Groundwater Management

An Overview of Hydro-geology, Economic Values and Principles of Management

Authors:

Phoebe Koundouri, Department of Economics, School of Business, University of Reading, UK and CSERGE Economics, Department of Economics, University College London, UK. E-mail: p.koundouri@reading.ac.uk

Ben Groom, CSERGE Economics, Department of Economics, University College London, UK. E-mail: b.groom@ucl.ac.uk

Glossary of Terms

Glossary of Terms

Aquitard: relatively impermeable geological layers which prevent the flow of groundwater.

Cones of Depression: reductions in the groundwater which are localised and centred around groundwater boreholes and caused by pumping

Dynamic Optimal Control: a mathematical modelling technique for maximising dynamic objectives. Can be used to determine the most efficient use of groundwater over time with regard to any particular objective whilst also taking into account the dynamic nature of the resource.

Fossil Water: groundwater contained in confined aquifers, which has been deposited many thousands of years ago.

Gisser Sanchez Effect (GSE): the phenomenon that intervention to ensure the optimal allocation of groundwater as defined by the dynamic optimal control modelling represents only an insignificant improvement in welfare compared to the decentralised status quo. The presence of the GSE depends crucially on the nature of the aquifer and the nature of demand.

Present Value: the value of a stream of benefits or costs that accrue over time from the perspective of today. The present value of £10, which accrues in 20 years time is equal to $10/(1+r)^{20}$ where r is the appropriate discount rate reflecting impatience/preference for the present or the returns from alternative investments. At a discount rate of 5% the present value of £10 in 20 years time is equal to £3.77.

Price Elasticity of Demand (PED): The responsiveness of the demand for a good to a change in price. Given by the formula: PED = $-(\partial q/\partial p).p/q$, where q represents the quantity of water and p represents the unit price of water.

Recharge: the flow of water the infiltrates into an aquifer adding to the stock of water.

Total Economic Value (TEV): the sum of all economic values associated with a resource. TEV is comprises both use values and non-use values, where the latter relate to the values held by individuals simply for the existence of the resource rather than the direct or indirect use thereof. In the case of groundwater this may apply to associated ecosystems for example.

User Cost: Also known as the scarcity rent, represents the costs of pumping groundwater that arise as a result of increases in the scarcity of the resource: the reduced stock of water for future use, the increased pumping cost in the future etc.

1. Introduction

The issues surrounding groundwater, its instrumental uses and ecological functions, and the management thereof typify the interaction of humankind with the resources that sustain it. Perhaps most importantly groundwater is an immensely important resource in that it is estimated to represent 94% of the planet’s freshwater resources. It is therefore inevitable that groundwater has become socially and economically important for a variety of reasons. Firstly, it is frequently a cheap source of water, providing costless water storage that economises on evaporation, whilst being accessible above ground without complicated transfer schemes. Secondly, groundwater is a key input in all of the conventional economic sectors: industry, agriculture, tourism, households etc., and in many countries groundwater represents the source of more than half of annual water consumption. This is especially so in arid countries and many small islands in which perennial surface water is scarce. In such regions groundwater can act both as a substitute for surface water, facilitating economic development where previously it would be absent, and a complement to surface water, acting as an insurance policy or buffer against climatic uncertainty and drought. Groundwater provides many of these essential services wherever it is found, in developed and less developed countries, arid and humid alike.

Although important from this purely economic viewpoint, like many natural resources, groundwater is an intrinsic part of wider ecological processes. It is frequently merely a component of the hydrological cycle and from a management perspective can seldom be considered in isolation. In this regard a common phenomenon is groundwater and surface water are conjoined, which means that the effects of groundwater abstraction will extend beyond individual users to the functions and processes sustained by surface water. These functions and processes not only include the conventional economic sectors but also the ecological functions such as the maintenance of riverine systems, their base flows, associated flora and fauna, and wetland ecosystems. Furthermore groundwater is a dynamic resource in that changes in the size and quality of groundwater stocks, induced by natural causes or human intervention, frequently have long lasting and occasionally irreversible effects. For example, land subsidence and aquifer collapse can be common yet often unpredictable and irreversible consequences of groundwater abstraction. Where quality is concerned, seawater intrusion represents another potentially irreversible change. Hence, the effects of abstractions upon groundwater reserves and associated ecological functions can be long lasting and almost always carry an element of unpredictability.

In addition, groundwater aquifers differ considerably in their geological and hydrological characteristics, which means that there is no ‘one size fits all’ model with which to analyse them. From the perspective of sustainable use perhaps one of the most important distinctions relates to the presence or absence of natural recharge. The potential for recycling withstanding, in the former case groundwater can be seen as a renewable resource like forests or fisheries, in the latter it can be seen as an exhaustible resource like oil or coal. Along with the issue of conjointness, each scenario will require a different management approach.

In light of the above characteristics, the planning and management of groundwater is a challenging and ever-evolving task. This challenge is compounded by the socio-economic context: the nature of human interaction and the legal and institutional backdrop, which provide the rules of engagement. It is widely argued that the inefficient use of groundwater, often reflected by premature exhaustion, is the result of weak or perverse property rights systems which make groundwater an ‘open access’ or a ‘common property’ resource. One extreme example is when groundwater is shared by two or more sovereign states: it is a trans-boundary resource. For example, the Qa Disi aquifer is shared between Jordan and Saudi Arabia. In the absence of cooperation, each country competes for the resource and mining is quickened as a result. A similar effect occurs between individuals sharing the same aquifer under open access. Again, the assignment of property rights and the details thereof are important determinants of groundwater use and the benefits to society that it affords.

Clearly there are a number of issues concerning groundwater, which indicate the need for intervention if such resources are to be used efficiently, in a sustainable manner and distributed equally across potential users. Indeed, whether or not groundwater use should be regulated, and the manner in which this is done represents one of the most important issues in the arena of water resource management.

2. Groundwater: Hydro-Geology

Groundwater systems are composed of saturated rocks and/or sediment in a variety of geological formations. In general if such a formation can produce useable quantities of water it is known as an aquifer. The geological variation in aquifers means that they vary in their physical characteristics, such as whether or not they are replenished or recharged by surface water or precipitation and hence the extent to which they can be seen renewable or exhaustible resources. In addition, the response of groundwater stocks to abstractions is determined by the geological structure. Therefore in order to understand the dynamics of a particular aquifer, it is important to determine the nature of the particular hydrological and geological environment. The important distinctions between and characteristics of aquifers are outlined in brief below.

2.1 Unconfined and confined aquifers

Broadly speaking unconfined aquifers are subject to recharge by precipitation and/or surface water, which infiltrates vertically downwards through the overlying ground structure. The upper threshold of an unconfined aquifer is known as the water table, and water contained therein can be considered renewable. A *perched* aquifer represents a special case of an unconfined aquifer and can be thought of as an impermeable shelf in otherwise permeable ground upon which water infiltrating from above is held for a period of time determined by the permeability of the surrounding ground.

Confined aquifers on the other hand, lie beneath less porous layers of rock, or aquitards, which either preclude recharge altogether or limit recharge to lateral underground flows from recharge zones where the aquitard is absent. Confined aquifers which are not subject to recharge can contain water which was deposited many thousands or even millions of years ago; so called fossil water, and water contained therein can be considered an exhaustible resource.

The distinction between confined and unconfined aquifers often lies in the pressure of the groundwater. Artesian wells such as the great artesian basins of east-central Australia and the south east Kalahari aquifer in Namibia contain water which, once tapped, is under sufficient pressure to reach ground level or higher. Such flows emanate from confined aquifers, which are under more than the atmospheric pressure associated with unconfined aquifers. However, in reality the division between confined and unconfined aquifers is less distinct, and in general both form component parts of a single hydrological system.

2.2 Conjoined surface and groundwater

A further distinction is also important, particularly when considering water resource management, is the extent to which aquifers are conjoined to other surface water bodies such as lakes or rivers. Tributary aquifers are those located adjacent to and beneath rivers and other such watercourses. The behaviour of these unconfined aquifers is directly linked to that of the watercourse and vice versa. The South Platte River in Colorado, US provides an example of surface water conjoined to an alluvial aquifer. The aquifer is recharged predominantly by the river, whilst abstractions from the aquifer affect the surface water flow. Furthermore, water stored in aquifers may also represent the source of springs and as such any economic use or ecological process linked to these springs will also be linked to the stock, rather than the flow, of groundwater.

2.3 Composition and Physical Characteristics

Aquifers vary in their geological composition and hence physical properties, most important of which are storage capacity and the subsurface flows of groundwater e.g. in response to pumping. Some important characteristics are as follows:

- **Porosity**: measures the percentage of a given rock made up by voids or holes (interstices) in which water can be stored. Such voids can represent the nature of the aquifer medium e.g. pores in limestone or inter-granular spaces in sandy aquifers, or from secondary effects such as rock movements or weathering.
- **Storativity**: also known as the coefficient of storage, represents the volume of water that can be extracted from a given surface area of an aquifer per unit change in depth (or head).
- **Transmissivity**: measures the extent to which a reduction in groundwater level due to pumping at a particular point is transmitted to the rest of the aquifer. I.e. the extent to which the water level goes down locally or uniformly across the entire surface area of the aquifer. Where transmissivity is low the water level only recedes locally and in extreme cases giving rise to cones of depression. Where transmissivity is high, local pumping affects the water level across the whole aquifer.

Aquifers also differ in the extent to which they are subject to irreversible changes as a result of abstractions. For example, coastal aquifers are frequently affected by saline/seawater intrusion. This has occurred for example in the Kiti aquifer in Cyprus and the Hermosillo aquifer in Mexico. Once this intrusion has occurred it is either irreversible or reversed at significant cost through the injection of recycled or semi-purified water: artificial injection. Similarly, the collapse of aquifers due to abstraction, and the associated loss of storage, is a common and irreversible occurrence. In central parts of

Arizona for example, land surfaces have subsided by up to 9m over the past 20 years as a result of abstractions.

3. The value of groundwater

Groundwater is a valuable resource for a number of reasons. When abstracted groundwater acts as a current input into the conventional economic sectors of industry, agriculture and households. This represents the extractive value of groundwater. When left in the ground, as well as supporting many ecosystem functions as an important component of the wider hydrological and ecological system, it leaves the option of abstraction in the future. Thus, in addition to the direct use or extractive values, groundwater also has an *in situ* value, i.e. a value associated both with saving for the future and maintaining ecosystem functions. In determining the pattern of use, which best fulfils societal objectives it is the tension between extractive and *in situ* values which best describes the trade-offs faced by the resource manager. Determining the trade-off requires the knowledge of all of the economic values associated with groundwater: i.e. the Total Economic Value (TEV).

TEV is defined to include both direct/extractive use and non-use values, i.e. those values generally associated with environmental goods. Whilst the extractive values are well represented and valued by the conventional economic sectors, there are a number of *in situ* values, which require special attention. *In situ* values include:

- **Buffer values**: The insurance value associated with the buffer that stocks of groundwater provide when used conjunctively with uncertain surface water.
- **Subsidence avoidance**: subsidence is one of the consequences of groundwater abstraction and as such subsidence avoidance is an *in situ* value.
- **Ecological service**: groundwater reserves are often the source of river base flow, springs and have other ecosystem linkages. Another ecosystem service is water purification. Maintaining groundwater stocks maintains any associated ecological services.
- **Recreational services**: the maintenance of surface water flows means that any associated recreational and other services are preserved.
- **Future values**: in general, the option to use groundwater in the future is defined as an in situ value

There are a variety of techniques available to make these values commensurate with one another and therefore to allow trade-offs to be made between them in the process of maximising that value. Economists have generally used monetary values as a yardstick and these values have been estimating the willingness to pay if individuals for the various aspects of groundwater value.

4. Groundwater scarcity: demand and supply side factors

Over the past 40 years a number of factors have conspired to reduce both the quantity and quality of groundwater resources to critical levels in many parts of the world. Groundwater overdraft, defined as using more groundwater than is naturally replenished, has occurred in countries such as Jordan, Mexico, the United States, Namibia and Yemen. The prevalence of these overdrafts is of particular importance in arid countries where groundwater is the predominant source of water such as Jordan, Namibia and Yemen. With the exhaustion of groundwater stocks expensive investments in long distance surface water transfers or desalination are frequently seen as the solution. Clearly these investments should be assessed in light of alternative management strategies for groundwater. Similarly, groundwater quality issues are of particular moment in many countries. One of the most frequently cited examples is that of Bangladesh, where groundwater is polluted by naturally occurring arsenic, causing considerable health problems to poor rural communities. Furthermore, in many areas groundwater stocks have been polluted by agricultural or industrial wastes and residues. This state of affairs has sparked renewed analysis of the causal factors of groundwater depletion and placed the principles of groundwater management under close scrutiny.

The causal factors are frequently categorised as either supply or demand side. On the supply side several factors are often credited with encouraging more intensive and extensive exploitation of groundwater. For example, improvements in pumping technology such as more powerful pumping equipment and submersible pumps naturally make it feasible to tap deeper reserves. Similarly, reductions in the financial cost: investment, operations and maintenance costs, have provided cheap access to groundwater. Naturally government policies concerning the inputs to groundwater pumping, such as the subsidised fuel provided to rural areas of Namibia and subsidised electricity in areas of India and Pakistan, although implemented with the objectives such as rural development and poverty alleviation in mind, have also accelerated the degradation, mining and occasionally the exhaustion of groundwater resources. In combination these supply side factors have allowed existing wells to be exploited more deeply whilst opening the door to further exploitation from new and lower cost wells.

On the demand side population growth puts pressure upon groundwater resources. The demand side pressure that population growth can impose upon groundwater resources is not exclusive to the less developed countries with which levels of national annual population growth of up to 3% are frequently observed. Indeed most countries have experienced localised population growth as a result of rural-urban migration, and many countries experience the seasonal population explosions associated with tourism. Nowhere is this more apparent than in the coastal resorts of the Mediterranean where the exploitation of coastal aquifers is often complete either with regard to quantity or quality.

Furthermore, in many countries macro economic factors such as economic growth have increased the demands for all water resources, particularly groundwater. One way to think about the effect of economic growth is as follows: income growth leads to increased demand for goods which embody groundwater resources; high value foodstuffs, manufactures, electricity, tourism etc. As a result private sector activities and often macro-economic policies reorient to reflect these demands. Irrigated agriculture, which represents perhaps the largest user of groundwater resources in many parts of the world, provides a good example of this. All year demand for seasonal fruits and vegetables combined with access to cheap groundwater resources has provided the backdrop for agricultural policies to promote export lead growth through high value irrigated foodstuffs. The promotion of tourism is another pervasive demand side factor in many island economies of the Mediterranean and Caribbean for example. Similarly groundwater is an essential input to manufacturing and industry, which for a long time and more generally were the main engines of economic growth. On top of this, it is frequently observed that as incomes rise, per capita consumption of water for household and domestic purposes rises in line with the purchase of consumer durables such as dishwashers, swimming pools, large houses with gardens etc.

In many of the above cases, the underlying factor and one of the most important demand side issues in groundwater management is that of water pricing. It is frequently the case that the incidence of groundwater overdraft arises in tandem with policies to subsidise water to household, agricultural and industrial sectors. That the demand and price of goods move in opposite directions is as true for water as it is for most normal economic goods. Therefore pricing policies represent another important determinant of groundwater use. In addition to micro level policies such as water pricing, macro economic and sectoral policies can also conspire to increase the pressure upon resources. For example, the availability of cheap or subsidised groundwater combined with perverse agricultural policies, such as national food self-sufficiency in arid water scarce countries, can lead to groundwater depletion for the purpose of growing low value goods. In this way groundwater is mined while providing very little contribution to social welfare.

Clearly, population growth, migration, economic growth and other supply and demand side factors reflect wider socio-economic, political and cultural trends making the causes of groundwater scarcity apparently complicated and difficult to disentangle. However, in order to determine whether or not the observed pattern of groundwater use is beneficial to society or represents some a management failure from the perspective of societal welfare it is important define some principles of groundwater management which can act as benchmarks for good practice.

5. Principles of Groundwater Management

Natural resource economics is perhaps the most relevant discipline from which to derive these benchmarks as it has well defined measures of societal welfare which incorporate natural resource dynamics and allow comparisons between many alternative objectives. The most important of these principles are efficiency, sustainability and equity.

5.1 Economic efficiency (and inefficiency)

Economic efficiency in resource use is achieved when no rearrangement of resources between individuals or across time can improve the welfare of society. This general definition implies two aspects to economic efficiency: static efficiency (efficient allocation of resources between potential users) and dynamic efficiency (efficient allocation over time). Both aspects can be brought to bear upon the management of groundwater resources and used as a benchmark for management practices.

Groundwater aquifers can be broadly categorised as renewable or non-renewable and the nature of efficient use differs in each case. In both cases however, groundwater represents a stock of resources as distinct from a flow such as a river. As such groundwater can be considered a dynamic resource because changes in the stock that occur today, as a result of recharge or abstraction by humans, have inter-temporal consequences. Hence, the concept of dynamic efficiency is particularly relevant to groundwater. Put loosely, the efficient use of non-renewable groundwater will reflect the long-run since with continued use it will eventually be either physically or economically exhausted i.e. abstraction will become too expensive. On the other hand, renewable groundwater has the potential to be used for all time if abstractions remain equal to recharge. Thus the efficient use of renewable resources will consider the balance between abstractions and recharge (stocks and flows). The management questions that remain concern the date at which aquifers should be exhausted, the path of abstraction over time, whether or not it is efficient to use groundwater sustainably and if so the level of the aquifer stock at which this use is maintained. However, as described above many aquifers are conjoined with surface water and/or are pivotal in maintaining wider ecological functions. Hence it is generally insufficient to consider groundwater in isolation since these wider effects are also important in determining efficient management. This section describes the efficient use of groundwater that would be chosen by a government wishing to maximise social welfare over time and the inefficiencies that arise when decision-making is placed in the hands of individual groundwater users.

5.1.1 Efficient groundwater management

The management of groundwater resources is deemed economically efficient when groundwater abstraction is chosen such that its allocation over time (time-path), exhaustion date, the stock and the impacts on conjoined resources and other third parties generate the maximum welfare to society. In other words economic efficiency is a question of choosing the temporal pattern of abstraction, which maximises the TEV of groundwater. This amounts to maximising the present value of the difference between social benefits and social costs of abstraction.

The economic value or social benefits of groundwater are derived from consumption over time by both conventional productive sectors of the economy; households, manufacturing, agricultural, recreational etc., and non-conventional sectors such as the environment. For example, in Colorado groundwater is pumped in order to augment surface water, which also maintains environmental flows. The social costs of abstraction are more complicated however, reflecting the dynamic nature of the resource, and can be usefully categorised as follows:

- **Contemporary Costs**: Contemporary costs are those incurred as pumping occurs. These include the costs of abstraction: the operations and maintenance of pumps for example.
- **Inter-temporal Costs**: Inter-temporal costs refer to the change in the level of the groundwater stock, which in turn affects the availability of groundwater for any of the aforementioned uses in the future. This includes the loss of amenity associated with the groundwater stocks. For example, springs that emerge from the Edwards Aquifer in Texas US support ecosystems containing many varieties of endangered fish. Inter-temporal costs may also include the value of groundwater as an insurance policy against climatic uncertainty or uncertain surface water flows: the so-called ‘buffer value’ that have been estimated in agricultural communities in many arid and semi arid environments.
- **Quality related costs**: Lastly there are quality related costs. These costs may be contemporary or inter-temporal and may arise as a result of the pumping itself or as a result of the use to which the groundwater is put. Seawater intrusion is an example of the former whilst groundwater pollution as a result of the infiltration of agricultural herbicide residues is an example of the latter. Both limit the contemporary and future uses to which groundwater can be put.

In short, in addition to the contemporary costs that current users face, abstraction today may preclude abstraction tomorrow as a result of physical or economic exhaustion. E.g., abstraction today may cause irreversible changes in the structure of the aquifer (collapse or compaction, quality reduction), which may make the abstraction of water impossible or too costly tomorrow. Inter-temporal costs reflect the dynamic nature of the groundwater and the value of leaving the resource in the ground. The extent of these costs will be determined as much by the properties of the aquifer as by the abstraction decisions and the demand for water. It is common to label those costs that are not directly faced by those who abstract groundwater as the **user cost** or **scarcity rent** since these values represent the properly reflect the value of the scarce resource in the ground and the economic impact of abstraction.

Determining the efficient use of groundwater is clearly a multidisciplinary task and informationally intensive. Firstly, hydrological models are required to characterise the nature and behaviour of the aquifer, e.g. the resource stock, storativity, transmissivity etc. Secondly, the socio-economic environment must be described. This requires identifying and placing a commensurate economic value upon all groundwater and conjoined uses and functions. Static efficiency requires allocating groundwater to the highest value uses at a particular point in time. In order to determine a dynamically efficient time path of groundwater use requires combining economic and hydrological models and defining the interaction between the uses/users and the resource. It is then possible to solve for the allocation that maximises present value of the difference between social benefits and social costs over a predetermined planning horizon. This is usually performed by dynamic optimal control methods.

There are several parameters of interest in determining the efficient allocation of groundwater. Perhaps the most important is the users’ responsiveness to changes in the price of groundwater, the so-called price elasticity of demand (PED). This will determine the way in which individual demands for water will change over time in response to the increased pumping costs associated with groundwater depletion. Similarly, it will be important to understand how the demand for water changes over time with incomes. The natural corollary is the need for projections for population and economic growth.

Although modelling these above and below ground aspects, and the interface between them is fraught with uncertainty, there have been great advances in hydro-geological modelling, economic modelling and economic valuation techniques. These advances have enabled comprehensive hydro-economic modelling and the determination of efficient abstraction plans. Examples of where dynamic optimal control of aquifers has been undertaken include Ogallala Aquifer, Colorado, the Kiti Aquifer, Cyprus, the South East Kalahari Artesian Aquifer in Namibia etc. Environmental values have been estimated for many aspects of watersheds, including the various values associated with groundwater.

5.1.2 Efficiency with water transfers and backstop technologies

The previous analysis has been assuming almost implicitly that groundwater users are those who occupy the overlying land. Another issue pertinent to the question of efficiency is whether or not the incumbent property rights holders to groundwater represent the highest value to society. This brings to light the potential for the transfer of water outside of the land overlying the aquifer, or even to en entirely separate river basin: an inter-basin transfer. The government or groundwater manager should be aware of such latent societal values in determining the efficient use of groundwater. The issues surrounding the property rights to groundwater and the extent to which they may be transferable to higher value uses either *in situ* or elsewhere is discussed further below.

Furthermore, the efficient use of groundwater should be not determined in isolation from alternative sources of water. For example, coastal aquifers should not be used if the costs of doing so are greater than for desalination. In Cyprus for example, groundwater augments the supply from desalination, and groundwater is managed such that the costs of abstraction do not rise beyond that of desalination. The existence of a backstop technology, e.g. water transferred from another river basin, also determines the efficient use of groundwater.

5.1.3 Inefficiencies in groundwater use

In reality groundwater use is not determined by a single water resource manager, but by numerous private agents to which property rights for groundwater have been assigned. Furthermore, since the aquifer itself acts as a conduit between all users the abstraction decisions of individual have implications for all users. Where aquifers are conjoined or linked to ecological systems the implications of these decisions have even wider implications. In the absence of regulation groundwater users, e.g. land owners overlying the aquifer, generally consider only their private benefits and costs in making their decisions and neglect the wider costs and benefits that such decisions impose upon the rest of society: the user cost or scarcity rent. Costs and benefits, which are absent from the calculus of individual decision makers are commonly referred to as economic externalities. These may be welfare enhancing or reducing but in either case they signal the presence of inefficiency. Thus groundwater externalities arise as a result of the nature of the resource, and the interaction of users with the resource and each other. These externalities can be categorised as follows and in sum they represent the value of the user cost/scarcity rent:

- **Contemporary Externalities**: when an individual abstracts water from an aquifer this can reduce the water level thereby increasing that individual's current pumping costs. However, to an extent determined by the characteristics of the aquifer (mainly transmissivity), this action reduces the water level for all users. Hence the behaviour of one individual imposes an additional contemporary cost (pumping costs) upon all other users. This externality is sometimes referred to as a *depth externality*.
- **Inter-temporal Externalities**: the reduction of groundwater stocks resulting from today's abstraction increases pumping costs for all users for all future periods, not just today. Similarly, that the reduction of the groundwater stock persists over time restricts the potential for using the water in future periods. At the extreme, individual abstractions may lead to irreversible loss of resources as described above, thereby removing the possibility of groundwater use for all time for all users. Such externalities are often referred to as *stock externalities*, whilst those associated with the loss of insurance provided by groundwater are often referred to as *risk externalities*.
- **Quality Externalities**: in the same way that individuals cause water levels to drop for all users for all periods of time, the same can happen with regard to water quality. If pumping leads to seawater intrusion, or if low quality water is found at lower levels of the aquifer then individual decisions lead to a reduction in the quality of water for all

users. A similar analysis extends to the pollution of groundwater through agricultural or industrial residues.

The analysis makes clear that there are some factors, which are peculiar to groundwater resources and make its management both complicated and important. The nature of the resource suggests that the presence of externalities is likely to be the rule rather than the exception although the extent of these externalities will depend upon characteristics of the aquifer. For example, where transmissivity is low the abstraction by one individual will barely affect the water levels faced by aquifer users, and all pumping costs are internalised by individuals. Ultimately, whether or not an observed pattern of groundwater use is inefficient or not, and hence whether or not groundwater should be regulated in some way, depends entirely upon the value of these externalities: i.e. the social costs associated with the status quo. Cases in which groundwater externalities are insignificant, and there are few social gains to be made from intervention are said to display the Gisser Sanchez Effect (GSE). This effect suggests that in aquifers in which recharge is close to zero with high storage and low pumping costs, the difference in terms of social welfare between the efficient centrally controlled outcome and the status quo is likely to be minimal. This effect is also more likely where the water managers do not give much weight to the future. This effect was found to be present in the Pecos Basin in New Mexico.

Another interesting point is that efficient management of groundwater does not necessarily lead to hydrologically balanced resource use. With societal benefits sufficiently high or costs sufficiently low, it may be economically efficient to mine groundwater to exhaustion even if it is renewable. Similarly, the inefficient resource use that arises in the presence of externalities can be sustained for all time. To elaborate on these issues requires a discussion about the principle of sustainability.

5.2 Sustainability

The notion of sustainability is open to several interpretations by several different disciplines. Many of these are relevant to the management of groundwater. Perhaps the most frequently cited definition of sustainable development is that contained in the so-called Brundtland Report which simply states that sustainable development is:

‘A development, which enables present generations to satisfy their needs without threatening the ability of future generations to satisfy theirs.’

This is a general definition in which the word ‘needs’ is open to interpretation. One hydrological notion of sustainability that could satisfy this definition is the notion of hydrological balance: sustainable groundwater use maintains the hydrological balance. This definition limits groundwater consumption to the recharge over a given period of time and therefore its objective is to maintain the stock of groundwater. In this way the resource is never exhausted and the benefits derived from the recharge are maintained forever. When recharge is uncertain, the quantity of water that can be abstracted from an aquifer without reducing the stock is usually defined with reference to the quantiles of the statistical probability distribution and referred to as the ‘safe yield’. For example, the 95% safe yield of an aquifer refers to the recharge that occurs 95% of the time.

However, this definition is deficient for a number of reasons. Firstly, it treats the resource as a flow rather than a stock, and says nothing about the level at which the stock should be maintained. Secondly, the notion of a hydrological balance is not an operational concept in relation to aquifers that are not subject to recharge: confined, exhaustible aquifers. In this case, maintaining the hydrological balance means not using the resource at all, which does not generate well-being. Indeed the objective of maintaining resource stocks ignores the social costs and benefits of abstraction, which underpin the notion of efficiency.

The efficient use of renewable groundwater as described above may satisfy the hydrological balance definition of sustainability. The efficient use of groundwater may lead to a stock that is unchanging over time and a demand satisfied by the recharge alone. In this sense the hydrological balance is also efficient. However, where the social benefits outweigh the social costs of abstraction at all levels of the groundwater stock, the efficient time-path of abstraction may prescribe exhaustion of the resource. Therefore efficiency may not be compatible with the hydrological balance. Clearly this is always the case with exhaustible groundwater.

Resource economists generally define sustainability in terms of particular measures of well-being such as consumption (of goods and services) or economic measures of welfare and wealth. For example, taking consumption as the relevant quantity, the use of a resource can be defined as sustainable if the consumption that emanates either partially or totally from its use is not decreasing for all time for the target population. Clearly water is an essential consumption good itself, however whether or not sustainability defined in terms of consumption precludes the exhaustion of groundwater depends upon whether there exists an affordable substitute. The same analysis applies to groundwater as an input to the production of consumption goods rather than a consumption good itself. If water is an essential input into the production process then sustaining consumption will depend upon the presence of some affordable substitute for groundwater.

Clearly it is the twin issues of necessity and substitutability, and the quantity, quality and cost dimensions that determine whether the resource economist’s definition of sustainability will preclude the exhaustion of the resource. For example, it is the subject of broad debate as to whether there are man-made or other substitutes for some of the essential ecological processes that many ecosystems provide; water purification; climate control; pest control etc. The concept of ‘strong sustainability’ has been applied to natural resources whose functions are deemed without substitute; such as tropical rainforests, biological diversity, and particular species. This definition of sustainability suggests that the stock of resources should be non-decreasing over time and cannot be exhausted. On the other hand, for resources that are agreed to have man-made or other substitutes the notion of weak sustainability has been applied. Weak sustainability states that the stock of resources can be reduced provided that it is replaced with a substitute, which maintains consumption, welfare or wealth. A real world example of this is the mining of diamonds in Botswana, where the profits of the venture are placed in a trust fund by the government for investment in education and health. In this case education and health are seen as suitable alternatives to diamonds as a means of generating welfare. Which of these definitions applies to a particular groundwater resource will depend upon the extent to which groundwater is substitutable or an essential input into non-substitutable ecological processes such as the maintenance of habitats for endangered species in the case of the Edwards aquifer. It is not inconceivable that groundwater could be managed in the same manner as diamonds in Botswana, with a fund developed in order to replace the supply of water upon exhaustion.

5.3 Equity

Another important principle of water resource management is that of equity or fairness. With regard to groundwater equity has a number of different dimensions. Firstly, perhaps the most difficult aspect of equity relates to the distribution of rights to groundwater at a particular point in time and its relation to the ownership of land. Where rights are tied in this way access to the resource will be inequitable should access to land be inequitable. It could be argued that this was (or is) the case in many of the former colonies in developing countries in which land is still owned by those associated with the dispensation prior to independence. Current examples could include Namibia and Zimbabwe, although such issues are not reserved to less developed countries. This is an area where water resource management policies and the concept of equity are closely linked to land reform policies.

Perhaps the most pervasive equity issue is that of Inter-generational equity. The use of resources today prevents future generations from using the resource and represents a loss of *in situ* values. For example, the irreversible exhaustion of groundwater aquifers today could be considered an inequitable distribution of resources over time and between generations. In this sense sophisticated resource managers need take a stance on what is likely to be the equitable inter-temporal trade off. This principle is not only intrinsically linked to the issue of sustainability, but also to the thorny issue of discounting i.e. the comparison of economic values that occur at different points in time from the perspective of today. It is common for a tension to exist between judgements concerning equitable and efficient allocations of resources, although this need not always be the case.

6. Groundwater Property Rights

It is widely believed that the demand and supply side factors described in section 4, although important are insufficient to explain the observed mining of groundwater. Indeed, that the demand for environmental quality has been shown to increase with income does not seem to tally with the many instances of reduced groundwater quality in rich countries such as the US. Neither do the demand side factors above explain why groundwater exhaustion is observed in many low growth countries. So whilst it is perhaps useful to classify the factors that determine groundwater use as being either demand side and supply side factors, ultimately demand and supply trends do not explain why individual groundwater users can oversee the exhaustion of the resources upon which they depend. A more complete picture is seen by considering the legal, institutional and decision-making backdrop to the management and exploitation of groundwater resources.

It is widely agreed that one source of inefficiency in groundwater use, and the associated problems of groundwater degradation and premature exhaustion is the pattern of ownership: the property rights to water. Property rights represent a bundle of entitlements to a resource that define the rights, privileges, obligations and limitations of the owner concerning the use of the resource. In short the property rights systems historically associated with groundwater have failed to recognise the confluence of the socio-economic, hydro-geological and ecological processes that govern groundwater use and as a result have failed to impress upon groundwater users the full user cost of abstractions. In many cases groundwater has been treated as a common property resource, a very weak set of property rights.

The reason for the inefficiencies that arise in the context of common property rights can be loosely described as follows. Common property rights to groundwater mean that the users overlying the aquifer can pump as much water as they like. In addition, the overlying landowners share the resources such that the pumping decision of any one user impacts upon all other users. When there are many users, a particular user will have little incentive to conserve groundwater resources since the stock of groundwater in the future will be largely determined by the sum of use by others, and the gains to conservation will largely benefit the other users. Effectively this relationship to the aquifer can be described as ‘use it or lose it’: if the agent in question doesn’t use the water some other agent will. The corollary of this is that users will face incentives to free ride on water conservation undertaken by other users. In combination these two incentives faced by the groundwater users describe the ‘prisoners dilemma’ faced under common property resources, which drives the non-cooperative inefficient outcome. Each user will impose the contemporary, inter-temporal and potentially quality externalities upon other users of the aquifer, and beyond where surface water and ecosystems are affected. Where groundwater is scarce: i.e. where recharge is limited or close to exhaustion, and where there are no close substitutes, the loss in social welfare is particularly acute.

More specifically there are a number of legal doctrines that are commonly associated with groundwater ownership each of which has been favoured to different degrees in different countries. The following represent two of the most common systems:

- **Riparian doctrine, absolute ownership or ‘rule of capture’**: derived from English law this regime attributes groundwater rights to the ownership of overlying land. In general there are no limits to the quantities of water that riparian landowners can abstract from underlying aquifers. Often associated with the ‘**reasonable use**’ doctrine
- **Prior appropriation doctrine or ‘first in time, first in right’**: assigns rights to the most senior of the claims, e.g. the person who first tapped the resource.

The riparian doctrine represents a common ownership property rights regime and there are a number of reasons why such regimes can lead to inefficient resource use. Firstly, the riparian doctrine frequently fails to limit abstraction explicitly, nor is water use always tied to the land associated with the rights. In combination these two attributes can lead to over abstraction by landowners and make the aquifer vulnerable to capture by water users beyond the boundaries of the aquifer, both of whom ignore the user costs as defined in Section 4. The most famous example of the purchase of land in order to obtain water rights was the case of the Los Angeles District Municipality and the Owen River Valley aquifer. A fictionalised account of this issue can be seen in Roman Polanski’s 1974 film *Chinatown*. The reasonable use doctrine, usually associated with the riparian doctrine, limits abstraction to some suitable definition of reasonable use. One common interpretation is to limit water use to the overlying land. However, such a property rights system precludes the transfer of rights to higher value uses beyond the land overlying the aquifer and can therefore limit the efficiency benefits that groundwater provides to society. The riparian doctrine is a common property rights regime for groundwater and has been found in countries as diverse as Namibia, South Africa, US and Israel.

The prior appropriation doctrine on the other hand is a system based on seniority. In general such property rights systems contain clauses that state that further rights can only be granted to additional groundwater users if their abstractions do not impinge upon the availability to prior users. Furthermore it is common for groundwater rights to be well defined in quantity terms.

In order to compare the two property rights regimes it is worth citing a particular example and noting the outcomes. In the 70's and 80's the Sahuarita groundwater area of Arizona, US, was subject to a riparian or absolute ownership regime. This was augmented by the reasonable use doctrine in 1953, the interpretation of which was that water abstracted could only be used upon the land associated with the groundwater rights. The rights to abstraction were ill-defined in the sense that they did not explicitly specify allowable abstraction. Conflict arose between the predominantly agricultural riparian rights holders and the demands for water from an increasingly active mining sector. The mining sector bought land overlying the aquifer and pumped water to the mines most of which also lay over the common aquifer. The agricultural sector took legal action stating that this behaviour was in contravention of the reasonable use doctrine, lowered the water table to agricultural users and forced them to invest in deeper boreholes, i.e. the mines were imposing an externality. The mines on the other hand argued that since both the points of abstraction and use overlay the groundwater area, this was did not represent a contravention of the reasonable use doctrine, the reason for which, they argued, was to limit the quantities of water abstracted in the absence of well defined groundwater rights. Ultimately, the court ruled in favour of the farmers thereby denying the transfer of water to higher value uses, and hence the mutually beneficial, efficient exchange of water rights. The riparian rights and reasonable use doctrines were ultimately abandoned in favour of the Arizona Groundwater Management Act in which groundwater allocation is determined centrally by government, rather than through the interaction of users.

In contrast to this system, the prior appropriation doctrine has seen some success in managing groundwater. In the case of Ogallala Aquifer, New Mexico, this was achieved by specifying clearly in the first instance the abstraction rights associated with particular aquifers. Most importantly however, the notion of consumptive use: abstraction net of return flows to the aquifer, was defined for each user and used as the basis of transfers from one area of the aquifer to another. Such a system allowed the transfer of consumptive use from one landowner to another, by means of pipes etc., and hence kept aggregate abstraction constant. Since water rights were sold from one user to another on a voluntary basis, and demands from the aquifer are kept constant, this implied the reallocation of water to higher value, more efficient uses and an improvement in social.

It should be noted that property rights defined in accordance with the prior appropriation doctrine do not necessarily lead to the efficient use of groundwater as defined above. This is primarily because the rights have been defined at some arbitrary point in time and without reference to the optimal path of depletion or the optimal steady state stock. However, in the case of the Ogallala aquifer, which is not subject to any significant recharge, it is widely believed that the system works well and the benefits to society from intervention would be minimal. This represents a distinct contrast from the riparian rights regime that was applied and failed in Arizona. In sum it should be clear that the property rights regime, and the definition of rights within those regimes is an important determinant of the manner in which groundwater is used by property rights holders and the welfare these resources can convey to society.

7. Groundwater Management approaches

As shown seen above, a case can be made for intervention in the management of groundwater resources where the legal and institutional framework is sufficiently weak that inefficiencies arise manifested in premature exhaustion of resources, low value entrenchment of rights and other wider external social costs. This section reviews the best practice in groundwater management policies from around the world.

7.1 Centralised Command and Control

Centralised command and control policies describe management policies in which a central government or agency explicitly specifies abstraction quantities or technological solutions for groundwater users in order to achieve its own resource management objectives. The central objectives commonly include:

- **Sectoral priorities**: the allocation of centrally administered water permits between sectors in accordance with government policy and the distribution of permits will reflect the relative priorities given to agriculture, industry and urban sectors.
- **Social equity objectives**: an allocation of permits in order to correct previous inequalities in access to water resources that arose under previous property rights regimes. This may happen de facto in response to land reform policies
- **Environmental and resource management objectives**: objectives such as sustainable resource use, habitat and ecosystem preservation, etc.

The most common approach is for the central agency, to assume the position of absolute owner of water resources (national resource rights) and to issue usufructary rights stipulating the conditions of use in terms of e.g. the number of boreholes, quantities (water quotas), type of use and the duration of the right. The agency may also prescribe, perhaps as a condition of the permit itself, technological standards or other regulatory rules in order to control the quantity and nature of resource use. Technological standards might include the use of particular technologies for the application of water to crops such as drip or centre pivot irrigation or the use of particular irrigation techniques such as scheduling of irrigation and deficit irrigation. Other regulatory standards include the limits on the proximity of boreholes or wells or limitations upon the uses to which groundwater can be put, e.g. crops that require low levels of water.

Examples of administrative methods of water allocation are frequent. Until 1992, Mexico had adopted the centrally administered system for water allocation and management. A similar approach was taken in Peru until approximately 1992, and in Chile prior to 1981. In the U.K. permits are issued by the agency responsible for water for abstractions from watercourses and groundwater in a broadly similar way. Restrictions on outputs have been imposed in Cyprus for example, where there have been efforts to reduce the extent of citrus production through a subsidisation programme for the removal of these permanent crops. Similarly there have been calls for a ban on the production of Kolokasia, a particularly water intensive crop grown only in Cyprus.

Another technical solution to groundwater scarcity, and the temporal fluctuations in water availability is the use of artificial groundwater recharge. This process involves physically pumping water into the aquifer in order for it to be stored for later use. This technique has also been used as an attempt to reduce the effects of seawater intrusion. It is sometimes used in order to prevent the evaporation associated with surface water storage, while semi-purified water is sometimes used. Such a system has been experimented with in the capital of Namibia, Windhoek, to varying degrees of success, and is common elsewhere.

On the positive side, command and control regulation put the responsibility for water resource allocation and management with the central agency. In this way, with proper monitoring and administration, the agency can influence the allocation of resources to achieve governmental objectives and address directly scarcity (e.g. groundwater mining), inequality of resource allocations and sectoral economic development objectives. Thus the government may also achieve definite reductions of water use in line with the standards set and address the common property externalities directly. Technological standards may also induce positive economic returns should users be currently unaware of the potential production options available to them. In the case of agriculture, assuming that the transition from prior crops to imposed cropping patterns implies no efficiency loss in production, and that less water intensive crops provide higher economic returns from the water inputs, centrally driven technological efficiency drive may generate higher economic benefits in the area.

However, the shortcomings of command and control centrally administered permits and quotas are well documented in both the theoretical, empirical and policy literature. Firstly, is difficult to determine the efficient distribution of quotas between sectors and agents within sectors. At the very least it is a data intensive exercise, particularly when considering the distribution between the numerous heterogeneous agents and where permits are not tradable or transferable they will not gravitate to high value uses through market exchanges.

The implementation of crop and technological restrictions may also have negative consequences. On the one hand crop restrictions may not be politically tenable and subject to vigorous objections from the farming community. This may be because the enforced changes in technique and outputs are likely to cause temporary and/or permanent adjustment costs to users, making the policy costly to implement and giving grounds for compensation. In addition has been shown theoretically and documented in the empirical literature that crop restrictions, or the imposition of technical standards can have a dynamic effect on farmers decisions which may cancel out, and even reverse any reductions in water use that are assumed to occur in the short run. In short, these standards ignore the potential adjustments that farmers might make in response to the policy. For example, farmers may increase land use in response to technical standards, since the marginal returns to water are often increased. Naturally this has the effect of increasing the demand for water.

Lastly, there is the potential for failures within the central authority such as regulatory capture. This occurs where certain sectors or agents may be able to divert the allocation of water permits away from national objectives and towards private objectives as a result of political or other influence upon the administering agency. Similarly these central approaches may be fraught with complexity and inertia with regard to practical issues of enforcement, monitoring and the evaluation of economic and hydrological indicators. In sum the costs of centrally administered schemes can be categorised as follows:

- **Information**: gathering information is costly for the central agency when local institutions or groups may know the area far more intimately.
- **Agency Costs**: This term represents the costs of regulatory capture described above. It can be the case that central agencies become unaccountable to the local inhabitants of the e.g. groundwater areas.
- **Monopoly Distortion**: central administrators might not be easily ousted from their position should they appointed by an elected body since elections are won and lost on a wider variety of issues than water management.

These issues are perhaps not limited to the command and control regulation outlined above.

7.2 Market Based Instruments

Market based instruments are justified on the basis that they decentralise the decision-making process to individuals whilst coercing them to behave in socially efficient ways. They reduce the information and other costs of implementation as a result of the decentralisation. There are two main approaches: price based instruments (taxes, user fees) and quantity based instruments (tradable groundwater permits).

7.2.1 Taxes and User Fees

In order to induce efficient groundwater use it is possible to apply a volumetric tax on water consumption equal in value to the scarcity rent or user cost associated with the aquifer. This is known as a user fee. The scarcity rent could be derived from the use of optimal control modelling as described above and represents the *in situ* value of the groundwater, i.e. the value of groundwater saved for productive uses in future periods, and also represents the extent of the externality imposed by users upon the other users of the shared resource.

Unit groundwater abstraction charges have been implemented in a number of groundwater aquifers in developed and developing countries alike. In each case the motivation and calculation of the tariff has a similar underlying rationale; control of abstractions, but only in the case of Cyprus has the scarcity rent of the resource been explicitly calculated. Table 7 shows that the revenues derived from such charges are directed towards different causes in each case.

Once the time path of the scarcity rent has been determined it will be necessary for the user fee to be altered over time in order to achieve the economic optimum. For the implementation of the ideal system further prerequisites include metering of abstraction, a meter reading/monitoring programme and the enforcement of payment. Naturally the costs of implementing this system need to be compared to the expected benefits of efficiency or demand management.

Table 7. International Examples of Groundwater Pricing Policies

Countries	**Basis of Tariff**	**Use of Revenues**
Netherlands	Volumetric: differ across sectors	Research into groundwater policy plans and state fund
United Kingdom	Volumetric: for volumes greater than 20m^3 per day	Fund administrative costs of custodianship
Belgium	Volumetric	Protection of groundwater
Cyprus	Volumetric: scarcity rents	(in proposal stages)
USA (Arizona)	Volumetric	Used to fund research into groundwater conservation, purchase of water rights and retiring them from use

Charging the scarcity rent or user cost induces dynamic efficiency. In this way the common property externalities are internalised. In addition, optimal pricing provides the correct incentives for farmers to invest in water saving technologies over time. Furthermore, charging the scarcity rent has the effect of reallocating water between competing users in a manner consistent with the maximisation of social welfare. Beyond this however pricing in general can be used to manage demand for water and achieve other policy goals, such as the hydrological balance, or some other definition of sustainability. In this sense it is worth noting that the user fee generates revenues which can be directed to a number of areas; state funds, local funds, covering the costs of administration, covering the investment costs associated with setting up the monitoring system: e.g. meters, subsidies for water efficient technologies, research. A significant body of literature concerning sustainable economic development has suggested that resource rents such as those generated from the optimal user fee should be invested in other sources of income generating capital. This will ensure that the overall wealth of the country is not diminished for future generations by the reduction of groundwater stocks. This is particularly pertinent to non-renewable water stocks.

7.2.2 Tradable Water Rights and Water Markets

The importance of property rights regimes in determining the manner in which groundwater is used and the potential for the adjustment and redefinition of property rights to groundwater to provide a solution to the common property externality has been highlighted above. In the case of the Ogallala aquifer it was suggested that water resources could gravitate to the highest value uses if they could be traded among users on a voluntary basis. This notion has been captured in the development of water markets and tradable water rights as a means of further decentralising allocation decisions to individual users. Such instruments have been implemented in many countries and shown to afford large gains in social welfare by facilitating the reallocation of water among sectors and over time. In order to effect an efficient outcome, property rights must be defined in order to induce the holder to maximise his own objectives, and in doing so, maximising societal objectives. In general this requires a movement away from public ownership and towards regulated private property rights to water. Like any market, in order for water markets and tradable water permits to function properly there are several qualities that they must have:

- **Universality**: all resources are privately owned and all entitlements are completely specified

- **Exclusivity**: benefits and costs as a result of owning the resources should accrue to the owner
- **Enforceability**: all sources should be secure from the encroachment or involuntary seizure by other parties
- **Transferability**: all resources should be voluntarily exchangeable from one owner to another whilst transactions costs should be low.

The introduction of this type of property rights system should be seen as distinct from the centrally administered quota/permit system, which emphasises the public ownership of water resources. In order to facilitate the economically efficient allocation of groundwater the aggregate quantity of groundwater permits needs to be defined in by reference to the path of groundwater use that maximises social welfare as described above. However, the absence of any one of the above qualities can reduce the ability of the management system to achieve efficient allocations of water. Water markets and tradable permits systems require the development of a property rights system with the qualities described above, and the subsequent trading of these rights between users. The authority responsible for overseeing the market should define these property rights and the regulations concerning allowable trades, whilst registering them in public registries. Clearly trading permits, or selling water requires the removal of the common stipulation that water rights are tied to the land that borders them (the riparian doctrine or English doctrine with respect to groundwater), and in certain circumstances will require that water rights are not tied to particular uses e.g. agriculture or irrigation. Thus the property rights must be well defined in law and yet not ‘over-defined’ in terms of the specific use.

With property rights thus defined, the ability to trade water allows the price of water permits to reflect the value of its alternative uses (the opportunity cost) thereby creating incentives for these rights to gravitate towards the most productive uses through the interface of willing buyers and willing sellers in the market. In short, those users with less than average willingness to pay or productivity in water use are likely to gain from selling their permits, whilst those with higher than average willingness to pay are likely to buy. The sale of permits may also be governed by the costs of reducing current water demands, e.g. through downsizing or improved technological solutions. Thus it is also widely reported that the existence of tradable permits can encourage investment in efficient water use technologies: investment in leakage reduction in urban areas, efficient irrigation technology in agricultural areas. Effectively, attaching a private value to all water resources reduces the likelihood that they will be used wastefully. Sales of permits for water can be temporary: e.g. seasonal or annual, or permanent. In this way the trade in permits can be used by farms to adjust inter-temporal shortages and ensure that scarce water resources are used efficiently at all times. In Australia the permits to the Murray Darling basin are defined as a proportion of the current water resource availability, whereas in parts of the US tradable permits have different levels of certainty attached to them, with different prices for different characteristics.

Despite this potential there remain a number of areas in which the government or monitoring agency may wish to intervene. Firstly, a tradable permits regime, or a water market may not be welfare improving as a result of third party effects or externalities that arise from the transfer of water: e.g. environmental costs or effects associated with conjoined surface water. Thus, provision needs to be made for constraining trades in areas where this might be a problem. Furthermore there may be a motive to intervene where the market is thought to be imperfect, such as in the presence of monopolistic permit holders or subject to strategic behaviour. For example, the authority may wish to guard against the speculative behaviour concerning permits, a practice which can lead to idle permits for water being kept solely for the role they have in increasing the value of the land upon which the farm is situated. A ‘use or lose’ policy has been adopted in many countries in which permits, which are left idle for longer than a specified period of time are confiscated for the benefit of the other parties. A further issue is that of equity. The initial distribution of permits is crucial for the political acceptability of the policy as a whole and determines where revenues from permit sales eventually end up. The regulating agency can address the issue of equity through the initial allocation of permits, without affecting the efficiency objectives of the mechanism.

Water markets have been implemented with some success in countries as diverse as Chile, Peru, USA, Pakistan, Mexico and India. Some of these have been informal markets (e.g. Pakistan), whilst others are fully entrenched in local and national law (e.g. Australia, USA, Chile, Mexico and Peru). There are several examples of the property rights approach and the use of formal water markets and tradable permit schemes for water management. Some of these examples relate to water resources in general, others relate solely to surface water.

7.3 Institutional and participatory approaches

The growing scarcity of groundwater and the presence of common property inefficiencies in groundwater management have lead to the emergence of a number of institutional approaches to groundwater management. There is a large body of literature and experience in the development of local solutions to resource management problems, which can be efficient, cost effective and/or tailored to specific circumstances. In what follows we describe some of the institutional approaches that have been witnessed in the field of water resource management. These examples have worked in specific ways but could be seen as providing an institutional framework for the implementation of some of the management policies described above.

7.3.1 River Basin Authorities (RBA)

RBA are frequently public authorities developed established specifically for the management of water resources in a particular river basin, watershed or catchment. They can often be considered more closely related to the government framework, acting like a local authority, or municipality, but represent all of the multifarious stakeholders within the river basin. In a well-documented case, the Tennessee Valley Authority implemented a basin wide management and development plan in which stakeholders’ interests were represented from sectors as diverse agriculture, residential and urban, hydro-electricity generators and environment and recreation.

In general RBA and related management institutions are closer to the pertinent management issues of the river basin or aquifer that has been used to delineate the jurisdiction, and thus are more adept at identifying problems, devising solutions and arbitrating the inevitable resource conflicts that arise. In effect RBA are uniquely placed to internalise the resource use conflicts within the river basin, including the common property resource externalities driving groundwater management failures.

Once developed the RBA could take on the responsibilities of administration (issuing and administration of groundwater permits, groundwater markets and/or tradable permits), conflict resolution (e.g. concerning water trading, evasion of permit conditions, externalities/third party effects), monitoring and enforcement (of terms and conditions of the permits, any technological or crop related standards, payment of fees) and revenue collection.

Evidence from around the world suggests that effectiveness and efficiency can be enhanced considerably by ensuring that the RBA is an independent, autonomous organisation (e.g. financially autonomous), rather then simply being an extension of the central administrative authority. In this way the participatory role of the local water users may be increased, and the incentives of the RBA and water users (e.g. Water User Associations) are aligned. However, RBA as an extension of the central authority has also met with success in countries like Spain and China. The RBA approach is being advocated in South Africa at present, indeed 19 water management areas have already been established as a preliminary step in developing river basin management plans, the decentralisation of water resource management efforts and the creation of Catchment Management Agencies (CMA). Similarly, the Tennessee Valley Authority, another RBA, has overseen the rapid and diverse economic growth in the river basin. This has been attributed in part to the clear representation of the relevant stakeholders therein and the rational and coordinated planning of water development and management policies that management units on the basin level have afforded. Europe has followed these examples to some extent in the promotion of River Basin Districts in the new Water Framework Directive. However, the strict use of RBA in order to manage water resources has been limited to France, UK and the Netherlands thus far.

As with all institutional changes or adaptations they are not undertaken without costs being incurred. In addition the hydrological orientation of RBA has been criticised in the case of groundwater, since it is not guaranteed that the geo-hydrological delineation will translate into sensible administrative boundaries above ground. In addition there is always the danger that additional institutions such as this may simply add to the bureaucracy and unnecessarily hinder the achievement of management objectives and/or water user objectives.

7.3.2 Water User Associations (WUA)

WUA are management organisations that represent the ‘users’ of the water resource: economic sectors, environmental groups, etc. WUA have been defined as:

‘*voluntary, self-governed, organised group…...who, although maintaining individual control of their land, crop choices, and marketing, work cooperatively to manage and maintain local irrigation systems that serve their farms.*

Indeed WUA have generally been described in terms of private institutions taking over formerly public owned infrastructure, e.g. for irrigation. The ‘privatisation’ of infrastructure in this way came in the wake of well documented failures in the public management of such projects and lower than expected returns on public investments. Examples of such failures and low returns abound. WUA obtain the responsibility for the operations and maintenance of the infrastructure taken over whilst the central authority or RBA retain control over the resources themselves. The WUA could take on a variety of additional responsibilities associated with the policy recommendations above and further decentralise groundwater management. In this sense the WUA could be seen as components of the wider RBA, or could be seen as the implementing agents for the central authority. Indeed once properly registered and legally recognised WUA become an effective way in which water users: e.g. farmers can represent their interests to a wide range of management issues and assist in the implementation and design of management policies.

WUA's could represent the users at the level of the River Basin Authority and thus guide and/or be responsible for the implementation of measures to ensure that the management objectives of the government are met. In this sense the WUA could tailor the measures taken to the WUA in question. For example, should taxes be implemented the WUA would become largely responsible for the collection of these taxes and the associated monitoring and billing. Were the WUA to decide that water markets represented the most desirable management solution, the WUA would be responsible for the allocation of water permits/quotas in line with locally or centrally perceived equity objectives, and for the monitoring of the subsequent market for water resources. Other responsibilities would involve the resolution of conflicts between local parties.

Water User Associations have been developed in developing and developing countries alike. WUA have arisen for specific infrastructure and irrigation schemes in Uzbekistan, Kazakhstan, in Andhra Pradesh in India, and for particular sectors within a river basin, as occurred within the Tennessee Valley. WUA exist, and are expected to be developed further, in South Africa under the new Water Act of 1998. In Chile and Mexico WUA are very important role in the allocation of water. In Chile WUA own infrastructure, monitor the trades in water permits and to resolve water allocation conflicts. In Mexico WUA have been crucial in establishing the new water rights. The main benefits of WUA are that they decentralise decision-making, are generally locally financed and cost effective, they are flexible and participatory and hence politically expedient. As an example of the latter, the implementation of water pricing and metering in Kazakhstan has been eased by the presence of WUA's.

7.3.3 Groundwater Management Areas (GWMA)

Another institutional and regulatory approach is the development of Groundwater Management Areas (GWMA) in the US. These represent a subset of water institutions insomuch as they tend to focus largely on the legal side of groundwater management, but the wide variety of approaches taken in the US serve as an example of the practical implementation of decentralised water management institutions such as WUA.

In many parts of the world the laws governing groundwater use started out as riparian or prior appropriation rules, essentially giving unlimited use to land-owners or on a first come first served basis. As scarcity increased, and the common property externalities began to bite, a shift has often occurred towards proportional sharing of groundwater as a public resource. This has become known as the 'management doctrine'. GWMA have arisen to control specific groundwater scarcity problems with a specific set of locally or regionally defined regulations for the internalisation of the common property externalities and the management of extreme groundwater scarcity. Such an approach has been initiated in 1989 by 27 states of the USA. Examples of the specific policies and regulations that have arisen include well spacing requirements, pumpage fees, emergency water use restriction powers, mandatory irrigation scheduling, drilling moratoria etc. Each of these regulations are drawn from the currently existing portfolio of state legislative measures, however, their application to specific GWMA allows them to be tailored to particular problems, and avoid unnecessary state-wide regulation.

Many states however, emphasise the local contribution to the development and finance of the management plan. Indeed, the participation of local stakeholders in Texas, through an election by land-owners, has lead to the development of a management strategy emphasising voluntary self-restraint and educational programmes. This represents a deferral to the rule of capture, with no mandatory reductions in groundwater abstraction. There is a great deal of diversity in the shape and implementation of the management plans as a result of local collaboration and organisation. For example, the heavily irrigated High Plain states (Colorado, Kansas, Nebraska and Texas) have allowed groundwater users to administratively impose controls themselves by forming management areas and restricting withdrawals. The remaining GWMA programmes are controlled by the central state agency.

However, experience in Asia with this type of local solution to groundwater management has suggested that without mechanisms to enforce the collective restraint imposed within the GWMA the users are left with the same incentives as drove the common property externality in the first place. In Texas, the GWMA's have not been successful because of ignorance of the technical questions by users and stakeholders: e.g. the nature of the resource allocation, the magnitude of the problem, and as a result of limited powers and territorial jurisdiction of the administrating institution. In addition, the administration associated with the GWMA can be subject to regulatory 'capture': its objectives become solely those of the users rather than society as a whole, potentially returning the situation to something resembling common property.

8. Introducing the Contributions in the Subject Area of Groundwater Management

The four contributions that follow this topic-introducing paper build on the principles and approaches analysed in this paper and provide a more detail treatment of four crucial aspects of 'Groundwater Management'. In particular, the first paper by Llamas identifies the difficulties involved in defining and implementing sustainable groundwater management. Then, Koundouri investigates the magnitude of economic benefits that can be derived by implementing sustainable groundwater management, while Emdid reviews the difficulties involved in the development of a legal framework for regulating sustainable groundwater management. Finally, Sahuquillo identifies how the recognition of the potential for conjunctive use of surface and groundwater resources can enhance the benefits and potential sustainability of various management schemes.

The first contribution to the topic of 'Groundwater Management' focuses on 'Sustainable Groundwater Use and Overexploitation'. In his contribution, Llamas presents a comprehensive summary of: 1) the many meanings of the terms groundwater overexploitation and sustainability; 2) the main factors to take into consideration in analysing the pros and cons of intensive groundwater development; and 3) the strategies to prevent or correct the unwanted effects of intensive groundwater development. Emphasis is placed on the basic ethical issues in relation to the use of non-renewable groundwater resources, given the complexity and variability that characterizes groundwater management problems. In particular, the author argues that because uncertainty is an integral part of groundwater management (this uncertainty relates to scarcity of data, strong non-linearities in groundwater recharge values and changing social preferences), honesty and prudence in recognizing current uncertainties is necessary, while at the same time, there needs to be a concerted effort to obtain more and better hydrological data to inform management decisions.

The author concludes that aquifer overexploitation is a complex concept that needs to be understood in terms of a comparison of the social, economic, and environmental benefits and costs that derive from a certain level of water abstraction. Llamas explicitly states that "… it is useless to define overexploitation in purely hydrogeological terms given uncertainties in recharge and abstraction values and the fact that the amount of available resources in a catchment is variable and can be influenced by human actions and management decisions. The assumption that a long trend (10 to 20 years, for example) of decline in groundwater levels implies real overexploitation or overdraft may be too simplistic and misleading."

Finally, and as has already been argued in the preceding sections of our paper, Llamas states that increasing emphasis on cost-effective and environmentally sensitive management practices places a new emphasis on broad public involvement in any water management decision-making process. However, guaranteeing effective public participation in management processes requires informing and educating the public on increasingly complex scientific and technical issues, while the conflicts that are often a part of water management processes require the use of innovative conflict resolution mechanisms that will allow for the discovery of feasible solutions that are accepted by all and can be successfully implemented.

While Llamas establishes the complexity of defining and implementing sustainable groundwater management, Koundouri goes a step back and asks the question of whether groundwater management is really needed. That is, the second contribution to the topic of 'Groundwater Management' focuses on a paradoxical empirical result that persists in and dominates economic studies that focus on groundwater management since 1980, when Gisser and Sanchez first identified it. In essence, Gisser-Sanchez's Effect (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. Koundouri's contribution critically reviews both the theoretical and empirical attempts to address GSE. In particular, it highlights the fact that in the theoretical literature the single most important cause for the presence of GSE is the prevalence of very steep marginal groundwater use benefit curves, which imply that groundwater usage is not very sensitive to price changes. Koundouri notes that this result was known even before the identification of GSE; that is, a well-established view characterized as the "the water-is-different syndrome", maintains that the derived demand for irrigation water is price inelastic and thus changes in prices will redistribute income to or from farmers but not alter significantly water usage in agriculture.

However there exist circumstances that its effects can be eliminated. Thus the case for different theoretical investigations is put forward. Moreover, this paper also points at various misconceptions, inaccuracies and omissions of the current state of the literature that could potentially resolve part of the existing puzzle. Firstly, the difference between 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. Secondly, the same empirical result was derived with non-stationary groundwater demand, which points to the importance of allowing time-varying economic parameters in infinite horizon optimal control models. Thirdly, in the absence of a backstop technology, GSE is eliminated when the assumption of infinite hydraulic conductivity is not imposed on the dynamic solutions of the optimal control model. Fourthly, driving interest rates down, in the light of suspected irreversibilities and uncertainty about future water demand and supply, would raise groundwater management benefits. Fifthly, Koundouri argues that there exist additional components of value in groundwater preservation, over and above “direct use values". Taking account of “indirect use", “quasi-option" and “existence" values of groundwater, could increase the derived social benefits from managing and effectively preserving the resource. Sixthly, incorporation of uncertainty, irreversibility and learning in a groundwater extraction game may increase the inefficiency of uncontrolled water pumping and further increase management benefits. Moreover, in tributary aquifers it is possible that additional negative externalities are involved in groundwater extraction, over and above pumping cost and risk externalities. These are the externalities caused by the presence of “river effects". Correcting for these externalities as well as the two pre-mentioned stock externalities could potentially increase management benefits and reduce the empirical robustness of GSE. Finally, already existing stochastic differential games and optimal control models assume risk neutrality, which does not allow derivation of possible management benefits caused by the reduction in the variability of returns that could arise in a managed but risk averse environment.

Koundouri concludes by arguing that the number of identified possible paths for future research on GSE emphasizes the significance of developing realistic models for groundwater policy evaluation. Unfortunately, and as argued by Llamas, the difficulty in obtaining appropriate hydrologic and economic data, and the computational burden arising as state and decision variables are added to a model, remain barriers to the development of sophisticated dynamic optimisation models. At best, current models provide only a general sense of the economic effects of various management prescriptions. The inability of most of these models to resolve the GSE paradox suggests the need for creative, decentralized forms of management.

The third contribution to the topic of ‘Groundwater Management’, by Embid investigates the legal and institutional framework needed to support sustainable groundwater management. In ‘Groundwater Legislation Principles’ Emdid, argues that although it is very difficult to give a general and abstract description of groundwater, since such a description is closely linked to the physical characteristics and historical evolution of each country, there are common trends in modern water law. These include the prevalence of public ownership of groundwater, the scant attention given to private ownership, the extensive intervention by the public authorities into public and private water, legislation that is heavily orientated towards environmental protection, as well as the value of hydrological planning in the regulation of water management and the problems in adapting this management to the limits of a particular basin.

Firstly, Emdid identifies the myths and ignorance concerning groundwater, which affect groundwater legislation and lead to discrepancies and difficulties in the regulation of groundwater ownership (private or public ownership), of the powers of the Public Authorities (regulatory, policing powers) that closely linked to environmental monitoring, of the way groundwater users organise themselves (compulsory or voluntary, and under what scheme), and of the economic/financial system (if a payment to the Authorities for water use is involved). Emdid’s contribution analyses each of the identified regulatory difficulties and argues that a major consequence of their existence is the great heterogeneity of groundwater regulatory systems and their institutional foundations.

However, there are certain causes or problems that are moving towards a process of standardisation between the various national legal systems. These are mainly aspects referring to the environment, which Emdid identifies and explains in detail. In particular, prevention principles applied to the quality of groundwater and the eco-systems linked to them, as well sustainable development principles in general have been incorporated into law and within the specific field of environmental protection, constitute clear trends in legal regulations towards the application of many more precautions with regard to the use of groundwater than with surface waters.

Embid concludes with the observation that the use of groundwater is increasing everywhere, (i.e. there are more irrigation areas using groundwater; more urban supply services using groundwater), which points to need for further development of the legal and regulatory framework that governs its use and ultimately defines its availability. In this context, there is a clear and important role for the European Union groundwater legislation, which, although not perfect, can provide valuable feedback to needed international agreements or treaties concerning groundwater.

The final contribution to the topic of ‘Groundwater Management’ focuses on ‘Conjunctive Use of Surface Water and Groundwater’. Sahuquillo, argues that the different and complementary characteristics and behaviour of surface water and groundwater make it possible to solve the specific needs of water quantity and quality more adequately and economically than if both resources were used separately. Groundwater can provide additional resources as well as the means for water storage, distribution and treatment, which can be advantageously combined with surface water resources. Likewise, groundwater possesses other advantages such as its adaptability to a progressive increase in water demand, the possibility of temporary overexploitation as a means of deferring costly construction projects and for mitigating the effects of droughts and alleviating drainage problems. Another virtue of groundwater in conjunctive use schemes is the insurance role it plays to offset the uncertainty surrounding surface flow, hydrological parameters or water demand.

The article describes the types of conjunctive use in existence. Aquifer storage can be used through artificial recharge, in alternative conjunctive use and in aquifer-river systems. In alternative conjunctive use, groundwater is used more in dry periods whereas its use decreases and, conversely, surface water use increases at times when there is more surface water available in rivers or stored in surface reservoirs. This strategy enables water supply to be increased without needing to neither augment surface storage nor resort to artificial recharge thanks to the use of natural aquifer storage. The article discusses information needs, uncertainty aspects and the economic implications of conjunctive use, in addition to the advantages with and need for integrating groundwater into water resources planning and management. Finally, the methods existing for analysis of complex conjunctive use schemes are briefly described.

Sahuquillo, concludes by saying that although planning decision-makers has very often overlooked groundwater, it can offer considerable technical and economic advantages of real benefit. Groundwater can provide additional resources as well as a means for water storage, distribution and treatment, which can be combined advantageously with surface water resources. Likewise, groundwater can provide other advantages such as its adaptability to a progressive increase in the demand for water, the possibility of temporary overexploitation as a means of deferring costly construction projects, mitigating the effects of drought and alleviating drainage problems. Another virtue of groundwater in conjunctive use schemes is the insurance role it provides to offset the uncertainty concerning surface flow, hydrological parameters and water demand.

We believe that our introductory paper, together with the four article-level contributions on specific issues of sustainable management of groundwater resources, constitute a comprehensive treatment of the increasingly important and strategic issue of managing groundwater resources, relevant for sustainable development all over the world.

References

Anderson T.L and Hill P.J (eds) (1997). 'Water Marketing, The Next Generation.' Rowman and Littlefield, London.

Backeberg G.M. (1997). 'Water Institutions and Decentralised Resource Management: Prospects for Innovative Policy Reforms in Irrigated Agriculture'. Agrekon, Vol 36, No.4.

Bowman J.A (1989). Groundwater Management Areas: An Example of the Management Doctrine'. In U.S. Environmental Protection Agency 'Exposure Factors Handbook. Available at http://www.uwin.siu.edu/ucowr/updates/pdf/V80.pdf.

Brundtland Report to the United Nations World Commission on Environment and Development, (1987) UNEP

Burger R (1998). 'Water User Associations in Kazakhstan: An Institutional Analysis'. Environment Discussion Paper No.45, NIS Project, USAID/Harvard Institute for International Development.

Chakravorty G, Shah F and Zilberman D (1993). 'Water Rights Doctrines and Technology Adoption'. In Karla Hoff, Avishay Braverman and Joseph Stiglitz eds. The Economics of Rural Organization: Theory, Practice and Policy. Oxford: Oxford University Press,

Chow, V.T (1964). 'Handbook of Applied Hydrology', New York: Mcgraw-Hill.

Cleick, P. H. (1993). 'Water in Crisis: A Guide to the World's Freshwater Resources'. Oxford University Press, New York.

Crane R (1994). 'Water Markets, Market Reform and the Urban Poor: Results from Jakarta, Indonesia'. World Development Vol 22, No. 1, pp 71-83. Pergamon.

Dasgupta P (1982). 'The Control of Resources'. Cambridge University Press

Dinar (ed) (2000). 'The Political Economy of Water Pricing Reforms'. World Bank, Washington DC.

Dinar, Ariel and J. Letey (1991). 'Agricultural Water Marketing, Allocative Efficiency, and Drainage Reduction'. Journal of Environmental Economics and Management, Vol. 20, No. 3 (May, 1991): 210-223.

Field B.C (2000). 'Natural Resource Economics: An Introduction'. Irwin/McGraw-Hill, New York.

Gisser M (1983). 'Groundwater: focussing on the real issue'. Journal of Political Economy 91(6), p1001-1027

Gisser. M, and Sanchez. D.A, (1980). 'Competition versus Optimal Control in Groundwater Pumping'. Water Resources Research. 31: 638-642.

Groom, B., Koundouri, P., and Swanson, T., 2003. Integrated Resource Management in Cyprus: Introducing and Applying a New Methodology, in "Economics of Water Management in Developing Countries: Problems, Principles and Policies" (eds. P. Koundouri, P. Pashardes, T. Swanson and A. Xepapadeas), Edward-Elgar Publishers. ISBN: 184376122X

Groom, B., Koundouri, P., and T. Swanson, 2003. Efficient water allocation in Cyprus, in "The Economics of Water" (eds. R. Brouwer and D. Pearce), Kluwer: The Netherlands (forthcoming)

Groom B and Swanson T (2003). “Missing Markets and Redundant Reservoirs: Dams as a Consequence of Inefficient Groundwater Management Policies”. forthcoming in Environmental and Resource Economics.

Haddock D.D (1997). ‘Must Water Regulation be Centralised?’. Ch3 in Anderson T.L and Hill P.J (eds) (1997). ‘Water Marketing, The Next Generation.’ Rowman and Littlefield, London.

Howe C (2002). ‘Policy Issues and institutional impediments in the management of groundwater: lessons from case studies’. Environment and Development Economics 7(4) p625-643.

Koundouri, P., 2003. Contrasting Different Methodologies to Deriving Natural Resource Scarcity Rents, in “Economics of Water Management in Developing Countries: Problems, Principles and Policies” (eds. P. Koundouri, P. Pashardes, T. Swanson and A. Xepapadeas), Edward-Elgar Publishers. ISBN: 184376122X

Koundouri, P., Pashardes, P., Swanson, T., and Xepapadeas, A., (2003). “Economics of Water Management in Developing Countries: Problems, Principles and Policies”. Edward-Elgar Publishers. ISBN: 184376122X

Koundouri, P., and Xepapadeas, A., (2003). Introducing the Special Section on Groundwater Economics and Policy. Water Resource Research (forthcoming).

Maria Saleth R and Dinar A (1999). ‘Water Challenge and Institutional Response: A Cross-Country Perspective)’. World Bank Policy Research Paper 2045. World Bank, Washington DC.

Miller B.A. and Reidinger R.B (1998). ‘Comprehensive River Basin Management: The Tennessee Valley Authority’. World Bank Technical Paper 416. Washington DC.

National Resource Council (1997). ‘Valuing Groundwater: Economic Concepts and Approaches’. National Research Council, Washington DC.

Pattanayak, S.K and Kramer R.A (2001). ‘Worth of Watersheds: a Producer Surplus Approach for Valuing Drought Mitigation in Eastern Indonesia’. Environment and Development Economics Vol 6, Part 1.

Provencher, B and Burt, O. (1993). ‘The Externalities Associated with Common Property Exploitation of Groundwater’. Journal of Environmental Economics and Management, Vol. 24, pp 139-58.

Provencher, B. (1994). ‘Conjunctive-use of Surface Water and Groundwater’. In the Handbook of Environmental Economics, Edited by Daniel W. Bromley.

Rosegrant M.W and Gazmuri S (1994). ‘Reforming Water Allocation Policy Through Markets in Tradable Water Rights: Lessons from Chile, Mexico and California’. Environment and Production Technology Division Discussion Paper No.6. International Food Policy Research Institute.

Swanson T, Groom B and Koundouri P (2003). ‘The Watershed Management Approach: An Application to Cyprus’. In ‘Water Management Policy in Developing Countries’. Koundouri P, Swanson T and Xepapadeas A (eds). Edward Elgar, London.

Ward R C and Robinson M (2000). ‘Principles of Hydrology’. 4th Edition. McGraw Hill, UK.

Ward R.C. and Robinson M (2000), ‘Principles of Hydrology’ 4th Edition. McGraw Hill.

Winpenny, James (1991). ‘Values for the Environment’ ODI/HMSO, London.

Winpenny, James (1994). ‘Managing Water as an Economic Resource, ODI/Routledge, London.

World Bank (1996). ‘Tradable Water Rights: A property Rights Approach to Resolving Water Shortages and Promoting Investment’. World Bank Policy Research Working Paper 1627. By Holden P and Thobani M. World Bank Washington DC.

World Bank (1999). ‘Groundwater: legal and Policy Perspectives: proceedings of a World Bank Seminar’. World Bank Technical Paper #456. Edited by Salman M A Salman. World Bank, Washington DC.

World Bank (1999). ‘Groundwater: Legal and Policy Perspectives’. World Bank Technical Paper 456. Edited by Salman M.A. Salman. World Bank Washington DC.

Young, R.A (1996), ‘Measuring Economic Benefits for Water Investments and Policies’. World Bank Technical Paper 338.

Zilberman D, Zeitouni N and Becker N (2001). ‘Issues in the Economics of Water Resource’. Ch2 in The international Yearbook of Environmental and Resource Economics (2000/2001). Tietenberg T and Folmer H (eds).

Groundwater User Associations websites:

Websites for some of the US groundwater districts and river basin authorities can be found at the following addresses:

www.texasgroundwater.org
www.gmda.nrc.state.ne.us
www.angelfire.com/tx/gcuwd