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Groundwater dependent ecosystems. Part II. Ecosystem services and management in Europe under risk of climate change and land use intensification

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ABSTRACT

Groundwater in sufficient amounts and of suitable quality is essential for potable water supplies, crop irrigation and healthy habitats for plant and animal biocenoses. The groundwater resource is currently under severe pressure from land use and pollution and there is evidence of dramatic changes in aquifer resources in Europe and elsewhere, despite numerous policy measures on sustainable use and protection of groundwater. Little is known about how such changes affect groundwater dependent ecosystems (GDEs), which include various aquatic and terrestrial ecosystems above ground and inside the aquifer. Future management must take this uncertainty into account. This paper focuses on multiple aspects of groundwater science, policy and sustainable management. Examples

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of current management methods and practices are presented for selected aquifers in Europe and an assessment is made of the effectiveness of existing policies such as the European Water Framework Directive and the Habitat Directive in practice and of how groundwaters and GDEs are managed in various conditions. The paper highlights a number of issues that should be considered in an integrated and holistic approach to future management of groundwater and its dependent ecosystems.

1. Introduction

Groundwater is undoubtedly one of the greatest providers of life support functions. About 75% of European Union (EU) residents depend on groundwater for their water supply (EC, 2008). Although groundwater and groundwater dependent ecosystems (GDEs) are protected by a number of EU directives, national legislation and environmental action programmes to preserve biodiversity, many GDEs in Europe are under threat and degrading (Boulton, 2005; EC, 2007a,b). An important threat to groundwater services is the lowering of groundwater levels due to aquifer over-exploitation (abstraction), drainage for agriculture, and dewatering due to infrastructure development and mining. Another important threat is diffuse pollution with nutrients, pesticides and heavy metals (Kløve et al., in this issue).

Public awareness of groundwater is still surprisingly poor. Groundwater receives less attention than surface water because it is not visible and the pollution problems are not as obvious as those in surface waters, e.g. dead fish or algal blooms (Boulton, 2005). The role of groundwater in wetlands, streams and other GDEs is often complex and poorly documented. Furthermore, the possible effects of climate change on GDEs are uncertain, partly due to a lack of rigorous studies. Consequently, it is difficult to provide evidence of causal links between an identified pressure (abstraction, pollution) via an 'environmental pathway' to a GDE, given the large variations in residence time, spatial hydrogeological variations and time dependent climatic factors. The GENESIS project was started in 2009 with the goal of bridging some of the knowledge gaps and providing a scientific basis for better future management of groundwater and GDE resources.

In the future management of groundwater resources, GDEs will require special attention (Kværner and Kløve, 2006) and future ecological status assessments of GDEs will have to consider how groundwater is connected to these GDEs (Eamus et al., 2006; Paetzold et al., 2010). In addition, various functions of ecosystems will have to be identified in order to obtain the best management option for future groundwater use. This paper reviews past development of the policy framework and theoretical concepts of sustainable use of groundwater and related ecosystem services, and presents practical examples to identify key knowledge gaps and to demonstrate problems in groundwater resource management. Recommendations are given for integrated groundwater management that takes better account of uncertainty, sustainable use and ecosystem services of GDEs.

2. Policy framework in Europe

2.1. *EU Birds and Habitats Directives*

International policy relating to the protection of habitats initially started as wetland conservation arising from the Ramsar Convention in 1971, which focused on protecting birds and their habitats. This resulted in the EU Birds Directive in 1979 and later in the EU Habitats Directive in 1992 (EC, 1992; EC 2009/147/EC). The latter Directive meant a shift from species protection to habitat protection, which now forms the cornerstone of Europe's nature conservation policy and the protection of GDE. This Directive is built around two pillars, the Natura 2000 network of protected sites and a strict system for species protection. The Directive protects over 1000 animal and plant species and over 200 'habitat types' (e.g. special types of forests, meadows, wetlands, etc.) of European importance. The Directive requires Member States to designate Natura 2000 sites. In 2004 the Directive was adopted by 10 new Member States and in 2007 by two additional Member States.

2.2. *Water Framework Directive*

The European Water Framework Directive (WFD) of 2000 clearly identifies the protection, restoration and enhancement of the water bodies in article 1a: '*The purpose of this Directive is to establish a framework for the protection of inland surface waters, transitional water, coastal waters and groundwater which: a) prevents further deterioration and protects and enhances the status of aquatic ecosystems and, with regard to their water needs, terrestrial ecosystems and wetlands directly depending on the aquatic ecosystems*' (EC, 2000). The WFD specifically mention a subgroup of GDE, i.e. wetlands and Groundwater Dependent Terrestrial Ecosystems GWDTEs. In WFD they are receptors of groundwater and therefore not directly monitored by the WFD. GDE is a more general term and can include small and large aquatic and terrestrial ecosystems. GDEs can be identified itself as a discrete and significant water body and protected directly by WFD, and they can be part of a hydromorphological element, and this sets the condition required for its ecological status (Killroy et al., 2005). The WFD is the most substantial part of the EU water legislation and aims to overcome the fragmentation of European water policy. It requires Member States to designate water bodies (surface, groundwater and coastal) and to reach 'good status' for these by establishing River Basin Management Plans (RBMPs), in

Table 1 – Relevant EU policies and their role in GDE management.

Policy	Overall aim	The role of GDEs and how they are included in the policy
Ramsar convention	Protection of habitats	This agreement provided the first framework for protection of wetlands on a voluntary basis.
Birds directive	Protection or birds	Protect breeding and resting areas of which some are GDE.
Habitats directive	Protection of habitats and biodiversity	Protect valuable habitats of which many are GDE such as wetlands and springs. Natura 2000 sites form a EU-wide network of protected areas.
Water Framework Directive	Sustainable use of water resources and to achieve good surface water quality	WFD Guidance document 12 state: (I) Protect, enhance and restore wetlands identified as water bodies, where this is necessary to support the achievement of good ecological status or potential. (II) Prevent more than very minor anthropogenic disturbance to the hydromorphological condition of surface water bodies at high ecological status including the structure and condition of riparian, lakeshore or inter-tidal zone and hence the condition of any wetlands encompassed by these zones. (III) Establish measures to control and mitigate modifications to the structure and condition of riparian zones within wetlands. (IV) Wetlands could play a relevant role in facilitating the achievement of other WFD requirements concerning protected areas that do not target wetlands directly.
Directive on Groundwater Protection	Achieve good groundwater status, prevent deterioration (quantitative and chemical), prevent or limit the input of pollutants, implement measures to reverse any significant and sustained upward trend in groundwater bodies	GDEs have a central role in since the update of the directive in 2006. Groundwater bodies are classified as poor if GDEs are damaged due to pollution from groundwater or less groundwater due to other groundwater uses. The directive requires to control and remedy anthropogenic alterations to groundwater quality and water levels to the extent needed to ensure that such alterations are not causing (I) significant damage to terrestrial ecosystems that directly depend on groundwater bodies and (II) significant diminution in the chemical or ecological quality of bodies of surface water associated with bodies of groundwater.
Flood Risk Management Directive	Reduce vulnerability to floods	This directive will be implemented in conjunction with the WFD through the coordination of flood risk management plans and RBMPs. Water retention measures are encouraged as an important buffer in the prevention of flooding. This will help to conserve wetlands (and other GDEs).
Climate change (EU white paper)	Reduce vulnerability to the impact of climate change	Actions mentioned include: (I) to address biodiversity loss and climate change in an integrated matter, and to (II) explore the potential for policies and measures to boost ecosystem storage capacity for water. Guidelines should be drafted by 2010 to deal with the impact of climate change on the management of Natura 2000 sites.

which specific environmental objectives and programmes of measures to achieve these are established. The WFD sets groundwater objectives that include obligations towards GDEs. The directives should meet the requirements in protected areas as requested specifically under the Habitats and Wild Birds Directives, and take protective or restorative action in the management of GDEs which are included in the register of protected areas (at least the Natura 2000 sites). The most important obligations of the WFD and its companion Directive on Groundwater Protection (EC, 2006) in relation to GDEs are to achieve good groundwater status and prevent significant damage to terrestrial ecosystems that directly depend on groundwater bodies (Table 1).

Risks to groundwater bodies in terms of both chemical and quantitative status should be assessed (EC, 2010a). For each objective, the risks of not meeting that objective must be assessed. The Source-Pathway-Receptor approach to assess these risks has to be applied at different scales, varying from individual dependent surface water or terrestrial ecosystems to aquifer scale. For GWDTE that depend directly on groundwater, no significant damage should occur to its chemical, quantitative and ecological status. The WFD identifies the need for protection and restoration of wetlands, but does not provide any specific definition of what a wetland is, nor does it provide details on how wetlands should be used to achieve the WFD objectives. Therefore, the role of wetlands in the WFD is explained further in the WFD Guidance document No. 12 (EC, 2003). This guidance is not legally binding, but is the most up-to-date reference document for European wetland policy (EC, 2007b). It mentions several important WFD provisions in relation to wetlands protection and restoration (Table 1). The Guidance Document outlines the best practices beyond the legal requirements of the WFD (EC, 2007b). It was prepared to assist Member States in wetland protection in the implementation of the WFD, EU nature conservation policy and, in particular, the Habitats and Birds Directives.

The WFD aims to achieve sustainable use of water resources and to maintain good ecological status in surface, transitional and coastal waters. It integrates key principles in water policy, such as the involvement and participation of stakeholders, management at the basin scale (with implications for administrative change) and integration of the economic dimension of water management. The WFD requires the application of economic principles (e.g. the 'polluter pays' principle) and the use of certain methods and tools (e.g. cost-effectiveness analysis), as well as the consideration of economic instruments (e.g. water pricing) to achieve the environmental objectives and to aid decision-making (WATECO, 2003; Heinz et al., 2007). However, to date the WFD has not clearly stated the scope that economic analysis should use (Meyerhoff and Dehnhardt, 2007).

2.3. *Adaptation to climate change*

The EC has recognised that its policy on Natura 2000 is a critical climate change adaptation measure because biodiversity will be more resilient to climate change if the ecosystems are in a healthy state, which in turn is vital to human adaptation to climate change. Human prosperity and wellbeing depend on the services that healthy ecosystems supply (EC, 2007a,b; EC, 2009). The EU recognises that resilience and adaptation will require actions outside the Natura 2000 network to enhance connectivity and coherence. Facilitating nature's adaptation to climate change also involves reducing conventional pressures on biodiversity such as intensification of land use, fragmentation of habitats, overexploitation and pollution. In a white paper (EC, 2009), the EC sets out a framework to reduce the EU's vulnerability to the impact of climate change. It requires Member States to present measures on adaptation to climate changes in the 2nd River Basin Management Plans of the WFD. It mentions that the EU is working with other partner countries in the United Nations Framework Convention on Climate Change towards a post-2012 climate agreement, which will address adaptation as well as mitigation. Some actions mentioned in the paper with regard to ecosystems, biodiversity and water (Table 1).

2.4. *Policy and action plans to stop biodiversity loss*

The European Commission agreed upon an EU biodiversity strategy in 1998 and adopted several biodiversity action plans to halt biodiversity loss by 2010 (EC, 2007a,b; EU, 2009a,b). These action plans resulted from a push in favour of nature conservation measures by the EU Member States. Unlike its predecessors, the latest plan does not suggest ambitious laws to protect migrating wild birds and natural habitats, but tries to assign responsibilities concerning the implementation of existing legislation. The latter includes not only the aforementioned Natura 2000, but also the Common Agriculture Policy and Common Fisheries Policies that have recently been reformed to take better account of wildlife, plants and forests. Funding has also been devoted to biodiversity research. LIFE is an important financial instrument of the EC for co-funding projects to support the implementation of EU policy and legislation (Oliver et al., 2005). The Action Plan identifies four priority areas, namely:

- Biodiversity in the EU: Greater commitment from member states to propose, designate, protect and effectively manage sites protected under the Natura 2000 network.
- The EU and global biodiversity: Strengthening coherence and synergies between trade and development cooperation.
- Biodiversity and climate change: Honouring Kyoto commitments and putting in place more ambitious global emissions targets post-2012.
- The knowledge base: Strengthening the European Research Area, its international dimension, research infrastructure, the connection between science and policy and improving comparability of biodiversity data.

In a mid-term assessment of implementation of the EU Biodiversity Action Plan (EU, 2009b), the Council of the EU stressed that biodiversity loss is extremely worrying not only for the important intrinsic value of nature and biodiversity, but also because it results in a decline in ecosystem functions that are essential in providing vital ecosystem services which underpin long-term sustainable development. The positive progress made within the Biodiversity Action Plan is not sufficient to meet the objective, and the Council strongly emphases that significant additional efforts are urgently needed to reverse these trends. It highlights the importance of strengthening the integration of biodiversity and ecosystem concerns into relevant policies and the effective implementation of existing EU policies and legislation to address the biodiversity challenge. The Council urges the EC and Member States to complete the terrestrial part of the Natura 2000 network by 2010. All available opportunities should be used to strengthen biodiversity conservation in rural development under cross-compliance arising from the health check of the Common Agriculture Policy. Conservation and sustainable use of biodiversity and ecosystem services in the outermost regions of Europe that are not covered by EU nature legislation should also be promoted.

2.5. Policies in practice: are they sustainable?

Despite these ambitious and promising policies, action plans and co-funded LIFE projects, the state and trends of GDEs and biodiversity are not in line with the objectives. In 2006, the World Conservation Union added some 530 species to its 'red list' of endangered species, illustrating that biodiversity loss is increasing, not slowing down. Environmental organisations such as the World Wildlife Fund and European Environmental Bureau say that there is 'ample evidence' that environmental protection has been 'politically downgraded' to a side role, to the benefit of the Commission's growth and jobs objectives (Pallemaerts et al., 2006). Greenpeace has pointed out that the EU must not only document and monitor loss of biodiversity, but also review its own destructive policies for their part in the crisis and take the necessary measures to revise them (Greenpeace, 2006). Unfortunately, some EU policy promotes measures that might result in degradation of water resources and GDE. An example of this is that EU promotes the increased use of biofuels, which leads to dramatic land consumption, thus counteracting all efforts to protect biodiversity. Another example are the subsidies for framing in the Common Agricultural Policy.

Most conservation efforts in aquatic ecosystems focus on surface waters, which is understandable given their public visibility, accessibility and stark evidence of their vulnerability to human impact. Groundwater protection and conservation is less common (Boulton, 2005). At Natura 2000 sites with GDEs that are not designated as water bodies, concrete targets on groundwater and related measures to reach these have generally not been established yet. In its mid-term assessment of implementation of the EU Biodiversity Action Plan (EU, 2009a,b), the EU Council noted that about half the species in the European Community and about two-thirds of the habitat types of interest have an inadequate conservation status. Based on this assessment, the EU Committee of the Regions called on the EU, Member States and local and regional authorities to set up a strict system of eco-conditionality for grants and funding. In a policy recommendation, the Committee of the Regions states that the Natura 2000 network sites need to be consolidated in most countries. The poor quality of the scientific reference data undermines any efforts to assess the extent to which such Natura 2000 land sites meet the criteria of the Habitats and Birds Directives. The Committee of the Regions also asks Member States to assume their responsibilities for marine areas and groundwater in this regard and stresses that tailor-made management plans for Natura 2000 sites need to be drawn up and implemented.

3. Sustainability concepts and methods for groundwater and GDEs

According to the Bruntland Report[1] sustainability refers to as 'a development, which enables present generations to satisfy their needs without threatening the ability of future generations to satisfy theirs'. For groundwater, sustainability has been regarded as a question of how much can be used compared with recharge. In recent decades resource management has also focused on how to (I) prevent pollution inputs, (II) keep contaminant concentrations to a safe level, and (III) reverse pollution trends. This has been motivated by drinking water standards and human health and by increasing risk of pollution. For GDE management, both water quantity and quality are important to maintain habitat and biodiversity (Kløve et al., in this issue).

[1] The term sustainable use is older and was used e.g. by Hans Carl von Carlowitz as early as 1713.

3.1. Safe yield concept

The term *safe yield* is an old concept used in efforts to quantify sustainable groundwater resource development. There have been several definitions of the concept of safe yields by different authors (Lee, 1915), considering storage, economic feasibility, water quality and water rights (Alley and Leake, 2004). Todd (1959) broadened the definition of safe yield for groundwater as 'the amount of water that can be withdrawn from a groundwater basin annually without producing an undesired result'. The concept of considering groundwater resource development as 'safe' if the average annual rate of withdrawal does not exceed the average annual rate of natural recharge is usually not as sound as is believed, especially during long-term climatic fluctuations and when GDEs are considered (see Sophocleous, 1997). Groundwater sustainability indicators such as use/percolation are discussed by Lavapuro et al. (2008).

Alley and Leake (2004) suggest that groundwater sustainability should concern the long-term effects of groundwater resource development. In addition to this, values of properties that relate to sustainability of a groundwater system at a given point in time may change with time. Groundwater extraction that is considered sustainable today may be considered unsustainable in the future due to stricter environmental concerns about the discharge rates to GDEs.

3.2. Environmental flow and ecosystem water requirements

Quantification of environmental water requirements (EWRs) is a promising method devised to ensure sustained streams of ecosystem goods and services related to water quantity and quality at safe minimum standards for the protection of ecosystem structure and function in both natural and socio-economic systems. Studies about the determination of EWRs for rivers, in particular in terms of fisheries, were initiated in the 1970s. However, recent attempts have been made to take into account other biota, biogeochemical cycles, trophic dynamics and biological productivity and diversity, including in GDEs (e.g. Brown et al., 2007).

Some key issues when determining EWR in a given space and time are listed below:

- Advanced capabilities by remote sensing, geographical information systems and process-based hydrological models should be integrated to fill the knowledge gap about the EWR dynamics of GDEs in response to interactive changes in groundwater attributes, and human-induced disturbances including global climate change.

- Restoration and rehabilitation of damaged GDEs can play a crucial role in sustaining steady state between EWRs by wildlife and socio-economic systems and water supply at safe minimum qualities and quantities of water in a way that all stakeholders are involved in the local process of decision-making.
- The precautionary principle requires that actions towards management practices and scientific research and outcomes should be linked by feedback mechanisms that promote adaptive measures in the face of unavoidable uncertainties.

3.3. Economic valuation

The overall objective of public policy is to maximise societal welfare over time from efficient natural resource use, despite externalities that may arise. The key objective of this policy is the allocation of resources in an efficient, sustainable and equitable manner. The impact of this policy should be the establishment of the resulting distribution of costs and benefits to society in such a way that social ideals are satisfied. Due to the public good aspect of groundwater quality, its other values are ignored in environmental policing and rational public decision making on financing preservation or improvement. Therefore, it is essential that the economic benefits of groundwater are clearly identified and valued. In other words, as the social opportunity costs and external costs of extracting groundwater are not reflected in market prices at all, non-monetary approaches to evaluate and suggest how these values and costs (scientific, economic, social and cultural) should be integrated in water resource management policies need to be developed.

A framework widely used for the valuation of natural resources is the total economic value. It comprises not only use and non-use values but also indirect use values (Turner et al., 2003). Groundwater use values can be direct (commercial and recreational) in that groundwater, when abstracted, functions as an input into economic sectors, such as water supply, recreation and irrigation (WATECO, 2003). This kind of value could be easy to measure with a market value. As groundwater generally supports ecosystems, there can be a number of indirect values as well. Groundwater extraction can have an indirect impact on e.g. certain surface waters and soil subsidence, (WATECO, 2003). In addition to these use values there is an option value, which reflects direct or indirect potential future uses of groundwater, e.g. the future value of biodiversity. Option values may depend on uncertainty over future resource demand and supply, while there is insufficient knowledge on whether and when the good is actually consumed. The non-use values of groundwater consist of existence values, derived from the demand to preserve groundwater in its natural state without any intention of using it whatsoever. Bequest and altruistic value categories capture the value individuals place on leaving groundwater resources intact for the use of others. In the case of bequests the use is destined for future generations, while altruistic value categories express specific concerns about whether groundwater resources are still available to other people living today (Görlach and Interwies, 2003). Two main categories of non-market valuation methods are used for eliciting the abovementioned values of groundwater: revealed preference and stated preference approaches. Both of these can often be time-consuming and costly to use (WATECO, 2003), but are appropriate to provide solutions to environmental issues that raise specific problems.

The concept of ecosystem services is used in sustainable resources management. Generally ecosystem services tend to fall into the categories of open access and pure public services. This means that they tend to have no producer property rights, ambiguous entitlement structures and prohibitive transaction costs. Aquifers have traditionally represented a classic example of a common pool resource. Collective action by groundwater users could solve the problems that common aquifers face under certain conditions (Schlager, 1995). Lopez-Gunn and Martinez-Cortina (2006) analysed the decisive role of collective actions by groundwater user associations in sustainable groundwater management in a comparative study applied to the three main aquifers in the central Mancha region, Spain. They concluded that while solutions such as subsidies and payments can help mitigate aquifer overuse and temporarily protect GDEs, these are not a long-term option (economically or sustainably) without sound institutional design of water use organisations, favouring self-governance. Valuation of ecosystem services can improve understanding of problems and trade-offs, can be used directly to support decision making, can illustrate the distribution of benefits and thus facilitate cost-sharing for management initiatives and can create market instruments that promote sustainable ecosystem management (Chee, 2004). The concepts of ecosystem services and natural capital can help us recognise the many benefits that nature provides. From an economic point of view, the flows of ecosystem services can be seen as the 'dividend' that society receives from natural capital. Maintaining stocks of natural capital allows the sustained provision of future flows of ecosystem services, and thereby helps to ensure enduring human well-being (TEEB, 2010).

4. Ecosystem services

Ecosystem services are the conditions and processes through which natural ecosystems and their constituent species sustain human life. According to the Millennium Ecosystem Assessment (MEA, 2005), ecosystem services are the benefits people obtain from ecosystems, and therefore the full range of benefits related to human well-being must be represented in any effective description of ecosystem services. The well-being of every human population in the world is fundamentally and directly dependent on ecosystem services (TEEB, 2008). An ecological understanding of the value of GDEs must be complemented with an awareness of the economic and social impacts of groundwater modification. This can be achieved through a multidisciplinary approach which links environmental, economic and social assessment (Danielopol et al., 2003).

Ordinary resource users may be unable to identify ecosystem functions directly, but rather recognise them through the goods and services they produce and can be assessed in economic, ecological and socio-cultural terms. These include

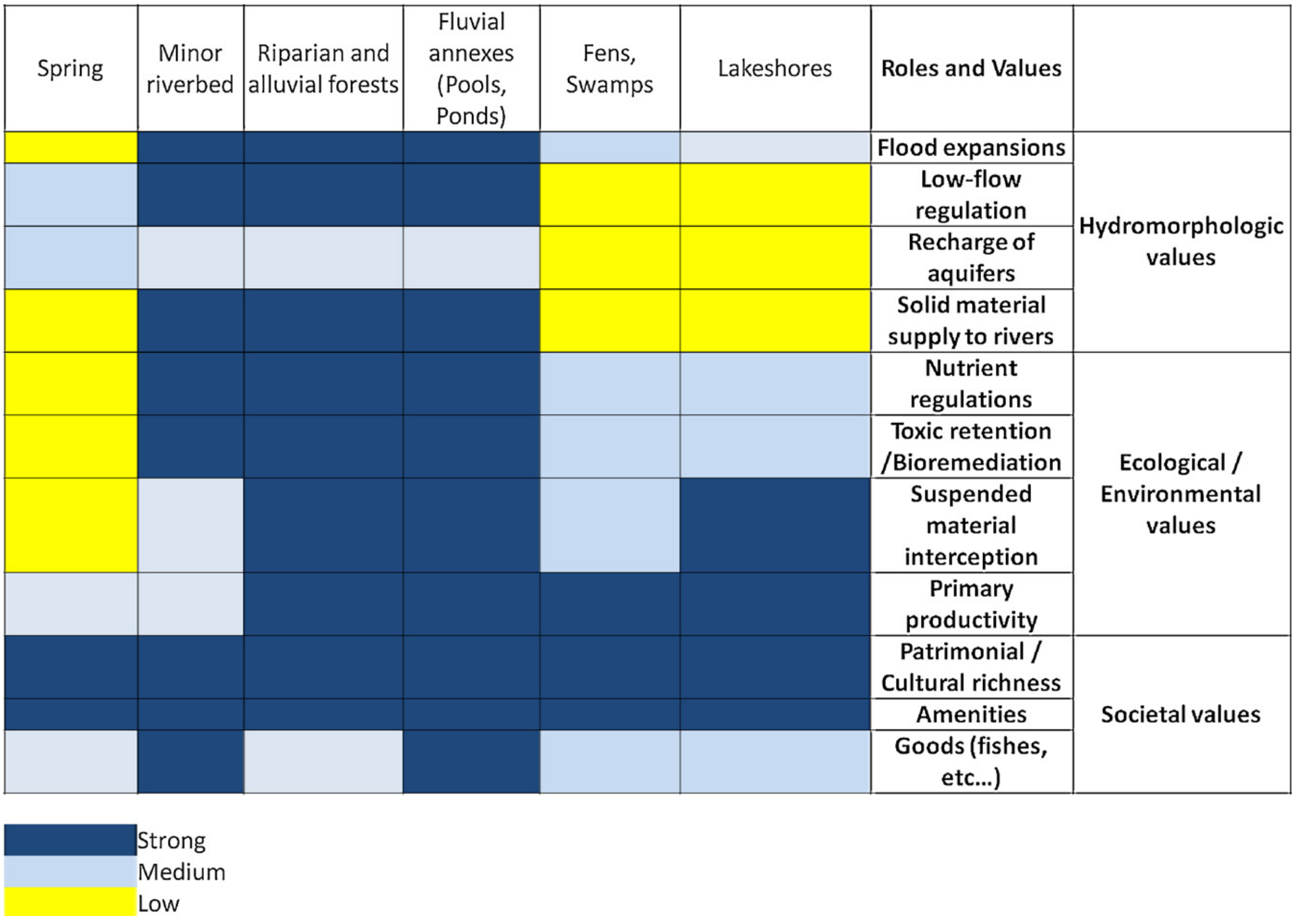

Fig. 1 – Roles and values of GDEs.

provisioning services such as food, water, timber and fibre; *regulating services* that affect climate, floods, disease, wastes and water quality; *cultural services* that provide recreational, aesthetic and spiritual benefits; and *supporting services* such as soil formation, photosynthesis and nutrient cycling (MEA, 2005).

GDEs provide valuable services for human populations. Ecosystems dependent on groundwater at or close to the surface, including rivers and streams, wetlands, flood plains, springs, estuaries, and lagoons, are of particular concern since they are crucial contributors to biodiversity and ecological productivity. They serve for flood control and mitigation; regulate runoff and water supply; improve the quality of surface waters and groundwater; withhold sediments, reduce erosion, stabilise river banks and shorelines and diminish the risk of landslides; improve water infiltration and support water storage in the soil; facilitate groundwater recharge; and improve drainage conditions and natural irrigation. The services or values delivered depend on GDE type (Fig. 1).

The functions and systems dependent on the subsurface presence of groundwater include GDEs, maintenance of global and local air quality, carbon dioxide sequestration, commercially important populations, breeding sites for game stocks, productive soils and arable land, as well as provision of building materials, energy and mineral resources (MEA, 2005; Boulton et al., 2008).

Aquifer and cave ecosystems, including karst, fractured rock and alluvial aquifers, and hyporheic zones of rivers and flood plains play a role in nutrient cycles through the storage, recycling, processing and acquisition of nutrients. For example, subsurface microorganisms recycle nutrients that are important in secondary productivity (Goldscheider et al., 2006). Biological compartments also provide an important ecosystem service in the form of water purification and waste treatment through microbial degradation of organic compounds and potential human pathogens. GDEs also provide cultural services, such as recreational, aesthetic, spiritual and educational benefits.

Groundwater is closely connected to surface water resources. Any pressure on groundwater may have a strong impact on the capacity of the dependent ecosystems to provide services. Water discharge from aquifers maintains and sustains river flows, springs and wetlands, especially during dry season and droughts. Thus, overexploitation of groundwater for irrigation or other usage may dry up wetlands, resulting in the collapse of the whole ecosystem, an increase in salinity and a decline in connected activities. Disruption or changes to regulating services (e.g. water regulation, water purification and waste treatment, climate

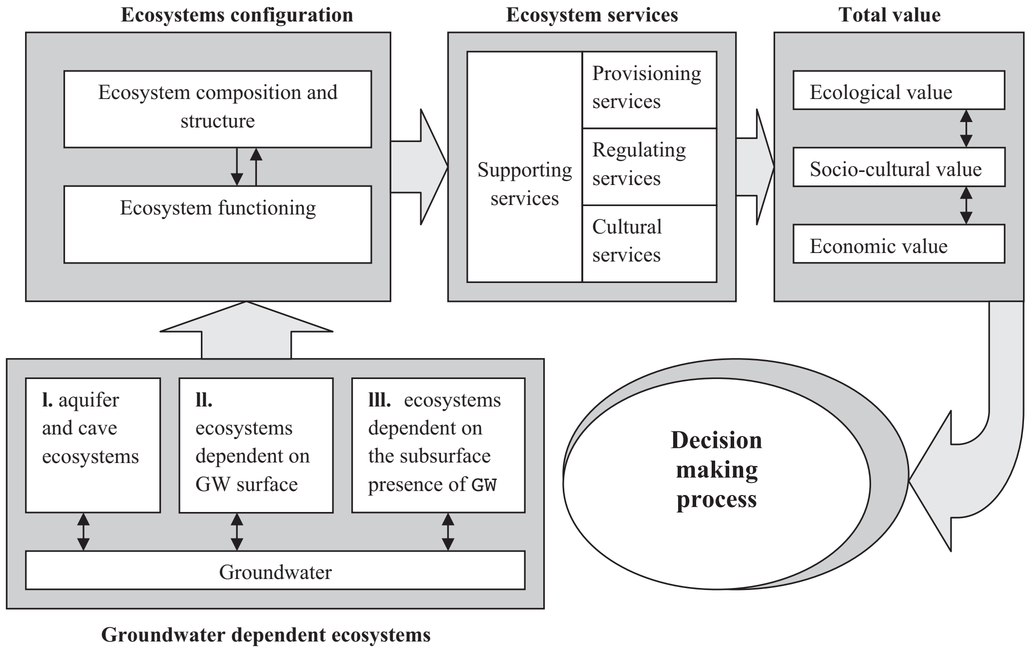

Fig. 2 – Framework for integrated assessment of GDE services (adapted after de Groot et al., 2002; MEA, 2005).

regulation) can have a major impact on groundwater, including a long-term decline in water storage, increased frequency and severity of groundwater droughts, groundwater-related floods, mobilisation of pollutants due to seasonally high watertables and saline intrusion in coastal aquifers due to sea level rise and resource reduction.

The interdependencies between ecosystem services provided by GDEs and groundwater are poorly recognised in decision making and management of water resources. The challenge lies in improving understanding and awareness of the linkages and incorporating these into decision making and management (Fig. 2).

5. Groundwater resources and GDE management in practice

Besides local and EU policy, the management of European groundwater resources is dependent on (I) past traditions and knowledge, (II) hydrogeology, (III) climate, (IV) land use pressures, (V) trends in water supply, and (VI) water scarcity. Some cases in Europe (Fig. 3) were reviewed for the GENESIS project (see additional material). Typical threats in Europe include leaching of nitrate and pesticides from agriculture. The increased production of biofuels will aggravate these threats. Leaking sewage pipes, particularly in urban areas, can also introduce nitrates and other contaminants. Nitrates are posing risk to at least 478 groundwater bodies in Europe and cause poor status of at least 504 groundwater bodies (EC, 2010b). Pesticides also pose a major threat and limits have been exceeded in some cases. Pollution threats in cold climate represent a special case, with a low rate of degradation and special conditions for focused recharge from snow melt. In coastal conditions salt water intrusion is a major threat, especially after severe groundwater level decline due to pumping for irrigation. Also population increase along the cost and tourism is an increased pressure in the Mediterranean region. GDEs were generally not well incorporated in the first RBMPs. Knowledge of pollutant pathways and conceptual models for pollutants are important for correct management actions. However, such models are lacking e.g. for emerging pollutants.

Two GENESIS cases are presented in the following sections to illustrate policy, management and regional aspects in groundwater and GDE management and decision making.

5.1. *The Mancha Occidental aquifer, Spain*

Conflicts between intensive groundwater use and GDE conservation are widespread throughout arid and semiarid regions. In some cases, groundwater depletion by intensive irrigation has led to the degradation of valuable wetland ecosystems and/or the salinisation of soil and groundwater. A remarkable example can be found in the western part of the La Mancha region (Fig. 3), a central plateau in Spain. In this area, farm subsidies (through programmes in the former EU Common Agricultural Policy) encouraged the expansion of irrigation, with positive social and economic effects, but leading to overexploitation of the large aquifer and subsequent degradation of the dependent wetland ecosystems, including the Ramsar-listed National Park 'Tablas de Daimiel'. Different wetland restoration policies have been implemented over the past two decades (Martinez-Santos et al., 2008). While national policies have focused on a *command-and-control* approach (legal bans and obligations on water users, by legal declaration of aquifer overexploitation), regional government and EU policy have focused on compensatory payments to encourage farmers to cut down water use.

Fig. 3 – Map of GENESIS sites.

In order to mitigate the effects of intensive pumping, the Guadiana Water Authority approved the official declaration of aquifer overexploitation in 1991, including a legal obligation on groundwater user associations, yearly pumping restrictions, and a ban on drilling new wells. Water quotas were controlled mostly by water meters. However, pumping restrictions were very difficult to control and enforce (there are currently about 40,000 pumping wells in the area), and illegal pumping became rampant as soon as farmers realised that the Water Authority lacked the resources to enforce its own regulations (Martinez-Santos et al., 2008). Given the limited success of compulsory pumping restrictions and their potential effect on farm income, the Regional Government launched an Agro-Environmental Plan in 1992, mostly funded by the EU, which granted income compensation payments in return for a reduction in farm water use. The programme had a larger impact than foreseen and was able to achieve its environmental and socio-economic objectives, although it has been criticised for being funding-intensive, as well as for providing a quick fix to the problem rather than instituting lasting changes in the irrigation sector (Fornés et al., 2000). An important effort to include active stakeholder participation within the new context of the EU WFD gave rise to a new Special Plan for the Upper Guadiana basin in 2006.

This case study shows that, unlike policies relying only on pumping quotas, which are very difficult to enforce, water conservation policies that include a quota system and a compensation scheme can achieve the conservation target, provided that the compensation payment is attractive to farmers and sufficient to compensate their income losses. However, these policies can be costly and are in conflict with the WFD requirement of cost-efficient policies for meeting the good status of all water bodies and the cost recovery of water services. Water pricing policies can also be an effective instrument to induce water conservation strategies. For simulating the impacts and effects of alternative policies, valuation of water productivity and estimation of the water demand functions for different uses are essential.

Blanco-Gutierrez et al. (2011) have explored the environmental and socio-economic impacts of alternative water conservation measures at the farm and basin levels, analyzing their comparative cost-effectiveness. Aggregate results show that net social costs are not substantially different across policy options. However, there are important differences between private and public costs (at farm and subbasin level), which may influence the political viability of the various options. This leads to the conclusion that the most cost-effective water management policy would be the establishment of a water pricing system: uniform volumetric and blockrate water pricing schemes have the lowest public costs (−314.5 and −210.5 €/ha respectively), but entail the highest private costs (399.8 and 295.8 €/ha respectively). Water tariffs would induce substantial water savings, especially in large crop-diversified farms, promoting the recovery of the aquifer, but also would bring substantial income losses upon small farms with rigid cropping patterns (Blanco-Gutierrez et al., 2011). According to this study, the water use quota system is the most costly water management policy: the highest net social cost (86.9 D/ha) and highest public cost (−89.8 €/ha). In between, the water market policy instrument has a net social cost of 85.8 €/ha, but entails the lowest private cost (176.5 €/ha).

5.2. *The Viinivaara and Rokua esker aquifers in Finland*

In large parts of the Fenno-Scandian shield, the most common aquifers are glacifluvial deposits. Due to these local geological conditions, several thousand groundwater bodies in Finland and Sweden have been delineated as part of the EC Directive work. These sand and gravel ridges form eskers and deltas that are the main source of groundwater. Use of groundwater is increasing and already represents 60–70% of drinking water consumption in Finland. This is due to the higher quality of groundwater and new demands on water safety plans that require several sources of potable water in order to achieve the highest safety standard.

In the Oulu region, the main conflict in groundwater use is related to the Viinivaara and Rokua eskers. Viinivaara is planned to be the main water source for the city of Oulu in the future. The esker discharges into a Natura 2000 peatland (fen) and to several headwater streams relying on groundwater. The main impact of future groundwater use will be on these GDEs, local wells, streams and a valuable ‘kettle’ lake lying above the aquifer. Different scenarios were considered in the environmental impact assessment for water extraction and as a result of this process the planned pumping intensity was moderated to reduce the environmental impact. The permit has finally been approved after several years of processing in the legal system, as the extraction will impact on the Natura 2000 fen. As compensation for decreased low flow, some small-scale reservoirs are planned, but this water is not of the same quality as groundwater. Local residents are strongly against groundwater use as they fear environmental impacts to the adjacent Nuorittajoki river, which is already heavily affected by peat harvesting. Former misuse of the catchment with severe consequences is partly the reason for the public mistrust of the environmental protection and decision making processes.

Another interesting and typical case for the region is the Rokua aquifer, the largest groundwater body in Finland with a 92 km^2 recharge area, aquifer depth around 30–80 m consisting of sand and a local deposits of gravel. The entire esker is protected in Natura 2000 and includes a nature reserve, national park. Recently the area was introduced as a member of the UNESCO GeoPark Network. It is a very popular recreation area and holiday resort. Several hotels and hundreds of summer cottages are located in the area. The site has exceptional recreational values, with crystal clear lakes and unique nature. In Rokua especially cultural ecosystem services are valued; the services that provide recreational and aesthetic benefits for the hikers and the cross-country skiers, for example, in a unique hilly forest landscape. Economic impacts of annual 100,000 visiting tourists for the local economy are significant, but the challenge is to in the same time to protect vulnerable habitats and sand erosion in particular. The landscape, geology and ecosystems of the Rokua esker area also offer information benefits for research and education. The area represents unique dune formations caused by wind, fluvial and coastal currents, and deep depressions and kettle lakes formed by preferential melting of ice.

As in most eskers, the system is unconfined and discharges into peatlands that confine the groundwater. These peatlands have been used for agriculture, forestry and peat extraction. Past protection of the site covered only the unconfined sand ridge, so drainage was allowed on the confined part of the esker. Drainage for forestry was supported by government subsidies and was conducted on a large scale in the period 1950–1980. The severe environmental impacts were detected later. For example, impacts on spring ecosystems caused by drainage have been noted (for references see Kløve et al., in this issue). At Rokua, lake declines were observed after a drought in the 1980s and also after later drought periods. The key question is whether this decline and variation in lake level is due to drainage or climate variation. As the climate in the past decade has been wet, it seems reasonable to assume that forest drainage is the cause of the reduced water levels. This case illustrates how lack of data can result in huge uncertainty. In Finland, good series of data exist for climate, river flow and snow cover, but downscaling to local conditions is difficult. Land use records are also sparse. Due to several aspects of uncertainty the precautionary principle should be used until more scientific evidence is available.

Even though more research is needed in order to better understand the extent and the nature of the problem, scientific observations give sufficient evidence that a policy to mitigate a possible future environmental deterioration is needed. However, decision making in groundwater management protection is complex because of heterogeneous stakeholder interests, multiple objectives, and uncertain outcomes. Conflicting stakeholder interests in particular are often an important impediment to the realisation and success of any regulations and policies. Therefore, the GENESIS project aims to study and develop groundwater management. In Rokua case this is done by applying methods of legal studies, economics, and sociology. We, for example, apply valuation techniques to assess the benefits of groundwater quality improvement, and conduct a multi-criteria decision analysis

(MCDA) as a mean to overcome the difficulty and complexity in including all stakeholders' interests, socio-economic objectives and various constraints in analyzing management decisions. MCDA is a well structured and transparent method to gather, integrate and present different kind of information from different disciplines, to evaluate alternatives systematically, to identify key trade-offs and to incorporate stakeholders' preferences (Belton and Stewart, 2002).

6. Conclusions

Groundwater provides valuable services for humans and ecosystems. It is also a major source of potable water and crop irrigation. The use of groundwater has impacts on ecosystems relying on groundwater, a fact that has received little attention thus far. For groundwater impact assessment in the future, significant impacts on ecosystems need to be included. The overall role of groundwater for both aquatic and terrestrial systems also needs to be better understood. This includes the role of groundwater in the hydrological cycle, and in specific ecosystems such as rivers, lakes and wetlands. More exact information is needed on the hydraulic contact mechanism between surface water, terrestrial ecosystems and groundwater. Special attention should be paid to the role of climate variability and change on spatial and temporal distribution of recharge, discharge and temperatures in GDEs. This knowledge is needed to protect and manage the various services that groundwater provides to both ecosystems and society. Currently most monitoring programmes focus on rivers, lakes and groundwater. GDEs should also be included in national monitoring networks and future monitoring should be carried out at the ecosystem scale. An ecological understanding of the value of GDEs must be complemented with an awareness of the economic and social impacts of groundwater modification. This will only be achieved through a multidisciplinary approach which links environmental, economic and social assessment and management.

Despite the development of new legislation, GDEs are at risk from land use and climate change. Groundwater resources have generally not been managed in an integrated way to date, because aquifer systems are difficult to observe. Aquifers are all different and complex, while their responses on impacts are slow as residence times are long. Lack of knowledge is partly also due to lack of long-term monitoring programmes. This is especially true for GDE and groundwater pollution. Efficient pollution management to determine impact and response, e.g. with mathematical modelling, requires time series of data on land use practices and fertiliser use, which are often lacking. Sustainable management is often in conflict with fundamental uses of potable water and food production. The increased production of so-called 'biofuels' further aggravates these conflicts. On the other hand, the value of other ecosystem services, such as recreation and tourism, has become very important. Consequently, the management of groundwater and its dependent ecosystems should better consider the total economic value.

Ecosystem services that GDEs provide for humans, including food production, water purification and recreation, are at serious risk of being lost. Effective management of GDEs and their ecosystem services requires prioritisation of the most valuable ecosystems. In some cases the losses may be irreversible, or at least difficult and costly to reverse. The integration of natural and social sciences can contribute to an increased holistic understanding of relevant processes and problems associated with GDE management and help to design consistent policies. This management approach is based on new technologies for sustainable groundwater exploitation, considering their support capacity and interactions with dependent ecosystems at wider spatial scales (watershed, national and EU scale), as well as involvement of stakeholders in the management and decision making processes. The approach also involves consideration of the socio-economic implications of different policies and a significant effort to educate the main water users and the general public to embrace the overall importance of wetlands and other GDEs.

It is important to note that the use of water resources, including groundwater resources, cannot be developed without affecting the natural environment. Groundwater use should not be defined as either safe or sustainable without carefully analyzing and explaining the assumptions about the acceptable long-term effects of groundwater resource development on the environment.

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REFERENCES

Alley, W.M., Leake, S.A., 2004. The journey from safe yield to sustainability. Ground Water 42, 12–16.
Belton, V., Stewart, T.J., 2002. Multiple Criteria Decision Analysis: An Integrated Approach. Kluwer Academic Publishers.
Blanco-Gutierrez, I., Varela-Ortega, C., Flichman, G., 2011. Cost-effectiveness of groundwater conservation measures: a multi-level analysis with policy implications. Agric. Water Manage. 98 (4), 639–652.
Boulton, A.J., 2005. Chances and challenges in the conservation of groundwaters and their dependent ecosystems. Aquat. Conserv. 15, 319–323.
Boulton, A.J., Fenwick, G.D., Hancock, P.J., Harvey, M.S., 2008. Biodiversity, functional roles and ecosystem services of groundwater invertebrates. Invertebr. Syst. 22, 103–116.
Brown, J., Wyers, A., Aldous, A., Bach, L., 2007. Groundwater and biodiversity conservation: a methods guide for integrating groundwater needs of ecosystems and species into conservation plants in the Pacific Northwest. In: The Nature Conservancy Report. The Nature Concervacy, p. 176.
Chee, Y.E., 2004. An ecological perspective on the valuation of ecosystem services. Biol. Conserv. 120, 549–565.
Danielopol, D.L., Griebler, C., Gunatilaka, A., Notenboom, J., 2003. Present state and future prospects for groundwater ecosystems. Environ. Conserv. 30, 104–130.

de Groot, R.S., Wilson, M.A., Boumans, R.M.J., 2002. A typology for the classification, description and valuation of ecosystem functions, goods and services. Ecol. Econ. 41, 393–408.
Eamus, D., Froend, R., Loomes, R., Hose, G.C., Murray, B.R., 2006. A functional methodology for determining the groundwater regime needed to maintain the health of groundwater-dependent vegetation. Aust. J. Bot. 54, 97–114.
EC, 1992. Council Directive 92/43/EEC on the conservation of natural habitats and of wild fauna and flora. OJ L 206, 22.7.1992, p. 7.
EC, 2000. Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for Community action in the field of water policy. OJ L 327, 22.12.2000, p. 1.
EC, 2003. Guidance Document No 12. Horizontal Guidance on the Role of Wetlands in the Water Framework Directive. European Communities, Luxembourg.
EC, 2006. Directive 2006/118/EC of the European Parliament and of the Council on the protection of groundwater against pollution and deterioration. OJ L 372, 27.12.2006, p. 19.
EC, 2009/147/EC. Directive 2009/147/EC of the European Parliament and of the Council of 30 November 2009 on the conservation of wild birds. 26.1.2010. Official Journal of the European Union, p. 25.
Ec, 2007a. Natura 2000 newsletter number 22.
EC, 2007b. European Commission DG Environment, LIFE and Europe's wetlands, Restoring a vital ecosystem. LIFE III EC, Luxembourg.
EC, 2008. Groundwater Protection in Europe, p. 35.
EC, 2009. WHITE PAPER, Adapting to climate change: towards a European framework for action. Brussels, COM (2009) 147/4.
EC, 2010a. 'Common implementation strategy for the water framework directive (2000/60/EC); Guidance document No. 26: Guidance on risk assessment and the use of conceptual model for groundwater'.
EC, 2010b. Report from the commission in accordance with Article 3.7 of the Groundwater Directive 2006/118/EC on the establishment of groundwater threshold values, Brussels, 5.3.2010 C(2010) 1096 final, p. 10.
European Union, Council (EU), 2009a. 'A mid-term assessment of implementing the EU Biodiversity Action Plan and Towards an EU Strategy on Invasive Alien Species'. Brussels, 25 June 2009, 11412/09.
European Union, Committee of the Regions (EU 2009b). 'Opinion of the Committee of the Regions on a new impetus for halting biodiversity loss'. 80th plenary session 17–18 June 2009, DEVE-IV-039.
Fornés, J., Rodríguez, J.A., Hernández, N., Llamas, M.R., 2000. Possible solutions to avoid conflicts between water resources development and wetland conservation in the 'La Mancha Húmeda' biosphere reserve (Spain). Phys. Chem. Earth Part B 25, 623–627.
Goldscheider, N., Hunkeler, D., Rossi, P., 2006. Review: microbial biocenoses in pristine aquifers and an assessment of investigative methods. Hydrogeol. J. 14, 926–941.
Greenpeace, 2006. Press release May 22, 2006. http://www.greenpeace.org/eu-unit/press-centre/press-releases2/plan-to-preserve-life-will-nee-2 from www April 2011.
Görlach, B., Interwies, E., 2003. Economic Assessment of Groundwater Protection: A Survey of the Literature. Ecologic, Berlin.
Heinz, I., Pulido-Velazquez, M., Lund, J.R., Andreu, J., 2007. Hydro-economic modeling in River Basin Management: implications and applications for the European Water Framework Directive. Water Resour. Manage. 21, 1103–1125.
Kløve, B., Ala-aho, P., Guillaume, B., Boukalova, Z., Ertürk, A., Goldscheider, N., Ilmonen, I., Karakaya, N., Kupfersberger, H. Kværner, J., Lundberg, A., Mileusnić, M., Moszczynska, A., Muotka, T., Preda, E., Rossi, P., Siergieiev, D., Šimek, J., Wachniew, P., Widerlund, A. Groundwater dependent ecosystems. Part I. Hydroecological status and trends. Environ. Sci. Policy, in this issue.
Kværner, J., Kløve, B., 2006. Tracing sources of summer streamflow in boreal headwaters using isotopic signatures and water geochemical components. J. Hydrol. 331, 186–204.
Lavapuro, M., Lipponen, A., Artimo, A., Katko, T.S., 2008. Groundwater sustainability indicators: testing with Finnish data. Boreal Environ. Res. 13, 381–402.
Lee, C.H., 1915. The determination of safe yield of underground reservoirs of the closed basin type. Trans. Am. Soc. Civ. Eng. 78, 148–251.
Lopez-Gunn, E., Martinez-Cortina, L., 2006. Is self-regulation a myth? Case study on Spanish groundwater user associations and the role of higher-level authorities. Hydrogeol. J. 14, 361–379.
Martinez-Santos, P., de Stefano, L., Llamas, M.R., Martinez-Alfaro, P., 2008. Wetland restoration in the Mancha Occidental Aquifer, Spain: a critical perspective on water, agricultural, and environmental policies. Restor. Ecol. 16, 511–521.
MEA, 2005. Millenium ecosystem assessment. In: Ecosystems and Human Well-being: Biodiversity Synthesis, World Resources Institute, Washington, DC.
Meyerhoff, J., Dehnhardt, A., 2007. The European Water Framework Directive and economic valuation of wetlands: the restoration of floodplains along the River Elbe. Eur. Environ. 17, 18–36.
Oliver, M., Sorkin, L., Kaschl, A., 2005. Science and policy interface: the LIFE programme and its links to the EU Water Framework Directive. Environ. Sci. Policy 8, 253–257.
Paetzold, A., Warren, P.H., Maltby, L.L., 2010. A framework for assessing ecological quality based on ecosystem services. Ecol. Complexity 7, 273–281.
Pallemaerts, M., Wilkinson, D., Bowyer, C., Brown, J., Farmer, A., Farmer, M., Herodes, M., Hjerp, P., Miller, C., Monkhouse, C., Skinner, I., ten Brink, P., Adelle, C., 2006. Drowning in Process? In: The Implementation of the EU's 6th Environmental Action Programme Report for the European Environmental Bureau. IEEP, London, p. 67.
Schlager, E., 1995. Policy making and collective action: defining coalitions within the advocacy coalition framework. Pol. Sci. 28, 243–270.
Sophocleous, M., 1997. Managing water resources systems: why "safe yield" is not sustainable. Ground Water 35, 561.
Todd, D.K., 1959. Groundwater Hydrology. John Wiley Pub., New York.
TEEB, 2008. The Economics of Ecosystems and Biodiversity: An interim report.
TEEB, 2010. The Economics of Ecosystems and Biodiversity: Mainstreaming the Economics of Nature: a synthesis of the approach, conclusions and recommendations of TEEB.
Turner, R.K., Brouwer, R., Crowards, T.C., Georgiou, S., 2003. The economics of wetland management. In: Turner, R.K., van den Bergh, J.C.J.M., Brouwer, R. (Eds.), Managing Wetlands. An Ecological Economics Approach. Elgar, Cheltenham, pp. 73–107.
WATECO, 2003. Guidance Document No 1. Economics and the Environment—The Implementation Challenge of the Water Framework Directive. European Communities, Luxembourg.