Groundwater and Ecosystem Services: towards their sustainable use

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ABSTRACT

Ecosystem services are increasingly recognised as important assets for sustainable development. A close interdependency between ecosystem services and groundwater exists. On the one hand, these services depend directly on the functioning of ecosystems such as wetlands, forests, lakes and coastal areas which derive freshwater for their functioning from sub-surface water, including groundwater. On the other hand, groundwater resources are dependent on recharge through infiltration of rainwaters. The rate and quality of recharge is amongst others determined by the type and spatial configuration of ecosystems. The close linkages between groundwater and ecosystem services are often not recognised and under valued. In this paper these relationships are clarified and an indication of their value is provided. Furthermore, a number of options for sustainable management of ecosystems services and groundwater are put forward.

1. INTRODUCTION

The recent study of the Millennium Ecosystem Assessment (MEA) has concluded that many of the earth's ecosystem services are seriously affected by over use and abstraction of resources by societies. Ecosystems services are defined as the goods and benefits provided to people by ecosystems. These include: a) provision services, such as the provision of food, fuelwood and water; b) regulating services, such as flood and erosion control; c) supporting services, such as soil formation and nutrient cycling; and d) cultural services, such as opportunities for recreation and spiritual experience (MEA, 2005). The MEA study concluded that freshwater dependent ecosystems are particularly affected through overabstraction of water resources, infrastructure development on river courses and drainage and conversion of wetlands to arable lands (MEA, 2005).

Many ecosystem services have a direct linkage with groundwater storage, recharge and discharge. Rainwater flows through ecosystems to recharge aquifers and the type of ecosystem and its configuration often, among other factors, determines the rate and quality of the recharge. On the other hand, groundwater discharge and exfiltration of groundwater often supports particular ecosystems of high value in terms of both their services and their biodiversity. The interdependencies between ecosystem services and groundwater are little recognised and valued in decision making and management of water resources and river basins.

It is becoming increasingly clear that while the importance of ecosystem services is recognised, their existence is often taken for granted by their users. Decision-making easily overlooks some of the critical inter-dependencies that exist between a natural resource and the ecosystem that provides services that supports the resources. For example, over-abstraction of groundwater resources has caused a loss of important riparian and groundwater dependent ecosystems. While the abstraction of groundwater has generated benefits, its over-abstraction has sometimes led to loss of highly valued services provided by those ecosystems, such as loss of fish, fuelwood and spring waters.

Currently, the challenge is to improve the understanding and awareness of the linkages between groundwater and ecosystems services and incorporate this into decision making and management.

In this paper, we explore the linkages between ecosystems services and groundwater and provide an examination of the values of those linkages. Furthermore, options are provided on how the sustainable management of ecosystems services and groundwater can be combined and how costs and benefits can be balanced.

2. THE LINKS BETWEEN ECOSYSTEM SERVICES AND GROUNDWATER

Ecosystems not only provide a wide variety of marketable goods, but also a myriad of other functions, such as nutrient recycling, regulation of climate, and maintenance of biodiversity, which are essential components for human survival (NRC, 2004). Groundwater is an important component to providing ecosystem services. For example, aquifers are connected to a greater ecological and hydrological landscape that includes adjacent riparian areas, upland terrestrial ecosystems, and surrounding river basins (NRC, 2004). Ecosystems that depend on groundwater include terrestrial vegetation, river base flow systems, aquifer and cave ecosystems, wetlands, terrestrial fauna, and estuarine and near-shore ecosystems (Sinclair Knight Merz, 2001).

Groundwater associated ecosystem services provide support to a wide range of production and consumption processes, which have high economic value (Emerton and Bos, 2004). In this section, we discuss the ways in which groundwater provides ecosystems in the form of provisioning, regulating, supporting and cultural services. For example, discharge to streams and rivers may provide essential nutrients to aquatic life and support downstream users of water for drinking or irrigation (NRC, 1997). These ecosystems depend on several groundwater characteristics, which include the quality of water, discharge flux from an aquifer, and the level of pressure of groundwater (Sinclair Knight Merz, 2001). Small changes can potentially cause extensive damage to dependent ecosystems. In addition we examine how ecosystem services, such as climate regulation and land-use are critical to maintaining groundwater systems. The challenge is to use groundwater and interrelated ecosystem services in a sustainable manner to provide for the present without compromising the needs of future generations.

2.1. Provisioning Service

The MEA classifies fresh water (including groundwater) as a provisioning service, which is defined as "products obtained from ecosystems" (MEA, 2005, p.40). Most freshwater is not in lakes and rivers, but in aquifers. In fact, groundwater is the earth's largest accessible store of fresh water (excluding ice sheets and glaciers) and constitutes about 94% of all fresh water (Ward and Robinson, 1990). Groundwater is also an integral component of regulating, supporting and cultural ecosystem services.

One of the critical functions of groundwater as a provisioning service is its storage and retention for domestic, industrial and agricultural uses. As many as two billion people depend directly upon aquifers for drinking water, and 40% of the world's food is produced by irrigated agriculture that relies heavily on groundwater (Morris *et al.*, 2003). Groundwater is also used for industrial activities such as food product processing, manufacturing processes, heated water for geothermal power plants, and cooling water for other power plants (NRC, 1997).

More than half of cities with a population over 10 million rely on or make significant use of groundwater (Morris *et al.*, 2003). The use of groundwater for domestic supply in smaller towns and rural communities is even more widespread. For example, in the US, more than 95% of the rural population depend on aquifers to provide their drinking water (Morris *et al.*, 2003). The scale and rate of groundwater abstraction for agricultural use has increased substantially over the past five decades due to the massive expansion in pumping capacity. In India, the number of diesel and electrical pumps has risen from 87,000 in 1950 to 12.58 million in 1990 to a current estimate of more than 20 million (FAO, 2003). Concurrently, the amount of land irrigated from aquifers has increased by 113 times between 1950 and the 1990s, so that aquifers supply more than half of the irrigated land (Morris *et al.*, 2003).

Groundwater provides biodiversity and genetic resources, specifically in the form of organisms that are able to breakdown contaminants (NRC, 2004). Groundwater also contains essential nutrients such as sulphate and nitrate derived from the surrounding geological formations and microbial activity. These nutrients are especially important for different microorganisms when biodegrading organic compounds. For example, sulphate reducing bacteria requires sulphate to break-down carbon based compounds.

2.2 Regulating Service

Regulating services are defined as "benefits obtained from the regulation of ecosystem processes" (MEA, 2005, p.40). For groundwater these include water regulation, water purification and waste treatment, erosion regulation and flood control, and climate regulation.

Groundwater serves the important function in the hydrological cycle of storing and subsequently releasing water. Water discharged from aquifers maintains and sustains river flows, springs and wetlands (Morris *et al.*, 2003; Shaw, 1994). Groundwater systems are tightly connected to surface water resources (Falkenmark and Rockström, 2004). Furthermore, groundwater has a very long residence time compared to surface water (averaging about 300 years), thus is able to sustain streamflow during dry season and droughts (Ward and Robinson, 1990).

Changes in hydrology will impact groundwater supplies. If groundwater is depleted and regulation disrupted fragile ecosystems such as wetlands can be at great risk of degradation. An example of how groundwater exploitation can ruin ecosystems is demonstrated by the Azraq Oasis in the heart of the Jordanian *Badia* (Shah *et al.*, 2000). The Azraq Oasis was a wetland that provided a natural habitat for numerous indigenous aquatic and terrestrial species as well as supporting migratory birds. However, the wetland dried up as a result of groundwater overexploitation from mechanical pumps used for irrigation and providing potable water to the city of Aman. Groundwater overdrafts caused shallow water tables to fall and natural springs to dry up, resulting in the collapse of the whole ecosystem, increase in the salinity and decline in the tourist industry around the oasis (Shah *et al.*, 2000).

The biological component of the groundwater environment provides an important ecosystem service in the form of water purification and waste treatment through microbial degradation of organic compounds and potential human pathogens (Herman et al, 2001). As water passes through the ground, natural processes attenuate the concentration of many contaminants as well as remove harmful microorgansisms. The degree to which attenuation occurs depends on the soil and rock types and contaminants present (Morris *et al.*, 2003). Attenuation processes tend to be most effective in the soil layer as both microbiological and some chemical contaminants are removed, retarded or transformed by biological activity (Morris *et al.*, 2003).

Groundwater aids in the control of erosion and floods by absorbing runoff (NRC, 1997). In addition, groundwater also indirectly regulates soil erosion by providing water to vegetation cover. For example, riparian and terrestrial vegetation generally are not entirely dependent upon groundwater, there is usually access to rainfall as well (Malanson, 1993). However, some vegetation communities have seasonal or episodic dependence on groundwater so it is necessary for the trees to have access to shallow aquifers at certain times. (Sincair Knight Merz, 2001, Le Maitre *et al.*, 1999).

Groundwater acts as the primary buffer against the impact of climate variability and spatial variability in drought (FAO, 2003). In addition, groundwater aquifers have the potential to be used for anthropogenic carbon dioxide sequestration. McPherson and Lichtner (2001) discuss how carbon dioxide could be injected into an aquifer through injection wells to remote storage sites, and remain isolated from the atmosphere for a considerable time period. This innovation has the potential to be used as a way to decrease carbon dioxide contribution to global warming.

2.3. Supporting Services

Supporting services are defined as "services which are necessary for the production of all other ecosystem services. They differ from provisioning, regulating, and cultural services in that their impacts on people are often indirect or occur over a very long time, whereas changes in the other categories have relatively direct and short-term impacts on people" (MEA, 2005, p.40). Freshwater, including groundwater, can be considered as a supporting service because water is required for other life to exist. Groundwater also plays a role in water cycling and nutrient cycling.

The interdependence and continuous movement of all forms of water, including groundwater provide the basis for the water or hydrological cycle (Ward and Robinson, 1990). Groundwater recharge and discharge is an integral part of this cycle and is essential for living organisms. Depletion and degradation of groundwater can have far reaching consequences on all components of the water cycle. Lerat (2005) states that above a critical abstraction rate groundwater flow to rivers and wetlands may be reduced to a level that threatens ecosystem health. This will result in disruption to other interlinked components of the water cycle such as evaporation, condensation, precipitation and soil moisture.

Approximately 20 nutrients essential for life (including nitrogen and phosphorous) cycle through ecosystems and are found at different concentrations in different parts of ecosystems (MEA, 2005). As discussed in Section 2.1, nutrients are one of the services provided by groundwater and subsurface aquifers play a role in the nutrient cycle through the storage, recycling, processing, and acquisition of nutrients. For example, subsurface microorganisms recycle nutrients which are important in secondary productivity (NRC, 2004).

2.4. Cultural Services

Cultural services are defined as "nonmaterial benefits that people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experiences" (MEA, 2005, p.40). Groundwater is an essential component of everyday life and is integrated throughout various cultural services including social relations, as spiritual and religious value, within knowledge systems and providing educational value.

Ecosystems influence the types of social relations that are established in different cultures and societies (MEA, 2005). As groundwater is depleted, deeper wells and more advanced equipment are needed to extract water. Those who can afford to drill and provide the necessary equipment have primary access and control over the water, thus enhancing the poverty gap and creating social stratification between those with direct access and those without. In Tamil Nadu, landowners with deep boreholes and electric pumps are becoming richer, while poor farmers who do not have access to water resources and pumpsets have to buy their water (Hayward, 2005). The added expense of purchasing water drives an already disadvantaged section of the population into poverty and widens the gap between rich and poor.

Ecosystems and their components often have religious or spiritual value to societies (MEA, 2005). For example, the Hopi tribe in Arizona, USA uses water for traditional ceremonies. The water source is an aquifer which feeds the springs and few streams in the area. However, this source has been compromised because the Peabody coal mine has a contract with the Hopi tribe that allows the mine to pump water from the aquifer. The Hopi streams are starting to dry up and the ceremonies that have always been integral to Hopi religion can no longer be performed, so that the religious base of the tribe is now at risk of being permanently lost (Groenfeldt, 2005).

Ecosystems can influence the type of traditional and formal knowledge systems developed in different cultures (MEA, 2005). To successfully drill groundwater wells, knowledge is needed of environmental features that indicate where groundwater can be found. This knowledge can range from geophysical methods to examining the surrounding vegetation. This knowledge can be transformed to others through formal and informal education and training.

2.5. Ecosystems provide services critical to maintain groundwater systems

Some aspects of the MEA have focused on how groundwater is important to maintaining ecosystem services, such as providing water, being an integral component of the water cycle and regulating climate. However, it is important to recognise that ecosystems provide services that are critical to maintaining groundwater systems. For example, groundwater aquifers are recharged by other parts of the water cycle such as wetlands, rivers and precipitation. Disruption or changes to regulating services such as climate change can have a major impact on groundwater. The UK Groundwater Forum (2004) predicts a variety of potential scenarios that may occur due to climate change (in the UK). These include: a long term decline in groundwater storage, increased frequency and severity of groundwater droughts, increased frequency and severity of groundwater-related floods, mobilisation of pollutants due to seasonally high water tables, and saline intrusion in coastal aquifers due to sea level rise and resource reduction,

Land-use can also have a significant influence on groundwater systems. Although forest and vegetation cover has been widely used to reduce run-off and increase infiltration, the effect on groundwater levels is not automatic (FAO, 2003). Increased recharge is dependent upon the balance between improvement in infiltration caused by increased vegetation and relative changes in evapotranspiration (FAO, 2003). In fact, removal of forest cover has been observed to cause an increase in groundwater levels in some areas.

3. THE VALUE OF GROUNDWATER SERVICES

Sustainable use of ecosystems requires that the stock of capital that is available for future generations be equivalent to the capital available at present. The term capital refers to the overall stock of material and information that generates services to ensure human wellbeing (Turner *et al.*, 2004). Capital consists of natural, human, social, manufactured and financial forms. Since natural capital has to be interpreted widely, many assets including groundwater services are essential to human life and cannot be replaced by or substituted with manufactured capital (Pearce, 1993; Turner *et al.*, 2004). Such essential ecosystem services are classified as critical natural capital and have an enormous value for livelihoods, economies and societies.

In this section, we discuss the value of critical natural capital in the form of ecosystem and groundwater services and why they are often neglected in planning, management and decision-making and costs are incurred. The ecological, economic, and socio-political impacts of groundwater depletion and degradation are also examined. Despite these costs, undervaluation of groundwater services continues. We investigate how this neglect stems from interactions between environmental, economic, social, political and institutional systems.

3.1. What is the value of groundwater services?

Total economic value (TEV) provides a useful framework for evaluating ecosystem goods and services, and for factoring them into economic calculations (Emerton and Bos, 2004). The TEV is calculated as the sum of a resource’s use value and its non-use value (Görlach and Interwies, 2003), which are further described specifically for groundwater in Table 1. In Uganda, the use value of inland water resources (including groundwater services) is worth almost $US 300 million a year. The value of forest catchment and erosion control services contribute more than $100 million a year to the national economy, and almost one million urban dwellers depend on natural wetlands for wastewater retention and purification services (Emerton and Bos, 2004).

Table 1. The total economic value of ecosystems for groundwater (adapted from Emerton and Bos, 2004).

	Use values	Non-use values
Direct values	Provisioning ecological services – (i.e. fresh water, nutrients, forest-products)	
Indirect values	Regulating and supporting ecological services – (i.e. flood control, regulation of water flows and supplies, climate regulation, water purification and wastewater treatment, nutrient retention, climate regulation)	
Option values	Premium placed on maintaining resources and landscapes for known and unknown future use – (i.e. preserving species dependent on groundwater, genetic biodiversity)	
Existence values		Intrinsic value of resources and landscapes, irrespective of its use (i.e. cultural services such as religious and spiritual significance, educational and knowledge systems)

The use and non-use values of groundwater services are difficult to determine because much of the necessary information is not available as most of the services provided by groundwater are nonmarket goods (NRC, 1997). There are well-established economic methods of assigning value to water for human uses such as domestic supply, irrigation or industrial use. However, it has proved to be difficult to agree on a way of assigning a value to amenity and habitat conservation. Historically, these are the water uses that have been under-prioritised (Morris *et al.*, 2003).

Nonetheless, there are valuation techniques for goods and services not traded on the market. NRC (1997) discusses a variety of methods to value groundwater. For example, the economic value of groundwater can be determined using the stated preferences approach with the contingent valuation method by assessing either someone's willingness to pay for water access or willingness to accept compensation for contaminated water sources (NRC, 1997). Case studies from the US summarised by Görlach and Interwies

(2003) found a substantial willingness to pay for cleaner water. For example, in Georgia, households were willing to give up roughly 2% of their annual income in exchange for reduced pollution from agricultural chemicals. Other ecosystem valuation techniques include using market prices, production function approaches, surrogate market approaches, cost-based approaches, and stated preference approaches (Emerton and Bos, 2004, NRC, 1997).

3.2. Impacts of groundwater depletion and degradation

Water declines and degradation have major environmental, economic and socio-political impacts. The increased pressure on groundwater means that this resource is under threat from problems that affect both the quantity and quality of water that aquifers provide. The scale and rate of groundwater abstraction has increased substantially over the past five decades due to the massive expansion in pumping capacity. Such an increase in demand has provoked over-abstraction, which results in wells drying up, conflict between users and sometimes the incursion of saline water. Problems with groundwater quality are a consequence of pollution from both point (i.e. urban, industrial and mining activities) and non-point sources (i.e. pesticides from agricultural use) (Morris *et al.*, 2003).

Environmental challenges

Depletion can result in a loss of ecosystem services, such as processing of organic matter by diverse microbes and invertebrates. These organisms perform the important function of breaking down organic matter and turning dead materials (detritus) into live biomass that is consumed in food webs (NRC, 2004). Furthermore, groundwater extraction may harm rare and endangered species restricted to very local habitats. For example, the Edwards Aquifer-Comal Springs ecosystem provides critical habitat for the Texas blind salamander as well as 91 species and subspecies of fish are endemic in this underground ecosystem (NRC, 2004).

Soil and groundwater contamination from industrial and population expansion is of widespread concern (FAO, 2003). Pollutants that enter the groundwater from agriculture, industry and urbanisation can have long-term and irreversible environmental effects. In rural areas, there has been concern over the rise in nitrate levels in many aquifers due to the heavy use of nitrogenous fertilisers in agricultural practices. Excessive nitrate from agriculture leaches through soils to stream water and groundwater, depleting soil minerals, acidifying soils, and altering downstream freshwater and coastal marine ecosystems (Vitousek *et al.*, 1997). Chemical spills or leaching from the surface can have a long-term environmental impact to underlying groundwater aquifers and associated ecosystem services because of the high residence time and relatively slow biodegradation rates in the subsurface (Morris *et al.*, 2003).

Economic challenges

As groundwater is depleted the costs for deeper drilling and pumping increase (NRC, 2004). Water may still be physically available, but the cost of extraction is prohibitively high for most users. For example, in Bangladesh only wealthy farmers can afford to deepen existing wells or install new ones, leaving those who are less wealthy without a reliable source of water for irrigation (FAO, 2003).

Irrigation using groundwater sources has increased agricultural production by both the expansion of cultivable area beyond that possible with just rainfed agriculture and through higher crop yields (Turner *et al.*, 2004). With an increasing global population, demands on aquifers will continue to rise to meet agricultural needs. The resulting overabstraction can result in decreased water availability leading to a loss of welfare from irrigation of crops, thus compromising food security.

Removal of water in the underground area may cause collapse of the overlying substrata. Such collapses decrease future storage capacity and may cause damage on the surface (NRC, 2004). In Mexico City, the underlying aquifer is used to provide water to the ever growing population. As the water table lowers, the city is subsiding resulting in cracks and buckling of pavements, roads and buildings (BBC News, 2005). This will likely lead to costly investments to repair damaged infrastructure.

The remediation of polluted groundwater can be extremely expensive and often ineffective. For example, during 1996, the US Department of Defence (DoD) operated 75 pump and treat systems to remediate contaminated sites. This technology remediated contamination slowly, cost more than $500,000 per site and did not allow DoD to meet the required clean-up goals within a reasonable time (US DoD, 1998).

Socio-political challenges

Groundwater sustainability needs to not only focus on the ability of the resource to produce key environmental services, but also on the economic costs and impacts of equitable access that arises from reduced groundwater availability (FAO, 2003). The poorer sectors of society are likely to be the hardest hit as they are the most vulnerable to ecosystem changes. For example, declining water levels generally have large equity impacts particularly in the developing world. Wells established for drinking supply often go dry, forcing women and children to walk long distances or wait in line to obtain water to meet domestic needs (FAO, 2003). This inequity also extends to future generations who will be deprived of groundwater resources due to current unsustainable use.

Environmental health impacts are another concern if poor quality water migrates into groundwater wells (FAO, 2003). For example, the mobilisation of naturally occurring arsenic by drilling deep tubewells in Bangladesh is directly affecting the health of some 30 to 35 million people. Long-term exposure to arsenic via drinking-water causes cancer of the skin, lungs, urinary bladder, and kidney, as well as other skin changes such as pigmentation changes and thickening (hyperkeratosis) (WHO, 2001).

Political tensions can deepen over access to groundwater and unequal rights of use of vital aquifers can potentially lead to conflict. Transboundary groundwater problems in the Middle East are an example of the socio-political impacts of groundwater depletion. Amery and Wolf (2004) discuss the importance of water resources in peace negotiations. For example, boundaries with Syria were based on precedent and international law along with hydrostrategic needs. In the case of Israel and Palestine, the coastal plain aquifer extends from Carmel (near Haifa) in the north to the Palestinian Gaza Strip in the south. According to Kandel (2003) serious conflict exists between Israel and Palestine over this aquifer, which is both directly and indirectly related to the conflict over land.

3.3. Why is the value of groundwater and related ecosystem services neglected?

The economic value of ecosystems in relation to water, including groundwater, has been poorly understood. The largely invisible nature of groundwater has resulted in development initiatives that do not take into account the hydronomic limits of the resource (FAO, 2003). For example, groundwater depletion and degradation due to contamination can continue unnoticed, unlike rivers and lakes where drying-up or pollution is more visible (Morris *et al.*, 2003). Ecosystems and their groundwater interactions are often omitted from decision-making, leading to a lack of investment in ecosystems, as well as depletion and degradation of groundwater resulting in a loss of economic value (Emerton and Bos, 2004).

Vicious cycle of groundwater depletion and degradation

Calls for groundwater management do not usually arise until a decline in well yields and/or quality affects stakeholders. If further uncontrolled pumping follows then the groundwater system can continue to deteriorate. A 'viscous cycle' of deterioration (or downward spiral) results as institutional, political, social and economic elements fail to provide enough of an incentive for intervention. Table 2 outlines how each of these factors contributes to compromising groundwater services, as well as potential solutions to manage groundwater resources.

Table 2. Obstacles and solutions to institutional, economic, social, political and environmental factors which compromise groundwater services

Elements that feed into the 'vicious cycle' of deteriorating groundwater services	Examples of Obstacles	Examples of potential solutions
Institutional	Lack of capacity, mismanagement	Capacity building
Economic	Groundwater is a common pool resource, thus vulnerable to overuse and pollution	Economic instruments
Social	Inequity of access to groundwater resources	Property rights, equitable water laws
Political	Interests of politicians override need for groundwater conservation	Transparency, involvement of community in decision making

Institutional obstacles to maintaining groundwater services are often a result of mismanagement or lack of capacity. For example, in Ho, Ghana, the collapse of conjunctive water use in the area was not due to minimal interest by the water authorities, but was an institutional failure due to the lack of detailed water resources planning and foresight in water management (Bannerman, 1997). Investment in training and education of workers, as well as hiring necessary professionals (such as hydrogeologists) would be a step forward in building the capacity of institutions involved in groundwater management.

The value of groundwater and related ecosystem services is neglected or underestimated because it has characteristics of a common pool resource. This means that exclusion through physical and institutional means is costly, and exploitation by one user reduces resource availability for others (World Bank, 1999). Consequently, people follow their own short-term interests by extracting or contaminating groundwater for their own needs without constraints and this produces outcomes that are not in society's long-term interests (World Bank, 1999). For example, if farmers require more pesticides and fertilizers to increase yield then they will buy and use more chemicals despite the impact on groundwater quality because the costs of groundwater contamination are an economic externality (they are not included in the price of chemical inputs) (Wandschneider and Barron, 1993). The external costs are borne by society in the form of contaminated drinking water and damage to the environment (i.e. eutrophication). Applications of economic instruments are a potential solution to regulating groundwater access and pollution. This is further discussed in section 4.1.

Social problems such as inequity of access to groundwater can intensify severe poverty. In turn, poverty affects water resources by contributing to desertification and deforestation, loss of topsoil, widespread nonpoint pollution, and land management practices that reduce groundwater discharge (Gleik, 1998). The apartheid-era water law in South Africa gave priority access to projects that increased economic power and production of the minority population, while ignoring the basic water requirements of millions of back South Africans (Gleik, 1998; Hayward, 2005). There was also implicit and explicit use of water deprivation as means of controlling the rural populations. However, with the departure of the apartheid government followed by democratic elections in 1994, the new government prepared a new National Water Policy which promoted equitable access and benefit of the nation's water resources to all South Africans (Gleik, 1998).

The political and economic incentives faced by decision-makers can lead them to choose an unsustainable set of policies. Groundwater is a hidden resource, so it is often unclear when depletion and/or contamination effects from overextraction or pollution would be felt by users. However, users will immediately feel any restriction in their allocations and will attribute their losses to decision-makers. Thus from a decision-makers perspective, a cut in allocation is a certain loss whereas depletion of the aquifer is a probabilistic loss. Consequently, it is politically rational for decision-makers to prefer that users over-pump the aquifer rather than cut allocations to farmers (Feitelson, 2005). Encouraging transparency and involving the community in decision making would provide more information to stakeholders so they would understand the benefits of conserving groundwater resources.

To transform the 'vicious circle' of groundwater depletion and degradation into a 'virtuous circle' it is essential to recognize that management of groundwater not only means managing aquifer resources but also people (water and land users). In other words, the socio-economic, political and institutional dimensions are as important as the hydrogeological dimension and integration of both is always required (Tuinhof *et al.*, 2003).

4. MODELS OF HOW TO MANAGE GROUNDWATER SERVICES

With the increasing pressure on groundwater resources, new models of groundwater management have emerged over the last decade. These models, often take the link between ecosystem services and groundwater explicitly into account. Thus a range of management approaches are now becoming available that can address groundwater depletion and deterioration of ecosystem services. Many of these approaches are based on a combination of using new technologies, improved planning and a wider participation of stakeholders in the decision making and management process. What those approaches have in common, is a vision of moving from simple abstraction to a sustainable use of groundwater resources: moving from mining to wise use. In this section, we briefly explore a few examples of options and tools that exist for sustainable management of groundwater resources and related ecosystems services. Examples that will be used include economic instruments, planning and legislation and integrated surface-groundwater management.

4.1. Economic instruments

One of the management options proposed to mitigate groundwater depletion is application of economic instruments. Morris *et al.*, (2003, p.109) suggests that "groundwater pricing needs to be introduced, based on the principle that water is an economic as well as a social good". This means that users need to pay for the full economic cost of groundwater, including marginal costs. Two forms of economic instruments are discussed in this section: taxes, which mainly applies to groundwater; and pollution and permits, which generally applies to groundwater extraction.

Taxes

Due to the common pool nature of groundwater overexploitation and contamination is usually not incorporated into private user costs but becomes an external cost to society. Incorporating externalities into the market price of groundwater would encourage users to conserve water and reduce contamination. In the case of contamination, the government agency would determine the clean-up cost of removing pollutants and incorporate this into the pollution source (i.e. fertilizers and pesticides) (Wandschneider and Barron, 1993). For example, (Henrickson *et al.*, Unpublished) found that a tax on herbicides, such as weed killers, was the most effective instrument with respect to the protection of the total groundwater resource, including groundwater reserves not currently utilised for drinking water. Such taxes are one of the common economic instruments used to reduce environmentally harmful behaviour be individuals or firms (Görlach and Interwies, 2003).

The difficulty of applying a tax directly to a pollutant such as pesticides is that contamination varies from one aquifer to another. Thus, the externality that is incorporated in to the price of the pesticide may not accurately represent remediation costs. A more effective and fair method would to be tax pesticides as they are applied in the field. However, this requires a high level of knowledge on contaminant impacts and continuous enforcement (Wandschneider and Barron, 1993).

Some countries (Netherlands, France and parts of Germany) have introduced taxes for groundwater abstraction (Görlach and Interwies, 2003). However, abstraction taxes or charges are more relevant for the quantitative management of groundwater protection, and therefore only indirectly relevant for the protection of groundwater quality (Görlach and Interwies, 2003).

Tradable Permits

Tradable permit systems allow achievement of a given environmental goal (for example only a specific volume of water can be extracted from an aquifer each year) with free market efficiency. A central authority can sell or issue permits that allow a finite use of groundwater. The user cannot abstract more than the limit corresponding to the number of permits held. If a company or individual has excess permits, these can be sold to other users who require a greater volume of groundwater. This scheme encourages efficient use of water and improvements in production technologies to minimise water use. (Görlach and Interwies, 2003). The Edwards Aquifer Authority in Texas has created a system of marketable groundwater permits, which were issued to all users based on historical use. All permits are subject to a pumping cap, but users are able to trade permits in order to increase their extraction volume (Howe, 2002). This example of permit trading appears to be a way to optimise groundwater use but still needs to be combined with an effective monitoring system and a system of penalties to enforce compliance (Görlach and Interwies, 2003).

Permits for groundwater pollution are more difficult to apply because of the high cost of monitoring, which reduces the efficiency of this economic instrument. Furthermore, the effects of emissions can vary temporally, spatially and seasonally, having very different effects on the groundwater and associated ecosystem services (Görlach and Interwies, 2003). For example, a contaminant may not be detected during spring runoff when water levels are high, but is found at high concentrations in dry seasons. These differences are usually not captured with a permit system.

4.2. Planning strategies

In many instances, groundwater interventions often tend to be too 'local' in their approach. Like surface water, groundwater resources need to be planned on a large scale and managed for maximum basin-level efficiency. This poses major challenges in terms of planning and decision making. As with surface water resources, consent of stakeholders is critical if a successful strategy is to be developed and implemented.

Groundwater zoning

A well know method for planning the sustainable use of groundwater resources, is the identification of different zones of recharge and discharge. Increasingly, these zonations are used in combination with other resource and protection planning, such as those under Natura 2000. At more local levels, groundwater protection zoning often relates to recharge areas critical for the aquifers used for drinking water.

Groundwater protection zones have three main hydrogeological elements: the vulnerability of the groundwater to contamination, the characteristics of the aquifer and the areas surrounding groundwater sources (GSI, 1999). These elements can be integrated to produce maps showing where higher levels of protection are needed to prevent groundwater contamination. In such vulnerable areas, restricted use of agro-chemicals may only allowed and any incident involving chemicals needs to be reported immediately to the respected authorities.

Land-use planning

Increasingly specific attention is given to the role of vegetation and forestry in the use of valuable groundwater resources. In some cases, invasive species can consume large amounts of groundwater resources, causing down-stream springs and wells to dry up (Calder and Dye, 2001). In South Africa, a country wide program was established to reduce the surface cover of several alien invasive species and replace these with native vegetation. The scheme is thought to have reduced evaportranspiration and to have contributed to recharge of shallow aquifers (Hayward, 2005).

Forestry is another form of land-use that can affect aquifer recharge. Evidence from a study in Karnataka, India found that evaporation rates from indigenous forests and eucalyptus plantations were twice that from unirrigated dryland agricultural crops (Hayward, 2005). Research in South Africa looked at the effects of forestry on water resources and found that compared to baseline vegetation (grassland or fynbos shrubland), forestry consumed a relatively large amount of water. For example, commercial plantations reduce surface run-off by 3.2% annually (Hayward, 2005). This suggests that the policy of advocating tree planting to conserve water could actually reduce water flow downstream and limit groundwater recharge. Consequently, this would put further stress on aquifers that are already used for drinking and irrigation needs. Some countries such as South Africa have recognised the problem and implemented progressive legislation that recognises forestry as a high water user and requires owners of plantations to pay an interception levy (Hayward, 1995).

4.3. Integrated management - Conjunctive use of groundwater and surface water

The integrated surface–groundwater management approach focuses mostly on a most effective use of storage capacities below the ground and on the surface. In many cases where rivers, reservoirs and lakes are highly regulated, groundwater storage opportunities can be integrated into the existing surface water storage and delivery system. In the Central Valley (California), for example, plans exist for such integrated schemes that involve the re-operation of the eleven existing terminal reservoirs located in various tributaries (Thompson, 2005). This re-operation is thought to provide source water to actively recharge the groundwater banks with water that would otherwise spill for flood control.

In the specific case of Central Valley, there are three ways to accomplish the recharge of the groundwater aquifer (Thompson, 2005).

Option 1. The storage and release regime is modified so as to allow for reservoirs throughout the river basin system to capture a larger fraction of the peak flow events. This water is then conveyed to secondary storage facilities, which are created by moving a substantial portion of the surface reservoir water into groundwater basins with currently unutilised storage capacity;

Option 2. In the case of full aquifers, which are most commonly found in the Sacramento Valley, native groundwater is extracted to create storage space, and is then subsequently replenished from an imported surface source; and

Option 3. Existing groundwater usage is substituted for surface water supplies, with recovery accomplished by reversing the arrangement. From an aquifer mass balance standpoint, this in lieu storage arrangement is indistinguishable from active recharge.

A combined use of groundwater and surface waters at the scale of entire river basins is a rather sophisticated mode of water management. It requires substantial capacity of agencies and stakeholders to plan and operate large complex water systems. Even when those capacities are available, much of the challenges lie in bringing together the various stakeholders to agree upon a set of options. Typically, this will require the participation and consent of at least four types of entities: the reservoir owner, the local groundwater management authority, the end-use beneficiaries, and the operators of the infrastructure needed to convey the water from a surface water reservoir to point of end-use. In many cases, other stakeholders such as representatives from tourist activities, nature conservation organisations and fisherman need to be involved if a more integrated approach is to become accepted.

Conjunctive surface and groundwater use is not necessarily as complicated as in the above case. In Maharastra (India), conjunctive water use was tried and tested at local levels (Simpson and Sohani, 1998). Here the integrated use of surface and groundwater is directly linked to rainwater harvesting. Surface waters are trapped behind small check dams and infiltrate into shallow aquifers. Due to this technique water availability to households was increased with 750 l/day per person (Simpson and Sohani 1998). The improved water management allowed people to withstand two consecutive years of reduced monsoon rainfall (1994-1996).

5. CONCLUSION

This paper has demonstrated that ecosystems are dependent on groundwater for a number of essential services, including provision, regulation, and support of ecosystems. These interrelated services point to the importance of groundwater as critical natural capital. In addition, ecosystems provide services necessary to maintaining groundwater systems. For example, changes in vegetation cover can influence the volume of recharge into groundwater aquifers.

Both groundwater and ecosystem services have a variety of use and non-use values that are an integral part of the environment and human society. However, the value of these services is difficult to determine when it is in the form of a nonmarket good. Valuation techniques are available, but for valid and reliable results, the method must be well-matched to the context and the groundwater service of interest. Due to the difficulty in valuation and relative invisibility, groundwater is often neglected in planning, management and decision-making.

Groundwater degradation and depletion has far reaching consequences to the environment, economy and society in general. For example, overabstraction can reduce habitat for species dependent on groundwater during the dry season. Pressure on groundwater sources can also reduce irrigation capacity, compromising food security, and further impoverishing the vulnerable sectors of society. Despite the consequences of mismanagement and neglect of groundwater, interactions between economic, social, political and institutional elements continue to feed into the vicious cycle of groundwater depletion and degradation. However, each of these elements can also provide solutions towards protecting aquifers. For example, institutions often have a lack of appropriate ability to effectively manage natural resources, but capacity building can be provided by other institutions to improve knowledge and management skills. To prevent further degradation and depletion of aquifers, a range of management approaches are now becoming available that can address groundwater depletion and deterioration of ecosystem services. These range from economic instruments, such as taxes and permits to control of vegetation to encourage recharge.

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The sustainable use of water and wetlands, by protecting the services they provide, is critical to enable so-ciety to achieve sustainable social and economic development, adapt to climate change and improve social cohesion and economic stability.The proposed United Nations Sustainable Development Goals (SDGs) offer a universal agenda that, for the first time, recognises the need for restoration and management of.Â Wetlands provide multiple ecosystem services supporting water security and offer a wide range of benefits and values to society and the economy. Values of both coastal and inland wetland ecosystem services are typically higher than for other ecosystem types. Ecosystem services are the many and varied benefits to humans provided by the natural environment and from healthy ecosystems. Such ecosystems include, for example, agroecosystems, forest ecosystems, grassland ecosystems and aquatic ecosystems. These ecosystems, functioning in healthy relationship, offer such things like natural pollination of crops, clean air, extreme weather mitigation, human mental and physical well-being. Collectively, these benefits are becoming known as 'ecosystem services', and Ecosystem services, natural capital and green economy. The state and social significance of ecosystem services.Â Towards A Sustainable and Genuinely Green Economy. The value and social significance of ecosystem services in Finland (TEEB for Finland). Synthesis and roadmap Jukka-Pekka JÃ¤ppinen and Janne HeliÃ¶lÃ¤ (eds.)Â Considering ecosystem services in policy-making can improve natural resource and land use planning, save financial costs, boost innovative enterprises and other job-creating actions, and enhance sustainable livelihoods nationally, regionally and globally. I sincerely hope that this TEEB for Finland study will encourage many other coun-tries to launch new findings in the field of ecosystem services and human well-being. The indiscriminate and sometimes excessive use of groundwater has led to questions regarding its sustainability. To what extent can groundwater be exploited without unduly compromising the principle of sustainable development? The sustainability of groundwater utilization must be assessed from an interdisciplinary perspective, where hydrology, ecology, geomorphology, and climatology play an important role.