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Groundwater Dependent Ecosystems and man: conflicting groundwater uses

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Groundwater Dependent Ecosystems (GDE) are important elements of biodiversity and providers of valuable goods and services to society. Preservation of their environmental functions in the face of increasing anthropogenic pressures on groundwater resources and progressive climate change depends on appropriate environmental policies and water resources management. A brief overview of current knowledge of the functioning of GDE and their relations with groundwater is given in the first part of the article. Effective incorporation of GDE into the policy and practice of water resources management depends on thorough understanding of how hydrogeological processes and human impacts influence the quantity and quality of groundwater available to ecosystems. Major scientific challenges in this regard are related to adequate representation of GDE in the conceptual and related numerical models of groundwater systems. An example of a GDE (Wielkie Błoto fen in southern Poland) is discussed in some detail in the second part of the article. It illustrates some of the pressures and threats which GDE located in densely populated regions of the European continent are experiencing nowadays. Selected research tools used to quantify those pressures and threats are described and discussed.

Key words: groundwater, ecosystems, modelling, indicators, tracers.

INTRODUCTION

Groundwater Dependent Ecosystems (GDE) are important but often overlooked elements of the groundwater-related environment. The significance of GDE has been first recognized in semi-arid regions of the world (Australia – Hatton and Evans, 1998; South Africa – Colvin et al., 2003). Nevertheless, GDE have important functions in all climatic zones as they contribute to biological and landscape diversity and provide important economic and social services (Boulton, 2005; Kløve et al., 2011a, b). An important category of GDE are wetlands, many of these being already lost or degraded due to land-use changes. Other significant threats to GDE functioning are related to the lowering of hydraulic heads due to over-exploitation of groundwater resources, to recent climatic changes and to environmental pollution.

European legislation aimed at protection of surface water and groundwater [Water Framework Directive – WFD (EC, 2000); Groundwater Directive – GWD (EC, 2006)] recognizes the fact that GDE are influenced by changes in the quantitative and chemical status of groundwater and that identification of such links is an indispensable element in characterization of groundwater bodies. The GWD clearly states that Groundwater Dependent Ecosystems and water supply for human consumption are two important groundwater receptors with respect to which groundwater should be protected from deterioration and chemical pollution. Reconciliation of these conflicting groundwater uses constitutes a new challenge in the management of groundwater resources that has to be addressed at various levels (research, management, policy). An integrated and multidisciplinary approach is needed to provide quantitative assessment of complex interactions between groundwater and GDE functioning in different climatic zones and different hydrogeological settings.

The first part of this article provides a brief overview of current understanding of how the GDE function as elements of a wider groundwater environment and how the GDE concept can be incorporated into hydrological practice, particularly into conceptual and numerical models of groundwater systems. Emphasis is put on the issue of time lags associated with the propagation of adverse effects of human activities to GDE. An example of a GDE (Wielkie Błoto fen in southern Poland) is discussed in some detail in the second part of the article. This case study illustrates some of the pressures and threats which the GDE located in densely populated regions of the European continent are experiencing nowadays. Selected research tools used to quantify those pressures and threads are presented and discussed.

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GROUNDWATER DEPENDENT ECOSYSTEMS AND MAN

DEPENDENCE OF ECOSYSTEMS ON GROUNDWATER

Ecosystems are groundwater dependent if their composition, structure and functioning rely on a supply of groundwater (Eamus, 2009). The degree of this dependence may change across a wide range, from a total reliance on groundwater supply to complete independence (Hatton and Evans, 1998). Such reliance may become evident when groundwater availability is limited for some period of time (Fig. 1). Consequently, for a given ecosystem, dependence on groundwater may vary seasonally or be episodic. A characteristic feature of the ecosystem response to changes in environmental drivers are ecological thresholds that stem from nonlinear dynamics of ecosystem behavior (Groffman et al., 2006). Exceeding these thresholds results in abrupt changes in ecosystem quality or, in the case of a highly-dependent ecosystem, even in complete collapse (Hatton and Evans, 1998).

Groundwater dependency of the ecosystems is considered with respect to four attributes (Sinclair Knight Merz, 2001): (1) groundwater supply (flux), (2) groundwater head (for unconfined aquifers), (3) groundwater pressure and its surficial expression (for confined aquifers), and (4) groundwater quality (chemical composition, e.g., contents of nutrients or pollutants). The composition, structure and functioning of GDE depend on the above-mentioned groundwater attributes in a way that is characteristic for a particular type of ecosystem. Due to the large diversity of GDE types, it is difficult to generalize the influence of groundwater quantity and quality on ecosystem characteristics. Several classifications of GDE have been proposed (Hatton and Evans, 1998; Boulton, 2005; Dresel et al., 2010) but they reflect primarily Australian conditions and experiences and might not be relevant for the northern hemisphere temperate zone. Kløve et al. (2011a) identified four classes of GDE: (1) rivers and lakes including aquatic, hyporheic, and riparian habitats, (2) subterranean aquifers and caves, (3) wetlands and springs, and (4) estuarine and near-shore marine ecosystems.

Pettit et al. (2007) discussed the whole range of relations between groundwater and vegetation that can occur along landscape gradients, from terrestrial ecosystems in which plants rely on soil moisture derived entirely from direct precipitation, to aquatic communities composed of vegetation floating or submerged in water (Fig. 2). Terrestrial GDE (GDTE) can be discussed within this context as those that require groundwater levels lifted by capillary rise in unconfined aquifers to be at least episodically or periodically within their root zone and as those that require groundwater flux to satisfy the evaporative demand of plants (Sinclair Knight Merz, 2001). Similarly, near-surface groundwater levels and a constant supply of groundwater are necessary to maintain wetland ecosystems whose plants require wet or waterlogged soils. Prolonged changes in water levels lead to shifts in species composition towards drier or wetter communities (Figs. 1 and 2). Wetland ecosystem properties depend also on the chemical composition of groundwater, examples being the high-altitude extremely rich fens in Colorado, dependent on nutrient-loaded and high-pH groundwater (Chapman et al., 2003) or parts of the Biebrza River wetlands in Poland where rich fens are supported by nutrient-rich groundwater seepage (Wassen et al., 1992).

Being related to surface or near-surface occurrences of groundwater, the GDE are commonly found in groundwater discharge areas. Fulfilling requirements of GDE is therefore related to the overall groundwater regime and has to be considered taking into account groundwater pathways and fluxes as well as transformations of its chemical composition on the way

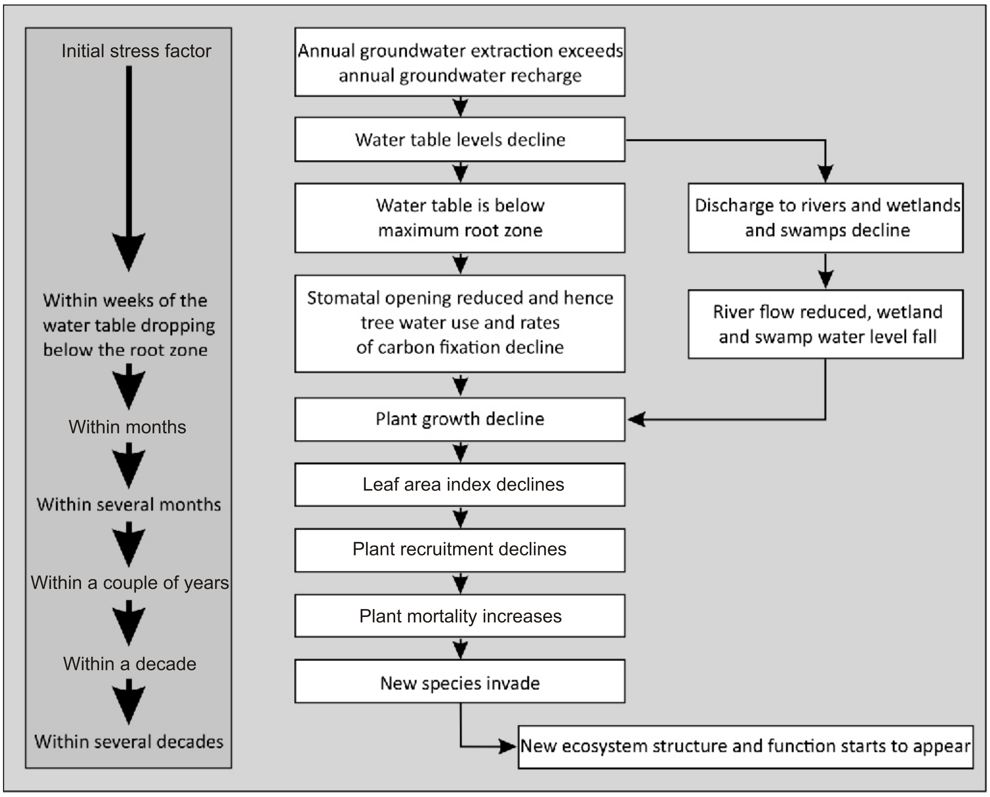

Fig. 1. Response of vegetation to reduced availability of groundwater (Eamus, 2009)

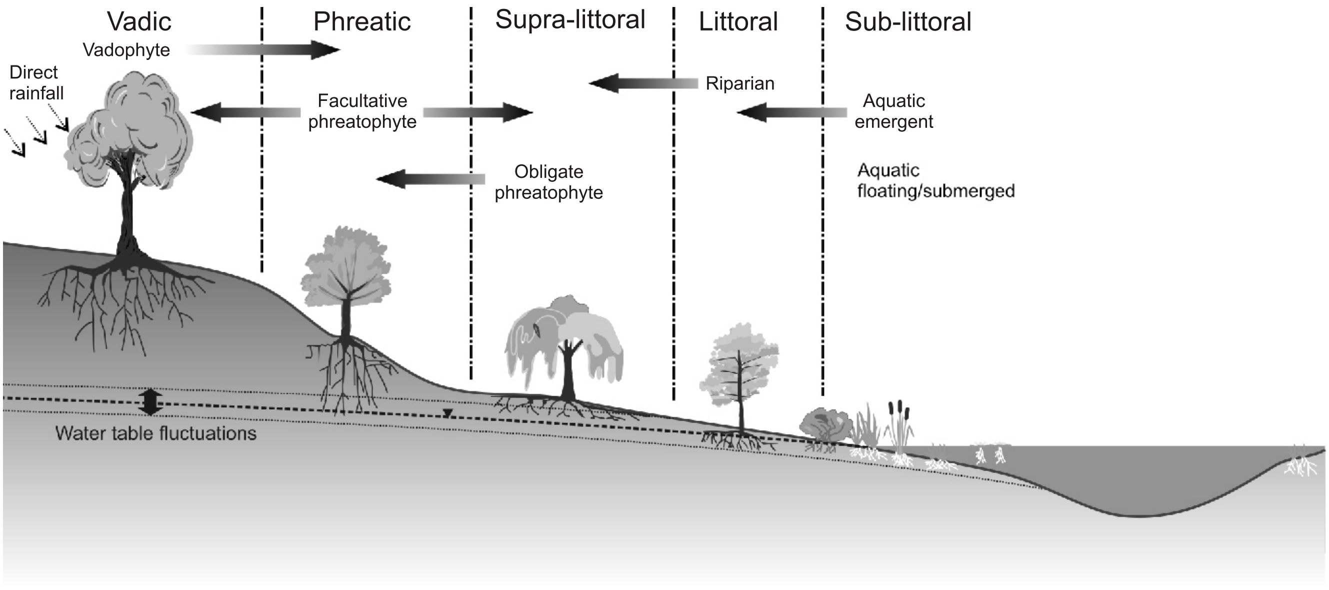

Fig. 2. Types of relationships between groundwater and vegetation along a landscape gradient (modified after Pettit et al., 2007)

from recharge to discharge areas (Krogulec, 2003, 2013). Conditions of GDE can be affected by anthropogenic pressures exerted even on distant parts of the supporting groundwater bodies, including their recharge areas. It should be emphasized that responses of GDE to such adverse effects are not immediate and have to be considered on time scales characteristic for water travel times through a particular groundwater system (Krogulec and Sawicka, 2012).

FUNCTIONS OF GROUNDWATER DEPENDENT ECOSYSTEMS

Natural ecosystems, including GDE, provide numerous benefits to human society (Groot et al., 2002; MEA, 2005; Barbier, 2007). Ecological and socio-economic goods and services that are associated with ecosystem functions can be subject to economic valuation (Barbier, 2007; Kløve et al., 2011b). Nevertheless, knowledge and awareness of GDE functions and services is limited even among policy makers and groundwater managers. There are four major categories of ecosystem functions that result from natural processes: (1) regulation functions, (2) habitat functions, (3) production functions, and (4) information functions (Groot et al., 2002).

The regulation functions are related to regulation and maintenance of the life environment. For example, the riparian and hyporheic ecosystems are capable of reduction in the levels of nutrients in rivers and of flood mitigation; wetlands influence local weather, climate and the hydrological cycle. The habitat functions of GDE are related to the environmental stability that these ecosystems are capable of providing which favours the occurrence of highly specialized and regionally restricted species (Gibert et al., 2009). The GDE develop at the interfaces between groundwater and surface water and as such they are examples of ecotones – the transitional zones between ecosystems that host large biodiversity. The production functions of GDE primarily stem from the net primary production by autotrophs. Wetlands provide such goods as game, water fowl, fruits and herbs. Wetlands are also a source of peat used as fuel and in horticulture. Informative functions of GDE are associated with their landscape and ecological characteristics. Springs, wetlands and surface water bodies are very distinct features of landscape and as such attract people's attention, being a source of aesthetic, cultural, artistic and spiritual inspiration. Finally, GDE are important subjects of scientific research and serve for environmental education.

VULNERABILITY OF GDE TO ANTHROPOGENIC IMPACTS

Human-induced changes in attributes of groundwater supporting GDE may lead to loss of ecosystem functions and of the related goods and services. Changes in the quantity and quality of groundwater supporting GDE functions have four major causes: (1) land-use changes, (2) groundwater abstraction, (3) groundwater pollution and (4) climate change. Drainage of wetlands, intentional removal of native vegetation and development of infrastructure may result in direct loss of ecosystems. Land-use changes affect the groundwater flow regime also indirectly through their influence on hydrological cycle, particularly on recharge fluxes. Groundwater abstraction affects not only groundwater levels and fluxes but may also change, or even reverse, the direction of groundwater flow. The response of GDE to groundwater pollution, such as high levels of nutrients and toxic substances, is not well-understood (Balderacchi et al., 2013). Climate change and its variability may influence groundwater and dependent ecosystems in many complex ways (Kløve et al., 2013). For instance, groundwater level and fluxes will be affected through climate-induced changes of recharge rates. Groundwater quality can also be affected, for example via increased leaching of pollutants from the unsaturated zone at higher recharge rates or via lowering of stream base flow discharges at reduced recharge. Increasing air temperature will lead to higher groundwater temperatures and consequently to lower levels of dissolved oxygen. Climate change influences GDE not only through its effect on groundwater attributes but also through direct influence of air temperature and other climatic variables on the structure and functioning of ecosystems. Finally, climatic change induces land-use changes through its influence on terrestrial ecosystems and on the agricultural use of land.

Sustainable management of GDE has to guarantee appropriate quantity and quality of groundwater. The basic question with respect to quantity is how much groundwater can be abstracted from the aquifer supporting a given GDE without adverse effects on this ecosystem. This leads to the Safe Yield (SY) concept applied to abstraction of groundwater (Kløve et al., 2011b). Other useful, operational concepts related to GDEs and applied in management of water resources are: (1) Environmental Flow (EF) – the quantity of water that nature needs for good ecological status to be achieved and the provision of ecosystem services to be maintained (EC, 2012a, b), and (2) Environmental Water Requirement (EWR) – a groundwater regime that sustains the ecological value of a GDE (Kløve et al., 2011b). EWR is identified based on knowledge of the nature of ecosystem dependency on groundwater, on the natural water regime and on the response of the given ecosystem to changes in key groundwater attributes (Sinclair Knight Merz, 2001).

Once EWRs are determined, GDE can be considered a target of vulnerability and risk assessments. Useful tools in the management of GDE are buffer zones (Groundwater Ecosystem Protection Areas – GEPA; Risk Management Areas – RMA) set to protect the ecosystems and to control spread of pollutants. These buffer zones complement the well-known concept of Drinking Water Protection Areas. For the time being there is, however, no common understanding and application of the concept of environmental flows in the management of water resources (EC, 2012a).

GDE vulnerability can be considered in the framework of the Source-Pathway-Receptor paradigm (EC, 2010) separately for threats related to groundwater quantity and quality. Vulnerability of a GDE (receptor) to pressures (source) is related to those properties of the groundwater system which govern propagation of disturbances to groundwater flow patterns and chemical composition (pathway). Assessments of GDE vulnerability should include quantification of the delays between the occurrence of disturbances or implementation of management actions and the respective deterioration or improvement of groundwater attributes at the GDE level. Such delays that, for typical groundwater flow systems, may reach tens of years are commonly not considered in water resources policies. It is already apparent that the time frame of the year 2015 set up by the Water Framework Directive for achieving a good status of groundwater bodies is unrealistic, mostly due to the large time scales of contaminant transport in groundwater systems.

SCIENTIFIC CHALLENGES

While subsurface water represents a hidden part of the hydrological cycle, the GDE are very distinct manifestations of groundwater presence close to the surface. They constitute an interface between the subsurface flow of water and the surface landscape and as such can be understood only within a framework of multidisciplinary studies combining hydrogeological and ecological, but also geomorphological and biological approaches. Despite the growing interest in their protection expressed in environmental legislation of many countries, the GDE and their interactions with groundwater are not sufficiently well-represented in hydrogeological practice and in water resources management. Incorporation of GDE into groundwater management schemes requires that they are accounted for in the conceptual and numerical models of the groundwater systems on which they rely. Yet, most models used in water resources management do not represent the groundwater – surface water interactions with sufficient detail.

Another indispensable element of GDE assessment and management is monitoring of their status. The development of conceptual models and monitoring of GDE are the two components of an iterative approach in which conceptualization of the system is a prerequisite for designing the monitoring programme, and the monitoring data and information obtained from other sources are subsequently used to improve the conceptual model (Richardson et al., 2011). An operational approach to monitoring can be accomplished through application of indicators of GDE status.

CONCEPTUAL MODELS OF GDE

A conceptual model is a simplified representation of a real system aimed at describing basic features of its functioning. Block diagrams, cross-sections, maps and other pictorial representations supplemented with explanatory text are used to identify basic components of the system studied. Conceptual models have become an essential tool in management of groundwater resources. Their application is recommended by a Groundwater Directive (EC, 2006) and relevant Guidance Documents (EC, 2010) as a part of risk assessment schemes. Conceptual models are usually the first step towards the development of numerical models. Definitions, examples and guidance on the development of conceptual models applied in groundwater resources management are provided by an extensive literature (e.g., Rushton, 2003; Spijker et al., 2009; Brassington and Younger, 2010). Conceptual models which include GDE are discussed by Reid et al. (2009) and Richardson et al. (2011).

GDE IN NUMERICAL FLOW AND TRANSPORT MODELS OF GROUNDWATER SYSTEMS

Modelling of interactions between groundwater and GDE requires a more comprehensive approach than is typically applied in models of flow and transport, which usually include only the saturated zone (e.g., MODFLOW, MT3D). Vertical migration of water and dissolved substances from the ground surface to the aquifer is commonly simulated by the coupling of models developed separately for the unsaturated and saturated zones. Such coupling is one of the major challenges in the modelling of GDE because the subsurface processes for the unsaturated and saturated zones have different characteristics such as representative physical dimensions as well as spatial and temporal scales (Gunduz, 2006).

Models which include GDE need to represent all components of the water budget relevant to groundwater surface water interactions, including precipitation, infiltration through the unsaturated zone, river bank filtration, hyporheic fluxes and evapotranspiration under variable land-use schemes and changes of climate (Howard et al., 2006). Attempts towards such integrated modelling were given by Mirosław-Świątek and Okruszko (2011) for the Narew catchment in Poland and by Refsgaard et al. (2010) for Denmark. Krogulec (2003, 2013) and Kopeć et al. (2013) characterized hydrogeological conditions of the Kampinos National Park in Poland and combined the hydrodynamic modelling with observations of vegetation cover in order to identify wetland areas with the potential for renaturalization. Modelling of filtration through river banks and the hyporheic zone requires discretization with locally increased resolution. Incorporation of the biogeochemical processes into the modelling practice is in its initial stage and depends on the results of process studies that shall provide knowledge of key model parameters (Environment Agency, 2009). Other obstacles in modelling are related to the wide range of time scales involved: from hours (exchange between groundwater and surface water) to months (hyporheic exchange) and tens of years (flow through the saturated zone; Howard et al., 2006).

A properly calibrated flow model can provide rates of propagation of hydraulic pressures (heads) in response to, for example, changes in groundwater abstraction (Sophocleus, 2012). Such a calibrated flow model does not, however, guarantee its good performance as regards transport of contaminants. Models simulating transport have to be calibrated independently, for example with the use of environmental tracers (Zuber et al., 2005, 2011; Kania et al., 2006; Witczak et al., 2013). The calibrated transport model allows quantification of spatially variable time scales associated with propagation of contaminants in groundwater bodies and in river catchments (Kania et al., 2006). The resulting knowledge of time lags between the measures undertaken and the expected improvements of water quality in GDE is a crucial element of effective management schemes.

An important feature of groundwater systems is the three-dimensional character of groundwater flow, even in relatively simple and homogeneous one-layer unconfined aquifers. Böhlke (2002) showed that riparian wetland in a discharge area may receive groundwater components with a whole range of ages and different chemical loads as a direct consequence of the three-dimensional nature of groundwater flow. In this specific example the nitrate content in discharging groundwater depends on characteristics of the recharge area (agricultural vs. non-agricultural) and on groundwater travel time (through denitrification and variations in historical input).

Finally, as stated by Voss (2005, 2011a, b) and Konikow (2011), the ability of numerical models to represent behaviour of inherently complex groundwater systems should not be overestimated and their users need to formulate realistic expectations towards the accuracy of model predictions. As the density of data available for large-scale models is usually not sufficient to adequately represent local heterogeneity of hydraulic parameters, such models are highly uncertain and there is a need for their experimental verification (Refsgaard et al., 2012). Methods for estimation of model uncertainty are reviewed in many publications (e.g., Hill and Tiedeman, 2007; Michalak et al., 2011). According to Refsgaard et al. (2012), uncertainty estimates will be more commonly performed in the near future. Refsgaard et al. (2012) stated that except for quantitative statistical evaluation, handling geological uncertainty due to uncertain geological interpretation is necessary. However, despite the large uncertainty of predictions inherent to even most advanced, state-of-the-art numerical models, the effort undertaken to build them is justified because such models can be treated as advanced conceptual models that enhance understanding of groundwater flow systems and associated GDE.

INDICATORS OF GDE STATUS AND RISKS

Indicators are constructed and used to express in a quantitative manner the status of complex systems. Environmental indicators are applied to describe the current status and trends of various components of the environment, particularly with respect to the effects of human activities on different environmental functions (EEA, 2005). The indicators convey scientific understanding of complex environmental interactions to policy makers, monitoring agencies and the general public. Despite the widespread use of indicators, there is no comprehensive and commonly accepted definition of an indicator. Numerous international programmes and national initiatives have produced their own methodological guidelines toward indicator development (ANZECC, 2000; EEA, 2005; GENESIS, 2012; Kløve et al., 2013). Here indicators are understood as elements or features of groundwater environment relevant to the sustainable functioning of GDE. Numerical values of indicators that describe the chemical or/and quantitative status of groundwater system, or a degree of changes within that system, are referred to as indices. Similarly, Richardson et al. (2011) distinguished between high-level indicators and lower-level statistical variables.

Table 1 presents examples of indicators and indices related to GDE functioning. There is, however, a contradictory understanding of these terms in the literature where indicators are sometimes understood as quantifiable properties of the system while indices aggregate single indicators that are more easily comprehended by policy makers and the general public (Brink, 2006). Regardless of different understandings of indicators there is a growing need for designing a set of indicators adequate for the assessment of GDE status and vulnerability (GENESIS, 2012).

A common feature of indicators applied in assessments of GDE status and susceptibility is that they do not express the temporal dynamics of the ecosystem responses to adverse impacts on groundwater. Observation of current trends in groundwater availability and quality does not suffice to predict the future status of a GDE. There is therefore a need for operational indicators of the temporal aspects of groundwater vulnerability, namely the time lags associated with the propagation of disturbances through groundwater systems. A clear distinction has to be made between propagation of the hydraulic and compositional disturbances to groundwater bodies. According to the general groundwater flow equation, the rate at which hydraulic disturbances propagate through the given aquifer are directly determined by its properties, namely by the ratio of hydraulic transmissivity to storativity. The rates of pressure propa-

Table 1

Indicators and respective indices suitable for GDE assessments (GENESIS, 2012)

Indicator	Example indices
Water balance	total groundwater abstraction/groundwater recharge, groundwater abstraction/available groundwater resources
Groundwater level and pressure	depth to the water table (piezometric level), rate of change in GW level/rate of recharge
Flow regime and its changes	reduction of low flows, reduction of annual streamflow, duration of wet/dry phases, abstraction amounts
Groundwater quality	temperature, pH, alkalinity, buffer capacity, electrical conductivity, turbidity, chlorophyll a, chemical composition: dissolved oxygen, NO_3, NO_2, NH_4, PO_4, metals, pesticides etc.
Vegetation and fauna	community composition species richness (phytoplankton, macro-invertebrates, fishes), diversity indices, indicative species

gation are much faster than the rates of solute transport because the latter is controlled by the advection and dispersion of solute particles, which, in turn, depend on the velocity field and on the presence of immobile water. Spatial distributions of hydraulic heads and of concentrations of solutes transported with groundwater flow are created by different processes (Voss, 2011a, b; Konikow, 2011).

Environmental tracers have a key role as potential indicators quantifying temporal aspects of groundwater vulnerability. These naturally occurring and anthropogenic substances can be used to infer properties of groundwater systems related to the origin, movement and mixing of water and to quantify origin, transport and transformations of solutes. Principles and examples of applications of environmental tracers are provided in detail in several monographs (Clark and Fritz, 1997; Kendall and McDonnell, 1998; Cook and Herczeg, 2000; Mook, 2001; Zuber et al., 2007; Leibundgut et al., 2009; Gat, 2010). Tracers can be also used to indicate occurrences of groundwater in rivers, wetlands or other types of GDE and even to directly indicate uptake of water by plants (Bertrand et al., 2012). Such applications rely on the occurrence of distinct differences in tracer signatures among groundwater and other sources of water feeding GDE. Once recognized, these differences can be further used to monitor changes in relative contributions of waters of different origin to the GDE. Herczeg et al. (2004) noticed that although environmental isotopic information rarely makes a basis for decisions in groundwater management, the isotopic approach provides an integrated view of groundwater systems behaviour that is not available by conventional methods. Environmental tracers are thus indispensable to address the issue of anthropogenic impacts on Groundwater Dependent Ecosystems, including pollution. Nonetheless, examples of tracer applications in studies of GDE are rare. Besides the isotopic and gaseous tracers introduced into the atmospheric part of the hydrological cycle, some other water properties and constituents such as temperature, major ions, silica, electric conductivity or even artificial sweeteners, can be used to study groundwater – surface water interactions, particularly in the hyporheic zone (Anderson, 2005; Kalbus et al., 2006; Engelhardt et al., 2011).

Environmental tracers provide also timescales of water movement (groundwater age). Knowledge of groundwater age distribution is a key factor in the assessment of GDE vulnerability to climate and land-use changes, groundwater exploitation and pollution (Newman et al., 2010). Dominant timescales of water flow and solute transport to the ecosystem determine time lags associated with its responses to both the commencement and cessation of such disturbances. Systematic observations of groundwater ages based on environmental tracers and numerical modelling help to assess the dynamics of interactions between groundwater and GDE and of timescales in which ecosystems react to exploitation and pollution. Bayari et al. (2006) provided three examples of such an approach applied to groundwater dependent ecosystems in Turkey. Concentrations of tritium or other tracers of anthropogenic origin in points of discharge can be used as direct indicators of vulnerability to pollution. The absence of these tracers in groundwater indicates significant travel times and the resulting low vulnerability of the system studied to recent anthropogenic pollution. In springs and other Groundwater Dependent Ecosystems the proportions between old and recent components may be different during the wet and dry season and tracer concentrations should be checked at different times accordingly. Environmental tracers can serve as operational indicators of vulnerability of the GDE to the adverse effects of groundwater pollution and exploitation but their application is case-specific and requires a thorough understanding of tracer methodology.

GROUNDWATER DEPENDENT ECOSYSTEM AT RISK: AN EXAMPLE FROM SOUTHERN POLAND

In the following, the example of a groundwater dependent ecosystem threatened by extraction of groundwater resources for human use is discussed in some detail. The results of tracer-aided study of this GDE carried out during the past few years show the potential of isotopic and geochemical tools in assessing the risk of intense abstraction of groundwater to proper functioning of the system discussed.

STUDY AREA

The study area is located in the south of Poland, in the vicinity of Kraków (Fig. 3). The Wielkie Błoto fen is located in the western part of Niepołomice Forest, a lowland forest covering around 110 km^2. This relict of once vast forests is protected as a Natura 2000 Special Protection Area "Puszcza Niepołomicka" (PLB120002) which supports bird populations of European importance. The fen itself comprises a separate Natura 2000 area "Torfowisko Wielkie Błoto" (PLH120080), a significant habitat of endangered butterfly species. The Niepołomice Forest contains also several nature reserves and the European bison breeding centre and has an important recreational value as the largest forest complex in the vicinity of Kraków. Due to spatially variable lithologies and groundwater levels, the Niepołomice Forest is a mosaic of various forest and non-forest habitats, including wetlands, marsh forests, humid forests and fresh forests. Dependence of the Niepołomice Forest stands on groundwater is enhanced by low available water capacity in the area. In the course of the 20th century, groundwater conditions in Niepołomice Forest, including the Wielkie Błoto fen, have been affected by land improvement and forest management.

The Bogucice Sands aquifer underlying the study area belongs to the category of medium groundwater basins in Poland (Main Groundwater Basin – MGWB 451) and is located at the border of the Carpathian Foredeep Basin. The aquifer belongs to the Middle Miocene (Upper Badenian) and is underlain by practically impermeable clays and claystones of the Chodenice Beds. To the north, it is progressively covered by mudstones and claystones with thin sandstone interbeds. Directional indicators of palaeoflow suggest proximity to a deltaic shoreline. In the south, near the deltaic mouth, the outcrops of the Bogucice Sands are covered only by thin Pleistocene–Holocene deposits (sands, loesses and locally by boulder clays). In the north, the aquifer is deeper and confined by marine mudstones and claystones. The mean total thickness of the aquifer is approximately 100 m, at the maximum up to 310 m.

The hydrogeology of the aquifer can be considered in three areas: (1) the recharge area related to the outcrops of the Bogucice Sands in the south, (2) the central confined area generally with artesian water, and (3) the northern discharge area in the Wisła River valley. Groundwater movement takes place from the outcrops in the south, in the direction of Wisła River valley where the aquifer is drained by upward seepage through semi-permeable clayey strata of the Grabowiec Beds. In the pre-exploitation era, artesian water existed almost across the whole confined area. Intensive exploitation decreased the water table in some areas causing downward seepage. The upper, shallow aquifer located in Pleistocene–Holocene deposits is related to the drainage system of the Wisła River and its tributaries. The unsaturated zone consists mainly of sands and loess of variable thickness, from ~0 in wetland areas to approximately 30 metres in the recharge area of deeper aquifer layers. Due to

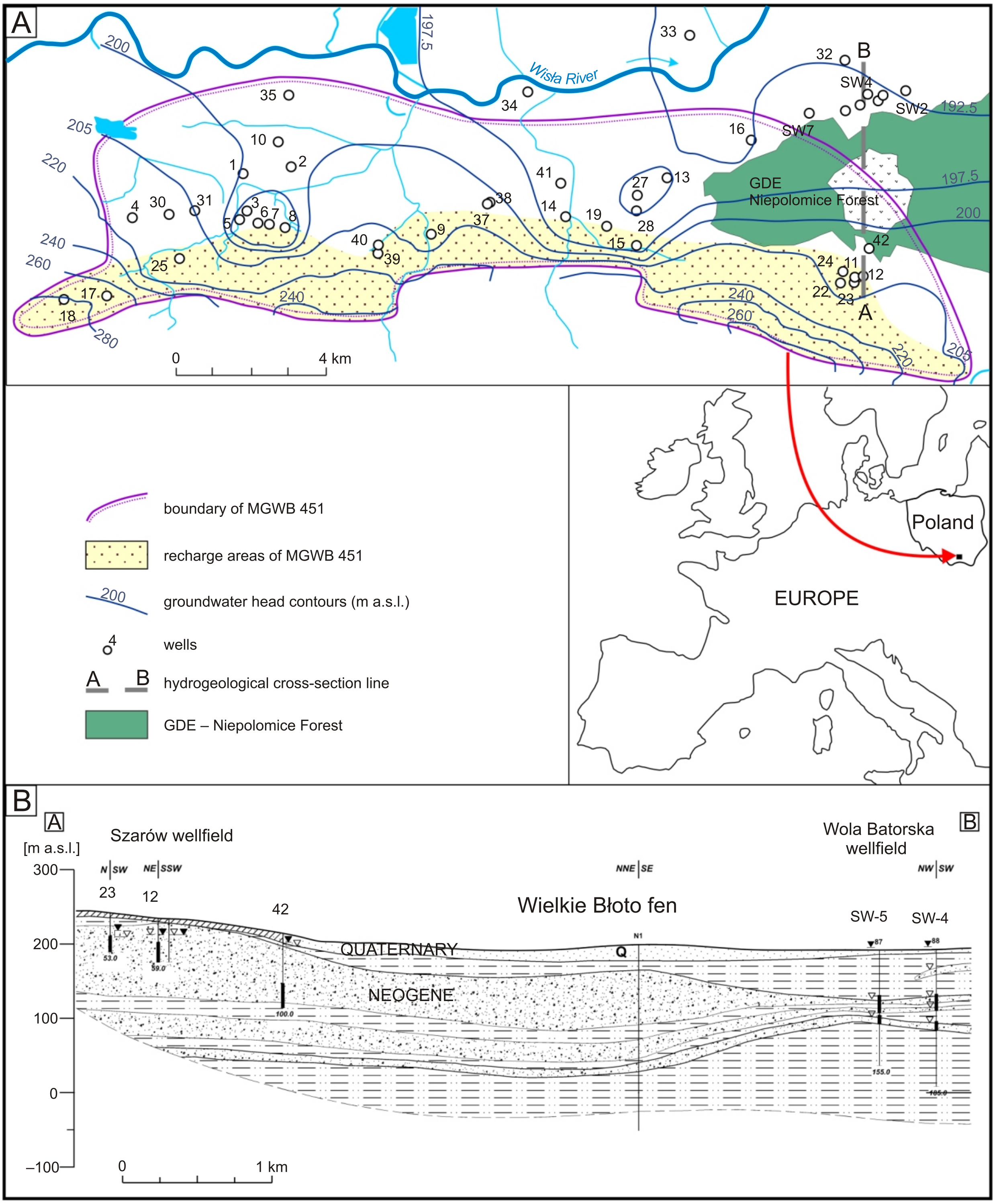

Fig. 3. Hydrogeological map (A) and cross-section (B) of the Bogucice Sands aquifer (Main Groundwater Basin – MGWB 451) with the location of Niepołomice Forest and the Wielkie Błoto fen

Cross-section according to Górka et al. (2010)

artesian conditions in the study area and a relatively thin clay layer separating the upper (Neogene) aquifer layers from the shallow Quaternary aquifer, upward leakage of the deeper groundwater may contribute to the water balance of the GDE investigated. The conceptual model of interactions between groundwater and the GDE is presented in Figure 4.

In July 2009 a cluster of new pumping wells has been set up close to the northern border of Niepołomice Forest. There is growing concern that exploitation of these wells, which operate at present at approximately 30% of their envisaged full capacity, may in future lead to lowering of water table in the Niepołomice Forest area and, as a consequence, trigger drastic changes of this unique, groundwater dependent ecosystem (Fig. 5).

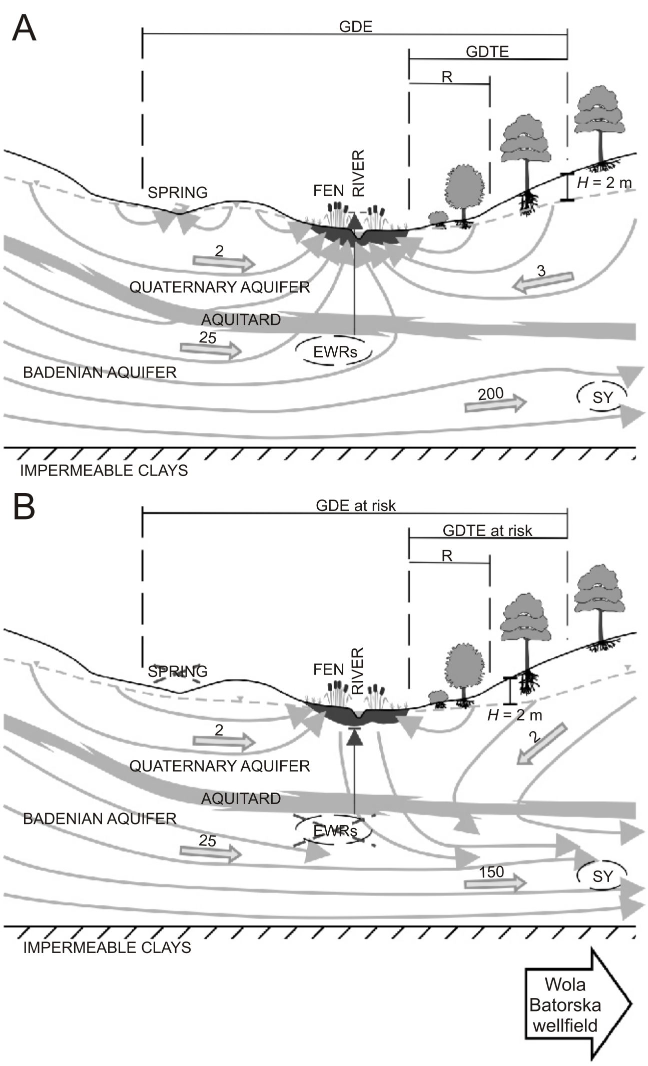

Fig. 4. Conceptual model of the Wielkie Błoto fen

A – natural state; B – envisaged future status as a result of intense exploitation of the Wola Batorska wellfield; GDE – Groundwater Dependent Ecosystems; GDTE – Groundwater Dependent Terrestrial Ecosystem, R – riparian forest, EWRs – Environmental Water Requirements, SY – Safe Yield of the aquifer exploited by the Wola Batorska wellfield; figures associated with block arrows reflect approximate travel time of water (in years) over the distance corresponding to the length of the arrow

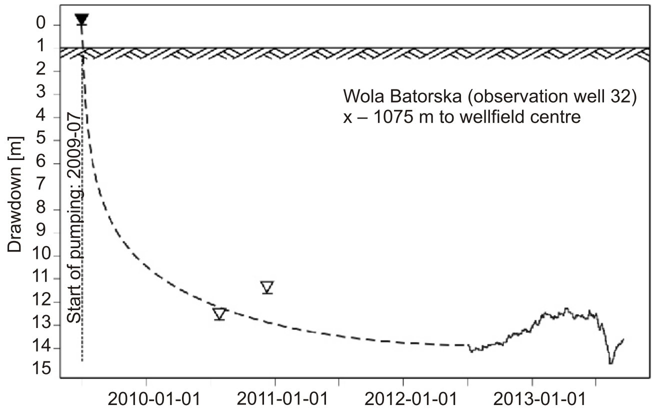

Fig. 5. Drawdown of water table in well no. 32 after initialization of the operation of the Wola Batorska wellfield in July 2009 (cf. Fig. 4)

METHODS

To follow changes in regional hydraulic gradients induced by operation of the new pumping wells, water table measurements were performed in well no. 32 located ca. 1 km north-west of the wellfield (Fig. 3). In order to quantify the dynamics of groundwater flow in the area of Niepołomice Forest and the Wielkie Boto fen, physicochemical parameters and concentrations of environmental tracers (stable isotopes of water, tritium, radiocarbon) were measured in wells located in the recharge area of the Bogucice Sands aquifer and in the newly-established pumping wells. To detect the potential discharge of deeper groundwater in the area of the Wielkie Błoto fen, dedicated sampling of water from different levels of the shallow phreatic aquifer down to a depth of 4.6 m was conducted. A GEOPROBE device was employed for this purpose (Butler et al., 2002).

Concentrations of environmental tracers in the water samples collected were measured at the laboratories of the Faculty of Physics and Applied Computer Science, AGH University of Science and Technology, using established methodologies. The chemical composition of water samples was measured at the chemical laboratory of the Faculty of Geology, Geophysics and Environmental Protection, of the same University. The results of isotopic and chemical analyses are given in Table 2.

RESULTS AND DISCUSSION

As seen in Figure 5, the position of the water table in well no. 32 has changed radically after pumping was initiated in July 2009. Initially slightly artesian, the water table has stabilized at ca. 12 m below the surface after approximately one year of operation of the Wola Batorska wellfield.

The chemical and isotopic data available to date (Table 2) indicate that groundwater in the recharge area, upstream of the Wielkie Błoto fen, is relatively young. The presence of significant amounts of tritium points to recharge in the past several decades. The radiocarbon content fluctuates between 48 and 65 Percent of Modern Carbon (pmc). In contrast, in the newly established wellfield tritium is absent while the radiocarbon content drops to a few pmc. The significant age of the groundwater in this area (higher more ca. 10 ka) is supported by the stable isotope composition of the water shifted towards more negative delta values indicating recharge when climatic conditions were

Table 2

Isotope and chemical data of groundwater in the area of the Wielkie Błoto fen

Site description Well no.	^{18}O [‰]	^{2}H [‰]	Tritium content [TU]	^{14}C [pmc]	SEC [uS/cm]	Na [mg/L]	Cl [mg/L]	Na/Cl	HCO_3 [mg/L]
Szarów wellfield:									
Well no. 11	–9.75	–70.3	9.0	64.6	733	10.1	23.3	0.4	383.6
Well no. 12	–9.93	–70.1	1.1	63.6	646	6.9	7.4	1.4	393.8
Well no. 22	–9.81	–69.4	16.1	n.m.	607	7.5	8.8	1.3	410.4
Well no. 23	–9.84	–68.5	0.7	n.m.	906	20.5	45.1	0.7	340.1
Well no. 24	–10.03	–72.1	15.2	n.m.	542	6.5	20.4	0.5	305.6
Well no. 42	–9.68	–69.2	<0.3	48.5	n.m.	25.7	15.5	2.6	350.3
Wola Batorska wellfield:									
Well SW-2	–10.19	–75.7	<0.3	2.9	743	178.6	29.5	9.3	390.71
Well SW-3	–10.67	–78.3	<0.3	n.m.	780	160.2	51.0	4.9	448.35
Well SW-4	–10.86	–79.9	<0.3	0.8	774	166.6	49.8	5.2	435.54
Well SW-5	–10.89	–79.2	<0.3	n.m.	824	173.8	60.4	4.4	435.54
Well SW-6	–10.83	–80.2	<0.3	n.m.	855	177.6	28.5	9.6	467.57
Well SW-7	–10.71	–78.2	<0.3	2.2	1150	258.8	80.0	5.0	473.97
GEOPROBE sampling:									
GP1-A (1.6 m)	–10.07	–70.8	8.1	n.m.	348	11.7	13.9	1.3	76.3
GP1-B (2.8 m)	–9.65	–68.2	5.4	n.m.	860	65.8	57.5	1.8	275.5
GP1-C (4.6 m)	–10.10	–71.0	0.9	n.m.	1098	123.1	118.7	1.6	430.6
GP3-A (1.6 m)	–8.83	–61.9	10.1	n.m.	546	8.9	25.9	0.5	221.1
GP3-B (3.1 m)	–9.86	–69.3	1.4	n.m.	1153	163.2	120.5	2.1	397.7
GP4-A (1.6 m)	–9.09	–64.4	6.5	n.m.	564	9.5	21.1	0.7	298.0
GP4-B (4.0 m)	–9.67	–69.6	2.1	57.2	1065	51.9	43.3	1.9	473.3

Concentrations of tritium and radiocarbon are expressed in Tritium Units (TU) and Percent of Modern Carbon (pmc), respectively; Deuterium and ^{18}O contents are reported as values with respect to the VSMOW standard; measurement uncertainties (one sigma) are of the order of 0.3 TU for tritium, 0.1‰ for ^{18}O and 1.0‰ for ^{2}H; n.m. – not measured

considerably colder than at present. The results of vertical profiling of the chemical and isotopic composition of shallow groundwater within the area of the Wielkie Błoto fen strongly suggest that upwards leakage of groundwater from the deeper aquifer indeed takes place at present. Decrease of tritium content with depth is associated with an increase in Na, Cl and HCO_3, towards values characteristic of the deeper aquifer.

If the Wola Batorska wellfield is operated in future at full capacity, there is a growing risk that this additional supply of water to the GDE will be reduced or even cut off, with potentially grave ecological consequences for the Niepołomice Forest area. Future monitoring of isotopic and chemical tracers will help to identify possible changes, induced by pumping, in the overall groundwater flow patterns in the aquifer and a reduced upwards leakage of groundwater towards the fen. For example, higher radiocarbon contents or higher delta values of water isotopes in the production wells will indicate increasing contribution of younger water from upstream portions of the aquifer. If accompanied by weakening of tracer stratification in the shallow groundwater, such shifts might point to reorganization of groundwater flow patterns in the aquifer – GDE system. This example shows that environmental tracers can provide valuable insights into the nature and current status of interactions between GDE and associated groundwater systems already at initial stages of investigation.

CONCLUSIONS

Groundwater Dependent Ecosystems are important elements of biodiversity and providers of valuable goods and services to society. Their sustainability depends on appropriate environmental policies and groundwater management practices that are able to reconcile the conflict between human and environmental water needs. While GDE are increasingly included in environmental policies, they are not sufficiently well-accounted for in the management of groundwater resources.

Better understanding of the functioning of GDE can be achieved through their incorporation into conceptual and numerical models of the associated groundwater systems. Challenges in the proper inclusion of GDE within the groundwater systems modelling framework are primarily related to the necessity for three-dimensional representation of interactions between groundwater and surface water, including the riparian and hyporheic zones, with sufficient level of detail. Also, incorporation of biogeochemical processes, which are intensified at the interfaces between groundwater and surface water, is hindered by lack of appropriate model parameters that need to be derived from process studies. An additional difficulty arises from the need for accommodating a wide range of timescales that govern different types of processes and interactions between a GDE and its surroundings.

While biogeochemical processes may influence water quality in GDE on diurnal time scales, transport of pollutants from recharge area(s) occurs on scales of years or tens of years. Such time lags associated with the propagation of disturbances through groundwater systems are a crucial but often overlooked element of water resources management. Any measures undertaken to improve the quantity and quality of groundwater supporting the ecosystem need to take into account timescales characteristic of the propagation of groundwater pressures and transport of pollutants from recharge areas to GDE. Environmental tracers play a key role in quantifying those timescales.

In the face of progressive global climatic changes, appropriate management of GDE should also take into account direct and indirect effects of those changes on GDE functioning. Interdisciplinary research into and management of GDE has to be, however, fully integrated and balanced. As GDE have multiple and interwoven functions, the management practices focused on preservation of only selected functions of these systems may lead to the loss of others.

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