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Are Hydrogeological and Hydrochemical Settings Informative of the Aquatic Ecological Situation? An Extended and Comprehensive Framework

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Abstract

This paper discusses exclusively the dependency between the ecological and hydro-geochemical criteria used to classify hydrogeological formations and provides an overview of the most measurable environmental factors characterizing the groundwater ecosystem. Compact, porous, fractured and karstic formations are complex hydro-geomorphological units which store variable amounts of water. They are considered the main habitats for stygofauna in many regions worldwide. The hydrogeological situation of a groundwater system varies spatially (both laterally and vertically) and temporally at different scales. Moreover, different factors (e.g. surface and groundwater interaction (hydrological exchange), precipitation, land use, land cover) play an active role in classifying groundwater systems. Therefore, many concepts have already been proposed to classify these systems. This paper focuses on the relationships between communities of groundwater invertebrates (occurrence, distribution and diversity of stygofauna) and special hydrogeological indicators, by examining the hypotheses and results of previous literature.

Keywords

Stygofauna; Abiotic; Biotic; Hydrogeological Formations.

Introduction

Groundwater and hyporheic systems comprise extensive underground habitats, which consist of loose materials of different grain sizes and which provide open porous spaces filled with water of variable hydrochemical composition [1]. Fractured and karst aquifers are important reservoirs containing vast amounts of freshwater [2]. The animals living in these interstices are aquatic and are generally called groundwater invertebrates or stygofauna [3]. Furthermore, groundwater ecosystems harbour diverse communities of microorganisms, which provide valuable ecosystem services [4]. Groundwater microbes, including bacteria, fungi and protozoa, are primary producers (chemolithotrophy) and consumers and may themselves be consumed by micro- and macro-invertebrates [5]. These stygofauna are considered a biomonitor by providing ecosystem services such as grazing biofilms and maintaining water quality through monitoring sources of pollution [6–11].

The factors that control observed stygofauna distributions are hydrogeological formations, geochemical conditions, permeability and physiochemical groundwater parameters [12,13]. Furthermore, agricultural activities have a clear effect on microbiological communities through water infiltrating downward from the surface. In addition, precipitation has an equally significant influence on aquifer ecology, especially on microbes and stygofauna [8,14]. Local physical and chemical variability within aquifers may affect groundwater ecosystems, although this is not easy to investigate because large parts of groundwater habitats are inaccessible and it is difficult to determine where stygofauna live in these aquifers [12].

Several studies have focused on the theoretical relationship between hydrogeological, geochemical and ecological patterns [3,15-17]. By contrast, other studies have categorized and charted the status of groundwater ecosystems depending on the environmental factors associated with living organisms in groundwater e.g. stygofauna [18,19]. Therefore, many researchers have tried to integrate geology, biology and hydrochemistry in their groundwater investigations, e.g. [15,17,20,21].

The present paper reviews theoretical principles and practical applications to investigate the relationships between the ecological, hydrogeological and hydrogeochemical characteristics of groundwater systems. The review aims to find interrelationships between stygofauna and the surrounding environment. According to the reviewed literature and the distributed results, a new extended and integrated classification scheme is proposed. This scheme depends on the most significant environmental factors that influence stygofauna and presents the major classifications of groundwater ecosystems, taking into account hydrogeological formations and distance to surface water (hydrological exchange), in addition to the potential effect of precipitation and land use.

Methodology

The overview was developed from surveying the available literature regarding ecological, geological and geochemical aspects of groundwater and the interactions between them. To understand the ecological effect on groundwater, one needs to characterize the processes shaping these ecosystems. Several reviews of groundwater ecosystems [11,21-24] have been based on analyses of the structural and functional relationships between abiotic (e.g. environmental and meteorological parameters, geological and geochemical parameters, physicochemical and hydrochemical data, hydraulic properties) and biotic (community assemblages) criteria. Thus, it is essential to shade light on these two criteria.

Abiotic criteria

Qualitative and quantitative assessments of groundwater depend solely on chemical and hydrological parameters [15,23]. At regional and catchment levels, geological and hydrogeological characteristics strongly influence the distribution of stygofauna in terms of abundance

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and richness [25,26]; moreover, stygofauna are very sensitive to changes in their habitat due to environmental stressors, such as water temperature (Temp.), Dissolved Oxygen (DO) and chemical constituents [25]. The factors controlling observed stygofauna distributions are hydrogeological formations, geochemical conditions, permeability and the physiochemical properties of groundwater [12].

In fine-grained sediment in many porous aquifers, small stygofauna are to be expected, whereas large stygofauna are mainly found in karstic aquifers. Furthermore, the majority of stygofauna, which together with microorganisms are involved in groundwater purification, react negatively to an increase in temperature [10].

From a hydrogeological point of view, precipitation (with no direct contact to groundwater) and surface water like watercourses (with mostly direct contact to groundwater) should be considered separately. Taking into account spatial and temporal variations in groundwater ecosystems, three hydrological exchange zones can be differentiated (Figure 1). In zone I, the groundwater level shows fluctuations due to fluctuations in the surface water level. In zone II, less temporal fluctuation is observed. By contrast, in zone III there are more pronounced groundwater fluctuations and thus a big difference between the highest (HGWL) and the lowest (LGWL) groundwater levels.

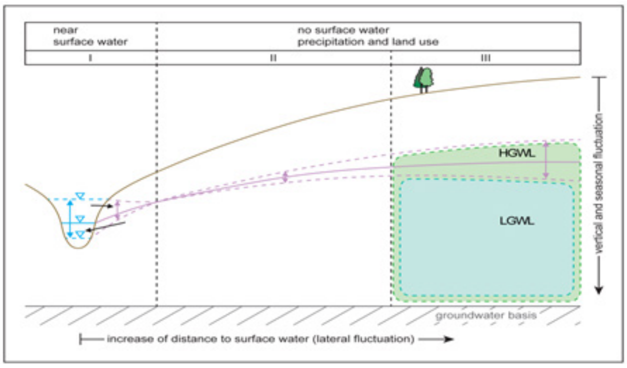

Figure 1: Schematic representation of a cross section of a groundwater system influenced by spatial and temporal variations (brown line: ground surface; blue lines: water surface; purple line: groundwater level; purple arrows: the fluctuation of the groundwater level; blue arrows: the fluctuation of the surface water level; I, II and III hydrological exchange zones).

The HGWL is characterized by particularly high rates of groundwater recharge, owing to higher precipitation rates at the end of the recharge period. The rise in groundwater level leads to an increase in hydraulic head and finally in groundwater discharge. The opposite occurs in the case of the LGWL before groundwater recharge takes place. In the case of direct recharge, the response of the groundwater level to precipitation events correlates inversely with the depth to the groundwater table and directly with hydraulic conductivity.

Biotic criteria

The objective of many groundwater ecological studies is to assess occurrences and biodiversity. The majority has focused on ecological patterns, such as functions and ecosystem services as well as interplay with environmental factors [12]. The most recent ecological groundwater monitoring is based on fauna and microbes, and the most important parameters are biomass (D), measured as prokaryotic cell density; and activity (A), and measured as prokaryotic intercellular ATP concentration. The D-A or B-A index is an important measurement in groundwater ecosystems which allows the microbiological and ecological status of groundwater to be characterized, assessed and monitored [27,28]. Faunal variables pertain to information such as body size (length, width and height), i.e. classical morphology-based variables. They are related to the interstitial dimensions; usually fauna are divided arbitrarily into macrofauna > 1 mm (ma), meiofauna 0.063–1 mm (me) and microfauna < 0.063 mm [28].

In the same context, less information is available regarding the movement of stygofauna in groundwater. The active mobility of stygofauna is called 'migration' whereas the passive mobility of stygofauna is called 'drifting'. Divided the mode of locomotion into fixed species with very limited mobility (e.g. ostracods), sliders or walkers with relatively slow movement on the grain surface (e.g. gastropods) and swimmers with high mobility in free groundwater-filled pores (e.g. cyclopoids) [28]. Furthermore, we believe that the movement and migration of stygofauna is a natural result of their search for food. The feeding of stygofauna is also categorized into three types [28]:

1. Carnivores, which feed on other animals in groundwater; this feeding type is characterized by self-movement (swimming) and a high possibility of migration, such as in the case of amphipods and cyclopoids.

2. Herbivores, which feed on biofilm with less migration (sliders or walkers), such as in the case of ostracods.

3. Detrivores, which feed on detritus (fine or coarse dead organic matter) and are often fixed and do not migrate. It is also very important to highlight the passive mobility of stygofauna because there are conditions that facilitate drifting, such as the velocity of groundwater flow. Differences in hydraulic heads through the aquifer (due to seasonal fluctuations of the groundwater table) lead to stygofauna drifting through large pores, fractures and karstic aquifers.

In the case of stygofauna drifting, it is useful to calculate the number of stygofauna per unit of groundwater discharge. This factor can be estimated very easily from springs. In the case of stygofauna migration, the number of stygofauna can also be related to the groundwater-filled volume available for migration (number of stygofauna individuals per groundwater-filled volume in cubic metres), which can be estimated by the level of the groundwater in a conceptual hydrogeological model. Real groundwater organisms in groundwater (stygobites) differ from those that temporarily enter the aquifer as immigrants (stygophile) and/or those that are known from the surface and enter the subsurface sporadically but cannot survive under the usually limited conditions in the subsurface (stygoxene) [29]. Therefore, the calculated ratio of stygobites to stygoxene fauna or non-stygobites is significant [4,19]. In addition to the ratio of stygobites and styoxenes, the crustacea taxa community and other parameters (e.g. recharge, stress) have been used to classify stygoregions [30,31].

Previous studies

Many researchers have focused on the "issues of classification and identifying the interrelationships" between stygofauna and the surrounding environment. The most relevant are presented here in chronological order.

Schmidt et al. [17] showed some types of exchange related to the groundwater faunal assemblages in an alluvial aquifer (porous aquifer system with shallow groundwater). They used a range of abiotic features including DO, land use and temperature concluded that the faunal assemblages reflected hydrological exchange at different zones throughout the aquifer. Dolo Oliver et al. [32] studied the effect of 16 environmental variables on the presence⁄absence of stygobiotic species. They focused on a porous aquifer system at a regional scale and demonstrated that the higher the permeability, the higher the level of stygobiotic biodiversity. The authors linked this correlation to the well-oxygenated parts of the aquifer. The main determinants of stygobiotic biodiversity were not related to the hydrochemical conditions, but to factors associated with hydraulic conductivity, with strong implications for supplementation with groundwater oxygen. Focusing on aquifers in interaction with nearby rivers, Korbel and Hose [18] collected data covering more than 18 environmental variables that influence groundwater biota, and used more than 25 potential indicators to test the health of groundwater ecosystem. They provided a tiered framework for assessing ecosystem health in groundwater and for differentiating between disturbed and undisturbed groundwater ecosystem sites. At regional and continental scales, Stein et al. [30] studied the distribution patterns of fauna in the groundwater of Central Europe and developed the concept of 'stygoregions', a biogeographical classification based on stygofaunal pattern distributions. They demonstrated that this term is significantly different from any classification scheme related to hydrogeology, geochemistry and surface fauna. Investigating the relationship between rainfall, surface water and groundwater, Gutjahr et al. [31] proposed five types of faunistic habitats in aquifers. The authors stated that groundwater is often affected by surface water, which influences faunal communities. On a small scale, Brancelj et al. [24] examined the distribution of stygofauna in the sediments of a perched aquifer. They showed that stygofauna were strongly influenced by sediment properties, being abundant in dense and fine sandy sediments and less abundant in coarser sedimentary layers. Korbel et al. [33] focused on the potential use of species as tracers of hydrological interactions and groundwater flow paths. The authors investigated classical karst in Slovenia and Italy and identified groups of indicator species which can be used to describe hydrogeological formations and habitat structure. Recently conducted a comprehensive review and presented an approach based on a combination of traditional concepts in groundwater ecology and additional, novel scientific techniques, specifically Compound-specific Stable Isotope Analysis (CSIA) of amino acids, radiocarbon analysis (14C) and DNA analyses of environmental samples, stygofauna and gut contents [11].

Result and discussion

A conceptual model is proposed in two steps. In the first step, abiotic parameters are discussed in relation to different hydrogeological formations and are merged into a single abiotic framework. In the second step, this abiotic framework is extended to include the most important biotic parameters.

Conceptual model of abiotic pattern

Most classifications of groundwater systems are based on several environmental factors, the majority of which depend on hydrogeological formation, e.g. compact, porous, fractured or karstic [34]. However, there are two exceptions to this classification, the first according to fauna in stygoregions [30], the second according to recharge and stress [31]. In general, compact formations are less permeable (aquitards) than others and are characterized by depleted stygofauna [34]. By contrast, porous aquifer systems are characterized by moderate to high porosity with low to moderate permeability and low to moderate flow velocity. Fractured aquifer systems are represented by moderate to wide cavities of low porosity with

Table 1: Conceptual model of general relationship between hydrogeological and environmental factors and different hydrogeological formations (SW: surface water; P: precipitation; GWT: Ground Water Table; DO: Dissolved Oxygen, DOC: Dissolved Organic Carbon).

Environmental factors		Hydrogeological formation												Ref.
		Aquitard			Unconfined aquifer									
					Porous			Fractured			Karstic			
Hydrological exchange	Hydrological zone	near SW	no SW but P		near SW	no SW but P		near SW	no SW but P		near SW	no SW but P		[35, 36]
		I	II	III	I	II	III	I	II	III	I	II	III	
	GWT Depth	low	med	high	low	med	high	low	med	high	low	med	high	
	GWT fluctuation	low	low	low	med	low	med	med	med	high	high	med	high	
Hydrochemical characteristics *	Ion concentration	++	+-	+-	++	+	+	++	+	+	++	+	+	[19, 26, 37, 38]
	Heavy metals	++	+-	+-	++	+	+	++	+	+	++	+	+	
	DOC	-	-	-	++	+-	-	++	+	+-	++	+	+	
Hydrogeological (physical) characteristics*	pH	-	-	-	+-	+-	+-	+-	+-	+-	++	+	+	[8, 19, 34, 39, 41]
	EC	+-	+-	+-	++	+	+	++	+-	+	++	+	+	
	Temp.	+-	+-	+-	-	+-	+	-	+-	+	-	-	+-	
	DO	-	-	-	++	+	+-	++	+-	+-	++	++	++	
	Detritus content	++	++	++	++	+	+	+	+	+	++	+	+	

Colour legend (Relative differences between four different hydrogeological formations):

↑ High concentration with no fluctuation in general

↓ Low concentration with no fluctuation in general

→ Medium concentration with no fluctuation in general

↕ Low and high concentration with high fluctuation in general

*An increase in the respective factor has: (-) negative, (+) positive, (++) highly positive or (+-) neutral on the occurrence and distribution of stygofauna.

moderate to high permeability and moderate to high flow velocity. Karstic aquifer systems have wide to very wide cavities of low to high porosity with high permeability and high flow velocity. This paper assumes saturated zones in the upper part of groundwater systems.

The conceptual model considers that the lateral fluctuation includes the hydrological exchange between the aquifer and the surface water, providing both food and oxygen (Figure 2, Table 1 and Table 2). According to Schmidt and Hahn [35], the vertical fluctuation is at least as important as the lateral fluctuation, particularly at distances from surface water bodies. The vertical fluctuation includes the depth to the groundwater level and the fluctuation of the groundwater level (Table 1). Previous studies have found that in addition to spatial and temporal fluctuations, there are many environmental factors that influence stygofauna, represented by hydrogeological and hydrochemical criteria. Furthermore, Korbel and Hose [18] have considered the impact of land use on groundwater ecosystems.

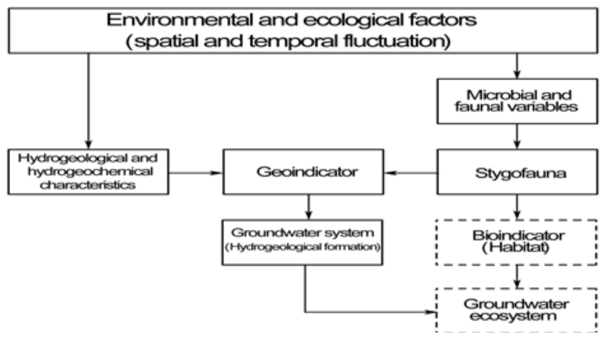

Figure 2: Proposed scheme showing stygofauna as a geoindicator for the purpose of classifying hydrogeological formations. The continuous box represents a hydrological system and the dotted box represents a habitat.

Table 2: Expected ecological patterns of biotic sum parameters within the four hydrogeological formations and their different hydrological exchange levels (Hn/Ln: high number/low number; Hm/Lm/Nm: high migration/low migration/no migration; Hdrif/Mdrif/Ndrif: high drifting/moderate drifting/no drifting).

Ecological factors		Hydrogeological formation												Ref.
		Aquitard			Unconfined aquifer									
					Porous			Fractured			Karstic			
Hydrological exchange		I	II	III	I	II	III	I	II	III	I	II	III	[34] [35]
Microbial growth	Prokaryotic cell density (D)	less	less	less	more	more	less	more	less	less	more	more	more	[26][18] [40]
	Activity (A)	less	less	less	more	more	less	more	less	less	more	more	more	
Faunal variable	Body size of stygofauna	me	me	me	me, ma	me, ma	me, ma	me, ma	me	me	ma, me	ma, me	ma, me	[29] [28]
	Migration of stygofauna	Lm	Nm	Nm	Lm	Lm	Lm	Lm	Lm	Lm	Hm	Hm	Hm	[41][34]
	Drift of stygofauna	Ndrif	Ndrif	Ndrif	Ndrif	Ndrif	Ndrif	Mdrif	Mdrif	Mdrif	Hdrif	Hdrif	Hdrif	
	Ratio of stygobites to non-stygobites	1	>1	>1	<1	>1	>1	1	>1	>1	<1	1	>1	[18] [4]
	Number of stygofauna individuals per groundwater-filled volume	Ln	Ln	Ln	Ln	Hn	Hn	Ln	Ln	Ln	Ln	Hn	Hn	[42]

The hydrochemical characteristics considered in this paper comprise major ions and heavy metals (Table 1). The sum of cation and anion concentrations have been mentioned as having an effect on stygofauna; in other words, stygofauna are very sensitive to changes due to environmental variables, such as water salinity and chemical constituents [26,37]. According to Brancelj et al. [37], the concentration of cations and anions from hydrological exchange is lower in deep aquifers than in shallow porous aquifers, because of the influence of land use. On the other hand, heavy metals have been found to reduce the abundance and the diversity of invertebrates when high concentrations or contamination occur [18].

The physiochemical characteristics consist of several parameters as presented in Table 1, including pH, electrical conductivity (EC), Tempareture and DO, which have an effect on stygofauna [37,39,40]. Detritus content is positively correlated with stygofauna [19,40]. The hydrochemical and hydrogeological characteristics governing the distribution patterns of the dominant stygofauna taxa in different hydrogeological formations are summarized in (Table 1). It is worth mentioning that the classification of four hydrogeological formations with three types of hydrological exchange each is according to Hahn [39]. Here the classification differentiates between high hydrological exchange (which usually occurs in surface waters) and low hydrological exchange (which occurs through recharge percolating through the soil column to the groundwater table, which decreases with depth) [35]. We would like to emphasise that this depends to a significant extent on the given sediment and geological conditions.

Extending conceptual model for abiotic pattern

Ecological factors may provide an indication of the hydrogeological formation in question via microbial and faunal variables. Thus, an attempt is undertaken here to extend the framework in (Table 1 and Table 2), taking ecological factors into consideration. These factors are divided into two parts: microbiological growth and faunal variables. Microbial measurements such as prokaryotic cell Density (D) and Activity (A) have been used as reliable and sensitive indicators of disturbance to groundwater ecosystems [26]. It has been found that prokaryotic and microbial activity increases with particle size and volume of sediment retrieved from a well [40]. Therefore, activity is higher in zones with good hydrological exchange (Table 2). The body size of stygofauna (length, width and height) is adapted to the nature and the size of the pore space of an aquifer. Size increases from meiofauna in porous aquifers to macrofauna in karstic aquifers [29].

Therefore, it is hypothesized that faunal size can be used to ascertain the pore size of an aquifer. The feeding of stygofauna can be divided into carnivores, herbivores and detritivores [28]. However, to date it has not been proved easy to identify whether feeding type varies from one aquifer system to another. According to [41], the migration of stygofauna in porous aquifers and karstic aquifers varies from low to high, respectively. The drift of copepods manifests clear differences in the number of individuals between high and low groundwater levels. The 'piston effect', which is very frequent in karstic and fractured aquifers, leads to faster water velocity with higher discharge through the same 'pistons', thereby dislodging more individuals [41]. Moreover, ecological criteria include the ratio of stygobites to non-stygobites (which varies from less than 1 to more than 1) and the number of stygofauna per groundwater-saturated aquifer system (which varies from low to high) (Table 2). According to Hahn and Fuchs [34], stygofauna in porous and karstic systems are more similar than the stygofauna of compact formations and fractured aquifers.

According to (Tables 1 and 2), karstic aquifer systems, by following the ecological pattern in the case of microbial growth, are represented by relatively more biomass and activity [43] and a faunal size ranging from small to large [44]. Migration and drifting are high [2], while the ratio of stygobites to non-stygobites ranges from lower than 1 to more than one [45]. The proposed model shows that in karstic systems, the number of stygofauna individuals per groundwater-saturated aquifer system is high. The model also assumes that fewer stygofauna per groundwater-saturated aquifer system exist at the HGWL than at the LGWL. This is because the high groundwater level as well as the expansion of the habitat presents few opportunities for stygofauna individuals to come together and reproduce.

A real-world application of the proposed model

Baumberge in the Münsterland region of North-Rhine Westphalia (NW Germany) is a 40 km^2-large agriculturally dominated and forested mountain ridge. The area was influenced by the last glacial maximum [46]; today its maximum height is 186 m a.s.l., with extensions of 15 km NW–SE and 4 km SW–NE. Topographically, Baumberge rises 100 m above its flat surroundings. Rainfall is considered the only source of water to groundwater and there is no surface water in the area. According to a published map of groundwater depth [47], the groundwater table in Baumberge ranges from shallow to deep and its fluctuations range from medium to high (the minimal depth of the groundwater table is 60 m with an average annual fluctuation of 10 m, depending on groundwater recharge and discharge).

Hydrochemically, the concentrations of the cations Ca, Na, Mg and K are in the range of 155–180, 7–12, 4–11 and 1.3–2.8 mg/L, respectively, while the concentrations of the anions HCO_3,SO_4 and Cl are in the range of 350–370, 40–52 and 15–37, respectively. The mean ion concentration is slightly low to high, with moderate fluctuations. These ions measured in the groundwater of Baumberge are not significantly correlated with stygofauna [$n=8$; $p>0.001$; Pearson's correlation]. The heavy metals measured in this area are Fe and Mn, which range in concentrations from 0.0011 to 0.0651 and from 0.0007 to 0.02 mg/L, respectively. Dissolved organic carbon (DOC) is in the range of 0.5–1.2 mg/L [49, 50], which is considered a medium concentration with no fluctuations. The physiochemical parameters show that pH, Temp. DO and EC are within the ranges 7–8, 9.0–12, 4–8 mg/L and 700–760 µS/cm, with averages of 7, 10, 6 mg/L, and 730 µS/cm, respectively. Therefore, these data reflect low to high ranges with low to high fluctuations. Moreover, these physiochemical parameters show no significant correlations with stygofauna [50].

The value of detritus is in the range 0–3, indicating a low to high concentration with high fluctuations; moreover, it is significantly correlated with stygofauna [50]. Ecologically, microbial growth and activity in Baumberge range from 6.23E+06 to 1.53E+08 L^{-1} and from 9.70E-01 to 6.79E+02 PM, with averages of 6.21E+07 L^{-1} and 1.96E+02 PM, respectively (Alqaragholi et al. 2021 – unpublished data). Preuss and Lugert [48] have found that biomass and activity in Baumberge are slightly low. Body sizes mostly fall into the meiofauna category. There are low numbers of stygofauna per volume water (ranging from 0.2 to 1.1 Ind/m^3) [12], and the ratio of stygobites to non-stygobites exceeds 1 in several samples.

Based on the aforementioned data and the measured parameters of the aquifer under consideration, the aquifer system of Baumberge is in the zone of an unconfined fractured aquifer with a hydrological exchange zone between II and III and an absence of surface water. This closed groundwater system has resulted in numerous overflow springs at the boundary between the Baumberge formation and the underlying and less permeable Coesfeld formation [47,52–54]. The unconfined aquifer is fractured with a slightly karstic system. Precipitation recharges the aquifer in the wet season and groundwater drains away, discharging through different springs at the edges of the Baumberge formation. Secondary recharge is absent as no surface water features are available, apart from some intermittent rivers.

Conclusion

This paper has reviewed different approaches developed for investigating and understanding hydro(geo)logical processes with stygofauna communities in four hydrogeological formations. We have suggested a new approach in which stygofauna taxa can be used as an indicator to describe a given hydrogeological formation. The special advantage of using stygofauna as a geoindicator is that they react to spatial and temporal variations in different hydrogeological formations in different ways. Furthermore, hydrogeological and hydro-geochemical characteristics have been used as geoindicators to describe and assess the hydrogeological formation under consideration. This combination of different geoindicators used has increased the possibilities available for classification purposes. Thus, this dual use of stygofauna both as a geoindicator for hydrogeological formations and as a bioindicator for habitats can improve assessments of groundwater ecosystems.

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