted dual cost minimization problem of the firm uses the unobserved shadow price of *in situ* groundwater. Below we attempt to solve the above cost minimization problem in a way that will allow estimation of (μ). The first-order conditions derived from the solution of the above unrestricted cost minimization problem will be used in this attempt.

Solving the restricted cost minimization version of our problem, involves considering the auxiliary problem of minimizing the total cost of agricultural inputs (excluding groundwater inputs that are exhaustible) in each period given the stock of groundwater (H), and the quantities of (Q) and (W) in each period. (Q^*) and (W^*) are the solutions to the firm's wealth-maximizing problem,

$$\min \; P_p X^p + P_w X^w$$

$$\begin{aligned} s.t.\; Q(X^P, W, T) &\geq Q^* \\ W\left(X^w, H, T\right) &\geq W^* && (5.13) \end{aligned}$$

As argued by *Halvorsen and Smith (1991)*, each individual firm will not explicitly solve the restricted cost minimization problem considered here, but instead will solve simultaneously for the wealth-maximizing quantities of output and rate of groundwater extraction, together with the quantities of agricultural inputs that minimize total costs. However, the optimal quantities of agricultural inputs given by the solution to the restricted cost minimization problem will be identical to the quantities implied by the more general wealth maximization problem (see, *Lau (1976)).* The Lagrangian of the constrained cost minimization problem of the agricultural firm is given by,

$$L^R = P_p X^p + P_w X^w + \theta^R \left[Q - Q\left(X^p, W, T\right) \right] + \delta \left[W - W\left(X^w, H, T\right) \right] \tag{5.14}$$

The first-order conditions for the cost-minimizing quantities of agricultural and groundwater inputs are, respectively,

$$\frac{\partial L^R}{\partial X^p} = P_p - \theta^R \frac{\partial Q}{\partial X^p} = 0 \tag{5.15}$$

$$\frac{\partial L^R}{\partial X^w} = P_w - \delta \frac{\partial W}{\partial X^w} = 0 \tag{5.16}$$

The solution of this cost minimization problem yields the following cost function for non-resource agricultural inputs,

$$C^R = C^R\left(Q, P_p, P_w, W, H, T\right) \tag{5.17}$$

where C^R is the minimal total expenditure on agricultural inputs other than groundwater stock, given Q, P_P, W, H, T. Applying the envelope theorem[6] gives,

$$\frac{\partial C^R}{\partial W} = \frac{\partial L^R}{\partial W} = -\theta^R \frac{\partial Q}{\partial W} + \delta \tag{5.18}$$

$$\frac{\partial C^R}{\partial H} = \frac{\partial L^R}{\partial H} = -\delta \frac{\partial W}{\partial H} \tag{5.19}$$

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[6] The Envelope Theorem establishes a connection between the derivatives of the value function and the derivatives of the Lagrangian function, with respect to the parameter of interest. More specifically, it states that we can find the effect of a change in the exogenous variable on the optimized value of the objective function, simply by taking the partial derivative of the Lagrange function with respect to the exogenous variable at the optimal solution to the problem.

The interpretation of the right-hand sides of equations (5.18) and (5.19) employs the solution of the cost minimization problem with (W) unrestricted derived in equations (5.9-5.12). The solution values for (X^p) and (W) for the unrestricted minimization problem, will be identical to those derived for the restricted problem with (W) set to its wealth maximizing level. From (5.10) and (5.14),

$$\theta^R = \theta^U \tag{5.20}$$

and from (5.12), (5.16) and (5.20),

$$\delta = -\mu + \theta^R \frac{\partial Q}{\partial W} \tag{5.21}$$

Substituting (5.21) in (5.18) we derive the following relationship that allows empirical estimation of the individual agricultural producer's marginal valuation of *in situ* groundwater,

$$\frac{\partial C^R}{\partial W} = -\mu \tag{5.22}$$

Lemma 1 (Hotelling's Lemma): The current value of the in situ resource price for the individual producer of a vertically integrated natural resource producing firm, is equal to the negative of the marginal final cost of production of the resource.

Lemma 1 and $\mu \geq 0$, imply that the final cost of gross production is non-positive. The intuition is that additional output, all else held constant, reduces the marginal cost of producing a given level of groundwater. This result (i.e. that the partial derivative of a restricted cost function with respect to a quantity variable is equal to the negative of its shadow price) was first noted by *Hotelling (1932)* and amounts to the Hotelling's lemma[7]. Lemma 1 also implies that the current value of *in situ* resource price can be observed by differentiating the estimated restricted final cost function with respect to gross production of groundwater. Moreover, it is worth noting that deriving the implicit shadow price of water from derivatives of the restricted cost function can be done for *any* values of (μ) and (Q), not just those associated with wealth maximizing paths. *Halvorsen and Smith (1984, 1991)* derive this result in their work as well[8].

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[7] Alternatively, the Hotelling's Lemma states that differentiating the profit function with respect to the prices gives the output-supply and input-demand functions for the firm.

[8] Moreover, taking the first-order conditions of equations (5.10) and (5.14) with respect to (H), and combining

The restricted cost function method employed in the analysis of this section, is often used in the literature for the analysis of the production technology of firms whose behaviour suggests systematic deviations from cost minimization. These are firms that fail to minimize costs due to lack of incentives faced by their operators, or function in regulated environments and as a result face additional (observable) constraints other than those implied by profit maximization (that implies maximizing possible output which can be produced from given quantities of a set of inputs) or alternatively cost minimization (that implies minimizing the level of cost at which it is possible to produce some level of output, given input prices). In this chapter we suggest that the dual input distance function to the restricted cost function, has a number of virtues that render it better equipped to analyze economic behaviour of vertically integrated firms for which cost minimization is a questionable hypothesis. As argued in the introductory section of this chapter, agricultural firms are traditionally heavily regulated and as a result they might be facing a number of additional constraints other than cost minimization, which are often not easily identifiable. Moreover, the agricultural sector, even if not heavily regulated, is traditionally found to exhibit systematic inefficient behaviour. Distance function measures are ideal for analyzing economic behaviour when cost-minimization is not the maintained hypothesis, because they (a) do not necessarily require any price data which might be distorted in regulated

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the results with equations (5.20) and (5.21) gives,

$$\frac{\partial C^R}{\partial H} = \frac{\partial C^U}{\partial H}$$

Hence, the change and the level of user cost (shadow value) of water in the aquifer, can be determined for each time period, from the derivatives of the minimum restricted cost function as,

$$\dot{\mu} - r\mu = \frac{\partial C^R}{\partial H} \qquad (A1)$$

$$\mu = -\frac{\partial C^R}{\partial W} \qquad (A2)$$

A restricted cost function can be postulated (e.g. Translog, Leontief , Cobb-Douglas, Generalized Cobb-Douglas) and the shadow value (μ) can be estimated. Estimation of the relevant restricted cost function, provides consistent parameter estimates, irrespective of whether or not the time path of the *in situ* price of the natural resource conforms to the dynamic optimality condition of equation (A1). However, under the null hypothesis that this dynamic condition is satisfied, more efficient estimates can be obtained by adding to the system of equations an additional equation incorporating the restrictions on the parameters implied by dynamic optimality. Estimation of the restricted cost function with and without the corresponding parameter restrictions imposed by the discrete version of (A1), permits a standard likelihood ratio test of the null hypothesis of satisfaction of the dynamic optimality condition. This has been proposed as a test of the Hotelling principle. A brief review of the literature on testing the implications of the Hotelling principle on natural resource scarcity, and suggestions for possible advancements to this literature, is presented in appendix B5.

industries (only quantity data is needed), (b) do not impose any behavioural assumptions which might not be directly observable in regulated firms, (c) allow inefficient behaviour and provide a way of estimating the degree of production inefficiency, and (d) allow flexibility in empirical applications through the duality result between conventional cost, profit and revenue functions.

5.3 The Use of the Input Distance Function to Deriving Groundwater Scarcity Rents.

5.3.1 Efficiency Measurement Concepts.

In recent years, there has been a growing interest in the use of distance functions in production theory. The pioneering theoretical work on distance functions in production theory dates back to *Shephard (1953, 1970)* and the recent extensions can be found in *Färe, Grosskopf and Lovell (1994)* and *Färe and Primont (1995).* However, it is only in the last few years that empirical applications of distance functions have become more widespread. Studies using distance functions to compute shadow prices of either inputs or outputs in regulated industries or services include, just to mention a few, *Grosskopf and Hayes (1993), Färe et al. (1993), Hetemäki (1994 a, b).*

Figure 5.3.1: Technical and Allocative Efficiencies.

One could argue that an input orientation may be more appropriate in agriculture because the managers are likely to have more discretionary control over inputs rather than outputs. For this reason, we focus on input oriented distance functions. We begin with *Farrell's (1957)* original ideas, which were illustrated in input/input space and hence had an input-reducing focus[9]. Farrell illustrated his ideas using a simple example involving firms which use two inputs (x_1 and x_2) to produce a single output (y), under the assumption of constant returns to scale. The constant returns to scale assumptions allows one to represent the technology using a unit isoquant[10]. Knowledge of the unit isoquant of the fully efficient firm, represented by (SS') in figure 5.3.1, permits measurement of technical efficiency.

If a given firm uses quantities of inputs, defined by the point (P), to produce a unit output, the technical inefficiency of that firm could be represented by the distance (QP), which is the amount by which all inputs could be proportionally reduced without a reduction in output. This is usually expressed in percentage terms by the ratio ($QP/0P$), which represents the percentage by which all inputs could be reduced. The technical efficiency (TE) of a firm is most commonly measured by the ratio,

$$TE_1 = 0Q/0P$$

which is equal to one minus ($QP/0P$). It will take a value between zero and one, and hence provides an indicator of the degree of technical inefficiency of the firm. A value of one indicates the firm is fully technically efficient. For example, the point (Q) is technically efficient because it lies on the efficient isoquant[11]. In quantifying the level of the inefficiency this research focuses on the notion of technical inefficiency, distinguishing it from the concept of allocative

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[9] The Farrell input- and output-oriented technical efficiency measures can be shown to be equal to the input and output distance functions discussed in *Shephard (1970)*. Further discussion on this can be found in *Lovell (1993, p.10)*.

[10] Farrell also discussed the extension of his method so as to accommodate more than two inputs, multiple outputs, and non-constant returns to scale.

[11] Moreover, if the input price ratio, represented by the line AA' in figure 5.3.1, is also known, allocative efficiency may also be calculated. The allocative efficiency (AE) of the firm operating at (P) is defined to be the ratio,

$$AE_I = 0R/0Q$$

since the distance (RQ) represents the reduction in production costs that would occur if production were to occur at the allocatively (and technically) efficient point (Q'), instead of at the technically efficient, but allocatively inefficient, point (Q) . One could illustrate this by drawing two isocost lines through (Q) and (Q'). Irrespective of the slope of these two parallel lines (which is determined by the input price ratio) the ratio ($RQ/0Q$) would represent the percentage reduction in costs associated with movement from (Q) to (Q') . The total economic inefficiency. As argued above, technical inefficiency implies that a firm is using an excessive amount of inputs to produce the fixed output levels. Allocative inefficiency instead implies that a firm, which might be fully efficient from a technical point of view, is using an economically suboptimal input mix when market prices are considered. The importance of this distinction is based on the fact that the notion of technical inefficiency can be clearly related to the lack of incentives faced by the operators of the firm, while allocative inefficiency could instead be caused by exterior environmental constraints under which managers operate.

Figure 5.3.2: Piecewise Linear Convex Isoquant.

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efficiency (EE) is defined to be the ratio,

$$EE_I = 0R/0P$$

where the distance (RP) can also be interpreted in terms of a cost reduction. Note that the product of technical and allocative efficiency provides overall economic efficiency,

$$TE \times AE = (0Q/0P) \times (0R/0Q) = (0R/0P) = EE$$

Also note that all three measures are bounded by zero and one.

This efficiency measure assumes that the production function of the fully efficient firm is known. In practice this is not the case, and the efficient isoquant must be estimated from the sample data. Farrell suggested the use of either (a) a non-parametric piecewise-linear convex isoquant constructed such that no observed point should lie to the left or below it (see figure 5.3.2), or (b) a parametric function, such as the Cobb-Douglas form, fitted to the data, again such that no observed point should lie to the left or below it[12]. A brief review of the merits and shortcomings of alternative estimation procedures is presented in section 5.3.3 of this chapter.

More general representations of the above concepts can be given as follows. Consider a $(k \times 1)$ input vector $x = (x_1, x_2, ..., x_k)' \geq 0$ used in the production of a $(m \times 1)$ output vector $y = (y_1, y_2, ..., y_m)' \geq 0$. Then, characterize the underlying technology by the production possibility set $L(y)$, which represents the set of all input vectors x, which can produce the output vector, y. Throughout this chapter we assume that the set $L(y)$ satisfies the following properties (i) $0 \in L(y)$, i.e. nothing can be produced out of a given set of inputs; (ii) non-zero output levels cannot be produced from zero level of inputs; (iii) $L(y)$ satisfies strong disposability of outputs; (iv) $L(y)$ satisfies strong disposability of inputs, i.e. if y can be produced from x, then y can be produced from any $x^* \geq x$; (v) $L(y)$ is closed and convex[13]. Given the above, *Shepard (1970, p. 64-78)* defines the input distance function as[14],

$$D_L(y, x) = \max_{\phi}\{\phi : (\frac{x}{\phi}) \in L(y)\} \tag{5.23}$$

The input distance function in (5.23) can be used to generate the input requirement set $IR_L(y) = \{x : D_L(y, x) \geq 1\}$ as well as the frontier isoquant of a production set $IS_L(y) = \{x : D_L(y, x) = 1\}$ *(Shepard (1970, p.67)).* The properties of the input distance function can be easily dderived using the assumptions made with respect to the production technology.

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[12] Farrell provided an illustration of these methods using agricultural data for the 48 continental states of the US.

[13] Convexity implies that if two combinations of output levels can be produced with a given input vector x, then any average of these output vectors can also be produced. This assumption implicitly requires the commodities to be continuous and divisible.

[14] Note that the definition of the input distance function in equation (5.23) could be made more rigorous by replacing "max" (which stands for "maximum") with "sup" (which stands for "supremum"). This allows for the possibility that the maximum does not exist (i.e., $\phi = +\infty$ is possible). However in this chapter we assume existence of a maximum and adopt the simpler notation of a "max".

Given the general axioms describing the production set, it is easy to show that (i) the input distance function is non-decreasing in x and increasing in y; (ii) it is linearly homogenious in x; (iii) if x belongs to the input set of y then $D_L(y, x) \geq 1$; and (iv) distance is equal to unity if x belongs to the frontier of the input set. Note that the input distance function completely characterizes the technology $L(y)$, and measures the proportional (or radial) reduction in all inputs x that would bring the firm to the frontier isoquant $IS_L(y)$.

As already mentioned, the input distance function has been of great interest in efficiency analysis. It is the reciprocal of the *Farrell (1957)* measure of technical efficiency graphically explained in figure 5.3.1 for the two input - one output case. That is, $1/D_L(y, x) = 1$ corresponds to technical efficiency while $1/D_L(y, x) < 1$ identifies technical inefficiency. In this latter case, $1/D_L(y, x)$ measures the proportional (or radial) rescaling of all inputs that would bring the firm to the frontier isoquant $IS_L(y)$ (*Färe, Grosskopf and Lovell (1985)*). Similarly, $[1 - 1/D_L(y, x)]$ can be interpreted as the proportional reduction in production cost that can be achieved by moving to the frontier isoquant[15].

5.3.2 The Model.

In this section we model production possibilities of a vertically integrated agricultural firm, by employing the input distance function measure. By using Shephard's input distance function to represent technology rather than a cost function, we can employ a dual Shephard's lemma to retrieve firm and input specific shadow prices. Let $L(Q)$ denote the input set which satisfies the

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[15] *Shepard (1970, p. 206-212)* alternatively defines the output distance function as,

$$F_L(y, x) = \min_{\phi}\{\phi : (y/\phi, -x) \in L\} \tag{5.24}$$

The output distance function can be used to generate the production correspondence $PC_L(x) = \{y : F_L(y, x) \leq 1\}$ and the frontier correspondence $FC_L = \{y : F_L(y, x) = 1\}$ *(Shephard (1970), p. 209).* It follows that $F_L(x, y)$ in (5.24) defines the substitution alternatives among the outputs (y), given inputs (x). As with the input distance function in (5.23), note that output distance function in (5.24) provides a complete characterization of the underlying technology. Also, note that $1/F_L(y, x)$ measures the proportional rescaling of all outputs (y) that would bring the firm to the frontier production correspondence $FC_L(x)$. Then, $[1/F_L(y, x) - 1]$ can be interpreted as the proportional increase in revenue that can be achieved by moving to the frontier correspondence. The properties of the two functions $D_L(y, x)$ and $F_L(y, x)$ have been analyzed in detail by *Shephard (1970, p. 207-208).* Note that there exists a simple relationship between these two functions under constant returns to scale. Indeed, $(y/s, -x) \in L$ implies $(y, -sx) \in L$ for $s > 0$ under constant returns to scale. From (5.23) and (5.24), this implies that $D_L(y, x) = 1/F_L(y, x)$. In other words, each distance function in (5.23) and (5.24) is a reciprocal function of he other under constant returns to scale.

properties mentioned in the previous section of this chapter. Then the restricted input distance function for the *ith* agricultural firm may be defined as,

$$D_i^R\left(Q, X^p, X^w; W, H, T\right) = \max\left\{\varphi > 0 : \frac{X}{\phi} \in L(Q; W, H, T)\right\} \tag{5.25}$$

where (X) is a vector of input quantities, i.e. $[X = (X^p, X^w)]$, $L(Q; W, H, T)$ is the input set which represents the set of all input vectors which can produce the output vector (Q), and (φ) measures the proportional (or radial) reduction in all inputs (X) that brings the *ith* firm to the frontier isoquant. The remaining parameters are defined as in section 5.2. As already mentioned, the input distance function $D_i^R(.)$, is non-decreasing, positively linearly homogeneous and concave in inputs, increasing in output and will take a value which is greater than or equal to one, if the input vector is an element of the feasible input set. That is, $(X^p, X^w) \in L(Q; W, H, T)$ if and only if $D_i^R\left(Q, X^p, X^w; W, H, T\right) \geqq 1$. Furthermore, the distance function will take a value of unity if (X) is located in the inner boundary of the input set.

Given the restricted cost function in equation (5.26) below, *Shepard (1953, 1970)* has shown that the input distance function may also be obtained as a price minimal cost function, as given in (5.27) below,

$$C_i^R\left(Q, P_p, P_w; W, H, T\right) = \min_{X^p, X^w}\left\{P_p X^p + P_w X^w : D_i^R\left(Q, X^p, X^w; W, H, T\right) \geqq 1\right\} \tag{5.26}$$

$$D_i^R\left(Q, X^p, X^w; W, H, T\right) = \min_{P^p, P^w}\left\{P_p X^p + P_w X^w : C^R(Q, P_p, P_w; W, H, T)\right\} \tag{5.27}$$

The Lagrangian of the cost minimization problem postulated in equation (5.26) is given by,

$$\Lambda = P_p X^p + P_w X^w + \phi\left[1 - D_i^R\left(Q, X^p, X^w; W, H, T\right)\right] \tag{5.28}$$

Applying the envelope theorem to this Lagrangian equation we get,

$$\frac{\partial C_i^R}{\partial W} = \frac{\partial \Lambda}{\partial W} = -\phi \frac{\partial D_i^R}{\partial W} \tag{5.29}$$

$$\frac{\partial C_i^R}{\partial H} = \frac{\partial \Lambda}{\partial H} = -\phi \frac{\partial D_i^R}{\partial H} \tag{5.30}$$

$$\frac{\partial C_i^R}{\partial X^p} = \frac{\partial \Lambda}{\partial X^p} = P_p - \phi \frac{\partial D_i^R}{\partial X^p} = 0 \tag{5.31}$$

$$\frac{\partial C_i^R}{\partial X^w} = \frac{\partial \Lambda}{\partial X^w} = P_w - \phi \frac{\partial D_i^R}{\partial X^w} = 0 \tag{5.32}$$

The first-order conditions of (5.28) with respect to input prices imply that,

$$\frac{\partial C_i^R}{\partial P_p} = \frac{\partial \Lambda}{\partial P_p} = X^P \tag{5.33}$$

$$\frac{\partial C_i^R}{\partial P_w} = \frac{\partial \Lambda}{\partial P_w} = X^w \tag{5.34}$$

$$\frac{\partial C_i^R}{\partial \phi} = 1 - D_i^R(.) = 0 \tag{5.35}$$

Following *Shephard (1970) or Jacobsen (1972)* one can show that $\phi = \Lambda = \widehat{C}^R(.)$ at the optimum[16], where $\widehat{C}^R(.)$ is the minimum restricted cost. However, $\widehat{C}^R(.)$ depends on the shadow prices we seek. Therefore, in order to obtain $\widehat{C}^R(.)$ we adopt the assumption suggested by *Färe and Grosskopf (1990, p.125)* that firms satisfy a balanced budget, and thus minimum restricted cost can be retrieved since costs must equal revenues. Thus, when the distance function (5.25) is known, then we can estimate the derivatives of the restricted cost function from the restricted distance function as given below,

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[16] **Theorem 1.** *Let* $v(\mathbf{p}) = \max_x\{\mathbf{px} : G(\mathbf{x}) \leq 1\}$, $\mathbf{p}, \mathbf{x} \in \mathcal{R}_+^m$, $G(\mu \mathbf{x}) = \mu G(\mathbf{x})$, *for every* $\mathbf{x} \in \mathcal{R}_+^m$ *and* $\mu > 0$. *Then* $v(\mathbf{p}) = \lambda(\mathbf{p})$ *where* $\lambda(\mathbf{p})$ *is the optimal Lagrangian multiplier associated with* $L(\mathbf{x}, \lambda) = \mathbf{px} + \lambda[1 - G(\mathbf{x})]$.

Proof. *Let* $x^* = x(\mathbf{p}), \lambda^* = \lambda(\mathbf{p}) > 0$ *be the solution to the Lagrangian problem, then the first-order conditions for this problem imply*

$$\lambda^* \bigtriangledown_x G(\mathbf{x}^*) = p \tag{A1}$$

$$1 - G(x^*) = 0 \tag{A2}$$

Multiplying (1) by x(p) we obtain

$$px(p) = v(p) = \lambda(p) \bigtriangledown_x G(\mathbf{x}^*)\mathbf{x}(\mathbf{p})$$

Then by linear homogeneity, $\bigtriangledown_x G(\mathbf{x}^*)\mathbf{x}(\mathbf{p}) = G(\mathbf{x}^*)$ *and by* $(A2)$, $G(x^*) = 1$. *Thus* $v(p) = \lambda(p)$.■

$$-\left(\frac{\partial D_i^R}{\partial W}\right)\left(\widehat{C_i}^R\right) = \frac{\partial C_i^R}{\partial W} \tag{5.36}$$

$$-\left(\frac{\partial D_i^R}{\partial H}\right)\left(\widehat{C}_i^R\right) = \frac{\partial C_i^R}{\partial H} \tag{5.37}$$

Going back to equation (5.22) and using the relationship between the derivatives of the restricted distance function and the derivatives of the restricted cost function given in equations (5.36) and (5.37), we can estimate the level and time path of the *in situ* groundwater scarcity. That is,

$$\left(\frac{\partial D_i^R}{\partial W}\right)\left(\widehat{C}_i^R\right) = \mu_i$$

Lemma 2: The current value of the in situ resource price for the individual producer of a vertically integrated natural resource producing firm, is equal to the absolute shadow price of the resource as derived from the restricted input distance function that describes firm-specific technology.

Moreover, combining equation (5.37) with equation (A1) in footnote 5, the derivatives of the distance function can be used to characterize the dynamic optimality condition of resource extraction and test the implications of the Hotelling principle.

It remains to show that a distance function can be estimated. As already mentioned, the assumption that $L(.)$ is a closed convex set, implies that the two approaches (5.25) and (5.27), yield the same distance function. From this observation it follows that $D_i^R(.)$ can be calculated using the formulation in (5.25) which only requires data on input and output quantities and not on prices, which given the possibility of market regulation and additional sources of inefficiency, might be less reliable. Moreover, once we have estimated the distance function we can discuss efficiency issues.

5.3.3 Econometric Specification, Empirical Estimation and Results.

Five alternative methods of estimating distance function frontiers have been used in recent years. Namely, (1) construction of a non-parametric piecewise linear frontier using linear programming (DEA) (e.g. *Färe et al., 1989; 1994),* (2) construction of a non-parametric frontier using the integer programming method known as flexible disposable hull (FDH) *(Deprins et al., 1984),* (3) construction of a parametric deterministic frontier using linear programming (e.g. *Forsund and Hjalmarsson, 1987; Färe et al., 1993*), (4) estimation of parametric deterministic frontier using corrected ordinary least squares (COLS) *(e.g. Lovell et al., 1994; Grosskopf et al., 1997)*, and (5) estimation of parametric stochastic frontiers using maximum likelihood *(e.g. Hetemaki, 1996; Coelli and Pereman, 1996).*

These five approaches to estimating distance functions have a range of advantages and disadvantages which may influence the choice of method in each particular application. The principle advantages of the DEA approach is that it does not require the specification of a particular functional form for the technology. However, the principle disadvantage of the DEA method is that when the calculation of shadow prices are desired, only a range of prices can be derived for the efficient firms[17]. One disadvantage shared by all four methods except the stochastic frontier estimation procedure, is that they are susceptible to the influence of outliers. More specifically, deterministic frontier methods do not account for the possible influence of data noise (e.g. as a result of measurement error or model mispecification) upon the shape and positioning of the frontier. The stochastic frontier method attempts to account for this problem. The stochastic frontier production function was independently proposed by *Aigner, Lovell and Schmidt (1977)* and *Meeusen and Van den Broeck (1977).* The original specification involved a production function specified for cross-sectional data which had an error term which had two components, one to account for random effects and another to account for technical inefficiency.

As suggested by *Färe and Grosskopf (1990),* the frontier distance function differs from the more familiar frontier production function mentioned above, in that it readily allows for multiple outputs and its frontier value is unity. In the remaining of this section we empirically estimate

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[17] This is because the production surface constructed by DEA is a series of intersecting planes. The efficient frontier points, that define this frontier surface (primarily) lie at the intersections of these planes. Hence, when one attempts to measure shadow prices for these efficient points, only a range of price ratios can be observed (corresponding to the slopes of the planes involved). This was the principle reason why *Färe et al. (1993)* used parametric methods to repeat the analysis of electricity utilities that were originally analyzed using DEA methods in *Färe et al. (1989).*

an input distance function that characterizes the production technology of vertically integrated agricultural firms, in order to derive the shadow price of groundwater left in the aquifer. One of the first decisions that must be made in a parametric empirical analysis is the selection of an appropriate functional form. The functional form for the distance function would ideally be flexible, easy to calculate and permit the imposition of homogeneity. The translog form has been selected by the majority of the authors in this literature since it satisfies these three requirements[18]. The translog distance function for the case of (K) inputs and (M) outputs is specified as,

$$\begin{aligned}\ln D_i &= \alpha_0 + \sum_{m=1}^{M} \alpha_m \ln y_{mi} + \frac{1}{2}\sum_{m=1}^{M}\sum_{n=1}^{M} \alpha_{mn} \ln y_{mi} \ln y_{ni} + \sum_{k=1}^{K} \beta_k \ln x_{ki} \\ &+ \frac{1}{2}\sum_{k=1}^{K}\sum_{l=1}^{K} \beta_{kl} \ln x_{ki} \ln x_{li} + \sum_{k=1}^{K}\sum_{m=1}^{M} \delta_{km} \ln x_{ki} \ln y_{mi} \\ i &= 1, 2, ..., N \qquad (5.38)\end{aligned}$$

where (i) denotes the (ith) firm in the sample. Note that to obtain the frontier surface (i.e., the transformation function) one would set $D_i = 1$, which implies that the left hand side of equation (5.38) is equal to zero. The restrictions required for homogeneity of degree +1 in inputs are,

$$\sum_{k=1}^{K} \beta_k = 1 \qquad (5.39a)$$

$$\sum_{l=1}^{K} \beta_{kl} = 0, \qquad k = 1, 2, ..., K \qquad (5.39b)$$

$$\sum_{k=1}^{K} \delta_{km} = 0, \qquad m = 1, 2, ..., M \qquad (5.39c)$$

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[18] The Cobb-Douglas form, which has been a popular choice in production analyses for a number of decades, although easy to calculate and make homogeneous, it is not flexible, because of its restrictive elasticity of substitution and scale properties. Furthermore, as noted by *Klein (1953, p. 227)*, the Cobb-Douglas transformation function is not an acceptable model of a firm in a purely competitive industry because it is not concave in the output dimensions. This is not a serious issue when the primary interest is in obtaining technical measures and optimizing behaviour is not an issue.

and those required for symmetry are,

$$\begin{aligned} \alpha_{mn} &= \alpha_{nm}, \qquad m,n = 1,2,...,M && (5.40a) \\ \beta_{kl} &= \beta_{lk}, \qquad k,l = 1,2,...K && (5.40b) \end{aligned}$$

Moreover, the restriction required for separability between inputs and outputs are,

$$\delta_{km} = 0, \qquad k = 1,2,...,K \qquad m = 1,2,...,M \tag{5.41}$$

A convenient method of imposing the homogeneity constraint upon equation (5.38) is to follow *Lovell et al. (1994)* and observe that homogeneity implies that,

$$D(y, \omega x) = \omega D(y,x) \qquad \text{for any } \omega > 0 \tag{5.42}$$

Hence by arbitrarily choosing one of the inputs, such as the *K-th* input, and set $\omega = 1/x_K$, we obtain,

$$D(y, x/x_K) = D(y,x)/x_K \tag{5.43}$$

For the translog this provides,

$$\begin{aligned} \ln(D_i/x_{Ki}) &= \alpha_0 + \sum_{m=1}^{M} \alpha_m \ln y_{mi} + \frac{1}{2}\sum_{m=1}^{M}\sum_{n=1}^{M} \alpha_{mn} \ln y_{mi} \ln y_{ni} + \sum_{k=1}^{K-1} \beta_k \ln x^*_{ki} \\ &\quad + \frac{1}{2}\sum_{k=1}^{K-1}\sum_{l=1}^{K-1} \beta_{kl} \ln x^*_{ki} \ln x^*_{li} + \sum_{k=1}^{K-1}\sum_{m=1}^{M} \delta_{km} \ln x^*_{ki} \ln y_{mi} \\ i &= 1,2,...,N \qquad \textit{and} \qquad x^*_k = x_k/x_K \end{aligned} \tag{5.44}$$

With the selection of a suitable functional form for our input distance function completed, we must now select an appropriate method of obtaining estimates of the unknown parameters of the function. That is, we must obtain estimates of the parameters of the function such that the function is a “good fit” to the data. This task can be described using simple algebra by rewriting equation (5.42) as,

$$\ln(D_i/x_{Ki}) = TL(y_{i,} \frac{x_i}{x_{Ki}}, \alpha, \beta) \qquad i = 1,2,...,N \tag{5.45}$$

$$\ln(D_i) - \ln(x_{Ki}) = TL(y_i, \frac{x_i}{x_{Ki}}, \alpha, \beta) \qquad i = 1, 2, ..., N \tag{5.46}$$

As already argued, one method that can be used to account for the influence of noise upon an estimate frontier is to apply the stochastic frontier approach proposed by *Aigner, Lovell and Schmidt (1977)*, which involves the specification of a frontier function with an error term with two components: a symmetric error to account for noise and an asymmetric error to account for inefficiency. We begin by appending a symmetric error term (V_i) to equation (5.45) to account for noise, and also change notation $\ln(D_i)$ to (U_i). We thus obtain a stochastic input distance function,

$$-\ln(x_{Ki}) = TL(y_i, \frac{x_i}{x_{Ki}}, \alpha, \beta) + V_i - U_i \qquad i = 1, 2, ..., N \tag{5.47}$$

Given appropriate distributional assumptions for (V_i) and (U_i), the parameters of this stochastic translog distance function can be estimated using maximum likelihood. (V_i) are random variables which are assumed to be identically and independently distributed with zero mean and constant variance [*iid* $N(0, \sigma_v^2)$] and independent of (U_i) which are assumed to be *iid* truncations at zero of the $N(\nu, \sigma_U^2)]$ distribution[19]. ($U_i's$) take account of technical inefficiency in production. The predicted value of the input distance for the *ith* firm, $D_i = \exp(U_i)$, is not directly observable because (U_i) only appears as part of the composed error term, $(\Omega_i = V_i - U_i)$. Predictions may, however, be obtained using the conditional expectation,

$$D_i = E[\exp(U_i) \mid \Omega_i] \tag{5.48}$$

as suggested by *Battese and Coelli (1988).* This conditional expectation measures firm-specific technical inefficiencies relative to the efficient isoquant. The stochastic frontier model is not, however, without problems. The main criticism is that there is generally no *a priori* justification for the selection of any particular distributional form for the U_is. The specifications of more general distributional forms, such as the truncated-normal (used in our empirical estimation) and the two-parameter gamma, have partially alleviated this problem, but resulting efficiency measures may still be sensitive to distributional assumptions.

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[19] The abbreviation (*iid*) stands for independently and identically distributed. Moreover, see appendix A4 of chapter 4, for a brief reference to the normal truncated distribution.

The maximum likelihood estimates of the unknown parameters and the distance function predictions obtained in this paper, are calculated using computer programme FRONTIER, Version 4.1, by *Coelli (1996).* The data used in this chapter were extracted from Production Surveys conducted by the Department of Economics, University of Cyprus, for the years 1991, 1997 and 1999. Our analysis focuses on a sample of 228 agricultural farmers located in the Kiti region. The data-set consists of a balanced panel that is composed by the same 76 farmers over the three years of the survey. The variable *(Output)* represents firm-specific total value of output (in Cyprus Pounds) from production of agricultural crops[20], *(Non-Irrigated Land)* represents firm-specific total area (in 0.1 hectares) of non-irrigated land, *(Costs)* represents firm-specific total value of input costs (in Cyprus Pounds[21]) involved in crop production (these include fertilizers, manure, pesticides, fuel and electric power for groundwater extraction). Groundwater extraction is measured in cubic meters and the water table head (specific to each firm, given non-homogeneous aquifer) is measured in meters above sea level. The negative of *(Irrigated Land)*, representing total area of irrigated land (in 0.1 hectares) is the dependent variable in the estimation of the stochastic frontier. Given that the results are based on estimation of a stochastic distance function, time invariance of the parameters is assumed. This means that the presence of technical progress is not accounted for in the empirical model to be estimated. The maximum likelihood estimates of the unknown parameters are given in table 5.3.1.

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[20] The most common crops cultivated in the area under investigation, are grapefruits as far as permanent crops are concerned and bran, cauliflower and tomatoes as far as temporary crops are concerned. Unfortunately, given the absence of crop-specific data, we can not estimate a multi-output distance function.

[21] Final output (Q) and agricultural inputs costs ($Costs$) , both measured in Cyprus Pounds are deflated by the wholesale agriculture price index.

Table 5.3.1

Estimated Stochastic Input Distance Frontier.

Dependent Variable: Irrigated Land.

Variable	**Parameter**	**ML Estimates**	**T-ratios**[*]
Constant	α_0	-0.48	0.60
Output	α_1	-0.30	5.68
Non-Irrigated Land	β_1	0.28	9.44
Labour	β_2	0.19	4.02
Costs	β_3	0.04	0.81
Water Extraction	β_4	0.09	4.15
Head	β_5	0.02	1.98
Irrigated Land	*By homegeneity condition*	0.38	
	Log (likelihood)	378.14	
	ν	-6.11	-1.37
	$LR - test$	22.87	
	$\gamma = \sigma_U^2/(\sigma_U^2 + \sigma_V^2)$	0.88	1.36
	η	1.40	2.02

Cross-sections: 76

Number of time periods: 3

Total number of restrictions: 228

[*] Hypothesis tests are carried out at 95% confidence level.

The estimated parameters presented in table 5.3.1 have the anticipated (positive for inputs and negative for outputs) signs[22]. The coefficient of ν is not significantly different from zero, suggesting support for the half-normal distribution as far as inefficiency effects are concerned.

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[22] Gross products and squared coefficients are not reported because they where excluded from the empirical model after a preliminary estimation, which indicated that their estimated effects were not significantly different from zero. Hence the stochastic distance function estimated in this chapter, has a restricted translog form in which all second order parameters associated with inputs are set to zero. This formulation imposes separability between inputs and outputs.

The one-sided likelihood ratio (LR) test, reported in table 5.3.1, tests the null hypothesis that there are no technical inefficiency effects in the truncated-normal model. If the null hypothesis is true, then the generalised likelihood-ratio statistic is asymptotically distributed as a mixture of chi-square distributions. The critical value for this mixed chi-square distribution is 5.138 for a five percent level of significance[23]. The calculated likelihood ratio reported in the table strongly suggests rejection of the null hypothesis, indicating presence of technical inefficiency effects in the model. Moreover, a value of γ (which is given by $\sigma_U^2/(\sigma_U^2+\sigma_V^2)$) of zero indicates that the deviations from the frontier are due entirely to noise, while a value of one would indicate that all deviations are due to technical inefficiency[24]. In our empirical estimation, the null hypothesis that $\gamma = 0$ is rejected at 95% level of significance, whereas the null hypothesis that $\gamma = 1$ is rejected at 95% level of significance, indicating the existence of technical inefficiency and the choice of a stochastic model, respectively.

Given the availability of panel data we are able to test for time-varying technical efficiencies. Following *Battese and Coelli (1992),* technical inefficiency effects in our model are assumed to be defined by,

$$U_{it} = (U_i \exp(-\eta(t-T))) \tag{5.49}$$

where U_is are assumed to be *iid* as the generalized truncated-normal random variable defined above, and (η) is a parameter to be estimated. If the hypothesis that $\eta = 0$ is accepted, then we can conclude that firm-specific inefficiencies are time invariant. In the specification of equation (5.49), if the *ith* firm is observed in the last period of the panel (T), then $U_{iT} = U_i$, because the exponential function $\exp(-\eta(t-T))$ has value one when $t = T$. Thus the random variable, U_i, can be considered as the technical inefficiency effect for the *ith* firm in the last period of the panel. For earlier periods in the panel, the technical efficiency effects are the product of the technical inefficiency effect for the *ith* firm at the last period of the panel and the value of the exponential function $\exp(-\eta(t-T))$, whose value depends on the parameter η, and the number of periods before the last period of the panel, $-(t-T) \equiv T-t$. If the parameter η is positive, then $-\eta(t-T) \equiv \eta(T-t)$ is non-negative and so $\exp(-\eta(t-T))$ is no smaller than one, which

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[23] The critical value, 5.138 is taken from Table 1 in *Kodde and Palm (1986).*

[24] It should be stressed, however, that γ is not equal to the ratio of the variance of the technical inefficiency effects to the total residual variance. This is because the variance of U_i is equal to $[(\pi-2)/\pi]\sigma^2$ not σ^2.

implies that $U_{it} \geq U_i$. The calculated $t-statistic$ for (η) reported in table 5.3.1 indicates that the estimated coefficient for (η) is significantly different from zero and positive. This result suggests that firm-specific technical efficiencies are increasing over time. These are reported in appendix A5, where it is shown that average mean technical efficiency for agricultural firms in the sample increased rather rapidly from 0.47 in 1991, to 0.78 in 1997, and finally to 0.94 in 1999[25]. Given that technical change is assumed to be constant in the estimated model over the relevant time period, these results allow the conclusion that the managers of the agricultural firms in the sample under consideration, learn from their previous experience in the production process and as a result their technical inefficiency effects change in a persistent pattern over time. The reported substantial increases in the technical efficiency of agricultural firms can be attributed to the major restructuring of the agricultural sector that took place in the last decade in an attempt to harmonize the Cypriot agricultural policies with those of the European Union, in the light of Cyprus accession in the EU[26]. Alternatively, these increases may indicate the existence of technological progress in the agricultural sector under consideration, which is not accounted for in our empirical model. These are the first estimates of the efficiency of the Cypriot agricultural sector and as a result there is no scope for comparison at the present.

At this point it is important to note that our empirical analysis identifies significant firm-specific technical inefficiencies, a result that suggests that if we used *lemma 1* to derive the shadow price of the resource *in situ* instead of *lemma 2* to be used below, our estimates would be biased. That is, the behavioural assumptions implied by cost-minimization are not satisfied by the firms in the data-sample under consideration. Hence, employing a restricted cost function for the estimation of marginal scarcity rents of the resource, as suggested by *Halvorsen and*

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[25] Another characteristic of the time-varying inefficiency model of equation (5.49) is that the technical inefficiency effects of different firms at any given time period t, are equal to the same exponential function of the corresponding firm-specific inefficiency effects at the last period of the panel. This implies that the ordering of the firms according to the magnitude of the technical inefficiency effects is the same at all time periods. Thus the time-varying model of equation (5.49) does not account for situations in which some firms may be relatively inefficient initially but become relatively more efficient in subsequent periods.

[26] A priority goal of this restructuring was the reduction in subsidies given to the agricultural sector. These subsidies amounted to lump-sum amounts of money, given to producers irrespective of their production efficiency. These subsidies were given for socio-political reasons and their aim was to help the agricultural population of the island to sustain their income levels in the face of increased foreign competition. However, the end effect of this policy was incentive reducing, and it can provide the intuition behind the very low levels of technical efficiency derived from the econometric analysis of this chapter for year 1991.

Smith (1984, 1991), would provide misleading results. This criticism is relevant for empirical analyses of most vertically integrated natural resource producing firms, as they traditionally suffer from inefficient management. Hence, the use of the dual input distance function for deriving marginal natural resource scarcity rents is indeed appropriate in such settings and generally useful[27].

In table 5.3.2 we present the calculation for the derivation of the mean estimated shadow price of *in situ* groundwater for each year relevant for our sample data, using *lemma 2.*

Table 5.3.2: Mean Groundwater Scarcity Rents.

Year	$\widehat{C}_i^R$	$\frac{\partial \ln D_i^R}{\partial \ln W_i}$	D_i^R	W_i	$\mu_i = \left[\widehat{C}^R \cdot \frac{\partial \ln D^R}{\partial \ln W} \cdot \frac{D^R}{W}\right]$
1999	£4312.33	£0.09/m^3	1.06m^3/£	42567.34m^3	£0.0097m^3
1997	£5003.56	£0.09/m^3	1.22m^3/£	62000.76m^3	£0.0089m^3
1991	£5687.39	£0.09/m^3	1.53m^3/£	88978.90m^3	£0.0088m^3

As established in section 5.3.2 of this chapter, the mean annual per farm minimum restricted cost function $\left(\widehat{C}_i^R\right)$ is approximated by the mean annual per farm revenue, which is measured in Cyprus pounds, 1999 constant prices. The change in the restricted distance function per unit change in groundwater extraction $\left(\frac{\partial \ln D_i^R}{\partial \ln W_i}\right)$, measured in pounds per cubic meter, is the estimated parameter of the quantity of groundwater extraction from the stochastic distance function estimation, the results of which are presented in table 5.3.1. Moreover, $\left(D_i^R\right)$ and (W_i) are the mean annual estimated distance function and mean groundwater extraction per farm, measured in $\left(£/m^3\right)$ and $\left(m^3\right)$, respectively. The mean shadow value of the per cubic meter *in situ* groundwater calculated in the table above[28], is slightly increasing over the years[29],

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[27] Of course, adopting the method proposed in this paper assumes acceptance of the notion of maximality. Thus failure to produce at the frontier is taken to be worth discovering, regardless of the reason for this failure.

[28] These values are calculated by taking into account that our empirical results give estimates of the derivatives of the natural logarithm of the input distance function, which equals,

$$\frac{\partial \ln D}{\partial \ln W} = \frac{W}{D} \cdot \frac{\partial D}{\partial W}$$

where $D = E[\exp(U) \mid \Omega]$.

[29] If a long enough time series of data was available, one could test the implications of the Hotelling principle by following the exact same procedure that *Halvorsen and Smith (1984, 1991)* suggested. See appendix B5 for further elaboration on relevant literature.

but very small compared to the optimal value of groundwater scarcity rent derived from the optimization model of chapter 3. In table 3.6.2 of chapter 3, we indicate that under a regime of optimal groundwater extraction this value should be equal to £0.2017 per cubic meter of water, which is approximately twenty one times larger than the corresponding value derived in this chapter for year 1999. In appendix B3 of chapter 3, we argue that the area behind a general equilibrium demand curve in an input market, measures the sum of rents to producers selling in all higher markets plus final consumer surplus. Moreover, existence of a general equilibrium non-distorted water demand implies that the marginal value for groundwater should be equal for both sectors of the economy. Hence, the *in situ* scarcity values of groundwater per cubic meter, derived from simulating the optimal control model of chapter 3 and by estimating the stochastic distance function in this chapter, should be equal, even though this chapter's analysis does not take into account the demand for groundwater by the residential sector. However, the two derived values of groundwater scarcity rents are markedly different.

What could rationalize this divergence? Given that the model developed in this chapter derives estimates of the marginal opportunity cost to the agricultural firm of one unit of natural resource left in the aquifer, the approximate inexistence of such scarcity rents indicates that agricultural producers in the region are not willing to pay the full social cost of their unit extraction. This implies that externalities arise as current users of the resource are willing to pay only the private cost of their resource extraction, and as a result the resource's scarcity value goes unrecognized. This pattern of behaviour is consistent with perfect myopic resource extraction, which arises because of the absence of properly allocated property rights in groundwater. That is, myopic extracting behaviour, also identified in the estimation of the hedonic shadow price of groundwater quality in chapter 4, can be rationalized because there exists no incentive for the individual producer to pay today for conserving groundwater in the aquifer that will probably be extracted by somebody else tomorrow. Thus, scarcity rents go unrecognized and groundwater extraction is dynamically inefficient. Hence the need for optimal management of this aquifer emerges, so that current users of the resource pay the social cost of their groundwater extraction and not only its private component. The significant improvement in welfare realized under an optimal control regime derived in chapter 3, implies that imposing the true scarcity rents of *in situ* groundwater on current users of the resource is practically important. Thus, the noninternalized costs of the currently observed myopic groundwater extraction are significant and benefits from optimally managing this resource could be non-negligible.

5.4 Conclusion.

This chapter derives shadow prices of inputs by modelling technology with a restricted input distance function, and through its duality with the cost function, retrieve shadow prices of natural resource inputs of vertically integrated agricultural firms. Then these shadow prices are used to calculated the scarcity rents of unextracted groundwater. This method has a wide applicability in modelling and empirically analyzing production possibilities of natural resource extracting/vertically integrated industries, and can be considered as an alternative methodology to deriving shadow prices of unmarketed resources. This method is particularly efficient when the industry under consideration is inefficiently managed or regulated, which is a very common phenomenon. Moreover this method can be employed to derive a series of *in situ* resource price, which can then be used to test the implications of the Hotelling principle as done in the literature reviewed in the appendix B5.

Appendix A5.

Predicted Technical Efficiencies of Agricultural Firms.

Technical Efficiency Estimates											
Year 1991				Year 1997				Year 1999			
Firm	Eff.	Firm	Eff.	Firm	Eff.	Firm	Eff.	Firm	Eff.	Firm	Eff.
1	0.58	39	0.61	1	0.86	39	0.87	1	0.96	39	0.97
2	0.54	40	0.13	2	0.84	40	0.55	2	0.96	40	0.86
3	0.54	41	0.18	3	0.84	41	0.61	3	0.96	41	0.88
4	0.53	42	0.66	4	0.83	42	0.90	4	0.95	42	0.97
5	0.60	43	0.62	5	0.88	43	0.87	5	0.96	43	0.97
6	0.54	44	0.30	6	0.84	44	0.70	6	0.96	44	0.91
7	0.53	45	0.52	7	0.83	45	0.83	7	0.95	45	0.95
8	0.54	46	0.53	8	0.84	46	0.83	8	0.96	46	0.95
9	0.53	47	0.51	9	0.84	47	0.82	9	0.96	47	0.95
10	0.66	48	0.58	10	0.89	48	0.86	10	0.97	48	0.96
11	0.62	49	0.33	11	0.87	49	0.72	11	0.97	49	0.92
12	0.30	50	0.64	12	0.70	50	0.88	12	0.91	50	0.97
13	0.45	51	0.55	13	0.79	51	0.84	13	0.94	51	0.96
14	0.43	52	0.05	14	0.78	52	0.44	14	0.94	52	0.81
15	0.42	53	0.10	15	0.78	53	0.52	15	0.94	53	0.85
16	0.44	54	0.35	16	0.79	54	0.74	16	0.94	54	0.92
17	0.47	55	0.20	17	0.80	55	0.62	17	0.94	55	0.89
18	0.63	56	0.10	18	0.88	56	0.53	18	0.97	56	0.85
19	0.43	57	0.43	19	0.78	57	0.78	19	0.94	57	0.94

20	0.39	58	0.17	20	0.76	58	0.60	20	0.93	58	0.87
21	0.47	59	0.08	21	0.80	59	0.49	21	0.95	59	0.84
22	0.36	60	0.17	22	0.74	60	0.60	22	0.93	60	0.88
23	0.58	61	0.70	23	0.86	61	0.91	23	0.96	61	0.98
24	0.52	62	0.66	24	0.83	62	0.89	24	0.95	62	0.97
25	0.48	63	0.69	25	0.81	63	0.90	25	0.95	63	0.97
26	0.25	64	0.73	26	0.67	64	0.92	26	0.90	64	0.98
27	0.56	65	0.05	27	0.85	65	0.42	27	0.96	65	0.81
28	0.61	66	0.08	28	0.87	66	0.49	28	0.97	66	0.84
29	0.29	67	0.68	29	0.70	67	0.90	29	0.91	67	0.97
30	0.29	68	0.71	30	0.69	68	0.91	30	0.91	68	0.98
31	0.60	69	0.69	31	0.86	69	0.90	31	0.96	69	0.97
32	0.68	70	0.61	32	0.90	70	0.87	32	0.97	70	0.97
33	0.55	71	0.61	33	0.84	71	0.87	33	0.96	71	0.97
34	0.61	72	0.60	34	0.87	72	0.87	34	0.97	72	0.96
35	0.64	73	0.70	35	0.88	73	0.90	35	0.97	73	0.97
36	0.27	74	0.67	36	0.68	74	0.90	36	0.91	74	0.97
37	0.07	75	0.66	37	0.49	75	0.89	37	0.83	75	0.97
38	0.20	76	0.72	38	0.62	76	0.91	38	0.88	76	0.98
Mean Eff. in 1991 = 0.47				Mean Eff. in 1997 = 0.78				Mean Eff. in 1999 = 0.94			

APPENDIX B5.

TESTING THE HOTELLING PRINCIPLE BY THE USE OF DERIVED IN SITU NATURAL RESOURCE SHADOW PRICES.

The value of having available a procedure for estimating the price of unextracted groundwater, or any other natural resource, from data for a vertically integrated natural resource industry can not be overemphasized if one wants to test the relevance of the theory of exhaustible resources. Does the economic theory of exhaustible resources adequately explain producer behaviour? Extant empirical tests show mixed support and are not encouraging in terms of usefulness of the theory in describing producer behaviour. There are many differences in extant tests, including differences in resource(s) and market structure analyzed; aggregation over time and resources; whether and, if so, how the *in situ* resource price, which is not directly observable, is estimated; and the type of test employed.

In an attempt to emphasize the contribution of this thesis that aims to suggest ways, in accordance with economic theory, to derive the *in situ* scarcity of a natural resource, in this appendix we review a relevant literature that can be enlightened and extended by suggestion of different approaches to deriving natural resource scarcity rents. First we give a summary of the implications of the theory of exhaustible resources (in its 'complete certainty' version) for the dynamic behaviour of private markets for exhaustible resources. Then we review existing tests of the Hotelling principle. These test could be applied to *in situ* resource prices derived by employing the methods suggested in the chapters of this thesis. However unavailability of long enough time-series restricts our analysis to theoretical suggestions without empirical application.

The Hotelling rule provides the fundamental no-arbitrage condition that every competitive or efficient resource utilization path has to meet. In its basic form it indicates that along such a path the price of exhaustible resource has to grow with a rate that equals the interest rate. Although the Hotelling rule is in principle relevant for all models of non-renewable resource use, its simplest application is that of a cake eating economy where consumption results from depleting a given stock of natural capital. In the basic resource model[30], the capital market clears when the price of the unextracted resource at time (t), which gives the *in situ* scarcity of the resource represent by (λ_t), increases at a rate r_t (the risk-adjusted interest rate). The extraction period is assumed to be infinitely long. This assumption together with profit maximization imply that no resource should be left at the end of time. Letting $Q(p, z)$ be the demand curve where z represents demand shift variables, equations (5.50) and (5.51) together, are the capital market equilibrium conditions.

$$\lambda_{t+1} = \lambda_t(1 + r_t) \tag{5.50}$$

$$x(0) = \sum_{t=0}^{\infty} q(t) \tag{5.51}$$

Equation (5.52) indicates that the price of the resource product equals the cost of the raw resource plus the marginal cost of converting the raw resource into that product. It ensures profit maximization in the processing industry.

$$p_t = mc_t + \lambda_t \tag{5.52}$$

The equilibrium condition in equation (5.53) says that the market for the resource product clears.

$$q(t) = Q[p(t), z] \tag{5.53}$$

As it is obvious from equations (5.50)-(5.53), the basic theory of natural resources differs from the theory for any other good only in its assumption that there is always storage of the raw resource. The holding of stocks does not depend upon demand conditions. The consequence of stock holding is that resource rents always rise at a rate sufficient to compensate their owners for holding them rather than another asset. In the basic model this rate is the rate of interest. Since it is continuous stock holding and continuous price increase that are unique to resource

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[30] The model can most easily be analyzed as conditions for equilibrium in a capital market for the unextracted resource, in a flow market for a resource product, and in the processing market for making the product from the unextracted resource.

theory, any test of the theory must make use of this information.

The implications of increased natural resource scarcity and its effect on economic growth have been discussed since the 18th century. *Malthus (1798)* and *Ricardo (1821)* held that agricultural land scarcity implied strict limits on population growth and the development of living standards. Harold Hotelling offered his well-known counterargument in his seminal article of 1931: competitive firms would manage exhaustible resource stocks to maximize present-value profits, competitive extraction paths would therefore match those chosen by a social planner seeking to maximize intertemporal social surplus, and subject to the caveat of social and private discount rates equality, equivalence between competitive and the work of a rational social planner would be achieved. This result implies that the invisible hand was sufficient and policy intervention inappropriate. However, the ability of the Hotelling's theory to describe and predict the actual behaviour of exhaustible resource markets remains an open question. The theory was not empirically tested until the second half of the 20th century. *Slade and Thille (1997)* categorized the existing empirical tests as (a) price behaviour, (b) shadow price, and (c) Hotelling valuation tests.

The earliest tests were price behaviour tests, which as the name implies focused on price paths as indicators of scarcity. Included in this group are *Barnett and Morse (1963)*, *Smith (1979)*, and *Slade (1982)*. Barnett and Morse examined trends in the prices and unit costs of extractive goods (including agricultural, mineral, and forest products) in the United States. They found that the unit cost of extractive output fell by 55 percent between 1870 and 1957. Although the price of forest products increased somewhat over the period, agricultural and mineral prices exhibited no clear long-term trends. These findings suggested that natural resources were becoming less scarce, not more scarce, in an economic sense. The authors argued that technological progress offsets declines in the physical quality and abundance of resource stocks[31].

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[31] This optimistic assessment came under renewed scrutiny in the 1970s when *Meadows et al. (1972)* argued that exponential growth in resource extraction and environmental degradation could not be sustained through the twenty-first century. According to the authors, fundamental reforms in technology and social institutions would be required to maintain the quality and physical environment for the benefit of future generations. The response from economists was uniform and emphatic. The model employed by Meadows et al. lacked price feedbacks and other mechanisms through which economic agents could adapt to changing physical conditions. Some argued that

Smith (1979) employed an econometric analysis of annual (1900-1973) price data of four aggregate resource groups and concluded that the trend in mineral prices was negative with the rate of decline decreasing over time in absolute magnitude. A similar study of twelve major metals and fuels by *Slade (1982)* concluded that the price paths for nonrenewable natural resources were U-shaped[32]. Slade hypothesized that the declining, flat and increasing price trends implicit in U-shaped price paths, come at different points in the life cycle of the exhaustive resource.

Limitations of these early tests include the level of aggregation[33]. Also, the hypothesis that unit prices increase over time at the rate of interest implicitly restricts the test to marginal costs being independent of extraction rate and costs being independent of cumulative extraction, or remaining reserves. Given the level of restrictions, it is difficult to think support for the theory of exhaustible resources would be found. Moreover, *Ahrens and Sharma (1997)* examine deterministic versus stochastic trends in resource prices. Their results suggest there may be a specification problem in these time series tests.

The empirical tests based on the shadow price can further be categorized by their use of either explicit price expectations or implicit price expectations. Tests that rely on explicit price expectations include *Stollery (1983), Farrow (1985), and Slade and Thille (1997).* Tests that employ implicit price expectations include *Halvorsen and Smith (1991)* and *Chermak and Patrick (1999). Stollery (1983)* extended the basic Hotelling model to account for the effects of depletion, possible technological change, and exogenous discoveries. He proceeded in stages. First he estimated a log-linear demand function for nickel and a Cobb-Douglas production

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the approach constituted "measurement without data" *(Nordhaus, 1973)* and was therefore wholly unjustified. The findings of Hotelling and Barnett and Morse were brought into the debate and new developments from the theory of economic growth added a third strand to the argument. By introducing an exhaustible resource to a standard model of intertemporal development, *Solow (1974)* established that a sustainable consumption level could be achieved, *in principle*, given sufficient substitutability between resource and capital inputs.

[32] When *Slade (1982)* performed her tests on real prices, she used the then current technology of fitting the observed series with a quadratic trend with autoregressive error. Using this trend model, the chance that prices in the year 2000 will be higher than they were in 1985 is 99.92 percent, which is certainly an affirmation of the theory that prices will almost certainly rise. There are two major reasons to believe that the case for rising prices is overstated by these results. First, the parameters of the quadratic trend model change with the period estimation. The second reason to doubt the prediction is that the series may be stationary around a stocastic trend rather than a deterministic one. This is the problem of spurious regression *(Nelson and Kang, 1981).*

[33] For further discussion of the difficulties associated with aggregation, see *Backorby and Schworm (1982).*

function for mining nickel. From these he found marginal revenue[34] and marginal cost, and resource rent was estimated as the difference between the two. The estimated values for rent were then treated as data and were used in an estimation of the capital market rule. The parameter to be estimated was the interest rate (r). The recovered estimate of the interest rate from this procedure was compared with an estimate of the required rate from the capital asset pricing model (CAPM[35]). Since the two estimates were not dissimilar, the exercise was seen as confirming the theory. The unobservable rents did rise at the rate of interest.

Farrow (1985) tested the exhaustible resource theory using monthly price and cost data (01/1975 through 12/1981) from an underground hard rock mineral mine that produced several joint product metal commodities. Their theoretical model is analogous to the Hotelling extension where costs are a function of current extraction, remaining reserves, and input prices. The cost function was estimated using data from company accounting records, which included monthly income statements from January 1975 to December 1981. The income statements were supplemented by information from invoices to obtain input prices, inventory records, and miscellaneous operating reports. The functional form of the empirically estimated cost function was a translog. The coefficients were restricted to be homogeneous of degree one in input prices. Employing information from the cost function, Farrow directly estimates the transition equation and then tests the appropriate restrictions on the transition equation parameters. In an AR(1) model, the parameter estimates are significant. However, Farrow points out the "weak link" between the data and theory, in that the sign of the parameter of the firm's discount rate is negative. Farrow derives a number of alternative tests that allow for, among other things, a changing discount rate. In all cases, the theory of exhaustible resources is rejected at the level of this single mine with joint products.

Slade and Thille (1997) integrated the theory of exhaustible resources with CAPM. They estimated user cost as the difference between price and marginal extraction costs under several different restrictions including certainty and risk. They directly estimated the transition equation employing a translog cost function and tested the statistical significance of the restric-

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[34] Marginal revenue rather than product price is used in calculating the implicit *in situ* price, because the firm is assumed to be a monopolist with a competitive fringe.

[35] CAMP is a form of equation (5.50) that is conditional on information observed at $t + 1$.

tions. A generalized method of moments (GMM) estimator was used with lagged values of the variables plus year rate of change of producer price index, and the rate of growth of aggregate consumption included as instruments. A Wald test indicated the basic Hotelling Model is not rejected. However, the parameter estimates are not statistically significant from zero, rending the results suspect. Additionally tests, which incorporate risk into the model via the Capital Asset Pricing specification, are not rejected, based on the Wald statistics. The addition of financial variables leads to a model with some empirical support.

Turning to tests that rely on implicit price expectations, *Halvorsen and Smith (1991)* as already argued in the main text of chapter 5, used duality theory to derive an econometric model that provides a statistical test of the theory of exhaustible resources. Following *Halvorsen and Smith (1984)*, a restricted cost function was used to obtain estimates of the shadow prices of unextracted resources from cost and production data for vertically integrated natural resource industries. The restricted cost function used, also provided estimates of the effects of cumulative extraction on the marginal cost of extraction. The implications of the theory of exhaustible resources were expressed as parametric restrictions on the restricted cost function model and were tested using a *Hausman (1978)* specification test. The procedure was illustrated with data for the Canadian metal mining industry. For this industry the parametric restrictions implied by the theory of exhaustible resources were strongly rejected.

Moreover, *Chermak and Patrick's (1999)* theoretic development refer to a price-taking firm that produces and, at least partially, refines the resource. An indirect final cost function is econometrically estimated, as are gross production cost and average cost functions. Each is then restricted by the dynamic optimality condition. Monthly production and cost data from 29 individual natural gas wells, located in three geographic regions in the US. and owned by five different firms is was employed to estimate the indirect final cost function. The dynamic optimality condition was tested under a range of discount rates. The results indicated support for the theory under all discount rate levels and all specifications. That is, relevant production decisions were found to effectively taking into account the opportunity cost of current production (the in situ resource price) and the path is economically optimal according to the theory.

Slade's and Thille's third category of tests are the Hotelling valuation approach. These include the test formulated by *Miller and Upton (1985),* which is based on the following implication derived from Hotelling's analysis: the value of a unit of reserves in the ground is the same as its current value above ground less the marginal cost of extracting it, regardless of when the reserves are extracted. Miller and Upton called this the Hotelling valuation principle[36] and tested it with a cross-section of oil properties. They found that (except for very small properties, which they excluded) the stock-market value of a property was its Hotelling value, $x_0\lambda_0$ and the size of deposit had no effect on value[37]. However, as noted by *Swierzbinski and Mendelsohn (1989)*, this is not equivalent to showing that the actual time paths of resource prices are consistent with the Hotelling predictions. Swierzbinski and Mendelsohn show that when the stock of a resource is uncertain, the Hotelling Rule may provide the best available prediction of future resource prices, even though unanticipated changes in expectations due to the arrival of information cause the actual time paths of resource prices to deviate from the Hotelling predictions.

Yet another approach to testing Hotelling's theory was suggested by *Livernois and Uhler (1987)*, who argued that a marginal cost of extraction function for a particular deposit should have the form $mc(q, n, x_t)$, where q is quantity extracted per year, n is the number of deposits discovered before the deposit in question, and x_t is the amount remaining in the deposit. Marginal cost is expected to increase in q and n, and decrease in x. Livernois and Uhler tested a stock-dependent cost function of this form for a cross-section of 166 Canadian oil wells that were producing in 1976 and found that costs do increase when stock decreases.

As it is obvious from the literature reviewed here, the primary difference in testing methodologies of the theory of exhaustible resources are: (a) directly estimating the dynamic optimality condition and testing whether the estimated parameters conform to the theory, which is the predominant test in the literature, and (b) estimating an indirect cost function restricted by

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[36] On a theoretical level, a different result could be derived from the valuation principle in a number of ways. Allowing for shut-down, abandonment, and positing definite fixed operational costs gives the *Brannan and Schwartz (1985)* model in which the option of operating is valuable. Rather trivially, a known but not operated deposit cannot be valued in this fashion, because its nonoperation indicates that it has more value in future then in current extraction.

[37] The same type of analysis with redwood stumpage prices has been done, with a slightly different conclusion (see *Berck (1988)* for more details).

the dynamic optimality condition and testing whether the parameters of this restricted cost function are consistent with those of the unrestricted cost function. Chapter four builds on the second methodology to suggest yet another way of estimating the relevant derivatives of a cost function, which is less data intensive in input prices, a considerable advantage we believe given the problems of pricing natural resources and other inputs used in heavily regulated or inefficiently managed industries, and does not impose any behaviour assumptions, again a considerable advantage given the diversity of firm objectives possible in heavily regulated industries.

Chapter 6

Epilogue.

Efficient pricing of a resource incorporates marginal cost of extraction and scarcity rents. Since groundwater resources exhibit natural supply constraints, scarcity rents must be imposed on current users. Due to the absence of clear groundwater ownership rights, extracting behaviour is myopic and extracting agents are willing to pay only the private cost of their groundwater extraction. As a result, scarcity value goes unrecognized and as such is difficult to estimate. This results in inefficient pricing and misallocation of the resource, and calls for intervention in the relevant resource market. The main aim of this thesis was to propose alternative theoretical and empirical methodologies that allow indirect estimation the shadow scarcity rents of *in situ* groundwater and the shadow price for groundwater quality, and derive inference on the potential for managing this resource. Empirical analyses are based on economic and hydrological data collected for the region of Kiti in the island of Cyprus, representative of coastal semi-arid regions.

In chapter 1 we establish the potential scarcity of groundwater and discuss the need for managing this resource in order to achieve its optimal dynamic allocation. In chapter 2 we investigate the potential for managing this resource through a review of the relevant theoretical and empirical literature, which suggests that under particular circumstances this potential is severely limited through the presence of the Gisser-Sanchez effect. More specifically, we identify the conditions under which this effect persists and we establish that the most important contributing factor to the practical insignificance of optimal price management of groundwater extraction, is the inelastic demand for this resource. Moreover, we argue that a number of factors that have been ignored by the Gisser-Sanchez literature, could prove important in establishing the practical significance of optimal groundwater management.

One of this factors is recognizing the possibility of complete depletion of the resource. In chapter 3 we develope an optimization model of groundwater extraction that incorporates the possibility of endogenous adoption of a backstop technology (namely desalination) and we apply this model to an aquifer that is seriously depleted. This model is used to derive scarcity rents of *in situ* groundwater as well as the benefits from optimally managing the resource. Empirical simulation of the model establishes that the potential for groundwater management is big, as it increases the value of welfare benefits by 409.4% (given sustainability of aquifer recharge to the indefinite future) if compared to the value of benefits derived from the competitive-commonality solution of groundwater allocation (where current users incur only the private cost of their extraction and free-ride on relevant scarcity rents). Hence our empirical results suggest the absence of the $\mathcal{GSE}$ in aquifers that face complete exhaustion in the near future, and establish that groundwater management is welfare increasing. Moreover, the initial optimal scarcity value (in year 1999) per unit of the resource derived from simulating the optimal solution of the problem, is equal to £0.2017 per cubic meter.

In chapter 4 we model the simultaneity between hedonic valuation and sample selection in the context of producer behaviour and investigate it empirically through an econometric model, in the case of land demanded for use as an input either in agricultural production or touristic development. The empirical analysis suggests that failing to correct for sample selection results in a biased valuation of groundwater scarcity rents. This argument has implications for hedonic price analyses applied to housing and other goods whose quality characteristics can affect sample selection. The estimated marginal producer's valuation for groundwater quality as far as reduced salinization is concerned, is statistically insignificant and equal to £1.07 per (0.1) hectare of land. The statistical insignificance and small magnitude of the marginal WTP for improvements in groundwater quality derived from the hedonic model with selectivity correction in chapter 4, could imply that extraction behaviour is myopic. That is, agricultural producers are not willing to pay a large amount for preserving groundwater quality today, because salt-free water might be extracted by free-riding extracting agents tomorrow. This is of course an artifact of the inexistence of properly allocated property rights in a common-pool aquifer. Moreover, another contributing factor towards a low marginal WTP for groundwater quality and existence of myopic extracting behaviour, is that current farmers value the prospect of switching to the more lucrative touristic sector of the economy (as compared to the agricultural sector), which is an economic sector that utilizes other existing sources of water (other than groundwater).

In chapter 5 a stochastic restricted distance function was estimated and through it duality with the cost function we were able to derive shadow groundwater scarcity rents. We argue that when price information is not available, or alternatively when price information is available but cost, profit or revenue functions representations are precluded because of violations of the required behaviour assumptions, distance functions provide an excellent analytical tool for deriving efficient input shadow prices. Violation of conventional behaviour assumptions are the norm rather than the exception in inefficiently managed and regulated industries like agriculture. The estimated technical firm-specific inefficiencies present in production technologies of agricultural firms in the sample under consideration, suggest that cost minimization is not the relevant behaviour objective in the industry under investigation. This empirical result provides support for the use of the distance function approach to deriving *in situ* resource shadow prices.

Moreover, these results indicate that the shadow values of the unit *in situ* groundwater is approximately equal to zero $\left(£0.0097m^3\right)$. Given that the model developed in chapter 5 derives estimates of the marginal opportunity cost to the agricultural firm of one unit of natural resource left in the aquifer, the above comparison indicates that agricultural producers in the region are not willing to pay the full social cost of their unit extraction. This implies that externalities arise as current users of the resource are willing to pay only the private cost of their resource extraction, and as a result the resource's scarcity value goes completely unrecognized. This pattern of behaviour is consistent with perfect myopic resource extraction, which arises because of the absence of properly allocated property rights in groundwater, and is consistent with the results on WTP for groundwater quality of chapter 4.

The main message that can be derived from the empirical application of the theoretical models developed in this thesis, is that in seriously depleted aquifers (where groundwater scarcity really matters) there is a significant difference between benefits realized under optimal management of the resource and those derived under myopic extraction of the resource; that is, the $\mathcal{GSE}$ is absent (chapter 3). Moreover, alternative empirical estimations of the marginal willingness to pay for *in situ* groundwater quantity and marginal improvements in groundwater quality, result in insignificantly small valuations for groundwater shadow prices (chapters 4 and 5). As already argued, these results imply myopic extracting behaviour, which is rationalized by the absence of properly defined property rights for groundwater. That is, in the absence of property rights defining ownership of the resource, there exist no incentive to conserve water quantity and quality today in order to reduce future costs, as water conserved by one agent today can be extracted tomorrow by another free-riding agent. The combination of a potentially significant increase in social benefits from managing the resource and evidence of myopic behaviour, point to the need and potential for optimal management of groundwater in the region under investigation, representative of arid and semi-arid regions in general. Hence, future research should be directed towards estimating cost and benefits from implementing optimal dynamic management of groundwater.

As mentioned in the introductory chapter of this thesis, the main conclusion of the work presented in this thesis amounts to the following statement:

> When groundwater scarcity is very acute and complete depletion of the aquifer is due in the near future, the $\mathcal{GSE}$ disappears; thus evidence of the empirical prevalence of myopic groundwater extraction should constitute a signal for the need for managing groundwater resources. Implementing optimal extraction is going to be neither easy, nor costless, hence future work should be directed towards deriving cost and benefits of different regulatory regimes of groundwater extraction.

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Thesis Attachment:
Survey of Production (1999).