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Protection of groundwater dependent ecosystems: current policies and future management options

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Abstract

Groundwater dependent ecosystems (GDEs) include many terrestrial and aquatic systems with high biodiversity and important ecosystem services. The need for protection of these systems has recently received increasing recognition in many regions, including the European Union (EU), as pressures on groundwater are increasing due to increased consumption in agriculture and intensive land use. A key issue is to provide legislative frameworks that safeguard the ecosystem services these systems provide. This paper reviews European legislation and present methods for theoretical frameworks, and hydrological and ecological observations of GDEs. Insights into the current state of research are provided and gaps in scientific knowledge identified. Different restoration and protection measures, such as buffer zones, are presented and evaluated. Recommendations are given for the future protection of GDEs. Future research should focus on nationally important GDE sites to establish conceptual models describing the individual and interactive impacts of multiple stressors on the hydrological and ecological functioning of GDEs. Proactive management is required to protect GDEs from contamination, for example by using extended buffer zones and careful land use planning in the groundwater capture zone.

Keywords: EU legislation; GDE; Groundwater Directive; Habitat Directive; Water Framework Directive

1. Introduction

Groundwater resources are facing increasing pressure from irrigation and extraction, which have resulted in reduced groundwater levels (Wada *et al.*, 2010), with a decline of up to 100 m in some

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important aquifers in Europe, the USA and Asia (e.g. Bartolino & Cunningham, 2003). In Europe, 30% of groundwater bodies are of poor status, with nitrate concentrations above 50 mg/L being the main cause of pollution (European Commission (EC), 2010). Besides the effects of agriculture, groundwater is contaminated by pollutants from a range of potential sources (Balderacchi *et al*., 2013). Intensive land use and groundwater exploitation or drainage have led to deterioration of springs (e.g. Howe, 2002), coastal wetlands (Halvorson *et al*., 2003), lagoons (Sousa *et al*., 2009), headwater lakes and peatlands (Kværner & Snilsberg, 2008).

Groundwater dependent ecosystems (GDEs) comprise a range of ecosystems from inland to marine ecosystems. They can be divided roughly into ecosystems residing in aquifers and caves and those dependent on surface or subsurface expression of groundwater (Eamus *et al*., 2006). GDEs comprise a range of ecosystems such as springs, rivers and wetlands (e.g. Kløve *et al*., 2011a, b). The ecosystem dependency on groundwater can be seen as high water level, flow in dry seasons and distinct water quality and vegetation cover (Orellana *et al*., 2012). In an EC policy context, GDEs are grouped as terrestrial (GWDTE) and aquatic (GWDAE). The Ramsar (1971) treaty classifies most surface water as wetland and reviews the role of groundwater in various ecosystems. In general, GDEs can be grouped into four main types: terrestrial ecosystems, wetlands, aquatic ecosystems and subterranean ecosystems (Table 1).

There is rapidly growing interest in the conservation and restoration of GDEs, as they provide valuable ecosystem services and unique biodiversity (Boulton, 2005). Important services include, for

Table 1. Main types of groundwater dependent ecosystems (GDE) and the role of groundwater in their functioning.

Ecosystem type	Role of groundwater in GDE hydrology and ecology
Terrestrial ecosystems	
Forests (e.g. alluvial forests)	Provides water and nutrients for growth of trees and ground vegetation.
Meadows and seepage fronts	Provides water and nutrients for plant community development.
Wetlands	
Peatlands	Vegetation on ombrotrophic peatlands (bogs) is less dependent on groundwater than vegetation on minerotrophic peatlands (fens). However, both systems are often maintained by groundwater.
Mineral soil-based wetlands	Comprise a range of systems such as swamps, mangroves, deltas and shallow lakes with various degrees of groundwater dependency. Groundwater provides a habitat for development/maintenance of characteristic vegetation (e.g. hydrophytes).
Other wetlands	Sole source of water in most cases. Provides moisture, nutrients, waterlogging and redox conditions.
Aquatic ecosystems	
Springs	Sole source of water; provides habitat for all biotic communities; support for all ecological processes.
Lakes	Major to moderate when lakes are connected to aquifers and receive little surface water from the surrounding catchment (e.g. some headwaters). Minor if groundwater contribution to a lake is small compared with the delivery of surface water from the surrounding catchment.
Rivers	Provides base flow during dry periods such as summer drought or winter cold; provides a habitat for biotic compartments during dry seasons.
Coastal ecosystems such as lagoons	Moderate to minor depending on the hydrogeological setting; provides a habitat for freshwater biotic communities.
Subterranean ecosystems	
Caves	Sole source of water in most cases. Provides water to maintain groundwater level. Provides habitats for characteristic biotic communities.

example, regulating effect of flows by wetlands, carbon sequestration in peatlands, aesthetic and spiritual value of springs and providing recreational experiences. European legislation related to management of groundwater was recently amended to also consider GDEs. However, the integrated management of groundwater systems and connected ecosystems is complex (Hinsby *et al*., 2008). This paper examines important aspects relating to GDEs and their future protection and management, including current policies, protection principles and management frameworks.

2. Past, current and future developments in groundwater protection and legislation of GDEs in the European Union

The complex legal architecture of the European Union's (EU's) water laws frames the protection of GDEs in various ways, including through the second Groundwater Directive (GWD) (EC, 2006), the Water Framework Directive (WFD) (EC, 2000) and the Habitats Directive (EC, 1992). Guidance documents have also been developed in the EU WFD Common Implementation Process (see e.g. EC (2003) on the role of wetlands in the WFD).

The WFD is concerned with ecosystem protection, but its focus is on surface water ecosystems. These should achieve 'good' status, within a five-fold ecological classification. The process for determining this must include an analysis of quantity, whilst chemical quality must also meet relevant standards. This analysis resembles the approaches used in environmental flow assessment (e.g. Tharme, 2003) where the quantity and quality of water required for ecosystem conservation and resource protection are determined. Groundwater can be classified only as 'good' or 'poor', as determined on the basis of chemical quality and quantity. There is no provision yet in EU legislation for the protection of subterranean aquatic ecosystems as such, although the WFD makes some mention of terrestrial and of aquatic ecosystems in both the Preamble and Art. 1. For example:

- Art. 1 of the WFD specifies the water needs and water dependency of terrestrial ecosystems.
- Art. 2 defines 'availability' of the groundwater resource as being sufficient to 'achieve the ecological quality objectives for associated surface waters' and to 'avoid any significant damage to associated terrestrial ecosystems'.

Thus damage to dependent terrestrial ecosystems is only relevant if it is 'significant'. Following on from this, Annex II (WFD), on characterisation, requires the identification of groundwater bodies with directly dependent terrestrial ecosystems. If the groundwater body is at risk, the further characterisation should make an inventory of 'associated' terrestrial ecosystems with which the groundwater body is 'dynamically linked'. Also in Annex II, where lower objectives are set under Art. 4, i.e. a groundwater body will not achieve good status, the effects on associated surface water and terrestrial ecosystems must be identified. Annex V requires that for both quantitative and chemical groundwater status to be good, it is necessary to avoid significant damage to directly dependent terrestrial ecosystems. Although the WFD annexes require that groundwater dependent terrestrial ecosystems should not be taken into consideration by characterisations of groundwater bodies, the primary target of the WFD is not these ecosystems but surface water ecosystems, whether dependent on groundwater or not.

The GWD is a more detailed instrument under Art. 17 of the WFD, to make specific provision for quality standards (at EU level) and 'threshold values' (set by member states). The former apply only to nitrates and pesticides; the latter to any substances potentially causing harm to groundwater at national (or river basin) level. In its Preamble, the GWD notes the need to protect GDEs and drinking water sources and hence this is part of the purpose of the Directive as a whole. The Preamble also notes the potential impact of upward trends in pollutants on associated aquatic ecosystems and dependent terrestrial ecosystems. The detail on ecosystems in the GWD includes the following:

- Art. 3 requires the national threshold values to be developed with 'particular regard' to associated surface waters, directly dependent terrestrial ecosystems and wetlands.
- Under Art. 4, a body of groundwater may exceed either a quality standard or a threshold value and still be of good quality, but in such cases member states must nevertheless take measures to protect terrestrial and aquatic ecosystems dependent on that body of groundwater.
- Under Art. 5, reversal of upward trends is required if there is a significant risk of harm to terrestrial and aquatic ecosystems.

Annex I requires the EU-wide quality standards for nitrates and pesticides to be tightened at national level (i.e. threshold values) if the existing standards could lead to significant damage to dependent terrestrial ecosystems. Annex II requires the interaction between groundwater and associated terrestrial and aquatic ecosystems to be considered when establishing threshold values, and to note directly dependent terrestrial ecosystems when reporting on bodies of groundwater at risk within the River Basin Management Plans (RBMPs). Finally, in Annex III, the likely transfer of pollutants to directly dependent terrestrial ecosystems is part of the assessment of chemical status.

Several other Directives work in tandem with the WFD (Figure 1). These may directly or indirectly assist with such protection and include the Drinking Water Quality Directive (DWQ) (EC, 1998), which controls drinking water quality after treatment, the Nitrates Directive (EC, 1991), which controls inputs of nitrates from agriculture, and the Birds and Habitats Directives (EC, 1979; 1992), which protects habitats and species. In relation to all of these, under the WFD 'protected areas' must be mapped in RBMPs. Art. 7, on drinking water, permits but does not mandate 'safeguard zones'. These are not required by the DWQ either, and hence are left to national law. Many member states have safeguard zones around drinking water abstraction sites. The World Health Organization (WHO) Guidelines on drinking water quality, with which the DWQ is intended to comply, suggest that states should undertake water safety planning which is likely to include some catchment-based measures and zoning around abstraction points (WHO, 2008). In addition to setting the 50 mg/L limit for groundwater that is now also included in the GWD, the Nitrates Directive requires member states to set up Nitrate Vulnerable Zones, which are then also protected areas, and to manage the application of fertilisers in these zones. New rules on the use of pesticides, not yet in force, will mandate the use of buffer zones, which will protect surface waters and groundwater indirectly, along with other use restraints on pesticides which will also benefit groundwater quality. However these rules, like the Nitrates Directive, may be difficult to implement uniformly and enforce.

The Birds and Habitats Directives may protect GDEs directly, as well as indirectly. Taken together, these establish a network of sites (Natura 2000, N2000, including Special Protection Areas under the Birds Directive and Special Areas of Conservation under the Habitats Directive), which should in turn protect a wide variety of listed species. As in other aspects of EU environmental law, these also give effect to related international agreements, especially the Ramsar Convention (Ramsar, 1971), the Convention on Biodiversity (CBD) (United Nations Environment Programme (UNEP), 1992) and the

Fig. 1. Link between European and member state legal settings and practices for GDEs. EC, European Commission; IUCN, International Union for Conservation of Nature.

Bern Convention (Council of Europe (CoE), 1979). The Ramsar Convention protects a network of wetlands to safeguard the migrating birds that use them; most Ramsar sites in the EU will also be designated N2000 sites. This includes many GDEs, as Ramsar defines wetlands in a broad way to include many ecosystems. The CBD addresses many different habitats and species, which is reflected in the development of the EU legislation. Wetlands, and other GDEs, may be designated for protection at international or EU level. Protection of natural resources including GDEs takes place at different scales, and many jurisdictions have multiple designations for habitats protection. The effectiveness of these designations will vary according to the sanctions available for breach. Designation may require only notification of any works or development, or it may require approval from an administrative authority. It may or may not provide for any sanction for breach, for example an unauthorised development. In some states, depending on the nature of their constitution, international rules such as the CBD or Ramsar will be applied directly in national law; in other states these treaties will require implementing law. In EU member states, the N2000 network provides an important layer of protection at a regional level and EU law is backed by legal sanction for non-compliance. Therefore in some member states that will be an effective regime for protecting habitats. In other states, national or local laws will be well-structured and implemented and the role of EU law will be less. Certainly, it is important to have local and national, as well as regional and international, protections; but EU law can also be a powerful tool.

3. Scientific basis for decision making: how to evaluate significant damage in GDEs

The changes in GDEs depend on the intensity of pressures and the local hydrogeological setting. Changes in GDEs can be seen locally, such as around wells, but also regionally, for example in rivers due to reduced river base flow, which can have impacts on water supply or dilution of waste discharges. Besides quantitative changes caused by groundwater abstraction and climate change for example (Kløve *et al.*, 2014), GDEs are also at risk from contamination such as from agriculture, wastewater or industrial sources. According to the GWD, if groundwater quantity or quality causes 'significant damage' to related terrestrial ecosystems, this may mean that the groundwater body will reach poor status and future action would be needed. It has recently been suggested that threshold values should also be set considering impacts on ecosystems (EC, 2011). In the sections below, scientific methods are presented on how to assess such damage to ecosystems.

3.1. Quantification of changes in hydrology and water quality

Monitoring and assessment of water quality and quantity in GDEs follow the principles of surface water and groundwater research. For hydrological assessments, this often includes water balance estimations to assess changes in flow on a regional scale and impacts on a local scale (e.g. around wells). Numerical integrated models are useful tools in understanding GDEs (Levy & Xu, 2012). The potential change in GDE hydrology can be assessed with various experimental methods, which can be grouped as follows (Table 2):

- Hydrometric approaches are basic measurements that provide information on the quantity and pressure of water at a given time and space. These measurements can directly indicate groundwater exfiltration or infiltration, such as when measuring changes in discharge at different points along a river course (Levy & Xu, 2012). Groundwater level measurements by piezometer are typical for most groundwater studies and show the flow direction to or from GDEs. Seepage meters can provide valuable information on groundwater interaction in lakes (e.g. Ala-aho *et al.*, 2013).
- Indicators comprise a large range of methods that are mainly used for river systems to calculate indices from measured runoff time series (e.g. Alba Solans & Poff, 2012). Indicators of Hydrological Alteration (IHA) based on flow magnitude, extreme point, frequency, duration and timing have been used (e.g. Yang *et al.*, 2012). The temporal patterns of flow variability can be considered by considering seasonal Indicators of Hydrologic Alteration (IAH) indices such as mean river flow for

Table 2. Suggested methods for measuring anthropogenic hydrological and ecological changes in GDEs.

	Method	Measured variable	Assessment in GDE made from measured variable	Restrictions with the approach
Hydrogeological monitoring	Hydrometric approaches and indicators	Runoff, groundwater level and pressure with piezometers in groundwater and GDEs, seepage meters, rainfall	Change in runoff along a stream or GDE (gain or loss), specific runoff in comparison with regional baseflow[*4], hydraulic gradient, water balance (e.g. P-ET), change in slope of cumulative Q line, discharge (Q) statistics and indices (e.g. mean)	Few restrictions, requires high-quality measured data
	Environmental tracers	Temperature[*2], electrical cond.[*3], pH, SiO_2[*1], geochemistry, isotopes[*5]	Groundwater–surface water interaction patterns, changes in flow direction to GDEs, water residence time in GDEs[*3], flow patterns in GDEs[*2]	Analysis of isotopes requires special laboratory and skills
	Aerial photography, satellite imagery	Spatial patterns of infrared radiation[*7], vegetation and snow cover, occurrence of surface water in lakes, ponds, etc.	Areas of cold or warm groundwater inflow to GEDs with water temperature different from groundwater, areal distribution of LAI (Leaf Area Index) and evapotranspiration patterns[*6]	Measures temperatures on GDE surface, requires special equipment
Ecological monitoring and assessment	Before-After-Control-Impact design	Species richness of a target group (e.g. benthic invertebrates, macrophytes, diatoms); ecosystem processes (e.g. decomposition, primary production)	Change in response variable(s) in affected vs control site(s)	Extremely labour-intensive; requires monitoring for several years before and after impact; often suffers from low statistical power[*8]
	Predictive modelling	(semi)quantitative samples of biological organisms in reference and test sites	Ecosystem integrity as assessed by deviation of the observed in relation to expected assemblage (O/E); 'expected assemblage' is based on community composition in near-pristine (or least impacted) reference sites.	Requires large numbers of reference sites; allows only relatively weak inference[*9]

*[1]Ala-aho *et al.* (2013).
[*2]Ronkanen and Kløve (2008).
[*3]Kværner and Kløve (2008).
[*4]Rossi *et al.* (2012).
[*5]Ronkanen and Kløve (2007).
[*6]Ala-aho *et al.* (2013).
[*7]Schuetz and Weiler (2011).
[*8]Vehanen *et al.* (2010).
[*9]Huttunen *et al.* (2012).

June–August (e.g. Döll & Schmied, 2012). A recent development is seasonally dimensionless indicators such as the River Regime Indicator (RRI) (Torabi Haghighi & Kløve, 2013).

- Hydrological analysis includes several methods whereby hydrological data are processed and impacts evaluated. Data can be generated from paired catchments (reference and potentially affected) with a before-after control approach where runoff and groundwater level characteristics are compared (see also section 3.3). As reference sites are difficult to find, a single time series and trend analysis of excess rainfall and ecosystem hydrological responses can be used when long-term data are available. If a considerable impact has occurred, this can be seen as trends in groundwater levels differing from trends in net rainfall. Another approach is analysis of long runoff time series by plotting the annual cumulative discharge, where the impact is seen as a breakpoint (change in slope).
- Environmental tracers such as stable isotopes and the geochemistry of groundwater (e.g. SiO_2, Ca, pH, EC) are usually different from those of surface water or precipitation, and can therefore be used to indicate groundwater in ecosystems (e.g. Ala-aho *et al.*, 2013). Tritium content, which shows waters formed before the atomic age (pre-1940s), has been used in many ways in hydrology, for example to detect leakage zones of lake water to tunnels during road construction (Kværner & Kløve, 2006). Stable water isotopes can be used to show groundwater inflow, as groundwater has stable isotope concentrations whereas surface water shows seasonal and daily fluctuations. Changes in isotopes due to evaporation can be used to estimate mass balances of lakes (Rozanski *et al.*, 2001) and flow patterns in wetlands (Ronkanen & Kløve, 2007).
- Aerial photography can be used to show areas of groundwater inflow to GDEs, as groundwater often has a different temperature to surface water (Schuetz & Weiler, 2011). Satellite imagery can be used to show vegetation and water surfaces (Orellana *et al.*, 2012). Photos of past vegetation cover in dry areas can show access to groundwater and past lake cover data can be used to estimate water balances and water use patterns.

3.2. Measurement of ecological change

For surface water ecosystems, there are well-established scientific methods for assessing human impacts. These methods rely on comparison of potentially affected sites against a regional reference that represents near-natural (or sometimes least-modified) stream conditions for a region. This gives the O/E ratio, or 'taxonomic completeness', i.e. the proportion of expected (E) taxa observed (O) at a site (e.g. Hawkins, 2006). Thus, the O/E ratio measures the degree of ecosystem impairment, sometimes also referred to as 'ecosystem health'. This technique, known as predictive modelling, is the cornerstone of river bioassessment but has only recently been applied to GDEs, particularly wetlands (Davis *et al.*, 2006) and springs (Keleher & Rader, 2008; Ilmonen *et al.*, 2012). Groundwater habitats and their biota are extremely diverse and present a formidable challenge to quantitative sampling of GDE environments. A hierarchical sampling scheme with careful selection of sampling sites and techniques is typically needed for a comprehensive assessment of regional biodiversity in GDEs (for a review on sampling of groundwater biodiversity, see Malard *et al.* (2003)). For example, Ilmonen *et al.* (2012) showed that 10 out of 20 forestry-affected springs could be identified as impaired using the BEAST (BEnthic Assessment of SedimenT) model to assess either benthic macroinvertebrates or bryophytes. However, only two sites were identified as different from reference conditions by both taxonomic groups. These sites had very low discharge, whereas many equally disturbed springs, but with a stronger groundwater flow, harboured species-rich biological assemblages. Indeed, the amount of groundwater discharge is known to be a key factor affecting spring communities (e.g. Hoffsten & Malmqvist, 2000), and sufficient and continuous groundwater flow may act as a buffer against anthropogenic disturbance in springs.

The most promising potential methods for the ecological assessment of GDEs are listed below:

- Before-After-Control-Impact is the most effective approach to environmental impact detection, but requires a considerable amount of spatial and temporal replication, both of which are often difficult to achieve in ecological monitoring. Insufficient replication results in low statistical power to detect an impact, if any exists, and only very strong effects can be detected (e.g. Vehanen *et al*., 2010).
- Predictive modelling (RIVPACS, BEAST, etc.), whereby potentially affected sites are compared against a large number of regional reference sites, is the prevailing paradigm for freshwater bioassessment. Different versions of this approach have been successfully applied across the world, yet the use of predictive modelling for bioassessment of GDEs is only beginning. This technique rests heavily on common species, but one of the first attempts to apply predictive modelling to GDEs suggests that indicators of spring ecosystem health should also include rare species, such as Red List taxa (Ilmonen *et al*., 2012).
- Traditional bioassessment is taxonomy-based, typically focusing on species diversity or community composition. More recently, trait-based approaches that use information on functionally important characteristics of organisms have gained popularity (e.g. Dolédec *et al*., 2006). It could be investigated, for example, whether species at affected sites have shorter life spans, higher dispersal ability, etc., than those at reference sites. Taxonomically unrelated groups may share the same trait; for example, some worms and mayflies are able to tolerate sedimentation, yet are not taxonomically related. A particularly appealing aspect of trait-based bioassessment is that it may provide an understanding of the mechanisms causing changes to ecosystem integrity.
- A recent trend in freshwater bioassessment is the use of ecosystem-level processes. A distinct benefit of this approach is that ecosystem processes are less dependent on the geographical setting and natural background variation than the more conventional structural measures (Gessner & Chauvet, 2002). Organic matter decomposition (leaf litter breakdown) has gained particular attention as a powerful tool in bioassessment. Other ecosystem processes (e.g. primary production, microbial respiration, nutrient spiralling) could be equally beneficial, but have been much less used. While the use of leaf breakdown assays to detect human impacts has long traditions in running water ecosystems, they have gained only limited attention in GDEs.

Tolerable impacts on GDEs (i.e. their resilience) have to be defined considering the ability of species to adapt to changing conditions. Impact assessment requires an estimate of the degree of change in favourable conditions that represents a threat to the ecosystem. Ecosystem-level effects of species loss and replacement of current species by invaders able to tolerate the modified conditions are other important challenges to be addressed in GDE research and conservation. This line of research is well-suited to experimental manipulation of multiple simultaneously acting stressors (e.g. warming, sedimentation, discharge) in replicate micro- and mesocosms, although bearing in mind the general limitations of small-scale laboratory experiments in community ecology (scaling problems, lack of realism).

4. Restoration and mitigation methods

Future management of GDEs in the context of the WFD and GWD includes the option to restore the groundwater system to receive good water quality status. Potential methods to prevent deterioration of GDEs include (i) restriction of groundwater use, (ii) change in land use practices and (iii) technical solutions (e.g. buffer zones or capture zones) to reduce impacts (Table 3).

4.1. Buffer zones as a control method

In Europe and elsewhere, groundwater abstraction wells are protected by a protection zone. These zones are based on the principle of intrinsic vulnerability to protect the water well from potential contamination (e.g. Mendizabal & Stuyfzand, 2011). If GDEs are to be also protected from contamination, originating from agriculture, for example, changes in land use practices or well-functioning buffer zones need to be implemented.

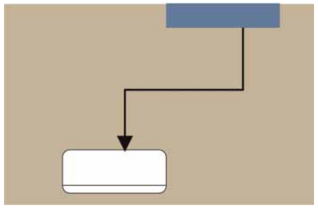
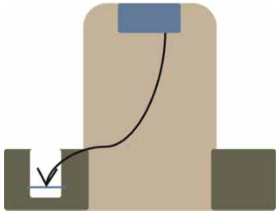
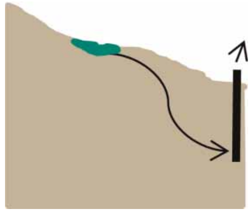
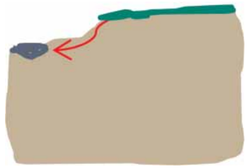
Vegetated buffer zones (BZs) or buffer strips are typically placed between actively used land and vulnerable recipients to reduce pollution from runoff (overland flow from excess rainfall) and drift (e.g. of airborne pesticides). BZs mitigate runoff-based pollutants when the soil permeability is sufficient for infiltration of overland flow (Muñoz-Carpena *et al.*, 2010). At the EU level, when considering environmental risk prevention and mitigation, there are three main policies that include vegetative field strips as a tool for risk reduction or ecosystem improvement:

- Protection of water from pollution with nitrate (Council Directive 91/676/EEC) calls for good agricultural practices to reduce the impact of nitrates.
- Sustainable use of pesticides (Directive 2009/128/EC) requires member states to support the use of mitigation measures that can minimise the risk of off-site pollution caused by spray drift, drainflow and run-off (Art 11.2.c).
- The Common Agricultural Policy (CAP) requires member states to monitor farm compliance with statutory standards (Annex III of Regulation 73/2009), including the protection of water from nitrates as described above. When assessing whether a farmer has complied with maintaining land in 'Good Agricultural and Environmental Conditions', there is a requirement to ascertain that landscape features including possible field margins have been preserved. However, there is no EU evaluation of the size and scale of such field margins, and no consideration of their structure, position or function. The draft legislation for the future CAP includes a provision requiring farmers to devote 7% of their land to ecological focus areas, with the purpose of enhancing the provision of ecosystem services via increased biodiversity. Such areas could include the establishment of vegetative field strips or field margins.

4.2. Restoration of GDEs

According to the GWD and WFD, if a GDE is not in a good condition, measures to restore and protect the groundwater needs of the GDE must be implemented to the extent necessary to avoid or remedy any considerable impact. This includes the hydro-morphological and quality conditions of a surface water body connected to groundwater. The target conditions for the improvement of a GDE must be defined in biological, physico-chemical and hydro-morphological terms related to existing pressures. In that context, an indicator of the expected impact may have to be defined to provide a rigorous

Table 3. Cases of GDE impacts and responses from different hydrogeological settings and land use pressures (GW, groundwater).

Case concept:	Tunnels in fractured rocks in contact with ecosystems in Norway (e.g. Kværner & Kløve, 2006; Kværner & Snilsberg, 2008) and Italy (Gargini *et al.*, 2008)	Esker aquifers with kettle lakes in Finland (e.g. Rossi *et al.*, 2012)	Multilayered deep confined aquifer with abstraction in Poland (e.g. Kløve *et al.*, 2011a, b)	Agriculture, diffuse loads and spring interaction in Italy (Kløve *et al.*, 2011a, b)
Hydrogeology and GDE Conceptual model for land use impact on GW and GDE				
Protection status and value	Nature reserve, valuable recreation close to major city	Natura 2000 sites, Geopark, valuable lakes for recreation	Natura 2000 site	Springs with recreational and ecological value (not protected)
Policy relevance	Habitat directive sites can be affected by tunnel drainage	Peatland drainage can influence GW levels, Natura 2000 sites and also GW body status	Abstraction influences GW body status if GDEs impacted significantly by abstraction	Cultivation influences spring water quantify and quality; CAP measures such as BZ could be used for mitigation
Pressure	Drainage by road, railroad and hydropower tunnels	Peatland drainage	GW abstraction	Pollution from agriculture, change in water regime
Primary effect	GW level drawdown, reduced flow to GDE	GW level drawdown	Changed flow pattern with less inflow to GDE	Pesticide and nutrient inflow, reduction of water flow to GDE
Potential damage	Wetland, lakes and springs damaged	Change in lake levels	Wetland (fen) damaged	Change in species composition
Remediation and regulation	Tunnel location, sealing of fractures, pumping of water to ecosystems	Drainage restrictions (buffer), peatland restoration, pumping water to lakes	Abstraction could be regulated by adaptive management if damage occurs	Land-use changes (crops); management practices (fertilisation; pesticide use; irrigation), buffer strips

measure for a specific pressure. The definition of goals for restoration of heavily modified surface and subsurface water bodies is a difficult task, and not all sites can be restored. Consequently, sites receiving a large amount of groundwater outflow should be prioritised because restoration success is likely to be highest at such sites. As the restoration has impacts on hydrology, the impact on droughts and floods downstream should be assessed. A review on various methods for river restoration is found in Palmer *et al*. (2009) and relevant issues related to floodplain management by Rohde *et al*. (2006).

Past restoration attempts have focused mainly on (i) restoring biodiversity, (ii) improving fish habitats and facilitating fish migration and (iii) sequestering carbon. In general, restoration of water systems has focused on rivers and lakes and much less on GDEs. However, GDEs may have been secondary targets in past restoration projects where the main target has been (salmonid) fish migration, landscape and/or biodiversity improvement, sediment transport limitation, etc. Restoration or rewetting of formerly drained wetlands has mainly focused on biodiversity or CO_2 capture. Such restoration projects normally include blocking of ditches to raise the groundwater level (Jauhiainen *et al*., 2002) which can also influence aquifer water levels (Rossi *et al*., 2012), but this may have the side effect of impairing the biodiversity of adjoining ecosystems such as springs (Ilmonen *et al*., 2013). To prevent damage on ecosystems due to leakage of groundwater to tunnels in bedrock, in Norway groundwater leakage has been reduced by injection of cement to seal cracks in rocks, and groundwater drainage has also been compensated for by injection of water in bedrock (Kværner & Snilsberg, 2011). A typical feature of all these restoration projects is that they have not been motivated by restoration of GDE function, but rather by several other functions that the ecosystem provides.

4.3. Groundwater abstraction management

Groundwater abstraction typically changes water level, pressure or discharge, which can have impacts on GDEs. The impact of abstraction can be seen locally around boreholes or on larger scales (Seward, 2010). Furthermore, some systems are more vulnerable to the impacts of abstraction due to their spatial location and the amount of groundwater they receive (Ala-aho *et al*., 2013). Assessments of the impacts of abstraction must consider changes in water balance, the spatial location of wells and spatial differences between GDEs. It can be argued that there is no safe yield but rather optimal yield, when the trade-off between abstraction and conservation is considered (e.g. Levy & Xu, 2012). The impacts of abstraction are not easily predicted due to complex geology, poor quantitative knowledge on the water requirements of GDEs and lack of data (Levy & Xu, 2012; Orellana *et al*., 2012), so the precautionary principle and conjunctive use (Nevill *et al*., 2010) with experimental allocation of groundwater have been recommended (Levy & Xu, 2012). The contribution of groundwater to GDEs can sometimes be assessed qualitatively (Eamus *et al*., 2006). For rivers in particular, baseflow separation techniques provide a good method to assess the contribution of groundwater (Levy & Xu, 2012). Different methods are available to assess the environmental flow required, based on methods ranging from expert opinions to habitat modelling (Wilby *et al*., 2011). When determining environmental flows for GDEs, it is important to understand the seasonal role of groundwater on ecosystems (Eamus *et al*., 2006).

To overcome the negative effects of groundwater abstraction on aquatic and terrestrial GDEs, different pragmatic methodologies are emerging that can be used to manage abstraction (Technical Advisory Group (TAG), 2005). In Australian policy, a recommendation is not to allocate more than 50% of the sustainable yield in hydrologically average years if groundwater is used as a buffer against drought (Nevill *et al*., 2010). In the UK, Catchment Abstraction Management Strategies (CAMS) have been adopted into the RBMPs required by the WFD. These basin plans are intended to assess water bodies, identify bodies where flow conditions result in poor ecological status and prevent deterioration of water bodies due to new abstractions. To monitor CAMS, environmental flow indicators (EFI) based on expert knowledge are set to indicate deviations between natural and environmental flow requirement. New abstraction licences are granted if water availability is above EF requirements. Wilby *et al.* (2011) showed that by smart licensing during droughts, river ecological status can be maintained without major economic losses.

5. Conclusions and future recommendations

GDEs have high biodiversity and provide important ecosystem services. In Europe, GDEs are partly considered in different legislation related to water quality, habitats and biodiversity. The knowledge base on different GDEs still needs to be developed to better manage these systems and provide science-based policies. A good scientific basis is a requirement for good policies at EU and national level. In the past, protection has focused on species and although the habitats protected under Natura 2000 may coincide with GDEs, the current protection level does not value the role of the water system itself, or the socio-economic values that should also be protected.

In the future, groundwater and GDEs should be managed based on an integrated approach that considers all current and potential ecosystem services. GDEs should be mapped and monitored in national monitoring networks and more scientific information about GDE function should be obtained. The monitoring on local and regional scales should be based on a scientific approach. Monitoring should preferably be coupled with current groundwater and surface water observation sites, as this will provide a reference point and an opportunity to understand the past variability in these systems. Monitoring sites should provide information about water quantity and quality, hydrogeology (aquifers) and the climate representative of the specific regions. Where land use changes are planned near valuable GDEs, monitoring should be carried out before and after the impact and also at reference sites. One way to improve scientific understanding of GDEs is to develop integrated conceptual models of GDEs, including hydrology, ecology and main pressures and risks, with the focus on nationally important sites (some simple conceptual models are presented in Table 3).

The determination of significant damage should be based on well-documented scientific methods outlined by hydrologists and ecologists, not only on threshold values. It is important to improve the legislation in such a way that the potential changes that may occur in groundwater and GDEs can be prevented. The term 'significant damage' is difficult, as this impact is not always possible to measure or detect. The legislation should focus on restricting measurable effects such as land use, water use and extraction. The sustainable use concept for groundwater needs to be further developed so that the resource, including GDEs, is maintained.

Future management of groundwater and surface water should consider GDEs. Abstraction causes impacts locally around wells and on a regional scale. In rivers, changes in baseflow can be observed and used to set abstraction plans. For many GDEs, the amount of groundwater or the water balance cannot be easily quantified and further research is needed to provide good methods. For such systems the impacts of abstraction are uncertain and so the precautionary principle and conjunctive use should be considered. As buffer zones are required by law to reduce environmental impacts, these should be more consistently used near GDEs to prevent pollution from agriculture (Figure 2). A change in agricultural

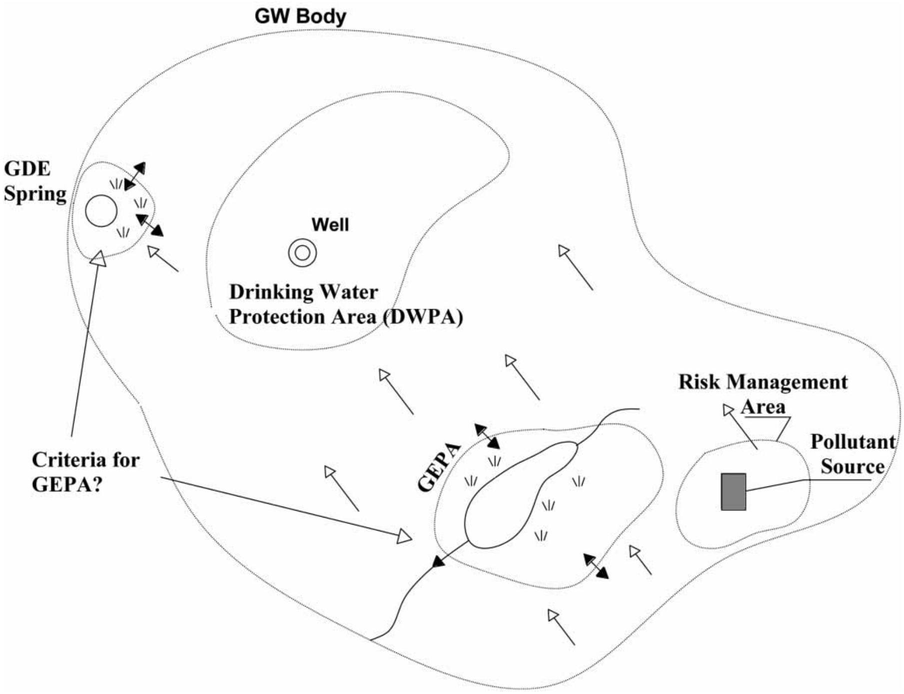


Fig. 2. Conceptual draft model for setting groundwater ecosystem protection areas (defined here as GEPA) or buffer zones for drinking water and for ecosystems. Buffers along lakes and streams are included in EU legislation (e.g. minimum 5 m around lakes larger than 10 ha in France). Protection is required for water bodies having good quality, but systems with high quality are not well protected with buffer strips. In addition, smaller water systems such as GDEs lack protective measures. GDE, groundwater dependent ecosystems; GEPA, groundwater ecosystem protection areas; GW, groundwater.

practices, with less intensive farming close to GDEs, is recommended. Restoration of GDEs should focus on sites with an obvious groundwater influence and the effects should be monitored for a long time, e.g. 10 years, to determine the success of restoration measures.

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