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About faunal life in Austrian aquifers – historical background and current developments

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Abstract

In Austria all general types of aquifers (porous, karstic and fractured) are present and are subject of hydraulic and hydrochemical investigations. However, in hydrogeological research it is a still widely neglected fact that groundwater flow is not only a flux of water, chemicals and heat within lithological units but that groundwater bodies may also act as habitats with very particular conditions for their inhabitants. In general groundwater inhabitants require three things: a place to live, oxygen and energy or food, respectively. Thus, the living conditions of groundwater animals are directly connected to hydrological and geomorphological conditions on a regional scale, and on a local scale, lithological and structural properties that control hydrogeological parameters such as porosity and hydraulic conductivity, recharge mechanisms and flow dynamics.

In this paper we view Austrian hydrogeology from the perspective of groundwater fauna in order to elucidate the connection between the hydrogeological conditions and biological patterns. A brief review of groundwater biology research in general and specifically in Austria, revealed that crustaceans are basically in the focus of groundwater research while other common groundwater dwellers, such as free-living nematodes, are less studied similarly. Porous aquifers are comparably well investigated by groundwater biologists, while fractured aquifers have rarely been considered as habitats to date.

Due to the complex hydrogeological situation in Austria, with a greater portion of fractured and karstic aquifers, a systematic biological survey considering hydrogeological aspects may lead to a pronounced progress for the both disciplines, hydrogeology and groundwater biology. For hydrogeological purposes, the studies may provide the basis for using groundwater species (similar to the established method of using stable isotopes) as natural tracers in future studies. From the biological perspective, progress in the understanding of complex habitat-biota relations is expected to result from the investigation of hitherto unknown habitats. In addition, such a survey would not only be an important contribution to biodiversity and biogeography in Austria, it would also promote groundwater research in a broader context, such as the need to protect groundwater as a valuable service providing system (e.g. water quality).

Preliminary results from six test sites distributed to four different geological settings (Quaternary basin fill, Flysch-Zone, Northern Calcareous Alps and the Central Crystalline Zone within the Alps) show evidence for a link between the hydrogeological conditions and the present biological assemblages. However, a systematic survey is still required to understand which environmental factors mainly govern live in Austrian aquifers.

In Österreich sind alle drei grundsätzlich unterscheidbaren Arten von Aquiferen (Poren-, Karst- und Kluftaquifere) sowie Bereiche mit sehr geringen hydraulischen Durchlässigkeiten (Aquitarden oder Grundwasserhemmer) vorhanden und Gegenstand hydrogeologischer, hydraulischer oder hydrochemischer Untersuchungen. In der Hydrogeologie werden Aquifere in erster Linie als Speicher und Fließwege für Wasser, die darin gelösten oder suspendierten Stoffe sowie als Transportweg für Wärmeenergie betrachtet. Es wird selten thematisiert, dass es sich auch um Lebensräume mit sehr speziellen Bedingungen für ihre Bewohner handelt. Grundwasserbewohner benötigen drei grundlegende Dinge zum Leben: ausreichend Platz, Sauerstoff und Energie bzw. Nahrung. Ihre Lebensbedingungen sind damit also direkt abhängig von den hydrologischen und geomorphologischen Verhältnissen im regionalen Maßstab sowie von lithologischen und strukturellen Bedingungen im lokalen Maßstab. All diese Aspekte kontrollieren hydrogeologische Parameter wie Grundwasserneubildung, Porosität und Durchlässigkeit sowie die Fließdynamik im Aquifer.

Dieser Beitrag beleuchtet die Hydrogeologie aus der Perspektive der Grundwasserfauna, um die Beziehung zwischen hydrogeologischen Bedingungen und Organismengesellschaften im Grundwasser aufzuzeigen. Ein kurzer Überblick über den Stand der Forschung in der Grundwasserbiologie generell und im speziellen in der für Österreich zeigt, dass hauptsächlich Crustacaea untersucht werden. Als Konsequenz ist wenig über andere, durchaus häufig im Grundwasser lebende Tiergruppen, wie z.B. freilebende Nematoden, bekannt. Zudem liegt der Fokus der Grundwasserbiologen bisher vor allem auf Porenaquiferen, während vor allem Kluftaquifere bisher nicht im Interesse der Grundwasserbiologie standen. Unter dem Aspekt der komplexen hydrogeologischen Situation in Österreich mit einem hohen Anteil an Kluftaquiferen, kann eine vertiefte Betrachtung der Grundwasserfauna in Kluftaquiferen Fortschritte, sowohl für die Hydrogeologie als auch für die Grundwasserbiologie, bringen. So könnte ein besseres

Verständnis der Aquiferbesiedelung eine Möglichkeit bieten, Grundwassertiere zukünftig als natürliche Marker zu nutzen, ähnlich wie die Hydrogeologie bisher beispielsweise die stabilen Isotope des Wassers nutzt. Aus biologischer Sicht sind wichtige Erkenntnisse über komplexe Zusammenhänge zwischen Habitat und Lebensgemeinschaft von bislang gänzlich unbekannten Lebensräumen und Regionen zu erwarten. Zudem werden wichtige Daten zu Biodiversität und Biogeographie der Grundwasserfauna gewonnen, die nicht nur für Österreich, sondern in einem größeren Zusammenhang eine Rolle spielen, wie zum Beispiel Schutzanforderungen für Grundwasser – als Ökosystem im Dienste der Aufrechterhaltung der Wasserqualität.

Frühere Studien anderer Autoren und erste Ergebnisse unserer Untersuchungen in sechs Testgebieten verteilt auf vier verschiedene geologische Einheiten geben Hinweise auf die Beziehung zwischen Aquifertyp und Organismengesellschaften. Eine vertiefte systematische Untersuchung ist jedoch notwendig, um besser zu verstehen, welche Faktoren im Detail die Besiedelung und damit das Leben in Österreichs Aquiferen steuern.

1. Introductionary basics

In hydrogeological research groundwater systems are essentially viewed as fluxes of water, abiotic particles, dissolved solids and heat (Bertrand et al., 2012). The existence and extent of groundwater flow is controlled by groundwater recharge in a catchment area, a network of interconnected voids (pores, fractures or conduits) in which groundwater can flow due to a gradient between hydraulic heads in recharge and discharge areas to drive flow dynamics. From the perspective of groundwater biologists, aquifers represent living environments (habitats) with very particular living conditions. Due to the lack of light, they lack phototrophic primary production and provide food resources such as already synthesised (heterotrophic) and imported (allochthonous) dissolved or particulate organic carbon compounds (DOC, POC often termed detritus). Together with oxygen and space, the food sources, the availability of which is often more or less limited, constitute the basic requirements for life underground (Humphreys, 2008). Considering all this, underground habitats are often considered to be harsh, extreme and inimical (Danielopol, 1989) places. From a different viewpoint, however, they might be regarded as a relatively stable (i.e. constant thermal regime, relatively constant lower oxygen and food concentrations) and sheltered environment to live for those organisms able to cope with the respective conditions.

The living space, or in hydrogeological terms, the network of voids basically structuring an aquifer, depends on the general geological setting and can occur in the forms of (1) a porous aquifer in unconsolidated sediments with intra-granular flow, (2) a karstic aquifer with conduit flow and (3) a fractured aquifer in hard rocks with fracture flow. Furthermore, some lithologies act as (4) aquitards or even aquicludes (classified as “compact aquifers” by Hahn, 2009) due to their very small pores or the lack of open fractures. Oxygen and food are delivered to groundwater either through seepage water or with infiltrating water from surface water bodies, which both contribute to groundwater recharge and depend on regional (geographical) and local (geological) hydrological exchange processes. At the regional scale, climate and geomorphology determine the amount of precipitation constituting the basic water input. At the local scale, the vegetation cover and hydraulic conductivity of the soil and unsaturated zone control the recharge to aquifers that are not directly connected to surface water bodies. Flow gradient and leakage factor are the driving forces behind the interconnections between the groundwater and surface water bodies.

In the context of describing driving forces governing underground living conditions, the organisms themselves must not be disregarded as important operators in (re) structuring their physical, chemical and biological environment (Navel et al. 2011). Since the subsurface harbours a range of organisms spanning several magnitudes of body sizes (from bacteria to macro-invertebrates and fishes), a complex range of processes is involved in altering the living conditions through uptake, transformation and secretion of nutrients and metabolic products. All these processes as well as abiotic degradation processes, result in oxygen reduction. Remineralisers among the microbiota (bacteria and fungi; sometimes also protozoa) transform organic compounds into inorganic ones (e.g. CO_2, NH_4^+, PO_3^-). However, similar to plants in a very broad sense, chemo(litho)autotrophic bacteria are also able to build up organic matter using CO_2 as inorganic carbon source. Animals consume various food sources such as detritus or other organisms (microbiota, other animals). All these complex transfer and transformation processes of energy and matter represent important aquifer functions (Castaney, 1982 in Danielopol, 1989) also with respect to sustaining water quality (Danielopol et al., 2004; Griebler and Avramov, 2015).

Breaking down the above exemplified complexity of the subsurface living space into a highly simplified perspective again, leads to the conclusion that life in groundwater relies on an abiotic and a biotic component. In the case of Austria, the essential knowledge regarding the abiotic component is far better than the understanding of the biotic component. Austria´s comparably small land surface is characterised by a variegated landscape. High mountain ranges and low land regions are the result of a diversified geology caused mainly by the alpine orogeny. Aside from the Eastern Alps and their northern Molasse-Zone foreland, the southern part of the Bohemian Massif and the westernmost part of the Pannonian Basin are important regional geological units (Neubauer and Höck, 2000). A complex setting of tectonic nappes with various lithologies, intensive brittle and ductile deformation and pre- and intra-alpine basins generate a complex small-scaled geological structure. The distinct relief affects a heterogeneous climatic situation with mean precipitation amounts of less than 600 mm/a in the eastern low lands of Lower Austria and Burgenland (e.g station Langenlebarn) and up to 2.500 mm/a in the high mountain regions in the central and western part of the country (e.g. station Rudolfshütte) (Lebensministerium, 2012).

The combination of diversified geological settings and various precipitation input leads to a variegated hydrogeological classification of the Austrian territory (Gattinger, 1980), wherein all above mentioned aquifer types (1 to 3) and aquitards or aquicludes, respectively (4) are represented. As a heterogeneous geology and climate stands for highly variable subsurface living conditions, life in Austria's subsurface must also be of a high variability. Thus, from the hydrogeological point of view groundwater animals, as an important component of underground life, may be ideal natural tracers for distinct hydrogeological situations (Eisendle-Flöckner and Hilberg, 2014). Consequently, a systematic survey of Austria´s groundwater inhabitants is considered to provide a basis for integrating ecohydrology into the research of complex hydrogeological settings.

In order to provide an initial approach to such a complex task as the mentioned study, this paper first presents a brief survey of groundwater biology (incl. its terminology) and then, as a basic background for a first systemisation, a survey of knowledge on abiotic and biotic groundwater components in Austria (incl. preliminary data). Finally, we discuss the potential impact of interdisciplinary groundwater research on Austria´s hydrogeological research in the future.

2. Groundwater biology in brief

Organisms that occur in groundwater can be microbiota (bacteria, fungi and protozoa), metazoan invertebrates, and vertebrates. Vertebrates comprise amphibians and fish, the occurrence of which is restricted to suitable larger spaces such as caves. A brief compilation of groundwater animals was published by Mösslacher and Hahn (2003). Metazoan invertebrates comprise, for example, crustaceans, nematodes, annelids, planarians, and snails. Crustaceans are the most prominent group in groundwater research, and comprise numerous species especially adapted to life underground. They display several adaptations such as the lack of pigmentation, reduced or lacking eyes, an elongated body shape and a reduced number of offspring.

The earliest observation in groundwater biology dates back to 1541, when a blind cave fish was allegedly observed in China (Chen et al., 1994 in Mösslacher and Hahn, 2003). However, this did not open a new area in biology. Groundwater biology's actual origin dates back to the 17th century with investigations of both the fauna (discovery of the olm – Proteus anguineus by Valvasor"in 1689" in Belles, 1992) and the microbiota (Danielopol and Griebler 2008). But only the fauna has continuously been in the focus of groundwater biology since then. While applied microbiology became better established as early as the 1950s (Griebler et al., 2014), fundamental microbiology has only been the focus as off the 1980's (Danielopol and Griebler, 2008). Successively to olm's discovery, groundwater biological research was concerned with the investigations of cave and vertebrates until around the turn of the last century when wells, tap water and invertebrates started to receive the attention of groundwater researchers (Brehm, 1930). Alluvial aquifers also first received attention in the beginning of the 20th century (Priesel-Dichtl, 1959), and have become an increasingly prominent sector in its last decades. Nevertheless, cave research persists as an important branch within groundwater biology continuously adding systematic, biogeographic and evolutionary work accompanied by several published textbooks (Spandl, 1926; Camacho, 1992; Wilkens et al., 2000; Culver and White, 2005).

Having developed from its originally biogeographic approach (in the widest sense incl. aspects of taxonomy, systematics and evolution), groundwater biology has begun to assess the relationships between organismal patterns and environmental conditions (= ecology) since around the 1950´s (Danielopol and Griebler, 2008) in order to better understand the driving mechanisms behind faunal distribution patterns. This relational approach is in fact the basis of biological groundwater investigations (microbiota, fauna) to date and has also been extended to discover the potential response of organisms to anthropogenic alterations (pollution, withdrawal of water, obstruction, conventional agriculture practices) and detect potential threats thereof to the underground organisms and habitats. A few such examples are outlined below. According to environmental degradation, eco-toxicological methods are also useful to assess harmful influences on groundwater organisms (Notenboom et al., 1992; Canivet et al., 2001; Avramov et al., 2013; Reboleira et al., 2013). Putting the fundamental and applied approach together, the patterns of organisms and habitats (in vivo and vitro) address the small scales along the spatio-temporal axis (local, generation), which are the basis for large scale patterns addressed by biogeography (regional, evolution). For both scales, imbalances in the focus (organisms, habitats) as well as observed patterns' high variability hamper progress in groundwater ecology towards generalisations that are helpful for monitoring purposes.

From the brief overview given in the preceding two paragraphs, it is already evident that groundwater biology has undergone permanent changes. These changes are also reflected by a terminological development as examples out of a summary (Camacho, 1992) show. The early definitions addressed life in caves and defined their light and geological characteristics, and the living preferences of animals ("troglo = greek for cave), as trogloxene (not able to live in caves but sporadically found there), troglophile (able to live in caves), and troglobite (typical cave dwellers). In 1925, Thienemann already added another terminology that addresses aquatic organisms living in any subsurface habitat. His terms (still in use), are derived from the terminus "styx" in the greek mythology: stygoxene (not able to live belowground, but occasionally found there), stygophile (able to live in surface and subsurface habitats), and stygobiont (typical groundwater inhabitants with certain adaptions to specific belowground conditions; originally as "stygobite"). Thienemann initially introduced the terminus "groundwater" the first time as "all water on the surface of earth and circulating in the outermost crust of the earth", and Spandl (1926) subsequently distinguished water bodies of caves, groundwater and fissures.

Addressing the above mentioned imbalances, biological groundwater research shows a distinct focus on crustaceans, and a distinct lack of investigations that include another important (abundant and frequent) groundwater faunal element, namely free-living nematodes. Furthermore, groundwater biology focuses on karstic and porous aquifer types and show a lack of attention towards organisms living in fractured aquifers as pointed out recently (Eisendle-Flöckner and Hilberg, 2014). This is also an imbalance concerning the investigated biogeographic regions. More comprehensive data are meanwhile avaible from France, Slovenia, Italy, Germany and the USA (e.g. Deharveng et al. 2009; Hahn and Fuchs, 2009), while other areas including Belgium (Martin et al. 2009) and Austria as European examples, still lack comprehensive data. The inclusion of all species living underground as well as the integration of several aquifer types and landscapes in groundwater biology, would hence offer new and important insights into ecological, biogeographic, systematic and evolutionary aspects.

Finally groundwater represents highly complex systems offering ecosystem services (ESS) of importance to humans. These free but invaluable services are defined, for example within the Millenium Assessment provided by the United Nations in 2005, as follows: 1) supporting, 2) provisioning, 3) regulating and 4) cultural services. Groundwater plays a role in 1) supporting nutrient cycling, biodiversity, habitat for specifically adapted species only able to live there, groundwater related habitats, 2) providing water (irrigation, drinking water, mineral water, heating and cooling, energy, genetic resources, 3) regulating water purification, disease control, maintenance of hydraulic conductivity, drought attenuation, flood mitigation and erosions control, alleviation of climate warming ("cold refugia", regulation of the water cycle, and 4) spiritual value, aesthetic value and bioindication (Avramov et al., 2010; Griebler and Avramov, 2015).

3. Overview of Austrian aquifers

With regard to their hydrogeological characterisation as different kinds of aquifers or aquitards (1 to 4) Austria can be divided into greater geological areas that are – except for quaternary basins – more or less arranged from North to South and cross the country from East to West (table 1 and figure 1):

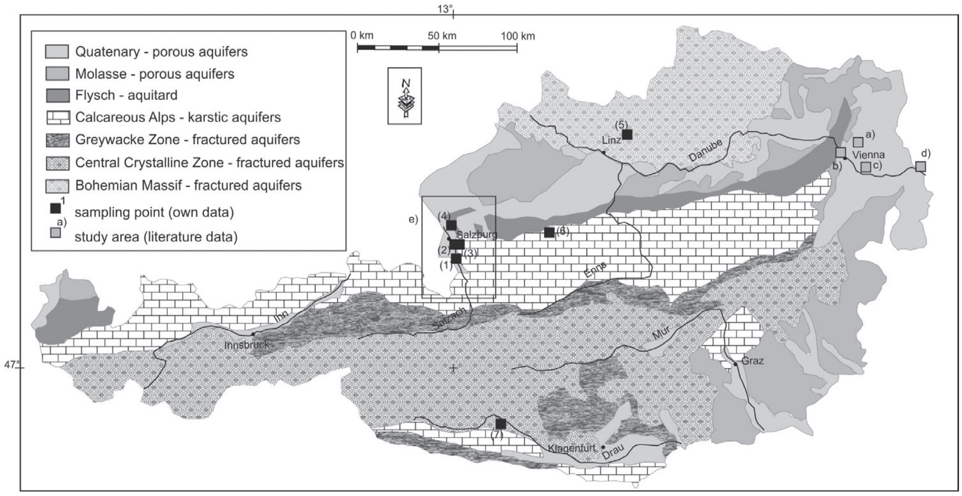

Figure 1: Overview of Austrian Aquifers (map simplified after Gattinger, 1980). (1) test site Glanegg, (2) test site Salzburg Freisaal, (3) test site Salzburg city, (4) test site Bergheim, (5) test site Freistadt, (6) test site Ebensee, (7) test site Goldeck, a) study area Danube (Danielopol et al., 2006), b) study area Danube – km 1932 (Danielopol, 1989), c) study area Lobau (Danielopol, 1989), d) study area Danube – km 1880 (Danielopol, 1989), e) study area Salzburg (Priesel-Dichtl, 1959)

(Hydro) – geological area	**major aquifer type**	**subordinate aquifer type**	**Test site**
Quaternary basins	porous aquifer		(1), (2), (3), a) – e)
Bohemian Massif	fractured aquifer	porous aquifer	(5)
Molasse-Zone	porous aquifer	fractured aquifer	
Flysch-Zone	aquitard	fractured aquifer	(4)
Calcareous Alps	karst aquifer		(6)
Greywacke-Zone	fractured aquifer	karst aquifer, aquitard	
Central Crystalline Zone	fractured aquifer		(7)

Table 1: Hydrogeological classification of Austria´s greater geological areas and the assignment to the investigated test sites, introduced in figure 1

3.1 Quaternary basins (porous aquifer)

Glacially overdeepened intra-alpine and pre-alpine basins of tectonic origin represent the biggest and, with respect to water economy requirements, most important porous aquifers in Austria. About 50 % of the Austrian drinking water supply is derived from these water reservoirs (Lebensministerium, 2015). Most of the groundwater bodies in unconsolidated sediments are bound to large alpine drainage systems such as the rivers Danube, Salzach and Inn. Quaternary fluvial transport and sedimentation is responsible for gravel and sand deposits with a thickness of up to several hundred meters within river valleys and basins (e.g. Bleibinhaus and Hilberg, 2012; Salcher et al., 2012). Postglacial lacustrine sedimentation lead to fine-grained clay layers that underlie the coarse-grained aquifer or separate several groundwater levels and act as aquicludes. The coarse-grained (sand and gravel) unconsolidated sediments are characterised by an effective porosity in the range of 10 to 30 % (Hölting and Coldewey, 2013) and pore sizes in the range of 0,05 mm or less depending on the grain shape (Blume et al., 2010). Hydraulic conductivities between 10^{-2} m/s and 10^{-5} m/s are common (e.g. Diem et al., 2009, Hoehn and Meylan, 2009). Quaternary basins are basically flat landscapes. Groundwater recharge is mainly derived from laminar infiltration of precipitation within the whole catchment area. In addition, percolation of tributaries and thus, surface water infiltration can play a significant role to groundwater recharge. Rivers act as recipients regulating the groundwater table and hence, the thickness of the covering unsaturated zone.

In coarse-grained sedimentary basin fills high hydraulic conductivities combined with short-term recharge and intensive interaction with surface water results in flow velocities in the range of several decimetres to a few meters per day. The groundwater composition is controlled by the mineralogical composition of the sediments. Groundwater can be classified as Ca-Mg-HCO3 water type (Geol. Bundesanstalt, 2004) (classification after Furtak and Langguth, 1967).

Austrian alpine basins and river valleys are not only favoured catchments for groundwater recharge and important groundwater reservoirs but are also preferred areas for settlements, agricultural or industrial activities. Thus, anthropogenic influences such as water extraction for the drinking water supply can influence the groundwater-surface water interaction. Groundwater use for heating or cooling in industrial plants as well as in private households has become more important for Austria´s energy supply in the last years with annual growth rates of 5 % (EHPA, 2014). Groundwater is extracted from the aquifer, used for temperature regulation (cooling or heating) and is re-infiltrated with a temperature difference of some K (temperature spread of 6K are allowed after ÖWAV, 2009). In addition groundwater pollution resulting from contaminations cannot be avoided in densely populated and intensely used areas.

3.2 Bohemian Massif (fractured aquifer, porous aquifer)

The Bohemian Massif in the northern part of Austria, mainly north of the river Danube, is an average mountain region with valleys and hills between 450 and 1.000 m a.s.l. Mean precipitation amounts are in the range of 700 to 950 mm/a (Lebensministerium, 2012).

The massif consists of granites and gneisses without any primary matrix porosity. Brittle deformation and surface-parallel cooling fissures result in a network of fractures that act as pathways for groundwater flow (Frederick et al., 2011) within the un-weathered deeper zones of the massif. Additionally, weathering of granites and gneisses under humid climate conditions and a flat topography lead to a strongly bulked structure in the uppermost tens of meters. With respect to the hydrogeological properties this uppermost weathered zone is comparable to a coarse-grained porous aquifer with intra-granular flow systems. Dewandel et al. (2011) describe hydraulic conductivity and porosity in deeply weathered crystalline aquifers. Weathered zones of the massif are favoured regions for groundwater infiltration and for storage during dry periods.

Due to the very low solubility of the silicate minerals of gneiss and granite, the groundwater has a low content of total dissolved solids (<50 mg/l according to Bender et al. (2001) and is slightly acidic (pH-values 6 to 7). The majority of the groundwater is of Ca-Mg-HCO3 or Ca-Mg-HCO3-SO4-water type according to the classification after Furtak and Langguth (1967) (Geol. Bundesanstalt, 2004). Groundwater within the upper bulked part of the aquifer is rapidly recharged by infiltrating oxygen – rich rainwater. The temperature of the shallow groundwater varies with seasonal influences whereas the temperature in the deeper fractured part of the aquifer is stable and corresponds to the mean annual air temperature in the catchment. With respect to the circulation depth it may even be geothermally influenced.

A peculiarity of the Bohemian Massif is a high content of the radioactive isotope Radon 222 that can also be detected in the groundwater (Schubert et al., 2010).

3.3 Molasse-Zone (porous aquifer, fractured aquifer)

The region between the Bohemian Massif in the North and the Flysch-Zone in the South reaches a maximum height of 400 m a.s.l. in a smooth hilly topography. It is characterised by mean precipitation amounts of 800 to 1.000 mm/a (Lebensministerium, 2012). The area is covered by deep soils, rich vegetation and partly intensive agricultural use.

The aquifer consists of tertiary marine and freshwater sediments, mainly represented by sands and conglomerates in alternation with marl or clay, in deeper sections as consolidated marl – or claystones. Local deposits of quaternary fluvial coarse-grained clastic sediments overlie the tertiary layers along the surface runoffs.

The sandy sediments represent the main aquifers in this geological setting. Hydraulic conductivities in the range of 10^{-3} to 10^{-5} m/s are detected in the medium-grained layers (Gattinger, 1980). The most important process of groundwater recharge is laminar infiltration of rain water from the surface. Alternating sequences of medium-grained sand (aquifer) and fine-grained clay or marl (aquiclude) create a multi-aquifer formation and local artesian basins (Schubert, 2003). In the locally overlying quaternary gravel the groundwater flow can be compared to the conditions in quaternary basin fills.

Carbonate sediments dominante since the provenance of both tertiary and quaternary material is the Northern Calcareous Alps. Thus, groundwater quality in the Molasse-Zone is characterised by Ca-Mg-HCO3 water type (Kilchman et al., 2004), alkaline pH-values and comparably a high electrical conductivity (around 600 µS/cm, Geol. Bundesanstalt, 2004).

3.4 Flysch zone (aquitard, fractured aquifer)

Although precipitation amounts of 1.300 mm/a year are detected in the hilly Flysch-Zone of the alpine foreland (Lebensministerium, 2012) there is a lack of groundwater in this geological unit. The dominant tertiary and cretaceous clay and marlstones in this region are of very low permeability. Groundwater recharge is low and springs are rare (Schubert, 2003). The mostly fine-grained consolidated sediments show reduced effective primary matrix porosity. Fractures resulting from tectonic stress are small and usually re-filled with fine-grained material. Thus, there is a lack of interconnected open voids. Groundwater flow is only possible in the uppermost zone as result of weathering structures.

3.5 Northern and Southern Calcareous Alps (karst aquifer)

The large triassic to cretaceous carbonate belt along the northern and southern margin of the Alps and paleozoic carbonates north of Graz are the main karst aquifers in Austria and represent the most important drinking water reservoirs for some of the bigger Austrian cities (Vienna, Salzburg, Innsbruck) (Schubert, 2000; Plan et al., 2008). Mean precipitation amounts are very variable with peak values around 2.000 mm/a (Lebensministerium, 2012).

Apart from highly permeable conduits the matrix permeability of carbonate rocks is very low and its influence on the hydrogeological processes in karst aquifers is negligible (Bakalowicz, 2005). As a result of tectonic stress, pre-developed fractures and faults are widened by dissolution processes when slightly acidic rain water infiltrates into the calcite – and dolomite – dominated rocks. Regionally well connected solution conduits result in a high permeability. Sinkholes are formed at the surface and are responsible for punctual infiltration of precipitation. Within the Calcareous Alps (Northern and Southern) more than 75 % of the precipitation infiltrates quickly through sinkholes into the karst system (Gattinger, 1980). The soil cover is thin or non-existent. The main characteristic of karst aquifers is the very short mean residence time of the fast flow component in the range of only some days (Lauber and Goldscheider, 2014) associated with fast flow velocities of up to several hundreds of meters per hour (Bakalowicz, 2005). Karst springs with a high discharge may drain large catchments (Rehrl and Birk, 2010). High variations in discharge are observed as a direct response to precipitation or snow melt in the catchment area.

The water table within a karst aquifer can vary seasonally in the range of several hundred meters. In times of high infiltration rates during flood events or snow melt the water table is high and groundwater quality is characterised by significant dilution effects (low electric conductivity, water temperature according to air temperature in the catchment). During longer dry periods the water table sinks, the spring discharge decreases and the base flow in karst groundwater is characterised by calcite saturation (Kilchmann et al., 2004), slightly alkaline pH-values as result of calcite dissolution, and electric conductivity values in the range of 200 to 400 µS/cm (Geol. Bundesanstalt, 2004). Due to fast infiltration and the lack of soil, the oxygen content is high but the content of dissolved or particulate organic carbon is usually low.

Karst aquifers are basically very vulnerable to pollution (e.g. Plan et al., 2008). Pollutants infiltrate as quickly as the rain water into the karst system. Expanded protection zones are obligate for catchments of drinking water supply plants.

3.6 Greywacke Zone (fractured aquifer, karst aquifer, aquitard)

South of the Northern Calcareous Alps a mountainous region, called the Greywacke-Zone follows. The annual precipitation amount is in the range of 1.500 mm/a (Lebensministerium, 2012). This belt consists of a lithological mixture of paleozoic greywackes, phyllites, greenschists, blackschists and carbonate ranges (calcite and dolomite) (Schönlaub, 1980). Due to these high variations in lithology, the Greywacke-Zone shows various kinds of aquifers and a general description of the hydrogeological characteristics is difficult (Gattinger, 1980).

Karst aquifers with little or no surface run off, strong variations in the water table and few springs with a discharge of 2,5 up to 10 l/s are typical in carbonate dominated regions. Regions that are dominated by insoluble phyllites or schists can be characterised as aquitards, or locally as fractured aquifers. Groundwater flow is restricted to open intra-connected fractures that are comparably sparse due to the lithological properties of the formations. Phyllites and schists tend to react to tectonic stress in a ductile manner and preferably form folds rather than fractures. In addition fine-grained (clay) weathering material tends to fill open fractures. The hydraulic conductivity within these filled fractures corresponds to the properties of a fine-grained sediment. The groundwater flow within filled fractures is very slow in very small pores. Long mean residence times are the consequence of the low flow conditions. Springs are frequent but very small (Gattinger, 1980).

The groundwater quality refers to the aquifer lithology, and is therefore very variable with alkaline pH-values and higher mineralisation in carbonate units, slightly acidic groundwater and low mineralisation in the fractured parts of the mountain range. Infiltration of oxygen and nutrients depends on the infiltration process. In the less soluble lithologies the contents of both is generally low.

3.7 Central crystalline Zone (fractured aquifer)

The Central crystalline zone and its schistose frame reach the highest elevations within the alpine belt with a maximum of 3.798 m a.s.l (Großglockner). Precipitation amounts can reach 2.500 mm/a in the highest regions (Lebensministerium, 2012). The central alpine zone in Austria is represented e.g. by the Tauern Window that consists of mica schists, phyllites and gneisses in its central part. Fractured aquifers in various forms develop in these insoluble lithologies.

The hydrogeological characterisation of schists and phyllites are comparable to those of the non-karstifiable parts of the Greywacke-Zone, and thus, will not be further discussed here. Of great interest as a special type of aquifer are the gneiss-formations. While matrix permeability is negligible (Pochon et al., 2008) in crystalline rocks open fractures with a width of up to several decimetres as a result of tectonic stress represent important pathways for groundwater. They may be re-filled with weathered gneiss components. The hydraulic conductivities depend on the fracture width and re-filling material. Based on tunnel inflow measurements (Masset and Loew, 2010) and slug tests performed in shallow depth boreholes (Beatrizotti, 1996; Ofterdinger, 2001 both cited in Pochon et al., 2008) the hydraulic conductivity ranges from 10^{-5} to 10^{-10} m/s for the crystalline units in the Central Alps zone in Switzerland.

Precipitation percolates through a soil zone of varying thickness into the fractures. According to the structure of the fracture network, groundwater flow velocities and mean residence times are variable. Mean residence times may be in the range of months to a few years (Kilchmann et al., 2004). The impact of dry periods as well as rainfall events or snow melt is dampened in the aquifer so that the water level and hydrochemical composition, temperature, and contents of oxygen and nutrients are relatively stable.

Groundwater in fractured gneiss aquifers is slightly acidic and has low mineralisation (Geol. Bundesanstalt, 2004, Kilchmann et al., 2004). The mixing of infiltration water from various events and various residence times lead to a mean mineralisation and mean temperatures that correspond to the situation in the catchment. Rapid changes at the surface do not usually result in significant changes in the water quality and quantity of the springs.

4. Potential impact of groundwater biology on hydrogeological research in Austria

A greater understanding and consideration of the groundwater ecosystems by hydrogeologists can provide great opportunities for hydrogeological research. This is especially true for the small-scaled groundwater bodies with complex flow dynamics that characterise Austria´s hydrogeology (see chapter 3) since groundwater animals can be used as natural tracers similar to the use of stable isotopes in hydrogeology. In the following we will discuss some benefits of groundwater fauna research and applications of ecohydrology to answer questions Austria´s hydrogeology and water management is confronted with.

4.1 Ecosystem services (ESS)

With relation to the already outlined ESS, it is widely accepted that groundwater ecosystems have an important influence on groundwater quality (Hahn, 2006). Groundwater invertebrates feed on microbes and particulate organic matter, and thus, improve water quality and keep the pore spaces of the aquifer open (Danielopol et al., 2004). This can be seen as a very important contribution to hydrogeologists efforts to guarantee drinking water quality and to fulfil the requirements of the "Directive on the Protection of Groundwater against Pollution (European Union Groundwater Directive – GWD)" assuming they are able to understand the functionality of groundwater habitats.

4.2 Groundwater animals as natural tracers in complex hydrogeological settings

A place to live, oxygen and food supply, as well as hydrochemistry and temperature regimes are fundamental factors for the colonisation of aquifers. These basics are strongly related to the geological, hydrological and hence, hydrogeological conditions. The size and geometry of voids are limiting factors for the maximum size of groundwater animals and control hydraulic conductivity and groundwater dynamics. The percolation of precipitation through soil and the interaction between surface – and groundwater – are processes that transport oxygen and food into the aquifer, and the relation between groundwater recharge and discharge and thus, the hydrostatic gradient are the driving force of subsurface flow. Lithology, flow velocity, mean residence times, and circulation depth are the determining factors for physio-chemical properties of groundwater and hence define the living conditions for aquifer inhabitants. The close relationship between groundwater habitats and the hydrogeological settings makes inhabitants optimal witnesses of the basic subsurface conditions in unconsolidated sediments and porous aquifers as well as in hard rocks with fracture or conduit flow conditions.

As described in chapter 3, a large proportion of Austria´s groundwater bodies are fractured hard rock aquifers. The scarcity of methods to investigate hard rock aquifers is a recent and not sufficiently solved problem since traditional hydrogeological methods developed for porous or karstic aquifers do not completely fulfil the requirements of fractured hard rock environments. The following two examples explain some of the specific problems hard rock hydrogeologists are confronted with:

- The interpolation between distinct boreholes is appropriate to describe the geological and hydrogeological conditions in a porous aquifer with comparably homogenous hydraulic conductivities but it is usually not possible to determine flow paths within a fractured hard rock system based on punctual drill hole information.
- Tracer tests were developed to investigate flow paths and mean residence times in karst systems. Due to comparably longer mean residence times and diffuse flow conditions the use of artificial tracers is no option for hydrogeological investigations in fractured hard rocks.

Thus, the delineation of spring catchments, the determination of flow dynamics and groundwater residence times is still afflicted with uncertainties and mistakes. Although some new approaches to overcome problems in heterogeneous fractured hard rock aquifers are introduced by Pochon et al. (2008) hydrogeologists can still benefit from new methods that aid in the understanding of flow systems in hard rock aquifers. With the implementation of biotic analysis a new and additional potential tool could help overcome some of these shortcomings (Eisendle-Flöckner and Hilberg, 2014).

4.3 Groundwater animals to identify anthropogenic influences on aquifers

Several studies on the impact of human activities on groundwater populations were published in the last decade. Here we present just a few examples on how the combination of hydrogeology and biohydrology can improve environmental sciences methodologies.

The use of groundwater fauna as an indicator of surface water influence at riverbank infiltration sites was introduced by Berkhoff et al. (2009) using the groundwater fauna index (GFI) according to Hahn (2006). Gutjahr et al. (2013) described the interaction of groundwater communities and natural or artificial lakes. Their study showed that human intervention through e.g. quarry ponds may have a significant and long-term impact on groundwater biology and thus confirmed the results of Berkhoff et al. (2009).

Matzke et al. (2004) described the assessment of contaminated sites using meiofaunal assemblage patterns. They figured out that different groups of animals are variously sensitive to specific pollutants such as volatile halogenated hydrocarbons (VOC). They recommend bioindicators as suitable alternatives to monitor contaminated sites.

In Austria – as well as in other European countries – the abstraction of geothermal energy from shallow aquifers is an expanding technology (EHPA, 2014). Brielmann et al. (2011) investigated the potential impacts of artificial groundwater temperature variations on groundwater ecosystems. They showed that selected groundwater invertebrates exhibit little tolerance to long-term exposure to increased temperatures.

5. Groundwater fauna research in Austria

In Austria, studies on groundwater fauna are sparse and concentrated on only a few study areas. In a more recent survey, Christian and Spötl (2010) date the beginnings of cave research in Austria to the second half of the 19th century. In addition, these authors point out that there is a greater interest in terrestrial than in aquatic animals in Austrian cave research. They, as well as Christian et al. (1994), have compiled surveys of the Austrian cave fauna. Dating back to 1959 and with respect to other groundwater habitats other than caves, Priesel-Dichtl noted that they have not been as systematically investigated as other sites in middle Europe until then. One exception was a study by Vornatscher ("Lusthauswasser" in Vienna, 1938). Until today, the study of Priesel-Dichtl (1959) represents the only comprehensive study from the Western part of Austria and is briefly described in the following.

225 sites were sampled mainly in Salzburg and to a lesser extent in Upper Austria within four different geological units (Quaternary, Molasse-Zone, Flysch-Zone and Northern Calcareous Alps). These sites comprised wells (191) and tapped springs (34) with water tables at varying depths. In most cases, 300 liters were pumped through a plankton net (Nr. 25) and only at a few sites were buckets used for scooping. A total of 102 species were recorded from 78 % (176) of the sampling sites; 20 of them were declared stygobionts and 28 terrestrial, introduced only by chance into the wells. The mean abundance was 280 animals per m^3 filtered water (range: 1-12.529 individuals per m^3 water), and crustaceans dominated the fauna in terms of species (59) and individuals. Among the crustacean the Paracyclops fimbriatus, Niphargus fontantus, and Asellus cavaticus were relatively frequently observed with appearances in 45, 25 and 12 wells, respectively. Other less frequent faunal elements were annelids, snails, planarians, mites, nematodes and rotifers.

Though Priesel-Dichtl (1959) did not undertake complex statistical analysis, her study can be seen as one of the first Austrian ecological approaches to groundwater observations due to the attempt to establish relationships between faunal patterns (mean numbers of individuals and species) and abiotic parameters including well characteristics (temperature, oxygen content, nutrients, well characters: depth, hydrogeology and age). Mean animal density was the lowest at 1mg/l O_2 (the lowest class out of five established), and highest (882 per m^3 l water) in the second class (1-4 mg/l O_2). The percentage of sites without animals decreased with increasing O_2 content. The number of species was the lowest at 1 mg/l O_2 (one oligochaete), and the highest in the class of 7-10 mg/l O_2 (19). Interestingly, a high percentage of stygobionts was found in the second and uppermost (> 10mg/l) O_2 class with 54 % and 57 % respectively. The temperature, nutrients and well depth also did not provide a better distinct pattern of relationships between fauna and abiotic characteristics. However, differences between the types of wells concerning the catchability were noted together with the differences between the sampled lithologies.

More comprehensive research efforts were undertaken in alluvial aquifers in the eastern part of Austria, which can basically be ascribed to the research group of Dan L. Danielopol. Aside from fundamental approaches to generally enhance knowledge on life underground in relation to abiotic patterns, these efforts have also included methodological developments (Danielopol and Niederreiter, 1987; Niederreiter and Danielopol, 1991; Datry et al. 2003) as well as evaluations of the indicator usability of the groundwater fauna (Mösslacher et al. 1996; Mösslacher 1998; Danielopol et al. 2006). Most of the studies were undertaken at the Lobau from the 1970s to 1990s (Griebler and Mösslacher, 2003), while other sites have rarely been investigated: Marchfeldkanal – Danielopol et al. (2006), Danube stream km 1932 – Danielopol (1989). The Lobau represents a floodplain area (2.400 ha) in Vienna, that has lost its direct main river connection due to regulation measures (flood protection) around 1870. It is now part of a Riverine Wetlands National Park "Nationalpark Donauauen". When compared internationally, this area is one of the best investigated according to Griebler and Mösslacher (2003). These authors provided a comprehensive description of the "Lobau research" at that time. Out of this, only an extremely condensed excerpt of one of its main aspects is subsequently described.

Three main study areas (mesohabitats) have been established along a gradient of decreasing surface water influence (flooding, infiltration). The influence of surface water ranged from high over moderate to extremely low (floods from backwaters, subsurface infiltration), and abiotic patterns as well as faunal patterns have been partly reflecting this gradient. In brief, the site with the least surface influence harboured only stygobiotic species, at the two other sites species ascribed as stygobionts, stygoxenes and stygophiles were observed. Species richness ranged from 20, 31, and 46 at the lowest, moderate and highest surface water influence sites, respectively. Since species richness of groundwater habitats is generally considered to be low, a total of 35 stygobiotic crustacean species, recorded during the course of the Lobau studies, represents a rather high number – in particular with regard to the relatively small sampled area (Danielopol and Pospisil 2001).

Species determination represents a basic and important aspect in biological groundwater research with its general additive value of enhancing biodiversity and biogeographic knowledge of often formerly unknown habitats and regions. Austrian groundwater investigations have led to the description of new species (Schiemer 1984; Pospisil 1989; Rogulj and Danielopol 1993, Senz 1996), redescription, new records and discussion of species/species groups (Eder, 1975; Rogulj et al., 1993; Haase, 1995; Pospisil, 1999; Haase et al., 2000; Stoch and Pospisil, 2000a; Stoch and Pospisil, 2000b, Namiotko et al., 2005). This list once again comprises mainly crustaceans while only rarely dealing with other animals such as gastropods, nematodes, and nemerteans. An interesting report describes unusual but repeated findings of beetle larvae in wells in Vienna and Upper Austria as specific adaptive behaviour (Klausnitzer and Pospisil 1991). Observations of gut contents and faeces have pointed to macroinvertebrates´ function in supporting the permeability of sediments (Danielopol, 1989). Ecotoxicological research using animals has only sparsely been applied for Austrian groundwaters (Helma et al., 1998) to our present knowledge. Finally, the importance of the groundwater fauna as an indicator of surface-subsurface connectivity, environmental status, as well as the need of the underground habitats' protection, in particular with regard to providing water quality, but also as a right on its own, have been emphasised by Austrian groundwater scientists (Danielopol et al., 2003; Danielopol et al., 2004; Danielopol and Griebler, 2008).

6. Living space for groundwater fauna in Austria

Due to the sparse studies it is currently not clear if ecoregions (Illies, 1978) play a role on the coarse scaled distribution patterns of groundwater fauna in Austria. As mentioned above, the main factors controlling the habitability of groundwater bodies are the size of voids and the supply of oxygen and nutrients. Additionally, the flow velocity and variations in water temperature and hydrochemistry may influence the faunal assemblage patterns. In some hydrogeological settings the groundwater animals are confronted with particular challenges such as artificial physio-chemical anomalies or geogenic pollution. A very rough assessment of the habitat conditions of the hydrogeological units described above is given in table 2. Due to the small-scaled heterogeneities of

Geological unit	Aquifer type	Void size	Flow velocity	Oxygen content	Infiltration of nutrients	Temperature	Special challenges for inhabitants
Quaternary basins	porous	µm to mm	up to some m/d	high	high	variable	anthropogenic influences on quality, temperature and flow
Bohemian Massif	fractured	µm to cm	low in deeper parts	high to low	high to low	stable in deeper parts	222 Radon, slightly acidic water
Molasse-Zone	porous	µm to mm	low	medium to low	medium to low	variable	
Flysch-Zone	aquitard	µm	low	low	low	stable	
Northern and southern Calcareous Alps	karstic	µm to m	up to m/s	high	low	variable	High temporal variability in physico-chemical parameters and flow velocity
Greywacke-Zone	fractured	µm to mm	low	medium to low	medium to low	stable	
Central Crystalline Zone	fractured	µm to dm	medium to high in (case of wide open fractures)	medium to low	medium to low	stable	slightly acidic water

Table 2: Properties of Austrian aquifers with regard to their suitability as habitats

aquifers divergences are likely when dealing with individual groundwater bodies.

7. Own preliminary results

7.1 Sampling sites

Our integrated hydrogeological and ecohydrological studies in Austria began with the search for suitable sampling points that represent the different general hydrogeological units described above. To avoid adulteration of the hydrochemical as well as biological composition, groundwater samples should ideally be extracted from directly within the aquifer through wells or boreholes. Springs may also be suitable sampling points if it is possible to prevent contamination with surface water or atmospheric influences and under the precondition that the geological situation in the catchment is unambiguous. These preconditions should be fulfilled for springs emerging in artificial excavations (e.g. tunnels) or for tapped springs under ideal sampling conditions.

For the presented preliminary investigations the sampling points were selected by consulting freely available databases (e.g. SAGIS in Salzburg) regarding existing groundwater observation wells. Initial efforts to select sampling sites showed that a large number of suitable wells are available to investigate unconsolidated sediments of the quaternary basins while wells tapping hard rock aquifers are obviously scarce. Hitherto, two wells in porous aquifers, one well tapping the uppermost bulked part of the Flysch-Zone, one well within the Northern Calcareous Alps, one spring emerging into a street tunnel in the Bohemian Massif and a spring emerging from a crystalline formation were sampled for first investigations. Some basic information about the sampling sites is given in table 3 and figure 1.

Sample-ID	Location	Geo-logical unit	Aquifer type	Level of with-drawal or discharge	Remarks	Sampling date
1	Salzburg Basin, Glanegg	Quater-nary basin	porous	5,8 m	Groundwater well	Dec. 2013
2	Salzburg Freisaal, lower Salzach Basin	Quater-nary basin	porous	4,2 m	Groundwater well	Dec. 2013
3	Northern Salzburg City, lower Salzach Basin	Quater-nary basin	porous	4,8 m	Groundwater well, potential contamination, nearby brownfield	Dec. 2013
4	Bergheim, North of Salzburg City	Flysch-Zone	Porous or frac-tured	4,6 m	Groundwater well, potentially influenced by a nearby surface runoff	Dec. 2013
5	South of Freistadt, street tunnel under construction	Bohemian massif	fractu-red	~2 l/s	Spring discharge in tunnel	Aug. 2013
6	Ebensee, tunnel in the southeast of lake Traunsee	Northern Calcareous Alps	karstic	~20 m below tunnel level	Groundwater well, influence of near lake Traunsee unclear	Feb. 2014
7	Goldeck Möll valley, Carinthia	Central crystalline zone	fractu-red	2,4 l/s	tapped spring	May 2014

Table 3: Sampling points incorporated in the preliminary investigations

7.2 Material and Methods

Because different sampling methods have had to be applied due to logistic constraints (availability, accessibility), fauna data are solely presented from a qualitative perspective but include portions of relevant biological aspects (e.g. faunal components, nematodes feeding types). The sampling equipment comprised an electric submerged centrifugal pump and a gasoline driven vacuum pump, as well as a plankton net. The gasoline pump was constructed specifically to prevent larger groundwater invertebrates from being destroyed by the pump's spinning top. The electric submerged pump is a standard hydrogeological equipment with no adaptations. It was used at the test sites 1, 3 and 6 and no destroyed animals (parts thereof), but moreover, undamaged larger crustaceans, were observed in these samples.

Faunal samples were preserved in 4% formalin and stained with Bengal rose to facilitate sorting. Animals were separated into groups such as nematodes, copepods, ostracodes, isopods, amphipods, insects, mites, oligochaetes, cladocerans, and tardigrades. Nematodes, copepods, isopods and amphipods were determined to the species level wherever possible. Nematodes were mounted on slides after stepwise transfer to anhydrous glycerin (Seinhorst, 1962).

A WTW multi-parameter in-

	(1) Glanegg	**(2) Salzburg/ Freisaal**	**(3) Salzburg city**	**(4) Bergheim**	**(5) Freistadt**	**(6) Ebensee**	**(7) Goldeck**
Abiotic							
Temperature (°C)	6,7	12,5	9,2	8,0	8,5	10,4	7,8
Elec. Conductivity (µScm-1)	267,0	654,0	809,0	640,0	59,0	347,0	390,0
pH	8,2	7,4	7,4	7,8	6,8	7,7	8,4
O2 (mg/l)	7,0	1,5	4,9	2,2	n.m.	6,8	8,0
Total Hardness (°dH)	8,2	20,0	19,2	14,2	n.m.	10,6	9,8
Nitrate (mg/l)	0,0	5,0	0,0	0,0	n.m.	7,5	2,0
Magnesium (mg/l)	4,6	41,0	19,3	0,0	n.m.	27,3	16,5
Calcium (mg/l)	54,0	102,0	118,0	110,0	n.m.	48,5	43,2
Water table (m)	5,8	4,2	4,8	4,6	0,0	20	0,0
Biotic							
Absolut Individuals	24	12	129	171	0	15	45
% Crustaceans	67	75	82	76	0	27	0
% Nematodes	29	25	6	24	0	33	94
% Other	4	0	7	0	0	33	6
% Nauplii	0	0	5	0	0	7	0
Taxa number overall	8	10	9	34	0	6	13
Taxa number crustacean	5	8	3	21	0	2	0
Taxa number nematodes	2	2	4	13	0	2	10
Dominant nematode feeding type	Deposit	Deposit	Deposit	Suction		Deposit	Deposit

Table 4: Main abiotic and biotic parameters of the sampled groundwater

strument was used to measure the water temperature, pH values, electrical conductivity, and oxygen content. The main ion composition was attained using photometric and titrimetric methods from filtered water samples stored in 500ml PE-sampling vessels. Hydrochemical analyses were conducted at the latest one day after the sampling.

7.3 Results and discussion

Samples from test site 5 taken from a spring emerging in the street tunnel south of Freistadt were free of any biotic components. The reasons may be manifold and are not completely clear as yet. One possible explanation is the sudden increase of flow velocity as a result of the abruptly opened artificial flowpath, namely the tunnel itself, which drains the aquifer. Groundwater animals in the influenced aquifer region may be flushed out of the fractures into the drainage long before the samples were taken. Hence, samples from this test site 5 are not discussed further.

The ranges of the abiotic data are basically well within those common in groundwaters (table 4). However, some of them are worth mentioning. Conductivity was generally around 300 to 400 µScm^{-1}. Only at one site (3), a significantly higher value of 800 µScm^{-1} was recorded close to a former unrestored municipal waste land fill. Test site 7 showed particularly high conductivity values despite the crystalline environment. Generally, one would expect values around 100 µScm^{-1}.

The lowest oxygen content has been measured at test site 2 (1.5 mg/l), with values only slightly higher than the assumed minimal requirement (0.5-1 mg/l) for life underground (Hahn 2006). The test site is close to a pond outlet considered to be at least mesotrophic. The two sites adjacent to running waters (2 – quaternary porous and 4 – flysch zone) revealed partly similar (relatively low oxygen and medium conductivity, 600 µScm^{-1}) and partly different values (nitrate and magnesium). Detectable nitrate values were recorded for test site 2, the already mentioned alluvial aquifer and for the northern calcareous site, test site 6, close Lake Traunsee.

This study intended to provide a first insight into groundwater fauna from different geological units. Since free-living nematodes represent a rather unknown component of the groundwater fauna, these animals were of particular interest with respect to 1) their overall contribution to the groundwater fauna in relation to widely known groundwater crustaceans, and to 2) their general community composition comprising number of taxa, kind of taxa, feeding types, and the relation of adenophorea to secernentea. The nematode focus was considered as a completion to the hitherto crustacean focus in groundwater research. But finally, this study was also intended to improve interdisciplinary work between hydrogeology and groundwater biology.

Overall, crustaceans and nematodes dominated the fauna with 66 % and 27 %, respectively. Copepods were the most abundant crustaceans (54 % of the total fauna), isopods and ostracodes each comprised nearly 4 %, and amphipods 5 %. Nematodes clearly dominated the crystalline habitat (93 %), while crustaceans were completely missing there; nematodes and copepods made up about 50 % at two sites (2 – Freisaal and

6 – Ebensee). The remaining sites were dominated by copepods. 28 taxa were observed for both crustaceans and nematodes, the number of genera was higher among nematodes (18) compared to crustaceans (12). Two sites related to fractured aquifers (4 – Bergheim and 7 Goldeck) revealed the highest taxa numbers, the Flysch-Zone site (overall: 34) additionally revealed the highest taxa number for both nematodes (13) and crustaceans (21), 10 nematode taxa were recorded at the crystalline site (site 7) (overall: 13 taxa). Stygobiotic crustaceans were observed at sites 1, 2, 3 and 4, but all three types (stygobiont, stygophile and stygoxenes) were observed only at site 4.

Comparing our results with those of other studies is not a straightforward task since different techniques and methods have been applied in the various relevant groundwater studies. The number of crustacean taxa observed in our approach is in accordance with ranges of taxa number reported for example from the Lobau (Danielopol and Pospisil, 2001). The few taxa found with higher abundances such as Acanthocylops robustus, A. sensitivus Diacyclops languidoides (table 5 – supplementary data) but also the more rarely found isopod [Proasellus coxalis Proasselus cavaticus) and amphipod [Crangonyx subterraneus] taxa are basically widespread and commonly found throughout Austria but also Europe (e.g. Gaviria 1998; Danielopol and Pospisil, 2001; Fuchs et al., 2006; Kaiser, 2005; Hahn and Fuchs, 2009; Martin et al., 2009). Comprehensive aquifer studies including other nematode data than their total numbers or relative portions are to our present knowledge not existent, but abundances of total nematode fauna can be relatively high in both alluvial and fissured aquifer types compared to other faunal elements (Fuchs et al., 2006).

The nematode community structure (table 5 – supplementary data) was highly variable between the investigated sites – not only in terms of individual and taxa numbers, but also with regard to both the taxa found and the feeding types. All habitats only had one taxon in common, namely the genus Plectus. Common freshwater taxa such as Eumonhystera and Tobrilidae were found only at site 4, where the Tripyla filicaudata, which has often been related to subterraneous habitats, was also observed. The nematode community was exclusively composed of deposit feeders at sites 1 and 2. Carnivorous nematodes were found only at the fractured aquifers – Flysch, site 4 (22 %) and crystalline, site 7 (7 %). At the former, secernentean suction feeders were dominant with nearly 60 %. Interestingly, secernenteans were lacking at Glanegg (site 1) and Ebensee (site 6) (both sites have been characterized by a (compared to the other sites) deep water level, 5,80 m and 20 m below ground, respectively.

8. Conclusions and Outlook

Our results indicated fractured aquifers as a potential habitat for a diverse and abundant aquatic invertebrate fauna. One of these sites (4 – Flysch-Zone in Bergheim) revealed a surprisingly high absolute number of individuals and a high overall diversity, which might, most likely, be ascribed to the combined and presumably varying influence of three different habitats there: the forested soil, the near-by river, and the groundwater itself. The presence of stygobiotic, stygophile and stygoxene crustaceans, as well as a diverse nematode fauna with its specific characteristics (mainly terrestrial, root sucking form) presents a rather good support to this assumption. In contrast, the second fractured site (7 – crystalline in Goldeck) was distinctly characterised by both a predominant genus Plectus, which is often ascribed to cold habitats (Procter, 1984) and a lacking crustacean fauna. Both aspects are interesting and might reflect certain characters of the respective habitat: north-facing forested slope, relatively high flow through concurrently (assumed) finer voids. In particular the latter might be indicated by the non-existent crustacean fauna.

This study has additionally shown that nematodes represent a common and partly abundant and diverse group among the groundwater fauna in general and in particular in fractured aquifers. Dominant feeding types, such as deposit feeders and predacious nematodes, play a role in the transfer of energy and matter and thus are most likely of importance to the function of their groundwater habitats. The observed variable portion of feeding types point not only to the variable function of nematodes within the system, it might also be an indication as to the variability of the functionality of the system itself. Interestingly, sites presumed to be subjected to certain anthropogenic stressors (adjacent organically influenced running waters, municipal waste) were dominated by copepods. Nevertheless, additional samples from a broader variety of different groundwater sites together with their closer surroundings should help to refine nematode and crustacean classifications with respect to their indicative value for the heterogeneous underground landscape in Austria.

This preliminary approach on the implementation of nematodes into the evaluation of underground faunal patterns can be seen as a promising starting point for further, in fact urgently required, comprehensive studies of Austrian aquifers. Such investigations should comprise crustaceans and nematodes and samples not only from the groundwater, but also from their terrestrial and aquatic surroundings to obtain clues for the habitats' abiotic structure and their potential connectivity. Overall, information derived from the combination and/or the lack of certain crustacean and nematode taxa is considered useful and a good reflection of the complex groundwater regimes. From the biological perspective, a comprehensive survey of the different aquifer environments and their surroundings would not only represent a "reopening" of a formerly decades-long area in Austrian groundwater research, but also an enormous contribution to Austria's biodiversity and biogeography knowledge currently lacking data regarding the aquatic subterraneous fauna.

From the hydrogeological point of view, knowledge about groundwater fauna and the factors controlling animal assemblages in aquifers can be extremely useful to understanding aquifer conditions and flow dynamics and thus enhance the hydrogeological toolbox.

This was already corroborated for alluvial aquifers in Austria based on the comprehensive research undertaken in the Danube floodplain area around Vienna (see for example Danielopol and Pospisil, 2001; Griebler and Mösslacher, 2003). The now presented approach gives reason for similar expectations targeting fractured aquifers. However, both the fauna and the habitat conditions of fractured aquifers represent still widely unknown Austrian groundwater elements. Due to this, it is evident, as already mentioned in the biological context, that 1) more comprehensive data are required before usage of fauna for the characterization of fractured aquifers, and that 2) such data will clearly benefit from the integration of smaller faunal elements such as nematodes. Nematodes are rather unknown for any type of groundwater habitat in Austria, yet representing a group with the potential providing additional information on respective habitat conditions.

Because minor progress of the groundwater biota research has taken place in Austria since the early 2000s, future planning for Austrian groundwater studies in such a context has widely to rely on studies continuously made by international groundwater research groups since then. Their efforts comprise various different aspects ranging from evaluation of sampling methods, biota for monitoring and description of ecosystem health, as well as establishing classifications schemes addressing different scales (e.g. Hahn, 2006, 2009; Cornu and Eme (2013); Korbel and Hose, 2011; Stein et al., 2010, 2012). Most of these efforts keep alive discussions of the "usefulness" of groundwater organisms per se (ecosystem services, functions see for example Griebler and Avramov, 2015) and, derived thereof, discussions of the usefulness of the groundwater biota as legislative monitoring tool additional to hydrochemical parameters. The so far exclusive hydrochemical monitoring is considered insufficient to depict complex environmental conditions and, more important, ecologically intact and thus healthy groundwater systems. Their status should optimally additionally characterized by measures of the groundwater biota.

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