Brkić *et al. Environ Sci Eur (2019) 31:75*
https://doi.org/10.1186/s12302-019-0261-6

Environmental Sciences Europe

RESEARCH

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Groundwater and connected ecosystems: an overview of groundwater body status assessment in Croatia

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Abstract

Background: Croatia, as a Member State of the European Union, has to shape its water policy in accordance with the European Union Water Framework Directive. One of the tasks is to determine whether groundwater are susceptible to anthropogenic changes that would result in a significant surface water status reduction as well as terrestrial and aquatic ecosystems that directly depend on the groundwater.

Methods: Quality and quantity data on groundwater and surface water, as well as ecosystems data were collected from multiple sources. Data were analyzed for the selection groundwater associated aquatic and groundwater-dependent ecosystems. Chemical time series data were analyzed and compared with the national guideline limits set by the Croatian water quality standard. The impact of the groundwater abstraction on the groundwater-dependent ecosystem was considered by analyzing the aquifer hydrogeological characteristics, as well as location of the pumping site in relation of the ecosystem, the pumping rate and groundwater level or discharge.

Results: In karst areas of Croatia, groundwater-dependent aquatic ecosystems are predominant; while in the Pannonian area of Croatia, typically, there are groundwater-dependent terrestrial ecosystems. The status of groundwater bodies was defined as good. The analyzed chemical parameters are at acceptable concentration levels. Groundwater abstraction does not adversely affect most ecosystems. However, many springs that are captured for the water supply dry up in the summer. Given that this is also a common phenomenon at springs not captured, it has to be expected that such environments will be inhabited by organisms that have already adjusted to these conditions. Many different bioindicators have been found to indicate a good chemical and quantitative state of groundwater.

Conclusions: To increase the degree of reliability, research monitoring has been proposed. The monitoring should reduce knowledge gaps including an increase of knowledge of the status of the ecosystems, the definition boundary conditions and threshold values of a good quantitative and qualitative status for individual ecosystems. In future prospects, unavoidable focus has to be climate change that may compromise the availability of groundwater resources.

Keywords: Groundwater quality, Groundwater quantity, Vulnerability, Bioindicator, Water management, Water Framework Directive, Croatia

Background

Croatia, as a Member State of the European Union (EU), has to shape its water policy in accordance with the Water Framework Directive (WFD) [1] that presents an environmentally oriented legal frame requiring EU countries to achieve good status all their waters by 2027 at the latest. This implies that groundwater must not be subject to anthropogenic changes that would result in significant surface water status reduction as well as terrestrial and aquatic ecosystems that directly depend on the groundwater.

The relationship between groundwater and related ecosystems is relatively complex. In the first six-year cycle of

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water management, in many EU countries, expert judgement has played a major role in defining the dependence of the ecosystem on groundwater [2]. In the meantime, research has begun to improve the understanding of this relationship and needs of the ecosystem for groundwater. These needs relate to dependence on the groundwater discharge, groundwater level and its quality.

Merz et al. [3] defined groundwater-dependent ecosystems (GWDEs) as complex communities of organisms in which groundwater is a key element needed for their sustainability. According to Kløve et al. [4] (adapted from [5]), GWDEs include: terrestrial ecosystems seasonally or episodically dependent on groundwater, river-based flow systems including aquatic, hyporheic and riparian habitats, aquifer and cave ecosystems, wetlands and springs dependent on groundwater inflow for all or part of the year, and estuarine and nearshore marine ecosystems influenced by groundwater discharge. Eamus et al. [6] discusses the three major classes of groundwater-dependent ecosystems: GWDEs that reside within groundwater (e.g., karsts; stygofauna), GWDEs requiring the surface expression of groundwater (e.g., springs; wetlands), and GWDEs dependent upon the sub-surface availability of groundwater within the rooting depth of vegetation (e.g., woodlands; riparian forests).

Groundwater is the main source of freshwater on Earth and plays a key role in the global hydrological cycle. It provides water for human consumption, agriculture, industry and many GWDEs, especially during drought [7]. Over the last few decades, the use of groundwater for human consumption and irrigation has increased, resulting in a reduction in groundwater levels worldwide [8]. Over-abstraction of groundwater is becoming an increasingly regional issue [9]. In addition, the predicted climate change will exacerbate these problems in many parts of the world due to decreasing rainfall and increasing evapotranspiration, which will reduce renewable groundwater supplies and cause groundwater-level decline [10].

Taking into account the fact that groundwater plays a key role in the sustainability of many ecosystems, it is of crucial importance not only for the human population and socioeconomic development but also for many species of flora and fauna [11]. The ecological role of groundwater in water management includes: (1) sustaining stream base flow and moderating water level fluctuations of groundwater-fed lakes and wetlands, (2) providing stable-temperature habitats, (3) supplying nutrients and inorganic ions, and (4) providing moisture for riparian and other groundwater-dependent vegetation [12].

The definition of environmental needs for water requires an understanding of the relationship between the elements on which the ecosystem depends and the nature of their time variations. GWDE will react to changes in any element, but the degree of reaction will vary. While some GWDEs will be destroyed if the value of any element exceeds a threshold value, others may only show a gradual change in structure or composition [4]. Therefore, groundwater threshold values must be set to protect associated aquatic ecosystems and human health [13]. In the United Kingdom, nitrate concentrations were compared with the altitude of the terrestrial ecosystem (fens, bogs, wet meadows, wet forests, etc.), and land use [14]. The threshold values are suggested for nitrate concentrations in groundwater on which these ecosystems depend. For groundwater-dependent terrestrial ecosystems (GWDTE) at altitudes of less than 175 m a.s.l., they range from 18 to 26 mg/L NO_3 while at higher altitudes from 4 to 9 mg/L. The same threshold values were also adopted in Northern Ireland [15]. Threshold indicator taxa analysis has discovered that plant community composition on peat bogs in Poland strongly converged at a water level of approximately 11.7 cm, indicating a community-level tipping point [16].

The process of WFD application is currently in the middle of the second six-year cycle of the river basin management. It can be concluded that many countries still experience a series of unresolved issues related to ecosystem and groundwater interconnections [17].

The aim of this study was to identify ecosystems associated with or dependent on groundwater in Croatia, to define the method of estimating the quantitative groundwater status and its quality in relation to ecosystem requirements and, accordingly, to assess the status of groundwater bodies. The study was conducted for the purpose of development of the river basin management plan in Croatia for the period from 2016 to 2021.

Study area

Croatia is a small southern European country, comprising an area of only 56.538 km^2. From a hydrogeological and even water management viewpoint, it can be divided into two hydrogeological regions: the Northern or Pannonian region and the Southern or Dinaric karst region (Fig. 1). Northern Croatia is situated in a southwestern part of the Pannonian basin where the large lowlands are dominant along two Danube tributaries—the river Sava and Drava and their major tributaries, as well as along the river Danube in the eastmost part of the region. In between the lowlands, there is a hilly region composed mainly of low permeable deposits ranging in age from Palaeozoic to Quaternary, while only smaller areas are occupied by permeable carbonate deposits of Triassic age, which represent the most important aquifers in the area. The altitude of the lowlands varies from approximately 120 m a.s.l. in the west to approximately 80 m a.s.l. in the east. Quaternary sediments form thick and

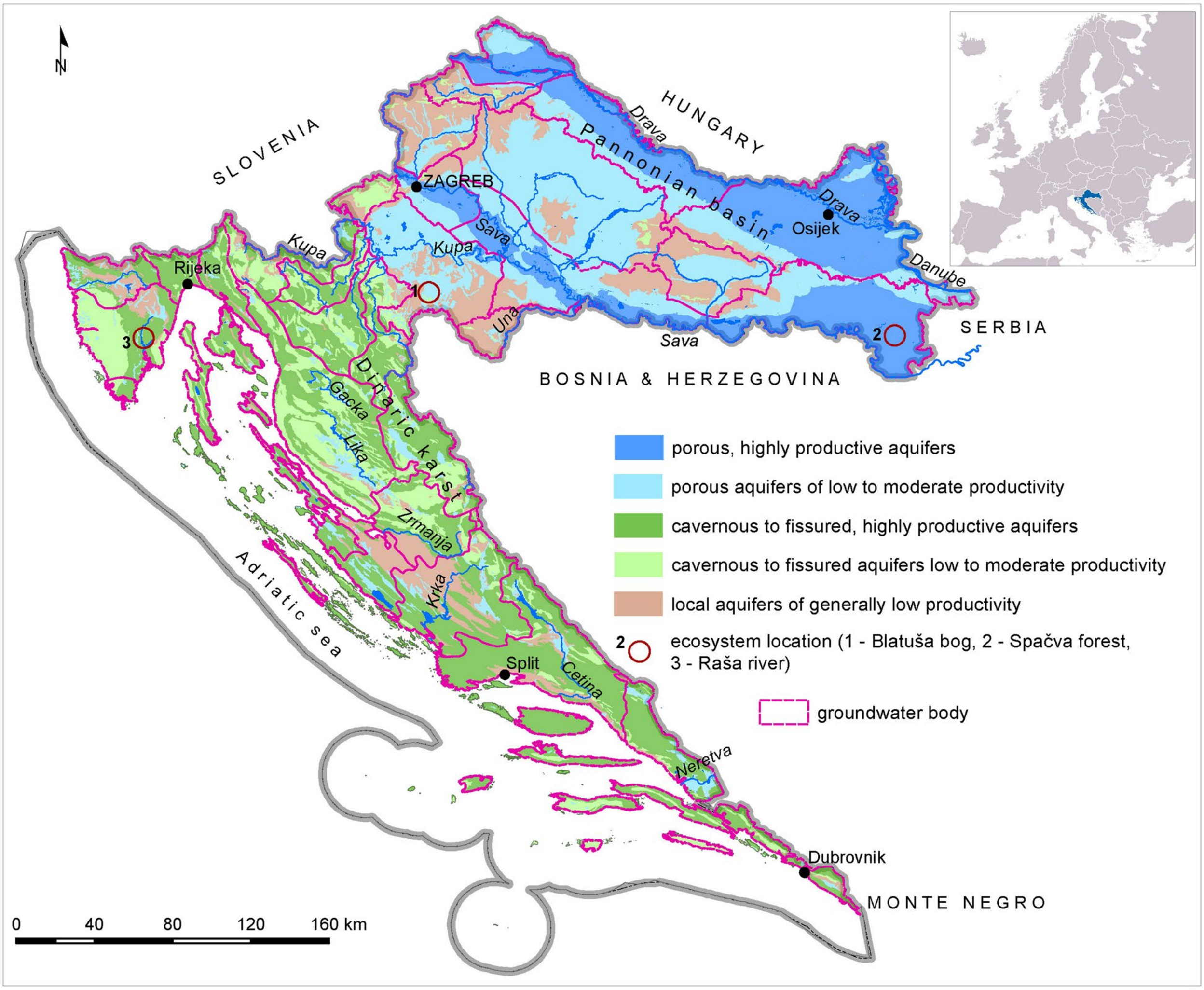

Fig. 1 Aquifer types in Croatia and the locations of the ecosystem, which will be discussed in greater detail in this paper

very permeable aquifers within these lowlands. Unconfined aquifers prevail in the western area; whereas in the central and eastern parts, aquifers are mostly semi-confined. Infiltration of precipitation is the main source of groundwater recharge, although the recharge from surface water bodies cannot be neglected and in some areas even plays an important role in the groundwater balance [18]. They discharge into surface water bodies for the most part of year. Feeding from the rivers mostly occurs during the season of high water levels. Groundwater velocities in the aquifer of intergranular porosity are relatively small and many times less than in karst aquifers. The properties of porous medium and relatively low groundwater velocities enable groundwater auto-purification, which has a beneficial effect on preventing damage to ecosystems.

The basic characteristics of the karst area are the existence of numerous geomorphologic forms, the absence of surface water, the high velocities of groundwater flow, the groundwater discharge at the springs of over ten m^3/s, significant groundwater amounts which discharge in the sea, and the strong impact of the sea on coastal aquifers. The altitude of these areas varies from approximately 1900 m a.s.l. in the high mountains to 0 m a.s.l. at the coast.

Ecologically significant and hydrogeological very complex phenomena of the karst area are karst poljes. In the Dinaric area of the Republic of Croatia, there exist fourteen larger karst poljes located at an altitude between 250 and 700 m. Morphologically, they are usually parallel to the Dinaric strike of geological structures (northwest–southeast) and situated between the mountains or mountain ranges of the same strike. The karst poljes are characterized by the presence of springs on one side of the polje and swallow-holes formed on the other side. Springs can be permanent or periodic, fed by upstream mountainous areas, most often characterized by increased rainfall. The water of these springs forms watercourses running to the opposite, slightly lowered, side of the field, where they sink underground. The formation of these watercourses and the sustainability of their streams are enabled by quaternary and occasionally Neogene or even older (semi-permeable) deposits underlying the particular poljes.

In periods of high water flow, their discharge can significantly exceed the sink capacity, causing periodical flooding of the lowest parts of or the entire karst poljes. The sinking waters of karst poljes are drained to the nearest local erosional base level (i.e., to the polje or river valley at the lower altitude) or directly to the ultimate base level of erosion (sea level), represented by the coastal springs and vruljas (Fig. 2). Due to the different altitude of individual erosional base levels, it is common that the same water sinks and reappears multiple times on several levels (poljes) before it reaches the ultimate erosion base [19–21]. The groundwater velocities in karst aquifers are high, and hence, the travel time of water and pollutants is short [22, 23]. The mean groundwater velocity in the Dinaric karst of Croatia is 3.55 cm/s (median 2.3 cm/s) [24].

In accordance with the hydrogeological features, Croatia is divided into 44 groundwater bodies (GWB), of which 25 are located in the catchment area of the Adriatic

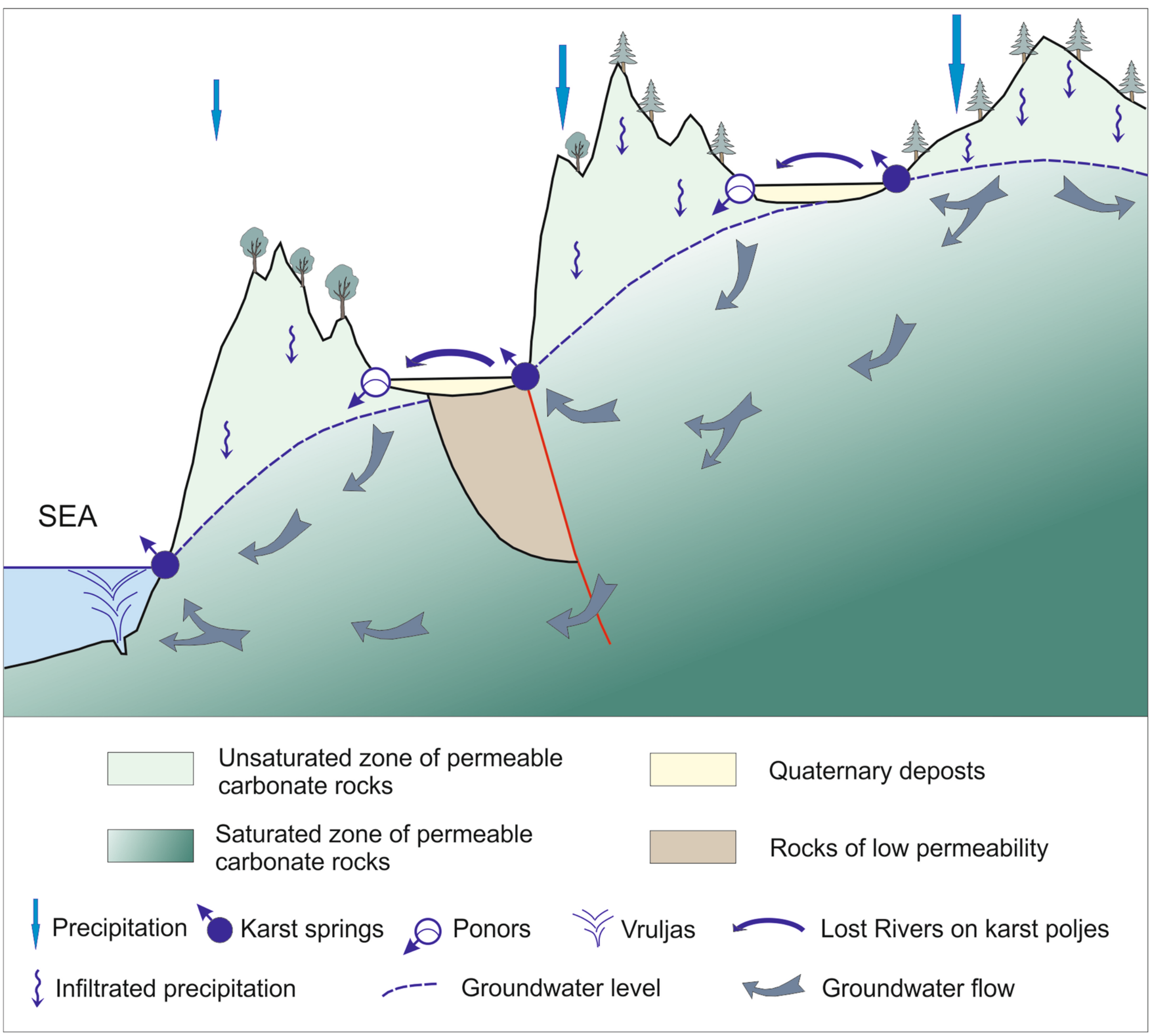

Fig. 2 Connection between groundwater and surface water in the karst of Croatia

Sea (11 larger islands and 14 GWBs on the mainland), as well as 19 GWBs in the Danube river basin (Fig. 1).

Croatia is divided into two main climate regions—Continental and Mediterranean—with some variations within those climate zones [25]. Summer is the driest season along the coast and winter is the rainiest season, with twice the amount of precipitation as in the summer. The continental part of Croatia has a different climate; winters are cold, and summers are hot, with the occurrence of heat waves becoming more frequent. The mountains have a lower average air temperature and experience more precipitation. Mean annual precipitations are on the outer islands of the southern Adriatic approximately 300 mm, in eastern Croatia 600 mm, and in the mountainous parts of karst area more than 3000 mm. As a result, there are different ecosystems that can be associated with or are dependent on groundwater.

Data

Groundwater quality data were collected from two types of monitoring. One is the national (state) monitoring which is within the competence of the Hrvatske vode (a legal entity for water management in Croatia), and the other one is carried out on public water supply facilities. Sampling frequency varies from 4 to 12 times a year. More frequent groundwater sampling is conducted in unconfined aquifers of intergranular porosity and in karst aquifers, and less frequently in semi-confined aquifers.

Data on groundwater levels and the spring discharge collected within the national monitoring network, as well as surface water data are obtained from the Hrvatske vode. Measurements are conducted either by automatic loggers, which record daily data, or manually—once or twice a week. Data on annual abstracted quantities at the public water supply wells were also obtained from the Hrvatske vode together with the volume of abstracted water for technological needs and irrigation.

For the purpose of defining groundwater-associated aquatic ecosystems (GWAAEs) and GWDEs, from both hydrogeological and ecological aspect, as well as indicator organisms, numerous data were used [18, 26–48]. Very significant data on the presence and distribution of indicator organisms in subterranean habitats have been collected from the Croatian Biospeleological Society and the Croatian Agency for the Environment and Natura.

Methods

Assessment of the status of the GWBs with regard to groundwater-associated and/or groundwater-dependent ecosystems included the following steps: (1) definition of groundwater-associated aquatic ecosystems (GWAAE) and groundwater-dependent ecosystems (GWDE), (2) GWB quality (chemical) status assessment and (3) GWB quantitative status assessment. GWB status assessment was performed on the basis of the methodology described in WFD Common Implementation Strategy (CIS) Guidance Documents No. 18 [49], which was modified to a certain extent and adapted to conditions in Croatia.

The definition of groundwater-associated and groundwater-dependent ecosystems

The definition of GWDE in Croatia has been made in terms of hydrogeological and ecological aspects. Hydrogeological aspects included the analysis of the hydrogeological properties of GWB and the groundwater dynamics therein. Particular attention was paid to the role of groundwater in the environment and the way it can convey the consequences of certain anthropogenic pressures (groundwater contamination, groundwater velocities, streamflow depletion, or lowering of the groundwater level) within the GWB. In the karst area of Croatia, the ecological aspects were based on the data on the presence of indicator organisms.

Procedure/protocol for assessing GWB quality status with regard to the groundwater-associated and/or groundwater-dependent ecosystems

The groundwater quality assessment within the GWB is carried out to prevent significant deterioration of the chemical status of the surface waters and ecosystems identified within them. The quality status is assessed on the basis of evaluation of the surface water and ecosystems status and evaluation of the transfer of pollutants from groundwater to them.

Groundwater quality standard (GWQS) below which groundwater is considered to be in poor status was defined. Chemical time series data were analyzed by descriptive statistics and compared with the national guideline limits set by the Croatian water quality standard.

GWB status from the GWAAE point of view is evaluated as good if the surface waters within it are evaluated as having a good status. The possibility of the transfer of pollutants from groundwater to surface water and ecosystems was also analyzed. If such a possibility exists and if this contribution is significant, the GWB status is poor. A significant contribution implies that more than 50% of the contamination of analyzed surface waters comes from groundwater.

If the GWDE is not significantly damaged or if the damage is low to moderate, then the status of GWB is also evaluated as good. If GWDE is significantly damaged, it is analyzed whether the relevant GWQS is exceeded in groundwater which is responsible for damaging the GWDE. If the exceedance of any of the GWQS parameters is not in the area from which the contamination can be transferred to the GWDE, the status of GWB is good. If the exceedance of one of the GWQS parameters causes significant damage to the ecosystem, the GWB status is poor. The term "significantly damaged" GWDE in Croatia is, unfortunately, not clearly defined. In the absence of a clear definition of this concept and in situations where there were no clear indicators of ecosystem damage, data on threats and pressures that could be transmitted via the groundwater to the ecosystem were used as a proxy. Threats and pressures are categorized into individual categories of the International Union for Conservation of Nature (IUCN) according to Salafsky et al. [50], which are used as a global standard for water and terrestrial ecosystems. The categories of vulnerability of certain groundwater-dependent ecosystems/habitats in Croatia, as well as the assessment of their strength (L—low; M—medium; H—high) are listed in the Natura 2000 standard data forms. For all pressures on groundwater (IUCN codes H02—pollution to groundwater—and J02.07—water abstraction from groundwater) less than high (H), it was assumed that they did not cause significant damage to the ecosystem.

Procedure/protocol for assessing GWB quantitative status with regard to the groundwater-associated and/or groundwater-dependent ecosystems

Assessment of the groundwater quantity in the GWB was also carried out to prevent deterioration in the status of GWAAE or GWDE. The anthropogenic influence on the quantitative status of groundwater was considered solely from the standpoint of groundwater abstraction. Ecologically acceptable surface water flow in Croatia is not defined. In the absence of biologically based criteria for the classification of surface waters in accordance with the changing quantity of water flow, the assessment of the quantitative status of GWB with respect to interconnection between groundwater and surface waters was defined on the basis of the "Surface Water Utilization Index (SWUI)" estimation.

SWUI shows the impact of anthropogenic changes to surface water utilization [51] which is expressed by the percentage of captured and redirected water flows with respect to the long-term average flow. The SWUI values are grouped into five classes (Table 1).

If the status of surface waters is evaluated as worse than good, analysis as to whether groundwater abstraction has a significant effect on such a condition was carried out. If the impact is not significant, the GWB status is good; while if that impact is significant, the GWB status is poor. The impact of groundwater abstraction is considered significant if the SWUI is >40% and the entire value can be attributed to the groundwater abstraction.

Table 1 Classes for assessing the quantity of water flow with respect to the Surface Water Utilization Index (SWUI) [51]

Index of use, SWUI (%)	Status assessment according to the quantity of water flow	Impact on the surface water status
0	Very good	No impact
0–20	Good	Small impact
20–40	Moderate	Moderate impact
40–75	Poor	Significant impact
>75	Very poor	Very significant impact

The groundwater status within the GWB as regards the GWDE has been assessed on the basis of environmental conditions related to streamflow and/or groundwater level and the assessment of the impacts of groundwater abstraction as well as environmental conditions. If GWDE is significantly damaged, analysis was carried out as to whether the damage was caused by the groundwater abstraction. The impact of the groundwater abstraction on the ecosystem was considered by analyzing the aquifer hydrogeological characteristics, as well as location of the pumping site in relation of the ecosystem, the pumping rate and groundwater level or discharge. If groundwater abstraction is not the source of significant damage to GWDE, than the GWB status is good.

Generally, the assessment of the groundwater body was based on the "source–pathway–receptor" model [52]. The assessment starts with the source, i.e., where pollution can come from or where groundwater is abstracted. After that, the pollution or abstraction impact can travel or expand through the environment (the pathway). Finally, the receptor (where the receptor is a GWAAE or GWDE) which is affected by pollution or abstraction must be considered.

If the groundwater status is good at the source location, in the area between the source and downstream receptor as well as at the receptor location, the status of the GWB is considered to be good. If the groundwater status is poor at the source location as a consequence of a large decrease in the groundwater level due to groundwater abstraction or leakage of the pollutant into the groundwater, but in the area between source and downstream receptor as well as at the receptor location the groundwater status is good, then the status of the GWB is considered to be good. However, as long as pollution is not remediated, a potential threat exists (a receptor is at risk). Finally, the poor groundwater status at the source and along the pathway, as well as at the receptor location, results in a poor GWDE status.

Results and discussion

Identification of the groundwater-associated aquatic ecosystems (GWAAEs) and groundwater-dependent ecosystems (GWDEs)

The relationship between groundwater and related ecosystems is relatively complex. In terrestrial ecosystems, it is often difficult to separate the impact of groundwater from the impact of surface waters on the ecosystem because the most of the terrestrial ecosystems are located close to the watercourses. Typically, the surface water levels cause a change in the groundwater levels, leading to the conclusion that the influence is mutual.

GWAAEs and GWDEs in Croatia have been identified by integrating the knowledge from hydrogeology and ecology. Special attention was paid to the role of groundwater in the environment and the means by which the groundwater is efficient in the transmission of a certain anthropogenic impact (streamflow depletion, or lowering of the groundwater level) within the GWB. Groundwater is virtually all water found beneath the surface of the earth. However, for the purposes of GWB status assessment regarding the interconnection of ecosystems with groundwaters, the most important are groundwaters in the saturated part of the aquifer. Only these groundwaters, either as such or subject to intense anthropogenic influences (whether by pollution or groundwater abstraction within the total observed GWB), can adversely affect the ecosystem. Seepage waters, for example, do not reflect the chemical groundwater status within GWB because they are exclusively influenced by local conditions. Furthermore, the use of seepage waters by abstraction is almost impossible, and the impact on GWB is unrecognizable.

As already mentioned, groundwater in Croatia is usually well associated with surface water bodies. GWAAEs are delineated in large rivers and smaller watercourses that are included in the Natura 2000 areas [53]. However, there are also larger rivers that are not entirely, or neither in their segments, included in the Natura 2000 areas but are of particular importance as GWAAE.

In the parts of Croatia built of karstified carbonate rocks, two types of groundwater-dependent aquatic ecosystems (GWDAE) are identified. One is represented by the springs (mark 1 in Fig. 3) as the location of the groundwater discharge, and the other by speleological objects reaching to the depths of the groundwater level, that is, the saturated zone of the permeable deposits (mark 4 in Fig. 3). These speleological objects do not necessarily contain groundwater throughout the year but only during the season of high water levels. Speleological objects that are located in the unsaturated zone of permeable carbonate rocks (mark 5 in Fig. 3) throughout the year, although they may occasionally contain water (seepage waters) that are not directly linked to the saturated zone, do not represent a GWDE that is considered with the aim of assessing the status of the GWB.

Another two ecosystems have been identified in the Croatian karst, one of which is a GWDTE (mark 2 in Fig. 3); while the other is a GWAAE (mark 3 in Fig. 3). Groundwater discharged on the surface through the spring and feeding, e.g., local aquifer associated with the terrestrial ecosystem that is dependent on the groundwater that represents area 2 in Fig. 3. The discharge of such an aquifer into the stream or the formation of streams immediately after the discharge of groundwater to the surface creates a groundwater-associated aquatic ecosystem (mark 3 in Fig. 3). Such ecosystems in Croatia are found in karst poljes and dolines built of clastic deposits.

GWDTEs in the Pannonian area of Croatia are generally found in valleys with the surface flow, and they are most commonly influenced by both groundwater and surface waters. Plant roots are not in contact with groundwater throughout the year, or at least not for most of the year. During low waters, in summer and dry months, the groundwater levels are so low that they do not affect vegetation (Fig. 4a). However, during medium, and, especially, during high water levels, the groundwater level may reach the roots; if not, given that it is sufficiently high, the roots obtain water by capillary lift (Fig. 4b).

GWDTEs are identified mostly near the surface flows on terrain built of clastic deposits, with a relatively low depth of groundwater and with a relatively small thickness of poorly permeable overlying deposits. This group includes GWDTEs, which are classified in the Natura 2000 areas, provided that their surface area exceeds 5 ha. GWDTEs encompassing larger regions that are not included into Nature 2000 areas have also been taken into account, but they are outlined within the National Classification of Habitats (NCH) (Table 2).

GWDAE are speleological objects included in the Natura 2000 areas, as well as all other important speleological objects that reach the groundwater level in the saturated part of the karst aquifer. Larger and more significant springs are listed on the grounds that they are specially protected under the Nature Protection Act [54]. Coastal ecosystems and ecosystems associated with brackish water have not been considered in this study. GWDE are shown in Fig. 5. A total of 65 GWDTE and 164 GWDAE were selected.

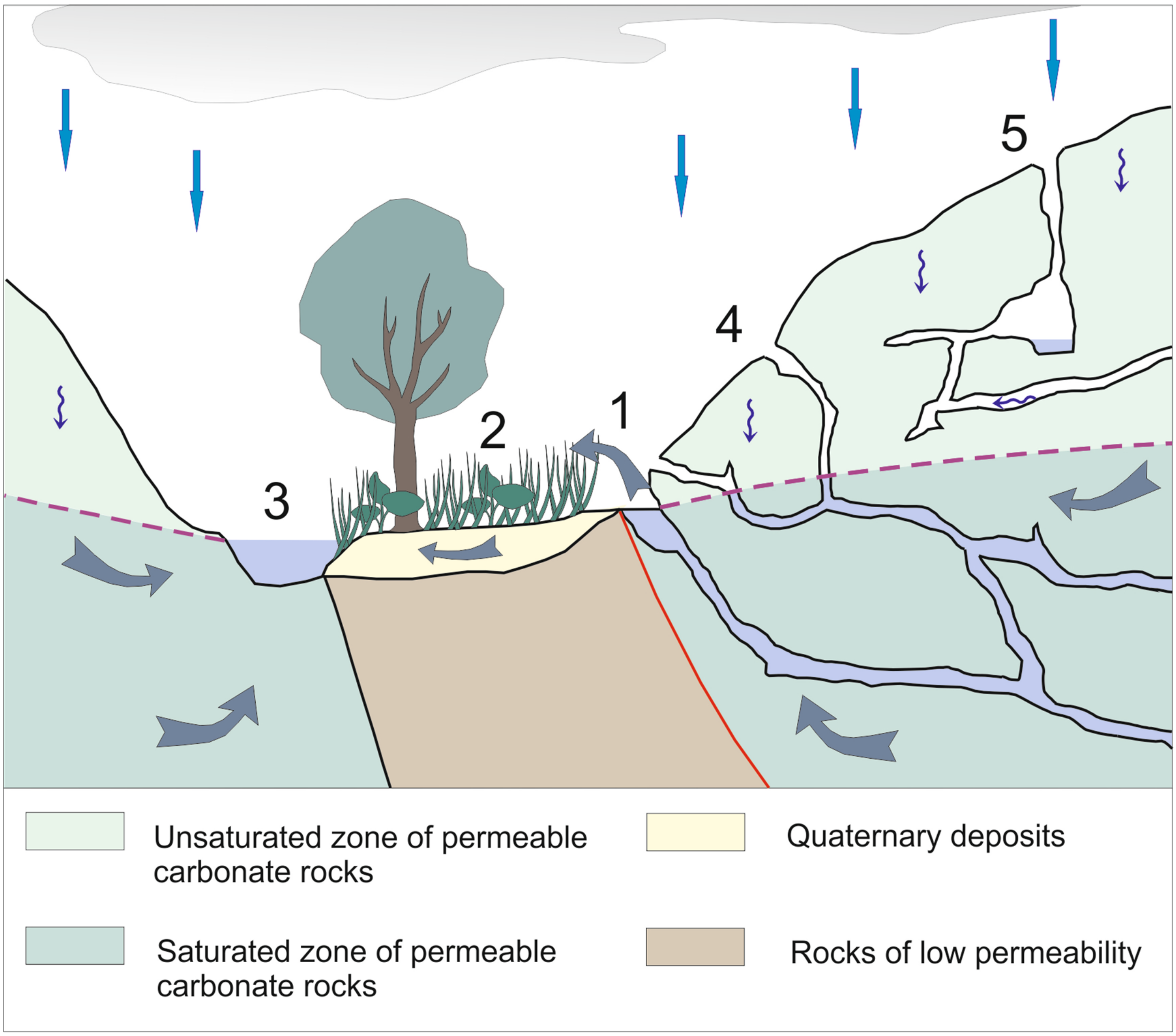

Fig. 3 Groundwater-associated ecosystems and groundwater-dependent ecosystems in Dinaric karst. (1) Spring; (2) Terrestrial ecosystems; (3) Watercourse; (4) Speleological object with a depth that reaches the saturated part of the aquifer; (5) Speleological object within unsaturated zone

Groundwater quality standard (GWQS)

GWQS with regard to GWAAE and GWDE were defined using legislation for the assessment of the status of surface waters in Croatia, and literature data on environments with protected flora and fauna within distinct ecosystems, with special emphasis on the presence of indicators that show the good status of the groundwater. According to the recommendation of the Guidelines on Groundwater Status and Trend Assessment [49], a "relevant environmental quality standard" (EQS) for priority substances and other surface water pollutants as laid down in the 2008/105/EC Directive [55] has been adopted as a relevant GWQS. The EQS was also imported into Croatian legislation [56].

For a more accurate determination of GWQS in these Guidelines, a dilution factor or attenuation factor was introduced. Both factors typically depend on the degree of understanding of the interaction between ground and surface waters, the conceptual model and the position of gauge points within the GWB with respect to the receptor, that is, the ecosystem. If the water quality is monitored only in the receptor (surface water), it is suggested that GWQS is equal to the surface water EQS. The same applies when the degree of understanding of the interaction between the ground and surface water is low. Due to the lack of data, a dilution factor and attenuation factor were not considered in the GWB quality status assessment in Croatia, which is why the EQS for

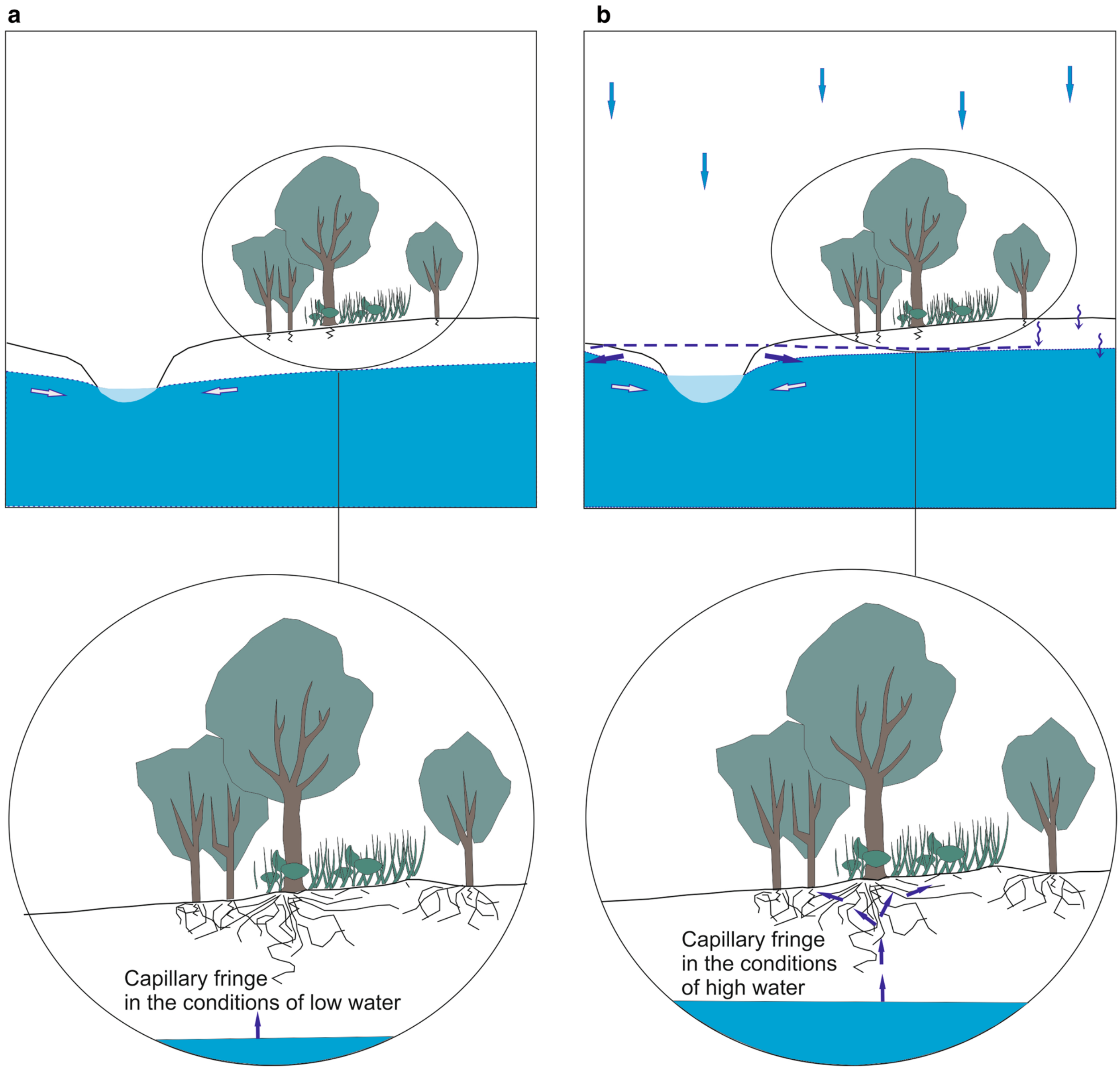

Fig. 4 Groundwater-dependent terrestrial ecosystems. **a** Hydrological low water; **b** hydrological high water

priority substances in surface waters was adopted for GWQS.

In addition to these parameters, the concentration of nitrates in the groundwater was further analyzed since nitrates are generally the largest issue with regard to the groundwater quality in Croatia.

Bioindicators of the good status of groundwater in Croatia

Werersson et al. [57] have proposed potential effect-based tools that could be used in the context of the different monitoring programs linking the chemical and ecological status assessment. In this context, findings of the bioindicators of the good status of groundwater were used in this study. Their great contribution to the determination of the GWB status is particularly evident in the karst area (Fig. 6).

The most important indicators of a good condition of river systems are numerous aquatic invertebrates, among which the stoneflies (Plecoptera), decapod crustaceans (crayfish) of the genus *Austropotamobius* (*A. pallipes* and *A. torrentium*) are particularly important. For a good condition within the hyporheic zone, the Perlodidae (Plecoptera) family is very indicative. Among the species of fish, it is the *Hucho hucho* (Danube salmon), which

Table 2 An overview of delineated Natura 2000 habitats and habitats by the Croatian National Classification of Habitats (NCH) that are more or less associated with or dependent on groundwater, indicating the range of susceptibility to quantitative and qualitative groundwater change

Natura 2000 code	Type of habitat (Natura 2000)	NCH code	Type of habitat (NCH)	Type of ecosystems	Sensitivity to quantitative groundwater change	Sensitivity to qualitative groundwater change
6410	Molinia meadows (*Molinion caeruleae*)	C.2.2.	Wet meadows of Central Europe	GWDTE	Low–moderate	Low–moderate
6430	Wet and nitrophilous tall herb edge communities, along water courses and woodland borders (*Convolvulion sepii, Filipendulion, Senecion fluviatilis*)	C.5.4.	Lowland communities of high green	GWDTE	Moderate	Moderate
7140	Transition mires and quaking bogs	C.1.2.	Acidophilic fans (transient and uplifted fans)	GWDTE	High	High
7220	Petrifying springs with tufa formation (*Cratoneurion*)	A.2.1.1.3.	Helocrene spring	GWDAE	Very high	Very high
8310	Caves and pits not open to the public	H.1.3.	Aquatic (freshwater) karst cave habitats	GWDAE	Very high	Very high
8310	Caves and pits not open to the public	H.1.3.1.	Underground streams	GWDAE	Very high	Very high
8310	Caves and pits not open to the public	H.1.3.2.1.	Underground lakes	GWDAE	Very high	Very high
9160	Sub-Atlantic and medio-European oak or oak-hornbeam forests of the *Carpinion betuli*	E.3.1.1.	Common oak and common hornbeam forest (typical sub-association)	GWDTE	High	Moderate
91EO	Alluvial forests (*Alno-Padion, Alnion incanae, Salicion albae*)	E.2.1.	Flooded forests of *Alnus glutinosa* and *Fraxinus angustifolia*	GWDTE	Moderate	Low–moderate
91F0	Riparian mixed forests (*Quercus robur, Ulmus laevis, Ulmus minor, Fraxinus excelsior* or *Fraxinus angustifolia*)	E.2.	Flooded forests of Common oak, *Alnus glutinosa* and *Fraxinus angustifolia*	GWDTE	High	Low–moderate
No code	–	A.2.1.	Springs	GWDAE	Very high	Very high
No code	–	A.2.1.1.1.	Rheocrene springs	GWDAE	Very high	Very high
No code	–	A.2.1.1.2.	Limnocrene springs	GWDAE	Very high	Very high
No code	–	H.3.2.1.2.	Hyporheic zone	GWDAE	Moderate	Moderate–high
No code	–	H.4.2.	Anthropogenic aquatic underground habitats (mines)	GWDAE	Very high	Very high

appears in the rivers of the Black Sea basin. When assessing the status of the fish population in terms of the population size, the reasons for the decrease in the population should be accounted for, as it may be influenced by excessive fishing, which is not an indicator of poor chemical or quantitative water status.

The karst and intergranular aquifers of Croatia support various representatives of the metazoan fauna, which are the obligatory (exclusive) inhabitants in groundwater, and among which the crustaceans (Crustacea) are the most dominant (e.g., Amphipoda, Copepoda, Decapoda, Isopoda, Ostracoda, Syncarida, and Thermosbaenacea).

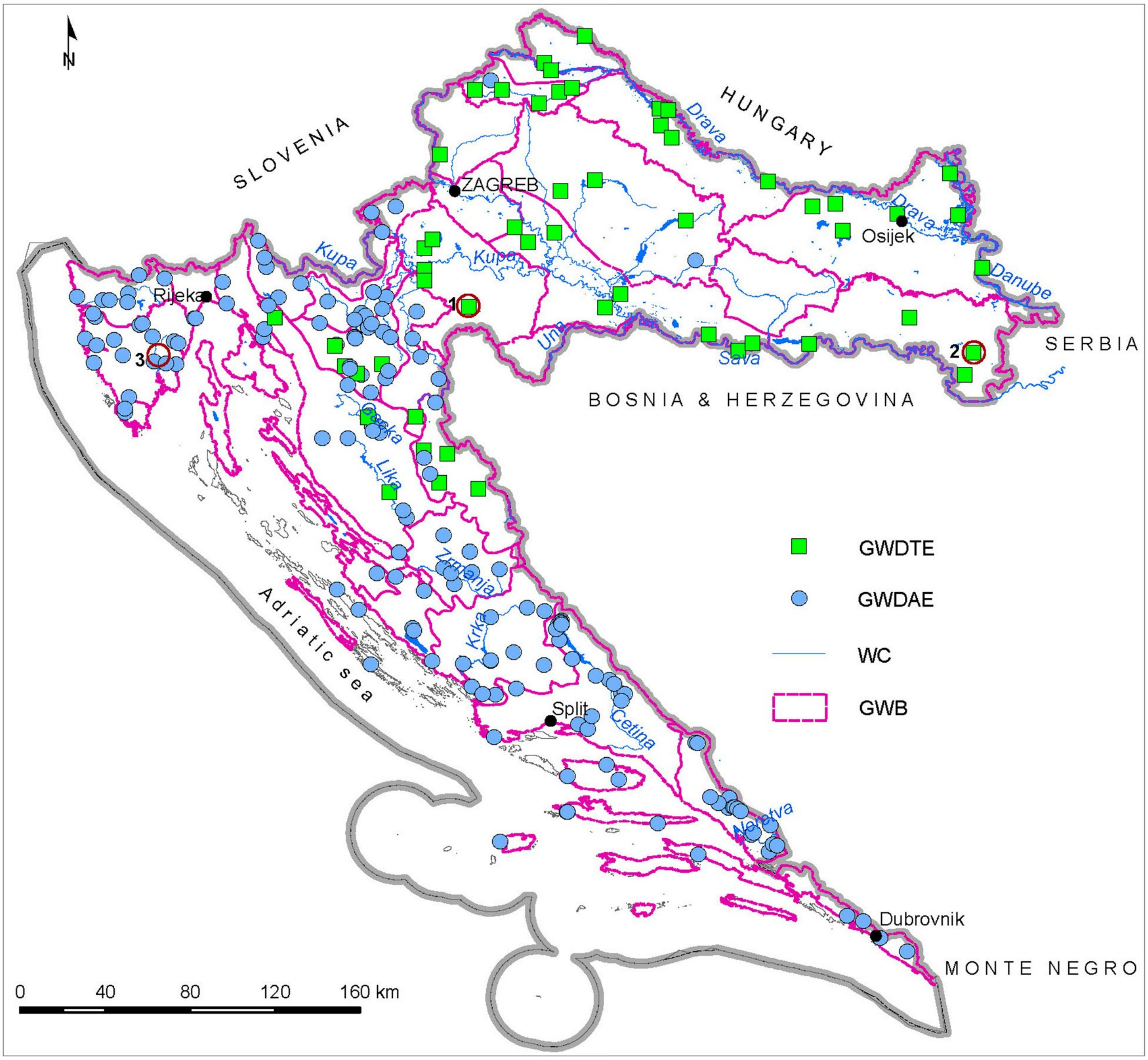

Fig. 5 Groundwater-dependent ecosystems in the Republic of Croatia. *GWDTE* groundwater-dependent terrestrial ecosystems, *GWDAE* groundwater-dependent aquatic ecosystems, *WC* watercourse, *GWB* groundwater body

Due to their frequency and abundance in various types of groundwater, it is important to mention other, no less important, highly adapted representatives of groundwater invertebrates of particular interest for monitoring the ecosystem status such as Protista and Micrometazoa (Gastrotricha, Nematoda, Nemertina, Rotifera, Tardigrada, etc.), sponges (Porifera), flatworms (Turbellaria), snails (Gastropoda), aquatic and terrestrial worms (Oligochaeta), bristle worms (Polychaeta), leeches (Hirudinea), aquatic insects (Insecta), water mites (Hydrachnidia) and amphibians (Amphibia) and fish among vertebrates [34, 35]. Many of them are narrowly distributed endemic species which results in difficulties in selecting the appropriate fauna representatives that would be unique to monitoring the status of GWDEs. However, the findings of representatives of underground fauna and their number over time in groundwater-dependent subterranean ecosystems are an extremely good indicator of the dependence of these systems on groundwater, and can be actively involved in the monitoring of the ecosystem status.

Subterranean crustaceans (Crustacea), as an extremely dominant group living in groundwater, are relatively poorly explored, as well as most other groups of aquatic

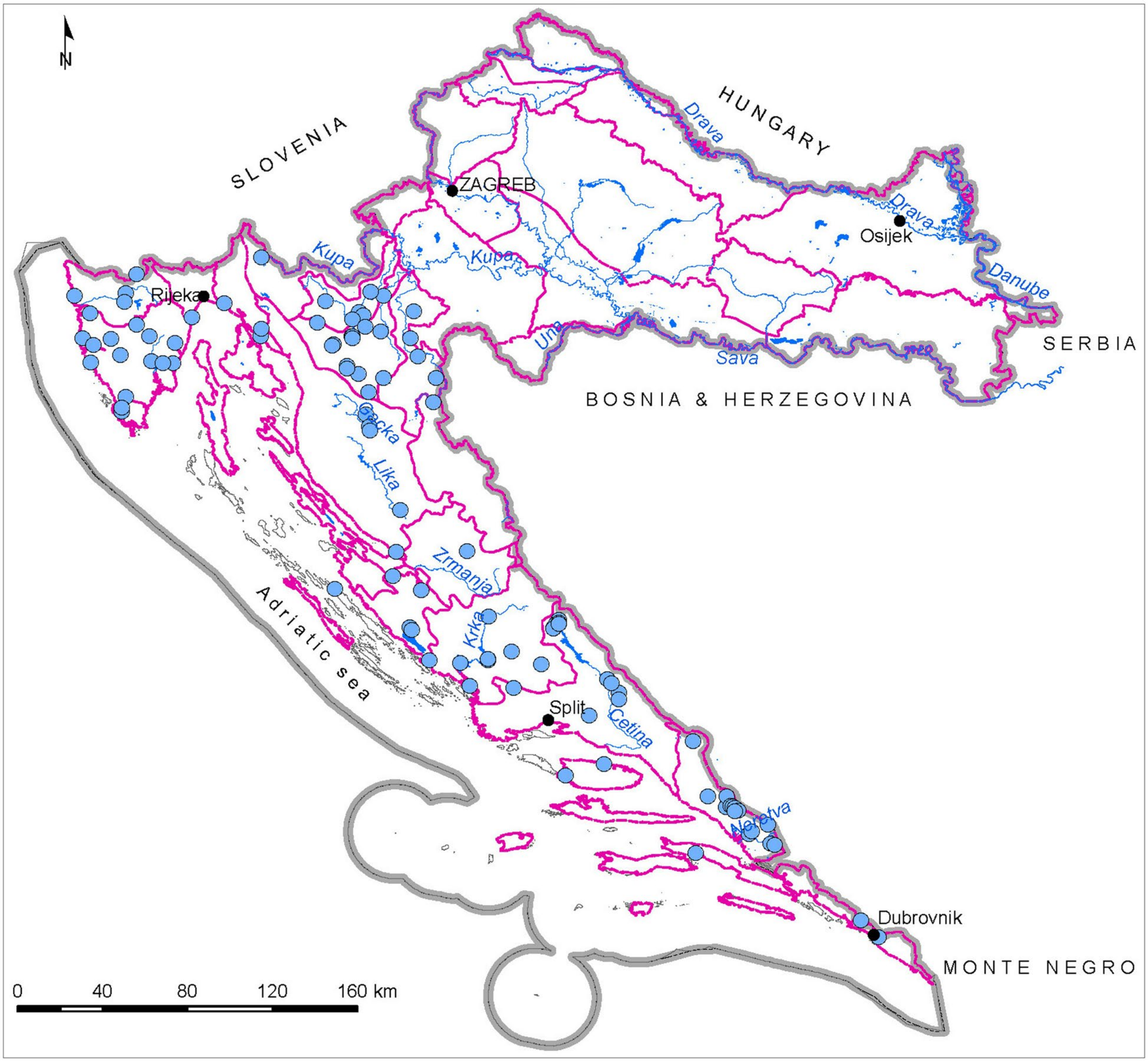

Fig. 6 Locations (blue dots) where indicator organisms of good groundwater status are recorded

invertebrates in Croatia. Among them, there are numerous species of *Niphargus* genus, including some surface representatives dependent on high-quality groundwater. Among the endemic subterranean isopod crustaceans included in the analysis is the troglobiontic genus *Monolistra* that inhabits karst springs and caves with flowing subterranean water. It lives in a community with the largest groundwater isopod crustacean in Croatia from the genus *Sphaeromides*, which is also an extremely suitable species for monitoring the ecological status of groundwater and GWDE. Within this community of crustaceans, the genus *Troglocaris* is also found, which is widely distributed in the Dinaric region of Croatia. Given the fact that it inhabits environments with high-quality groundwater, it represents an extremely valuable representative of the stygobiont fauna and is, therefore, included on the bioindicator list for GWDEs.

Among the inhabitants of the Croatian karst groundwater, it is important to highlight underground sponges, whose findings are not only an indicator of the GWDE but also a marker of the ecological status of these waters, signifying a high degree of stability and conservation status of the subterranean ecosystems. The Ogulin cave sponge *Eunapius subterraneus* [58], which has been recorded so far on five localities pertaining to the Dobra and Mrežnica River basins, is the only known representative of the freshwater sponges (family Spongillidae) among the world's stygobiont fauna. So far, two subspecies have been identified: the Ogulin cave sponge *E. s. subterraneus* and the Rudnica cave sponge *E. s. mollisparpanis*.

Olm (*Proteus anguinus*) is included in the list of endangered species of the European Union Natura 2000, Annex II and Annex IV. In the Red Book of Cave Fauna of Croatia, it is found in the category of sensitive species (VU B1 + 2bc; C2a). In Croatia, it is strictly protected by the Nature Protection Act. Given that the main causes of this species endangerment are uncontrolled urbanization, changes in groundwater regime and groundwater contamination, it is extremely suitable for inclusion in the list of bioindicator species for GWDEs. *Proteus anguinus* inhabits caves and sinkholes in the area from Istria to Dubrovnik [35], which leads to the conclusion that the groundwaters of Croatia in which *Proteus* lives are of extraordinarily high quality. Experts estimate that the critical oxygen concentration for olm in the groundwater is 2.9 mg/L (at 10 °C) [59]. However, it can survive in groundwater at concentrations of less than 1% O2/L [60]. In the groundwater of the Jelševnik area (Slovenia), an anoxic value of 0.3 mg/L has been reported for the *Proteus anguinus parkelj*; however, these are exceptionally rare extremes [61]. The highly vulnerable genus *Proteus* has a huge potential to become the symbol of a successful balance between conservation and sustainable management of the karst environment [62].

The troglobiotic bivalve species from the genus *Congeria* is an important bioindicator of aquatic ecosystems dependent on groundwater. In the Republic of Croatia, 16 localities of these freshwater cave molluscs are known; however, most of them are only empty shells for which the cause of mortality is not known. Live populations were recorded in only six localities. The species Congeria kusceri inhabits the Neretva River basin in Southern Dalmatia and in neighboring Herzegovina [30, 35, 37, 42].

The bioindicators of the springs used in this study comprise the crenobiont taxa of invertebrates, i.e., species exclusively inhabiting the springs and that are extremely sensitive to any changes in the habitat and, therefore, to changes in the physical–chemical conditions in the groundwater (especially temperature variations). Among the crenobiont species of Croatia, water insects are important, such as some species of water beetles (Coleoptera) from the genus *Agabus* and caddisflies (Trichoptera) from the genus *Drusus* and *Micropterna*, and some species of flatworms (Turbellaria), such as the species *Crenobia alpina*, large number of snails (Gastropoda) such as the species from the genus *Belgrandiella*, amphipod crustaceans (Amphipoda) of the genus *Fontogammarus* and some species of the genus *Niphargus*, decapod crustaceans (Decapoda) from the genus *Austropotamobius* (*A. pallipes* and *A. torrentium*) [63].

Assessment of the groundwater chemical status in areas with groundwater-associated and groundwater-dependent aquatic ecosystems

According to EQS indicators, considered surface waters are usually of good quality. The deviations from this standard are only related to the monitoring sites located immediately downstream of the settlements and discharges of municipal wastewaters and are not caused by poor groundwater quality. In general, the quality of groundwater in Croatia is good. Sporadically, water contains increased concentrations of nitrates that have been decreasing for several years. Under the program of state (national) groundwater monitoring, most of the analyzed EQS parameters (priority substances) were defined as "less than the limit of quantification" (< LOQ). Since the quantification limit is lower than the EQS, it is obvious that such substances cannot significantly damage groundwater and ecosystems. Other values of the analyzed EQS parameters are, as a rule, always at acceptable concentration levels. Nitrate concentrations in groundwater are generally below 20 mg/L, while in the southern, karst areas, they rarely exceed 5 mg/L (Fig. 7). However, in the western (Istria peninsula) and north-western parts of Croatia, concentrations of nitrates in the groundwater may exceed the threshold value of 37.5 mg/L [64, 65].

In this paper, it is not possible to describe analyses of the assessment of the impact of groundwater on all the ecosystems identified. Therefore, some specific examples demonstrate the way in which their interaction was considered.

The Raša River valley is an example of a groundwater-associated ecosystem (Fig. 8a). It is situated in the south-eastern part of the Istrian Peninsula. This ecosystem is described as significantly damaged and subject to high pressures [66]. The catchment of the Raša River is a karst area covered by meadows, forests, agricultural land, and fish ponds. The groundwater discharges at several springs situated along the Raša River and flows into the river (Fig. 8a). Occasionally, they contain slightly higher concentrations of nitrates with regard to the rest of the karst terrains of Croatia, and ranging 7–10 mg/L (Fig. 8b). Nitrate concentrations in the waters of the Raša River are a bit lower, ranging 4–7 mg/L. In accordance with the Croatian legislation [56], the maximum value of nitrates (50th percentile) in the waters of the Raša River is 5.75 mg/L, indicating their ecological status is good. The nitrate concentrations are very variable year after year. From Fig. 8b, it is evident that sometimes this value may be exceeded. Data from 2008 to 2012 have been analyzed for the purpose of this study. During the first 3 years, the

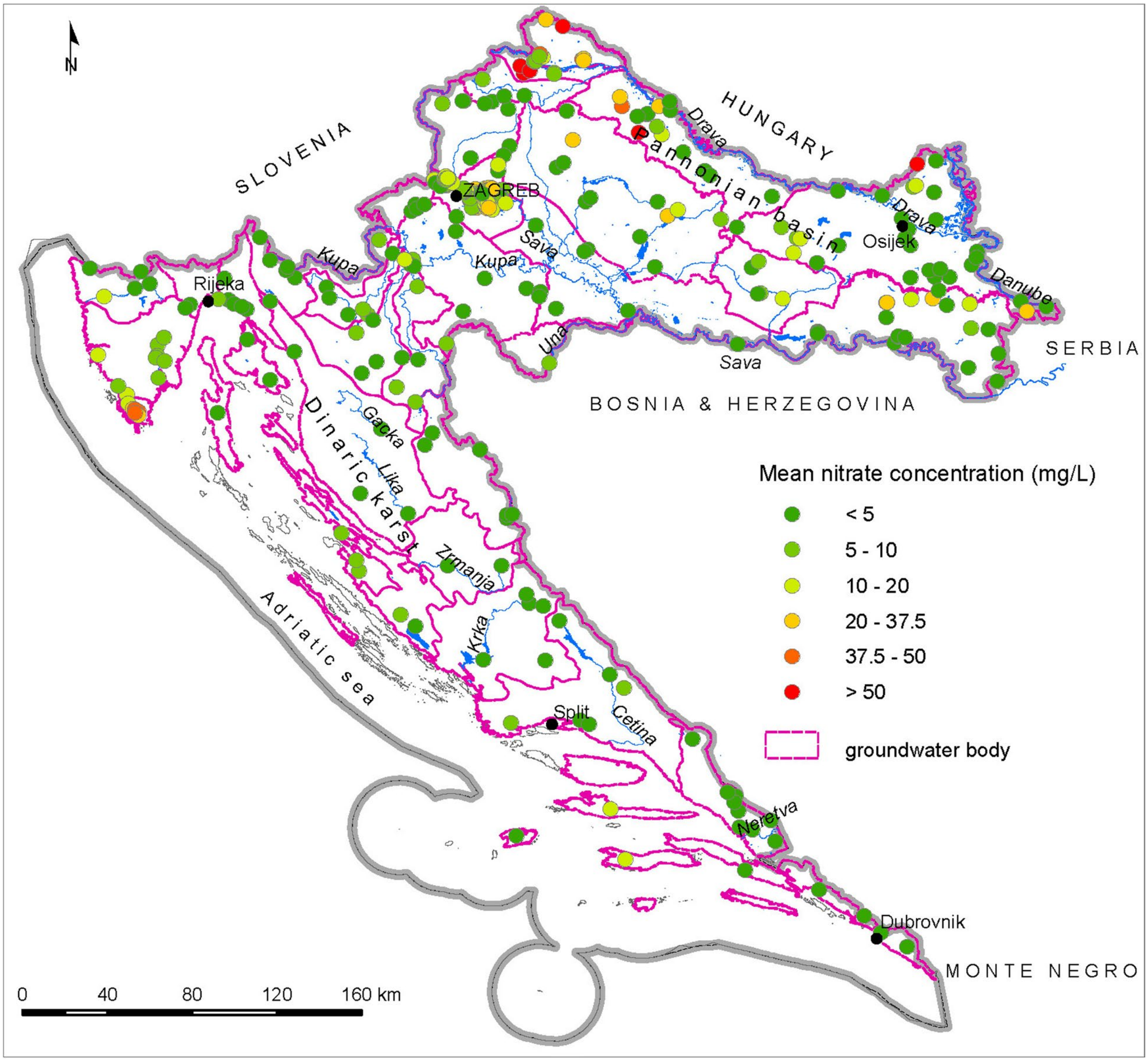

Fig. 7 Nitrate concentrations in groundwater in Croatia

nitrate content has gradually increased and exceeded the maximum values. During the last two observed years, the lower values were measured, both in Rasa River and springs. Because of that the quality status of this GWB is evaluated as good. However, the Rakonek spring is known habitat of the olm (*Proteus anguinus*) [67]. It is estimated that a concentration of nitrates greater than 10 mg/L can harm these organisms [68]. The proposed threshold concentration of nitrates for Proteus in Slovenia is 9.2 mg/L [69]. Considering all the mentioned area of Raša River valley requires careful attention and increased monitoring.

Assessment of the groundwater chemical status in areas with groundwater-dependent terrestrial ecosystems

The main factors that regulate environmental conditions for GWDTE are the amounts of groundwater and changes in the groundwater levels, as well as groundwater salinity, acidity and the concentrations of nutrients and pollutants [4]. Although it is commonly known that the groundwater quality is very important for the presence and development of plant species and vegetation in general in terrestrial ecosystems, scientific knowledge of the potential effects of chemical groundwater pollution on such ecosystems is insufficient [70]. Consequently, it

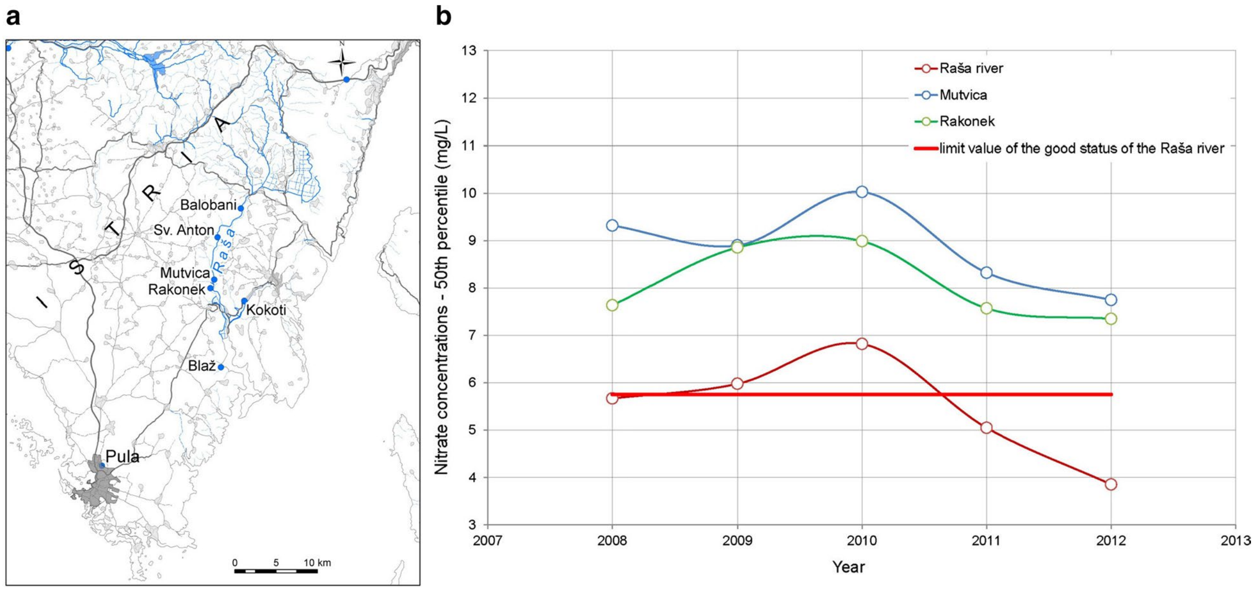

Fig. 8 Rakonek spring and the Raša River: **a** location map; **b** the annual concentration of nitrates in groundwater and in the surface water

is difficult to develop a methodological approach to the determination of groundwater quality parameters for the purpose of conservation of the GWDTEs [71]. Since GWDTEs are most often located near the surface waters, it can be assumed that both aquatic and terrestrial ecosystems will be adapted to similar natural conditions. Provided this assumption is valid, EQS can be used for a similar level of protection of terrestrial ecosystems and plant communities as well as in the case of surface waters [49], which is hereby accepted.

There are no data on the negative impact of groundwater quality in particular GWDTEs in Croatia. Since the concentrations of EQS indicators are very low and lower than the quantification limit, it was concluded that the chemical status of the groundwater bodies is good.

Assessment of the groundwater quantitative status in areas with groundwater-associated aquatic ecosystems

The GWB quantitative status from the standpoint of the groundwater-associated ecosystems is also evaluated as good. According to the SWUI, which for most surface waters is 0–20%, the status of surface water is generally rated as good to very good. The exceptions are the smaller sections of particular rivers (Drava, Cetina and Neretva Rivers), where the influence of river utilization for hydropower purposes [51] is prominent. For example, the construction of hydropower plants in Bosnia and Herzegovina caused a major disruption in the natural regimes of surface water and groundwater, with a negative effect on the spring regime in the left bank of the Neretva River [21]. Given that the negative effects are not the consequence of the groundwater abstraction (i.e., direct impact on groundwater), but to the utilization of surface water, according to the protocol described in the methodology, the quantitative status of groundwater relative to GWAAE should be assessed as good.

Assessment of the groundwater quantitative status in areas with groundwater-dependent ecosystems

Most of the considered GWDTEs in Croatia are situated close to surface waters. Groundwater abstraction sites are not, as a rule, situated in the immediate vicinity of the considered GWDTEs. However, the trend of lowering groundwater levels has been observed. This is particularly evident in the city of Zagreb [72], but it has been noted in many other areas as well. The lowering groundwater levels are a consequence of the deepening of the Sava riverbed, and thus the lowering of its water levels. Erosion of the Sava, as well as of the Drava riverbed, is caused by significant morphological changes brought about by the regulation of the rivers and its tributaries and the exploitation of gravel from the riverbed.

The quantity of groundwater is an important component of the sustainability of groundwater-dependent groundwater ecosystems. Peat bogs are rare and poorly developed in terrestrial ecosystems in Croatia, especially the groundwater-dependent ones. The Blatuša peat bog [73] is the largest and oldest peat bog in Croatia and represents a GWDE (Fig. 1). The surface of this peat bog is 11 ha. It is located in an area built of clastic sediments (sand and gravel with clay layers). Two streams flow in close proximity (Fig. 9). From an ecological point of view,

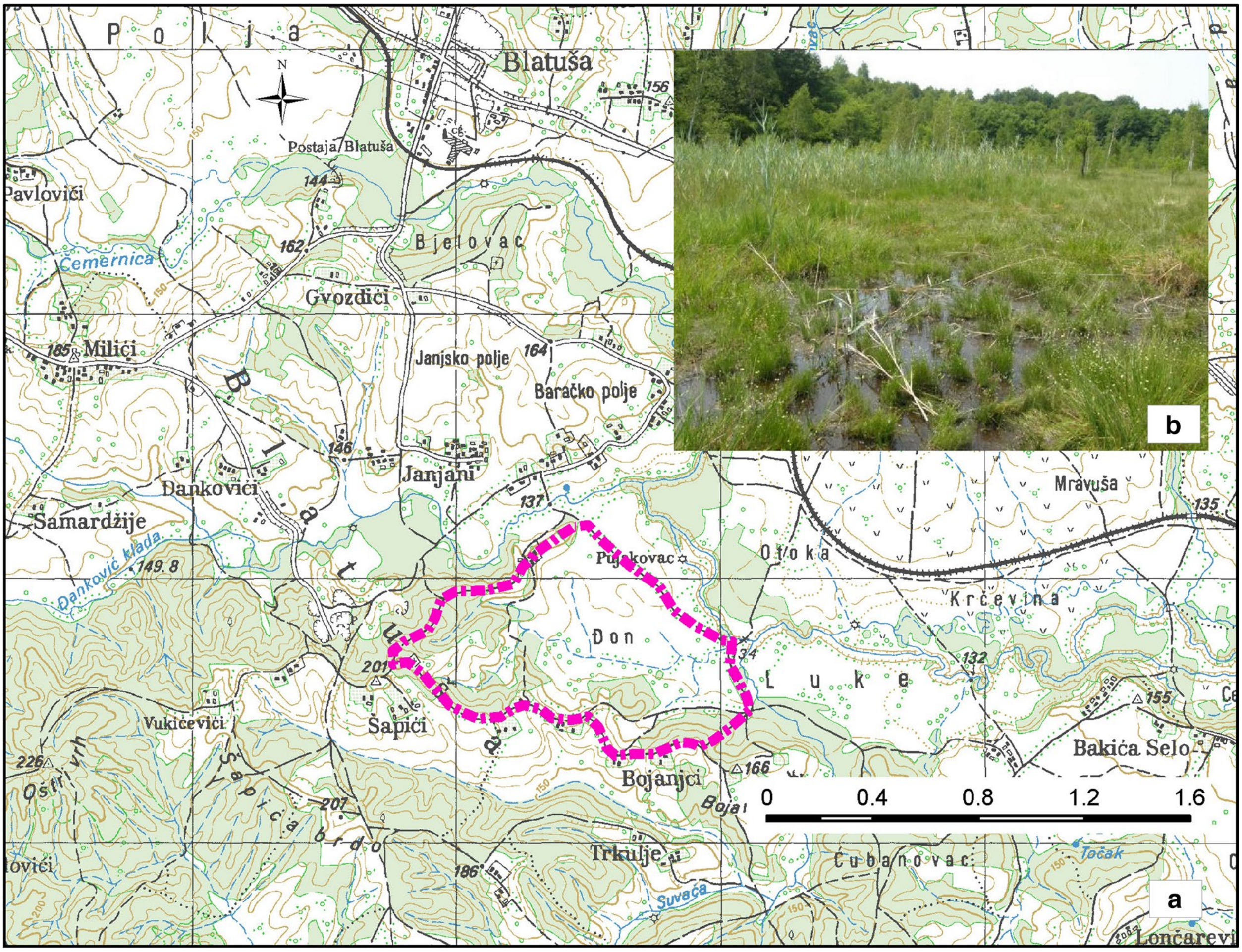

Fig. 9 The Blatuša peat bog: **a** water catchment area; **b** photo of the ecosystem (photo: S. Gottstein)

the status of this peat bog is not good because the change is recorded in the species composition (succession) [73]. The peat bog water catchment area is not inhabited and developed, does not exhibit contamination or contains groundwater pumping sites (Fig. 9). Therefore, the cause of these changes is not groundwater that could convey the pressure consequences to the ecosystem and thus cause harm.

The common oak forests are another type of GWDTE that develops in river valleys in the northern part of Croatia (Fig. 5). In addition to these, the flooded woods of black alder and the narrow-leafed ash are also found. One of the most important common oak forests is located in the Spačva Basin [74] in Eastern Croatia (Fig. 1). Before the construction of the levees on the Sava River, there was a natural depression in which the Sava River regularly flooded, which resulted in the existence of forests. Drainage from surrounding agricultural land, as well as forest canals, lowered groundwater levels and caused sporadic drying of forests and the transition to plant communities that had adjusted to drought conditions. Presently, the oak-grove community with hornbeam prevails. Although the ecosystem is located in the lowland part of Croatia which is covered with numerous agricultural areas, irrigation using groundwater has not been developed. In the wider area of the ecosystem, there are several wells used for the water supply, but the pumping rates in total did not exceed 20 L/s and thus were not a cause for a regional decrease of groundwater levels. According to the IUCN categorization and criteria, groundwater abstraction is not identified as a threat to or pressure on this Natura 2000 area [74].

Given that the lowering groundwater levels are not the consequence of the groundwater abstraction, the status of groundwaters with respect to the GWDTE associated with watercourses is evaluated as good. The reliability of the groundwater quantity estimation depended on the availability of data concerning the quantity of the abstracted water, quantity of spring and surface water discharge, and/or groundwater levels.

The groundwater quantitative status with respect to GWDAE is also evaluated as good. The abstraction of groundwater from speleological objects in the strict sense of the word is not being carried out. However, many springs are captured for the water supply. In the summer, during dry parts of the year, naturally, fewer discharges from the spring occur; while, at the same time, the pumping capacity is increased as the number of users in the water supply area is several times greater during the tourist season and irrigation of agricultural areas is being carried out. Under such conditions, at some springs, the groundwater discharge and surface water runoff cease. Such a situation may last several weeks. Given that this is also a common phenomenon at locations not captured for water supply, it has to be expected that such environments will be inhabited by organisms that have already adjusted to these conditions. Rohde et al. [75] emphasize that GWDEs include organisms that have evolved complex physiological and biochemical adaptations to adjust and adapt to short-term water-deficit stress. In this case, the identification of key species within a GWDE that can serve as an indicator of biotic responses to groundwater drawdown helps in detecting ecosystem change. Of all the springs that were separated as GWDAE in Croatia, the pressure due to groundwater abstraction for irrigation has been determined only for two springs. Both these springs were included in the NATURA network and this pressure was not ranked as being of high strength. One of the springs belongs to the GWB where twenty GWDAEs were separated, of which only one (this spring) was estimated as having a poor status. Another spring belongs to the GWB in which four GWDAEs were separated. At this spring, the groundwater flows out of the cave in which Proteus is determined. In view of these circumstances, both GWBs are estimated as having a good quantitative status. In general, an ecologically acceptable flow in Croatia has not been defined. However, Carvalho et al. [17] state that in many cases, the implementation of an environmentally acceptable flow is not yet sufficient, which is why the effects of water abstraction are often underestimated. This conclusion, however, is not applicable to the cases discussed above.

Improving the monitoring network

Groundwater quality as well as groundwater level and discharge are monitored within the national monitoring network. However, the impact of groundwater on ecosystem is rarely monitored. In addition to regular groundwater monitoring, cooperation between scientists and experts from different disciplines (e.g., hydrogeology, hydrology, biology, ecology) is also important. To increase the degree of reliability of the GWB status assessment in Croatia with respect to groundwater-associated and groundwater-dependent ecosystems, research monitoring has been proposed, the aim of which would be to diagnose the causes of ecosystem degradation and to assess the actual status of the ecosystem with respect to WFD requirements. This kind of monitoring should take a more exploratory approach with regard to the monitoring design, ideally with consideration of paired control and intervention sites to evaluate the effectiveness of management measures [76]. Carvalho et al. [17] recommend further WFD implementation guidance (after 2027) because there is a concern that the goal of all EU waters achieving a good status by 2027 is a long way off in many countries.

Conclusions

The status of GWBs in Croatia is evaluated as good from the standpoint of the groundwater-associated and groundwater-dependent ecosystems. The groundwater status is a consequence of relatively poor development of the country. Over the last three decades, there has been a steady downward trend in industrial production, particularly in rural areas (catchments). The main economic branch is summer tourism. The number of Croatian inhabitants has decreased to only 4 mil. in the last few years. Although northern Croatia abounds in agricultural land, agricultural production gradually decreases due to the smaller number of inhabitants. According to the Commission Report on the Implementation of Council Directive 91/676/EEC on the Protection of Water Pollution from Nitrogen from Agricultural Sources in Croatia, the total use of mineral fertilizers in the 2012–2015 period decreased by 30% over the 2008–2011 period. The irrigation using groundwater is poorly developed. Due to the decreasing of water users, the abstracted groundwater quantity has been reduced and there is no regional groundwater drawdown. Today, the largest financial resources are invested into construction of adequate wastewater collection and treatment facilities, as well as reducing water supply losses.

Reliability of the GWB status assessment with respect to groundwater quality was contingent on the amount of available surface and groundwater chemistry data and/or indicator organisms of good groundwater status in the ecosystem. The accuracy of information and reliability of assessments varied significantly between analyzed Croatian regions and types of data. Smaller GWAAEs and GWDEs at this stage of the investigation were not identified. The investigations pointed out great contribution of bioindicators as tools to the determination of the GWB status, particularly in the karst area. In this regard, further research into their presence and distribution in GWDE is encouraged. To increase the degree of reliability, research monitoring has been proposed. The monitoring should reduce knowledge gaps including the establishment of a priority list of GWAAEs and GWDEs, an increase of knowledge of the status of the ecosystems, the definition of significant ecosystem damage, as well as the definition of the boundary conditions and threshold values of a good quantitative and qualitative status for individual ecosystems. In future prospects unavoidable focus has to be climate change which may compromise the availability of groundwater resources.

Abbreviations

EU: European Union; WFD: Water Framework Directive; GWB: groundwater body; GWAAE: Groundwater-Associated Aquatic Ecosystem; GWDE: Groundwater-Dependent Ecosystem; GWDAE: Groundwater-Dependent Aquatic Ecosystem; GWDTE: Groundwater-Dependent Terrestrial Ecosystem; NCH: National Classification of Habitats; CIS: Common Implementation Strategy; IUCN: International Union for Conservation of Nature; GWQS: groundwater quality standard; EQS: environmental quality standard; LOQ: less than the limit of quantification; SWUI: Surface Water Utilization Index.

Acknowledgements

The authors wish to express their gratitude to Hrvatske vode for the project financing, as well as to Mr. Želimir Pekaš, the member of the CIS Working Group on Groundwater for constructive discussions. The authors greatly appreciate the revisions of reviewers and editor which improved an earlier version of manuscript.

Authors' contributions

Conceptualization, ŽB; Methodology, ŽB; Investigation and analysis, ŽB, MK, OL and SG; Writing-original draft preparation, ŽB; Writing-review and editing, MK, OL and SG; Visualization, MK and OL. All authors read and approved the final manuscript.

Funding

This research was funded by HRVATSKE VODE.

Availability of data and materials

The quality and quantity data on groundwater and surface water that support the findings of this study are available from [HRVATSKE VODE] but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available. Data are however available from the authors upon reasonable request and with permission of [HRVATSKE VODE].

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests. ZB, MK and OL are employed at public research institute. SG is professor at the university.

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Received: 30 June 2019 Accepted: 21 September 2019
Published online: 04 October 2019

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