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Impact of extreme hydrological events on the quantity and quality of groundwater in alpine regions – multiple-index application for an integrative hydrogeo-ecological assessment

Final project report

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Abstract

Freshwater ecosystems in mountain areas are considered important water resources and biodiversity hotspots that are highly sensitive to changes in climate. The Alpine region is known to be particularly affected by climate change, including changes in hydrological extremes such as droughts and floods, which are expected to become more frequent and intense. Despite the importance of groundwater as a primary water resource, climate change impacts on groundwater quality, including those resulting from hydrological extremes, have been rarely addressed to date. Moreover, groundwater monitoring is currently focused on physical-chemical indicators, whereas groundwater ecological features such as biodiversity and ecosystem functioning are hardly considered. Against this background, this project addressed the following overarching research question: How do groundwater systems in an alpine and prealpine environment respond to extreme hydrological events in terms of water quantity and chemical quality as well as ecological status? To address this question, the valley of the river Mur from its alpine source area at 2000 m a.s.l. to the Austrian–Slovenian border at 200 m a.s.l. was considered. Thus, the investigation area included alpine and prealpine areas, different type of hydrogeological settings and different human impacts. Existing long-term data was complemented by high-resolution monitoring over time and sampling campaigns addressing wastewater-borne micro-pollutants, microbiological parameters, and groundwater fauna. Our results demonstrate a deterioration of water quality from the alpine source area towards the foreland, corresponding to the more intense agricultural and urban land use in the foreland. The vulnerability of groundwater systems to hydrological extremes is closely related to linkages between water quantity and water quality, which are found to be determined by the groundwater recharge mechanisms and their spatiotemporal dynamics. To achieve a more holistic assessment of groundwater systems, we recommend that their ecosystem nature is taken into account by microbiological indicators that complement existing hydrological and hydrochemical indices. The B-A-(E) index is proposed for this purpose but needs further development by transciplinary research involving local experts and stakeholders to define appropriate reference conditions that enable classifications into meaningful water-quality categories.

Kurzfassung

Süßwasserökosysteme in Gebirgsregionen gelten als wichtige Wasserressourcen und Hotspots der biologischen Vielfalt, die sehr empfindlich auf Klimaveränderungen reagieren. Es ist bekannt, dass der Alpenraum besonders vom Klimawandel betroffen ist. Dies umfasst auch Veränderungen bei hydrologischen Extremen wie Dürren und Überschwemmungen, die voraussichtlich häufiger und intensiver werden. Trotz der Bedeutung des Grundwassers als primäre Wasserressource wurden die Auswirkungen des Klimawandels und hydrologischer Extremereignisse auf die Grundwasserqualität bisher kaum untersucht. Darüber hinaus konzentriert sich Grundwasser-Monitoring derzeit auf physikalisch-chemische Indikatoren, während ökologische Merkmale des Grundwassers wie die Biodiversität und die Funktionalität von Ökosystemen kaum berücksichtigt werden. Vor diesem Hintergrund widmete sich dieses Projekt der folgenden übergreifenden Forschungsfrage: Wie reagieren Grundwassersysteme in einer alpinen und voralpinen Umgebung auf extreme hydrologische Ereignisse in Bezug auf die Wassermenge, die chemische Qualität und den ökologischen Zustand? Zur Beantwortung dieser Frage wurde das Tal der Mur von ihrem alpinen Quellgebiet auf 2000 m ü.A. bis zur österreichisch-slowenischen Grenze auf 200 m ü.A. betrachtet. Das Untersuchungsgebiet umfasste somit alpine und voralpine Gebiete, unterschiedliche hydrogeologische Gegebenheiten und verschiedene menschliche Einflüsse. Vorhandene Langzeitdaten wurden durch ein zeitlich hochauflösendes Monitoring und durch Probenahmekampagnen ergänzt, die sich mit abwasserbürtigen Spurenschadstoffen, mikrobiologischen Parametern und der Grundwasserfauna befassten. Unsere Ergebnisse zeigen im Zusammenhang mit der zunehmend intensiveren landwirtschaftlichen und städtischen Nutzung eine Verschlechterung der Wasserqualität vom alpinen Quellgebiet in Richtung Vorland. Die Vulnerabilität von Grundwassersystemen gegenüber hydrologischen Extremen steht in engem Zusammenhang mit Beziehungen zwischen Wassermenge und Wasserqualität, die durch die Grundwasserneubildungsprozesse und deren räumlich-zeitliche Dynamik bestimmt werden. Um eine ganzheitlichere Bewertung von Grundwassersystemen zu erreichen, empfehlen wir, deren Ökosystemcharakter durch mikrobiologische Indikatoren zu berücksichtigen, die die bestehenden hydrologischen und hydrochemischen Indizes ergänzen. Der B-A-(E)-Index wird zu diesem Zweck vorgeschlagen, muss jedoch durch transdisziplinäre Forschung unter Einbeziehung lokaler Experten und Interessengruppen weiterentwickelt werden, um geeignete Referenzbedingungen zu definieren, die eine Einteilung in sinnvolle Wasserqualitätskategorien ermöglichen.

Introduction

Groundwater represents the primary water resource for more than 1.5 billion people worldwide (Clarke et al. 1996). In Austria, groundwater (including springs, i.e. natural outflows of groundwater) provides nearly the entire drinking water (Brandstetter et al. 2007). As part of the hydrological cycle groundwater is also important in sustaining streams, lakes, and wetlands (e.g., Alley et al. 2002, Kløve et al. 2014). Climate change is expected to alter the hydrological cycle and thus also the amount and timing of groundwater recharge, storage, and discharge. Within the Alpine region, precipitation is expected to decrease in summer, particularly in the southern region, and to increase in winter; in addition, climate projections indicate more intense precipitation extremes (Gobiet et al. 2014). As a consequence, more frequent flooding but also more severe droughts appear likely. Assessing the impact of climate change on groundwater resources thus requires a sound understanding of the effects of extreme events on the quantity and quality of groundwater.

A holistic assessment of the vulnerability of groundwater systems to impacts of extreme events needs to account for interactions of multiple drivers and receptors. These include, on the one hand, various hydrometeorological, hydrogeological and hydrogeochemical variables and parameters, such as the spatio-temporal characteristics of the extreme event and the hydraulic and geochemical properties of soils and aquifers, and on the other hand, the ecosystem nature of aquifers providing essential services but facing acute and chronic anthropogenic impacts, such as land use and water management practices. Thus, there is a need for comprehensive event-based monitoring and evaluation of groundwater systems in terms of water quantity, quality and ecological status. For this purpose, the use of indicators is often recommended, particularly to bridge the gap between scientific investigations and the needs of policy makers (Kløve et al. 2014). Yet, it remains an open question, which indicators are best suited for assessing the vulnerability of groundwater systems to hydrological extreme events. To answer this question the purpose of the assessment, i.e. the specific policy and research questions to be addressed, need to be well defined (Hinkel 2011). Thus, the development of indicators and monitoring strategies for groundwater vulnerability assessments requires collaboration between scientist and stakeholders in the field of water resources.

Objective and aims

Against the background outlined above, this project addressed the following overarching research question:

How do groundwater systems in an alpine and prealpine environment respond to extreme hydrological events such as droughts, heavy rain and floods in terms of water quantity and chemical quality as well as ecological status?

Answers to this question need to account for the spatially and temporally changing interaction of groundwater with other components of the hydrological cycle (e.g., precipitation, surface water) and the interrelations between hydrological, hydrochemical and ecological processes. Characterizing these interconnected processes and how they control the responses of groundwater systems to extreme events requires the identification of indicators that are sensitive to short-term effects and long-term trends resulting from extreme events.

To address this research question, field sites within the valley of the river Mur from its alpine source area at 2000 m a.s.l. to the Austrian–Slovenian border at 200 m a.s.l. were considered. Thus, the investigation area included alpine and prealpine areas, different types of hydrogeological setting and different human impacts. Hydrological time series covering several decades were available from the state hydrographic service. In addition, groundwater quality data including, e.g., concentrations of major ions and selected contaminants, was available from the Austrian groundwater quality monitoring network operated since 1991. Within this project, the existing long-term data was complemented by high-resolution monitoring over time and by water-quality parameters that are not measured in the existing monitoring programs, such as wastewater-borne micro-pollutants, microbiological parameters, and groundwater fauna.

The project specifically aimed to

- Characterize the groundwater hydrological, hydrochemical and ecological status, short-term responses to hydrometeorological extremes and long-term trends in hydrological and hydrochemical conditions from the Alpine region to the foreland as well as within the different types of hydrogeological settings and related to human impacts.
- Characterize correlations between hydrological, hydrochemical and ecological trends and responses, disentangle the effects of different drivers and identify causal relationships between water quantity and quality parameters.
- Identify indicators that can be used for evaluating and monitoring the effects of hydrometeorological extremes on groundwater quantity and quality, taking into account the needs of both scientific and non-scientific actors in the field of water resources and environment.

Achieving these goals was only possible by a transdisciplinary process involving non-university experts and stakeholders. In particular, the evaluation of the existing monitoring data and the selection of sampling points suitable for different types of sampling (water, fauna) and analyses (e.g., chemical, microbiological) required knowledge about the local conditions at the different sites within the investigation area. Thus, the experts involved in the existing water-quantity and water-quality monitoring of the provincial authorities (Province of Styria, Province of Salzburg) and the Environment Agency Austria were closely integrated into the project work. In addition, two stakeholder workshops were held and an advisory board was established, which included stakeholders from the water resources and agriculture sectors and provided more general advice and feedback with regard to the project activities and results.

The following three sections provide an overview and examples of the results obtained with regard to the aims described above. Subsequently, experiences from the transdisciplinary process and the collaboration within the 'ESS groundwater cluster', which brought together four projects addressing soil water and groundwater, are described. Finally, key findings and main recommendations are briefly summarized. At the end of the report a list of dissemination and transdisciplinary activities is provided.

Groundwater hydrological, hydrochemical and ecological status

Sampling points in streams, springs and observation wells of the existing monitoring net were assessed for their suitability for the additional sampling and measurement activities conducted in this project in close collaboration with the experts from the provincial authorities (Province of Styria, Province of Salzburg) and the Environment Agency Austria. In total, 87 sampling points were selected within the Austrian part of the Mur valley, stretching from the river's alpine origin to the national border in the foreland (Fig 1). Two comprehensive sampling campaigns were conducted in summer and fall 2020. Subsequently, the monitoring was continued at selected locations (see also following subsection).

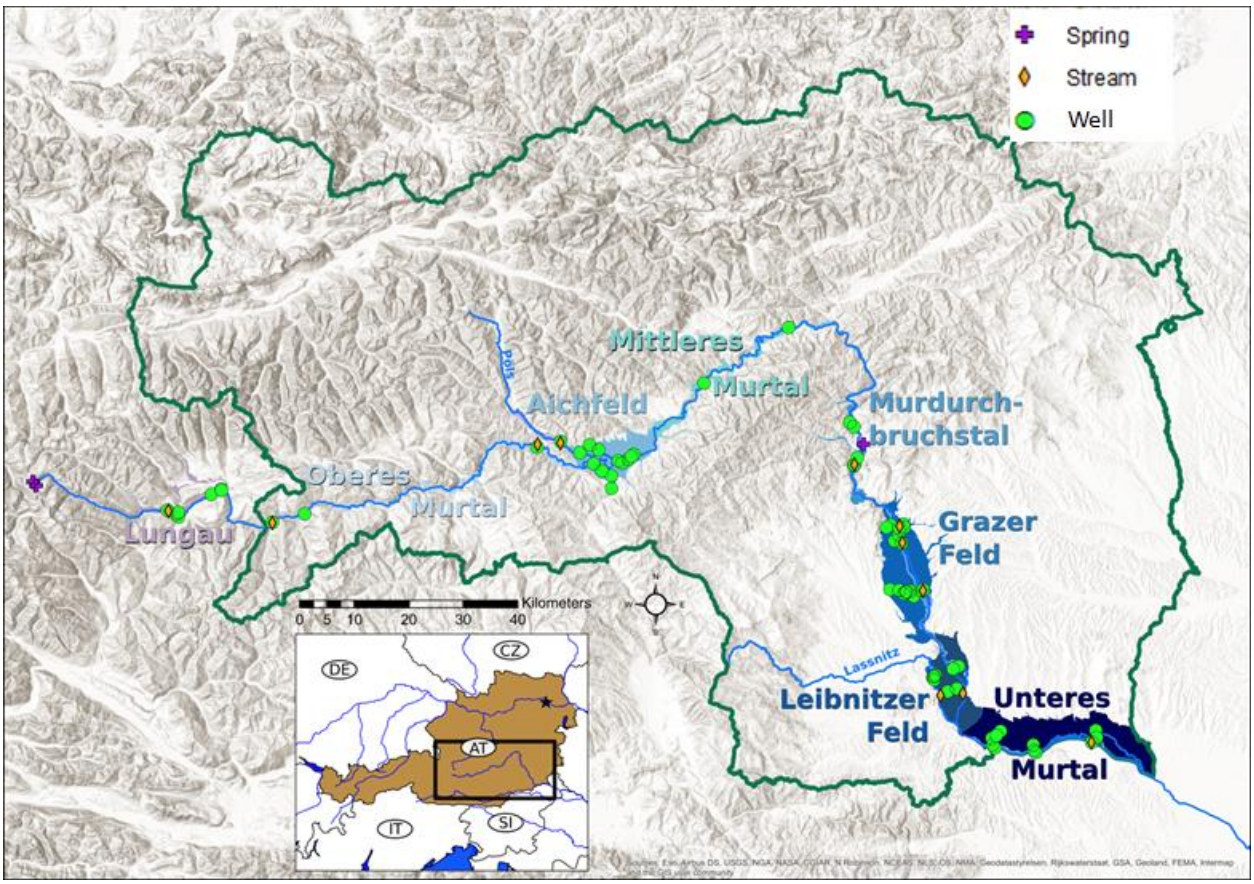

Figure 1: Selected sampling points of the existing state hydrographic monitoring net within the Mur river basin from the alpine origin to the national border in the foreland. An overview of the hydrogeological characteristics of the individual groundwater bodies is provided by Brielmann et al. (in prep.).

As can be seen in Fig. 2, the groundwater levels in the selected observation wells display fluctuations ranging from less than 1 m to approximately 4 m within a 20-year time period. The groundwater body of the Grazer Feld aquifer, situated in the alpine foreland, displays this full range of fluctuations, though the majority of observation wells exhibits fluctuations between approximately 2 and 3 m. The other two groundwater bodies in the foreland behave in a similar way. The alpine aquifers comprise groundwater bodies exhibiting large fluctuations (Mittleres Murtal), low variability (Lungau), or diverse pattern of fluctuations (Aichfeld).

With regard to the fluctuations of the groundwater levels, it is noteworthy that the thickness of the Quarternary sand and gravel deposits composing the aquifers within the Mur valley tends to decrease towards the south. Thus, the groundwater thickness in the foreland aquifers Leibnitzer Feld and Unteres Murtal is much lower (generally well below 10 m, in some parts less than 2 m) than that in the alpine aquifers of the Mur valley. This suggests that the groundwater quantity in the southern foreland aquifers is more vulnerable to drought than that of the aquifers in the northern part of the Mur valley. Analyses of groundwater drought indices support this assessment (Haas and Birk, 2017; Birk and Haas, 2018).

Similar to Haas and Birk (2017, 2018), correlations between groundwater levels and stream stages in the investigation area were calculated and visualized as correlation matrix (Fig. 3). The groundwater levels of many observation wells are highly correlated with each other, sometimes even between different groundwater bodies. This is particularly evident for some observation wells in the upper part of the Mur valley from Lungau to Mittleres Murtal and partly even further downstream. Observation wells close to a stream often display high correlation of the groundwater levels with stream stages. In particular, the river Mur is an important driver of groundwater level fluctuations and thus propagates the effect of hydrological anomalies, such as droughts or floods, from the upper Mur valley to the groundwater bodies downstream. Yet, the effect of stream stages on groundwater levels diminishes with increasing distance of the observation wells from the surface water. Towards the southern part of the foreland, the groundwater levels generally appear to be less correlated with stream stages and more strongly controlled by precipitation (see also Haas and Birk, 2017).

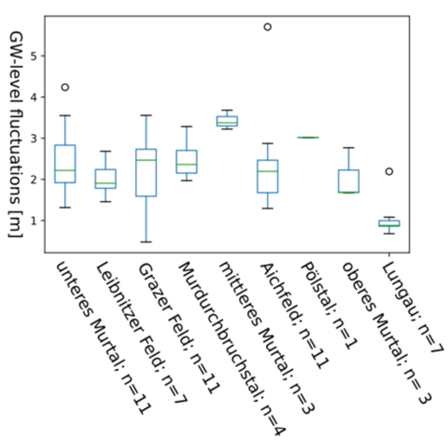

Figure 2: Range of groundwater level (GW-level) fluctuations in the selected observation wells in the time period from 2000 to 2020.

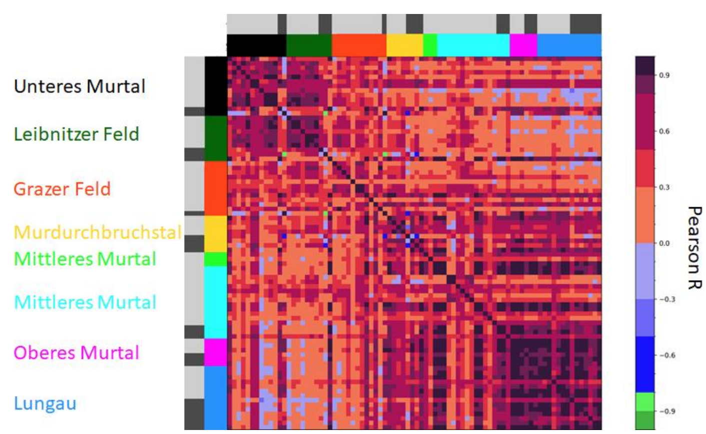

Figure 3: Correlations between groundwater levels (light grey) and stream stages (dark grey) within the Mur valley.

The hydraulic interaction between groundwater and surface water, illustrated by the above-mentioned correlations between groundwater levels and stream stages (Fig. 3), is not in itself an indication of indirect groundwater recharge through the infiltration of surface waters. Increasing stream stages reduce the hydraulic gradient and thus groundwater discharge to a receiving stream. This results in an increase of storage, manifested by an increase in groundwater levels, i.e. the groundwater levels correlate with the stream stages. Yet, only a reversal of the hydraulic gradient, i.e., stream stages that locally exceed groundwater levels, result in the infiltration of surface water into the aquifer. To identify potential contributions of surface water to groundwater recharge, environmental tracers were employed in this project, in particular, wastewater indicators and the stable isotopes of water.

Micro-pollutants from municipal wastewater may enter groundwater through infiltration of surface waters into which treated wastewater has been released. Thus, observation wells that show wastewater impacts are suspected to receive indirect recharge from surface waters. As illustrated by Fig. 4, wastewater indicators were found in some observation wells close to the river in the alpine parts of the Mur valley. In the prealpine foreland, the impact of wastewater is most evident in the northern parts of both the Grazer Feld and the Leibnitzer Feld. In contrast, none of the observation wells in the groundwater body Unteres Murtal, even if close to the river Mur, shows wastewater impacts. A report by the Environmental Agency Austria, which is currently revised for publication (Brielmann et al., in prep.), provides a detailed description and interpretation of the results obtained for each of the investigated groundwater bodies and the individual indicator compounds.

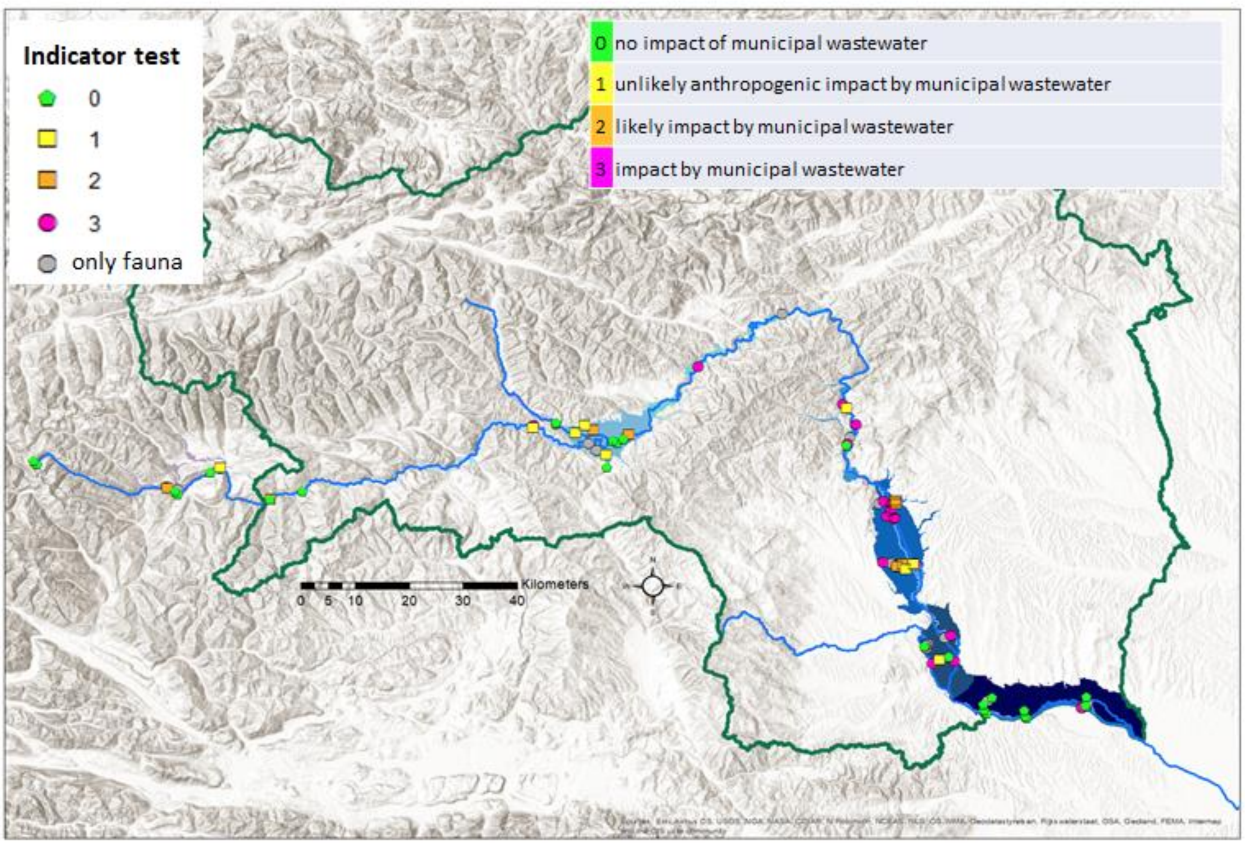

Figure 4: Results of an indicator test for municipal contamination of groundwater and surface water based on eight lead compounds (for details see Brielmann et al., in prep.).

The stable isotopes of water also provide information about the contribution of surface water to groundwater, as the stable-isotope signature of the surface water generally deviates from that of the local recharge from precipitation. The general pattern obtained from the analyses of the stable isotopes of water agrees well with that from the wastewater indicators, but on the level of individual observation wells the interpretation can be ambiguous, for instance, because in the urban area wastewater micro-pollutants detected in groundwater may originate from sewer leakage instead of (or in addition to) surface waters.

As the interpretation of individual environmental tracers may be ambiguous, a more comprehensive approach combines multiple environmental parameters to characterize the status of the different water bodies (Retter et al., 2023). Based on principle component analysis (PCA) one can see that the basic hydrochemical and microbiological characteristics of the surface waters (river Mur and its two tributaries Pöls and Lassnitz) can be clearly distinguished from the groundwater (Fig. 5, left chart). In general, the river has significantly less nitrate, a lower electrical conductivity, and a lower water temperature (p adj. < 0.05). On the other hand, the river water contained higher dissolved organic carbon (DOC) and dissolved oxygen (DO) concentrations and is characterized by a higher pH and higher microbial productivity (in terms of cellular ATP and cell count) (p adj. < 0.05). In contrast, a clear distinction of the eight groundwater bodies is not possible based on the groundwater samples (Fig. 5, right chart). Nevertheless, individual features of some groundwater bodies are striking. The highest microbial productivity is found in the groundwater body Unteres Murtal (UM) and high DO in the Grazer Feld (GF) and Aichfeld (AF) areas. AF also delivered groundwater with slightly alkaline pH values. Moreover, individual groundwater samples, for example from the Mur wetlands in UM (right chart in Fig. 5: four samples in the lower right of the red ellipse), which were characterized by reducing conditions, deviate.

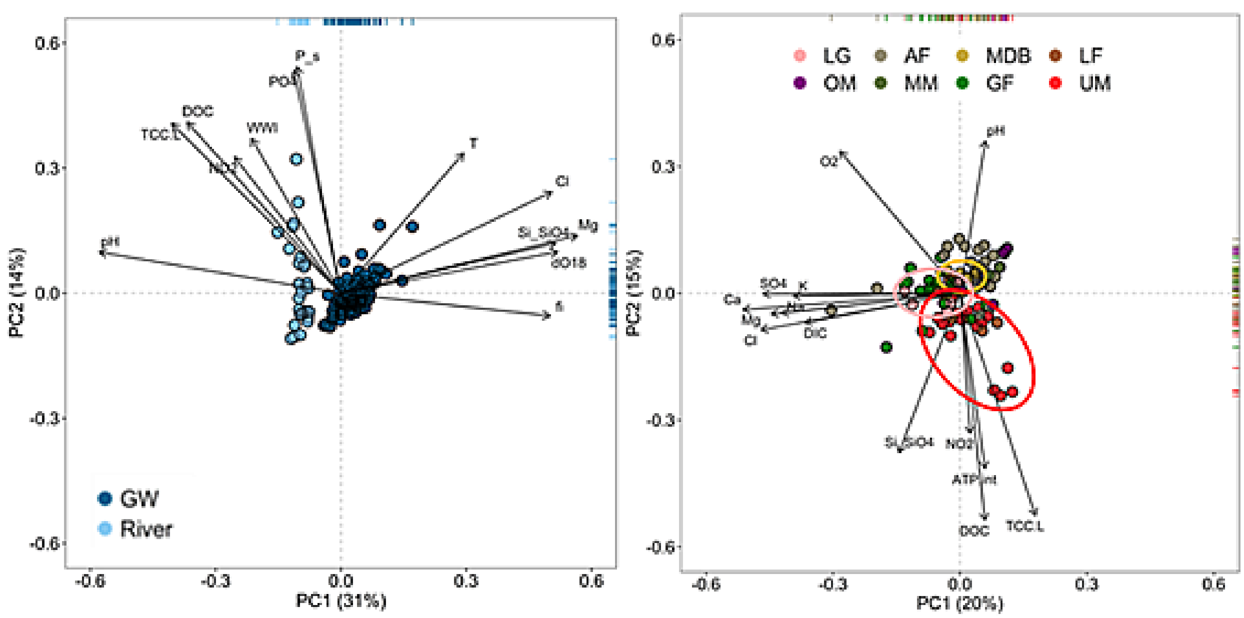

Figure 5: Principal component analysis (PCA) based on selected environmental parameters clearly separates groundwater and river water samples (left chart). Groundwater samples colored to their origin in terms of sub-regions (right chart). TCC: total cell counts; ATP: cellular adenosine triphosphate; DOC: dissolved organic carbon; T: water temperature; DO: dissolved oxygen; EC: electrical conductivity; ^{18}O: stable ^{18}O isotope signature in water; NO_2^-: nitrite; PO_4^{3-}: orthophosphate; Na^+: sodium; K^+: potassium; Ca^{2+}: calcium; Mg^{2+}: magnesium; Cl^-: chloride; SO_4^{2-}: sulfate; soluble P: soluble phosphorus; total P: total phosphorus; SiO_4: silicate; DIC: dissolved inorganic carbon. LG: Lungau; OM: Oberes Murtal; AF: Aichfeld; MM: Mittleres Murtal; MDB: Murdurchbruchstal; GF: Grazer Feld; LF: Leibnitzer Feld; UM: Unteres Murtal (Retter et al., 2023).

Following the river Mur from the source to the Austrian border, a trend of increasing water temperature (as expected, following the decreasing altitude), nitrate concentrations, and DOC concentrations is observed (Fig. 6). The trends were much less developed in the river Mur when compared to the shallow aquifers. The increasing trend in nitrate, a groundwater contaminant mainly originating from the application of fertilizers in agriculture, is attributed to increasing agricultural activities and urbanization (with potential wastewater impact) from the narrow mountain valley to the broader valleys and basins of the lowland. The aforementioned low concentrations in dissolved oxygen in groundwater samples from UM are attributed to the specific setting within wetlands, where reducing conditions prevail. Also, water stable isotope data and the absence of wastewater indicators (see Fig. 4) underlines a restricted exchange between the river and the wetland aquifer in this region. DOC is negatively correlated with DO; highest median values are found under forest, lowest under pasture (Retter et al. 2023). Thus, besides the hydrogeological setting (e.g., controlling stream-aquifer interaction), the land use is an important control on the hydrochemical status of the groundwater and its trends along the Mur valley.

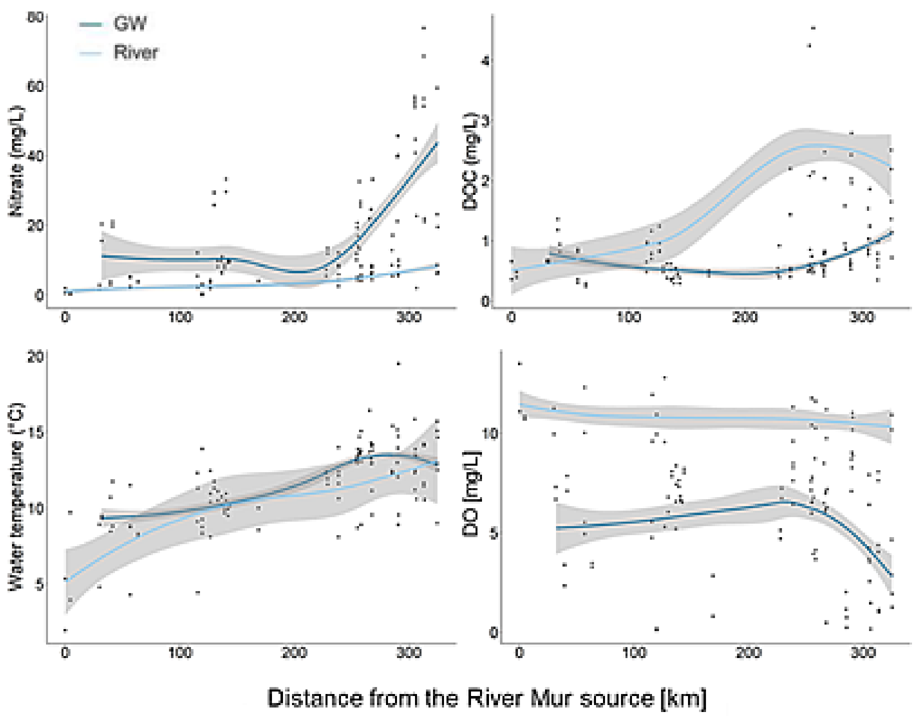

Figure 6: Nitrate, DOC, and DO concentrations, and water temperature of groundwater (GW) and surface-water samples (each sampling site represented by an early summer and late autumn value) plotted against the distance to the source of the river Mur. Blue lines represent the moving average. Grey shading indicates the 95% confidence intervals (Retter et al., 2023).

Microbial community composition, the dynamics of shallow groundwater ecosystems and their potential impact on ecosystem processes and functioning are closely related to groundwater quality. In comparison to surface water ecosystems, microbial biodiversity and its mediated functions are hardly investigated (Karwautz et al. 2022). To characterize the ecological status of the groundwater bodies in the Mur valley, the groundwater microbiome was analyzed regarding its composition, related to the different land use types, and difference to the river (Retter et al., 2023). Community composition and species turnover differed significantly. At high altitudes, dispersal limitation was the main driver of groundwater community assembly, whereas in the lowland, homogeneous selection explained the larger share. Land use was a key determinant of the groundwater microbiome composition. The alpine region was more diverse and richer in prokaryotic taxa (Fig. 7), with some early diverging archaeal lineages being highly abundant. Our dataset shows a longitudinal change in prokaryotic communities that is dependent on regional differences affected by geomorphology and land use.

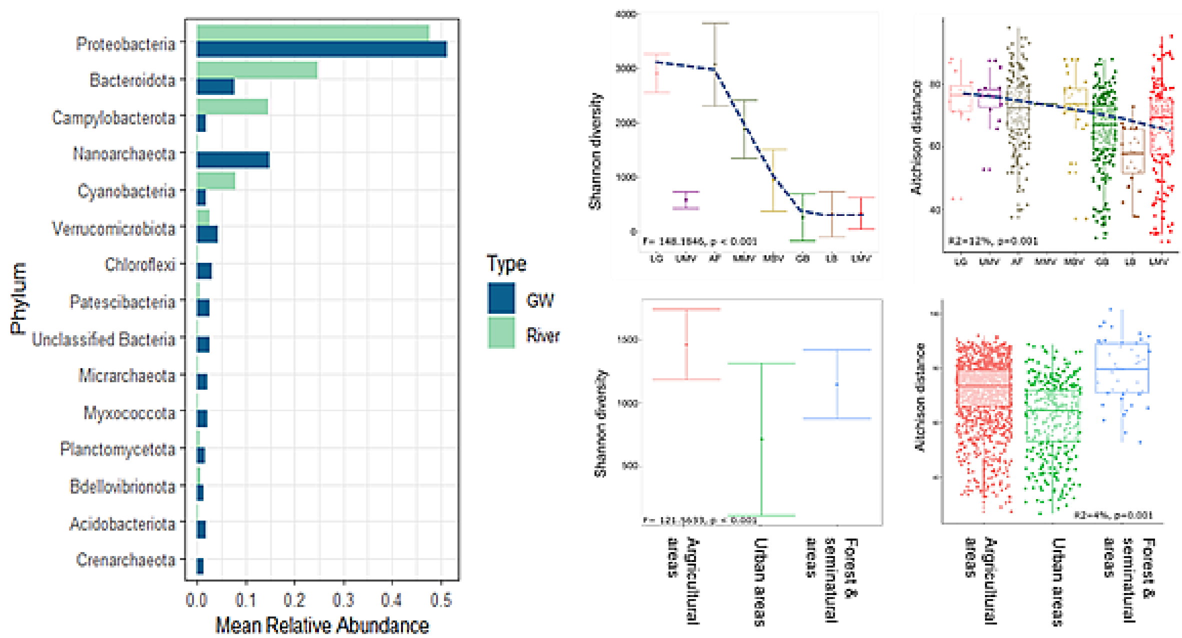

Figure 7: Prokaryotic biodiversity of the active (RNA-based) community in shallow groundwater of the River Mur valley. The charts depict the overall composition of bacteria and archaea communities (left), as well as the spatial change of α-diversity and β-diversity along the river valley and related to different land use. For more information see Retter et al. (2023).

While prokaryotic communities in groundwater, i.e., Bacteria and Archaea, received some attention in the recent past (Griebler and Lueders 2009; Karwautz et al. 2022), fungal communities in groundwater are hardly studied. Fungi are a diverse group of heterotrophic eukaryotic organisms that can be found in a variety of environments. They include molds, mushrooms, and yeasts, as well as many other types of fungi that do not produce visible fruiting bodies. To our current knowledge, the occurrence and diversity of fungi in groundwater is limited (Grossart et al., 2019; Retter and Nawaz, 2022). In this project, we found that various fungal groups were of significant difference in abundance between the surface water and groundwater (Fig. 8). Fungal phyla such as Chytridiomycetes, and basidiomycetes for example were clearly more abundant in the river, whereas Mortierellomycetes, Ascomycetes, and Rozellomycetes showed a higher relative abundance in groundwater. In fact, Olpidiomycetes only occurred in groundwater. In all cases, fungal community composition in the river was richer and more diverse.

The groundwater was mostly inhabited by three different fungal phyla, of which the most abundant one was Ascomycota (46.1%). In this phylum, the most abundant classes were Dothideomycetes (20.7%), and Sordariomycetes (12.6%), where by far the most abundant taxon was a *Cladosporium* species (24% of all ascomycete OTUs) which also represented the core taxon in groundwater. The second most abundant phylum comprised of fungi belonging to Basidiomycota (16.3%) of which members of the classes Tremellomycetes (6.9%) and Agaricomycetes (3.1%), and the genus Filobasidium (4.5% of all basidiomycete OTUs) were most abundant. The third most abundant phylum was Mortierellomycota (15.3%), with fungal members belonging to the genus *Mortierella* predominantly making up this phylum (98% of all mortierellomycete OTUs). Fungal diversity changed over the course of the Mur valley and was highest at lower altitudes and beneath forest and semi-natural areas, which were coinciding with sites at lower elevations. Differences between sub-regions and hydrological conditions seemed to be the most important drivers for fungal community composition we could identify in this groundwater dataset.

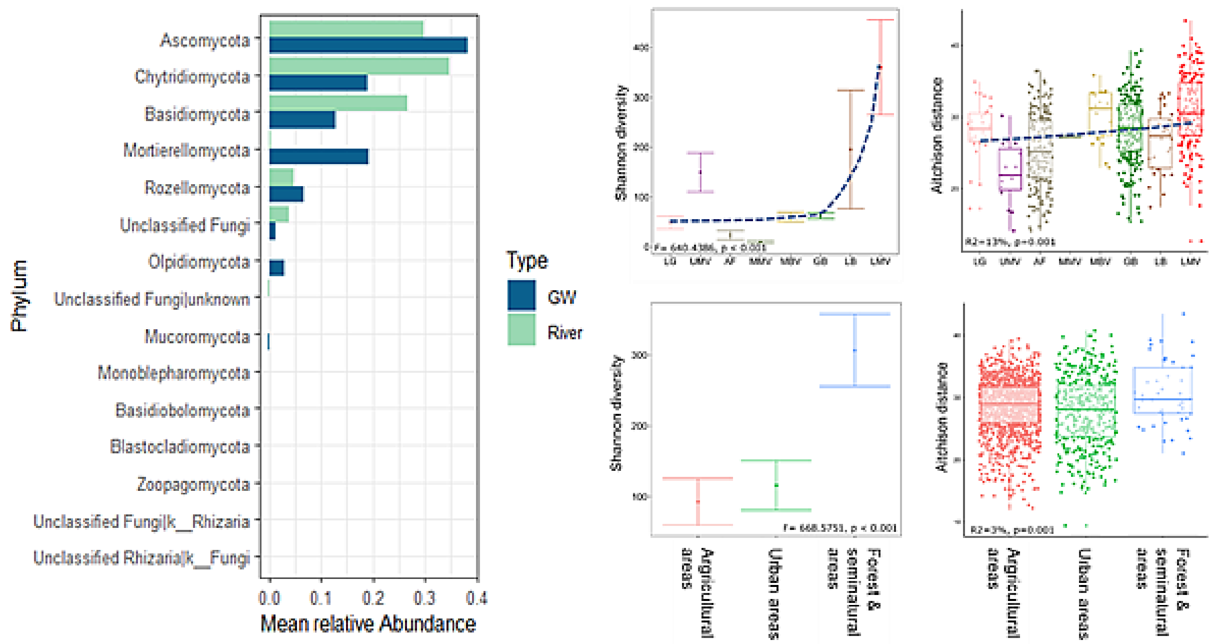

Figure 8: Fungal biodiversity of the total (DNA-based) community in shallow groundwater of the River Mur valley. The charts depict the overall composition of fungi communities (left), as well as the spatial change of α-diversity and β-diversity along the river valley and related to different land use (Retter et al., in prep.).

Similar to the overall fungal diversity in groundwater, it is not understood which route most fungi take that are found in groundwater but do not originate from there. Possible sources are river water and soils, and transport triggers are precipitation, snowmelt or flooding events. Such hydrological events can potentially also alter the water chemistry, nutrient availability, and redox conditions. However, fungi are likely transported also from groundwater into surface waters. Temporal dynamics of fungi in groundwater were investigated at three selected sites (Retter et al., in prep.). In general, the input of fungal communities from soils and the river into the groundwater varied greatly in its temporal and quantitative characteristics. The groundwater at the site in the alpine region seemed to receive a large proportion of operational taxonomic units (OTUs) derived from soil (21% on average), with a proportion of up to 47% in March 2021, but only a small proportion of OTUs stemming from the river (2% on average). The fungal communities at the farmland site seemed to be influenced by the river as well as the soil, with a river share of river derived OTUs of up to 11% in December 2021. The groundwater at the floodplain site was hardly influenced by fungal communities originating from the soil or the river, although the observation well is located only a dozen meters away from the river Mur. This agrees well with other observations at this site, such as the absence of wastewater indicators in the groundwater samples, indicating that the groundwater is not recharged by the river.

Up-to-now, hardly any data was available for groundwater fauna in the alpine and pre-alpine regions of Austria. Thus, this project is the first to shed light on the diversity of groundwater fauna in such settings. The assessment of groundwater fauna of the Mur valley revealed a high biodiversity. Overall, we found a negative relationship between the number of major animal groups and the depth of the water table. Moreover, with an increase of altitude the abundance and richness of groundwater fauna decreased. In consequence, a positive relationship between fauna richness and groundwater temperature was found. However, as found for the Leibnitzer Feld, areas characterized by intensive agricultural activities showed a reduced number in major taxonomic groups (Fig. 9).

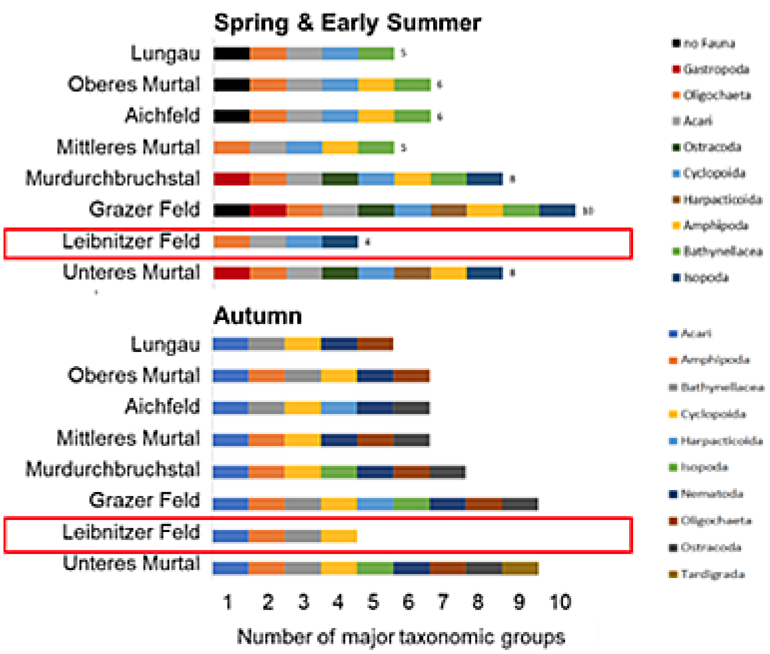

Figure 9: Results from the sampling of groundwater fauna in spring/early summer 2020 and autumn 2020.

Interrelations between water quantity and quality parameters

Responses of groundwater quantity (e.g., groundwater levels) to hydrological extreme events are determined by the interplay between hydrometeorological/hydroclimatological conditions and the characteristics of the hydrogeological setting, both of which change along the river valley in its transition from the alpine source to the prealpine foreland. In addition, direct human impacts, such as groundwater abstraction and hydraulic engineering measures, may strongly affect the groundwater dynamics, particularly in urban areas. This has been illustrated by examples from the groundwater body Grazer Feld, where effects of groundwater pumping and the construction of a hydropower plant were identified in time series of groundwater levels (Kokimava et al., in prep.).

Groundwater quality is found to be governed by an even more complex interplay of various drivers related to both water quantity (and its controls as outlined above) and other environmental conditions, in particular, anthropogenic activities and land use. This can be illustrated by the aforementioned impacts of municipal wastewater on the groundwater bodies within the Mur valley (section 'Groundwater hydrological, hydrochemical, and ecological status'; Fig. 4). Based on the concentrations of wastewater indicators found in surface water and groundwater samples, estimates of average wastewater contributions were obtained (see Brielmann et al., in prep.). Fig. 10 shows for the example of the sampling campaign in summer 2020, how the estimated wastewater contribution in surface waters changed along the river valley. One can clearly see that the anthropogenic impact on the water quality of surface waters increases with increasing distance from the river source area. In contrast, the estimated wastewater contribution to groundwater reveals a more complex pattern (Fig. 11). The presence of wastewater in surface waters creates a potential source for wastewater inputs to groundwater. However, whether or not groundwater is affected by wastewater impacts depends on other factors too, in particular (but not only – note the potential impact of sewer leakage), on the existence of indirect recharge through the infiltration of surface water, which in turn is dependent on the hydrogeological setting, but also influenced by human intervention (e.g. groundwater abstraction lowering groundwater levels relative to stream stages) and the occurrence of extreme events (e.g., floods temporarily rising stream stages relative to groundwater levels). As a result, some groundwater samples in the southern parts of the Grazer Feld and Leibnitzer Feld and most obviously in the groundwater body Unteres Murtal are devoid of wastewater indicators, although wastewater contributions to the surface water are evident in these areas (compare Figs. 10 and 11).

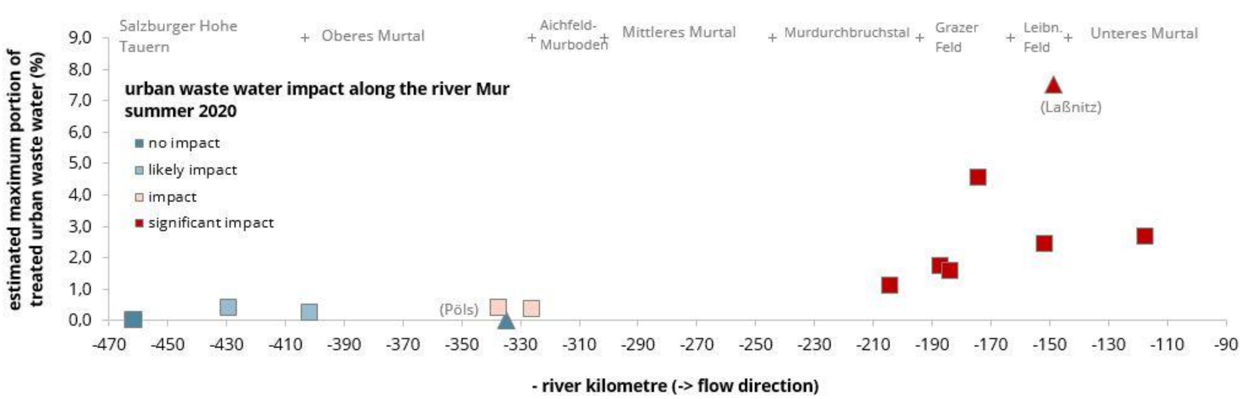

Figure 10: Estimates of the wastewater contributions in surface waters resulting from the spring 2020 sampling campaign.

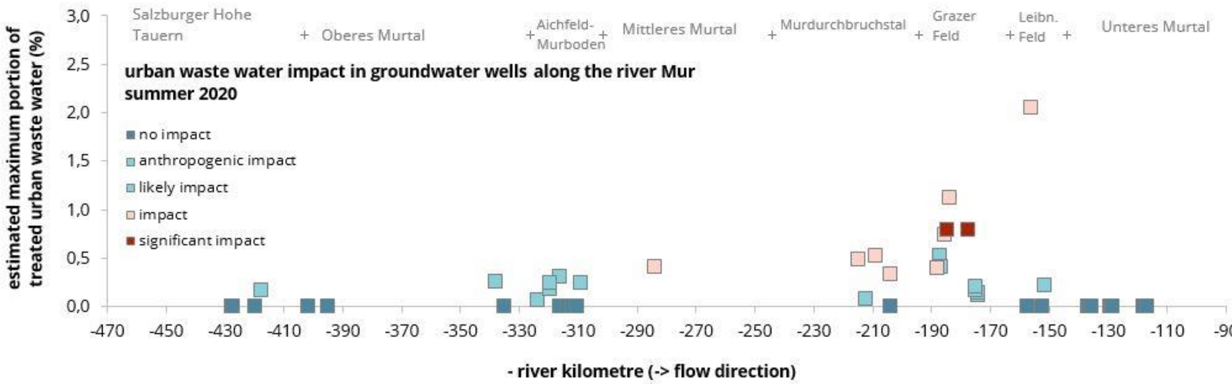

Abbildung 11: Estimates of the wastewater contribution in groundwater resulting from the spring 2020 sampling campaign.

The above example highlights that groundwater quality generally is controlled, on the one hand, by the presences of contamination sources and, on the other hand, by the contamination pathways into groundwater. The latter is strongly dependent on water quantity and thus on effects of extreme events on water quantity. Increasing frequency and severity of floods suggests more frequent occurrence and overall more relevance of indirect recharge from surface waters as a contamination pathway into groundwater. Likewise, declining groundwater levels can turn currently gaining streams in loosing streams, providing indirect recharge and thus potential pathways for contaminants into groundwater (Uhl et al., 2022).

Another highly relevant example of interrelations between water quantity and water quality is provided by the nitrate contamination of groundwater bodies in the Mur valley. Fertilization in agriculture is a major source of nitrate and the main contamination pathway, thus, is through direct recharge from precipitation. As a result, groundwater in foreland areas with intense agricultural land use is prone to nitrate contamination, particularly if direct recharge from precipitation rather than indirect recharge through surface waters dominates, which applies to most of the Leibnitzer Feld (LF) and to the Unteres Murtal (UM) groundwater bodies.

Since groundwater recharge from precipitation exhibits variations on different (event-based, seasonal, multi-year) time scales, monitoring the temporal dynamics of nitrate concentrations and identifying the mechanisms underlying the observed changes is challenging. Within this project, we therefore combined data from long-term monitoring with high-resolution measurements of the short-term nitrate dynamics (Haas et al., 2023). An example of the short-term responses to recharge events and seasonal changes in nitrate concentrations is shown in Fig. 12. In 2021, short-term responses of groundwater levels to individual recharge events are superimposed on a recession. Overall, the nitrate concentrations appear to follow the decreasing trend of the groundwater levels. In the case of LF, several short-lasting drops in nitrate concentrations coincide with individual recharge events. Yet, the nitrate concentrations recover quickly, suggesting a rapid recharge component that is low in nitrate but highly localized. Pronounced short-term increases in nitrate concentrations are observed in the late spring and early summer of 2022. Remarkably, the concentrations again drop quickly, but remain at levels higher than before the event. Again, this suggests a localized, rapid recharge component high in nitrate causes the strong short-term response. Yet, these events also appear to involve more distributed inputs of nitrate that result in a longlasting rise of concentrations.

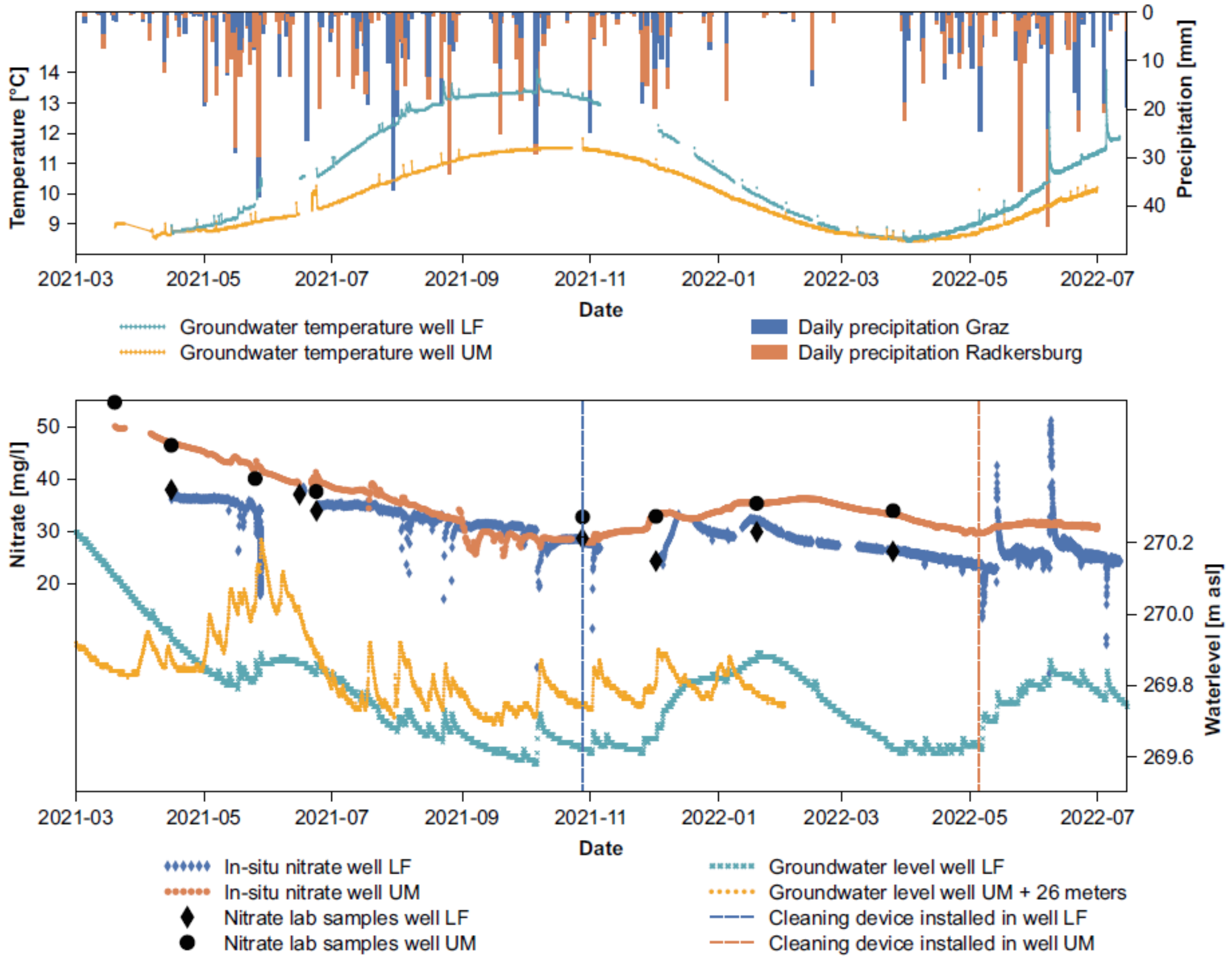

Figure 12: Groundwater levels, water temperature, and nitrate concentrations at observation wells in LF and UM (Haas et al., 2023). Precipitation data: Stations 16400 Graz Airport (20km north of well LF) and 20903 Bad Radkersburg (25km east of well UM; ZAMG 2022).

The results from the high-resolution monitoring improve the understanding of the long-term pattern of nitrate dynamics shown in Fig. 13. It can clearly be seen that on a multi-year time scale the most pronounced increases in nitrate concentrations follow drought periods in which groundwater levels exhibited recessions, because nitrogen that has accumulated in the soils during drought is mobilized in the subsequent wet period (Borken and Matzner, 2009; Jutglar et al., 2020). A snapshot of the most recent high-resolution measurements and data from the observation wells of the long-term monitoring reveals that threshold concentrations for nitrate were locally exceeded in the spring of 2023 (Fig. 14). Our results from the high-resolution monitoring thus suggest that the nitrate inputs are associated with distinct recharge events after drought periods, which needs to be taken into account in agricultural management.

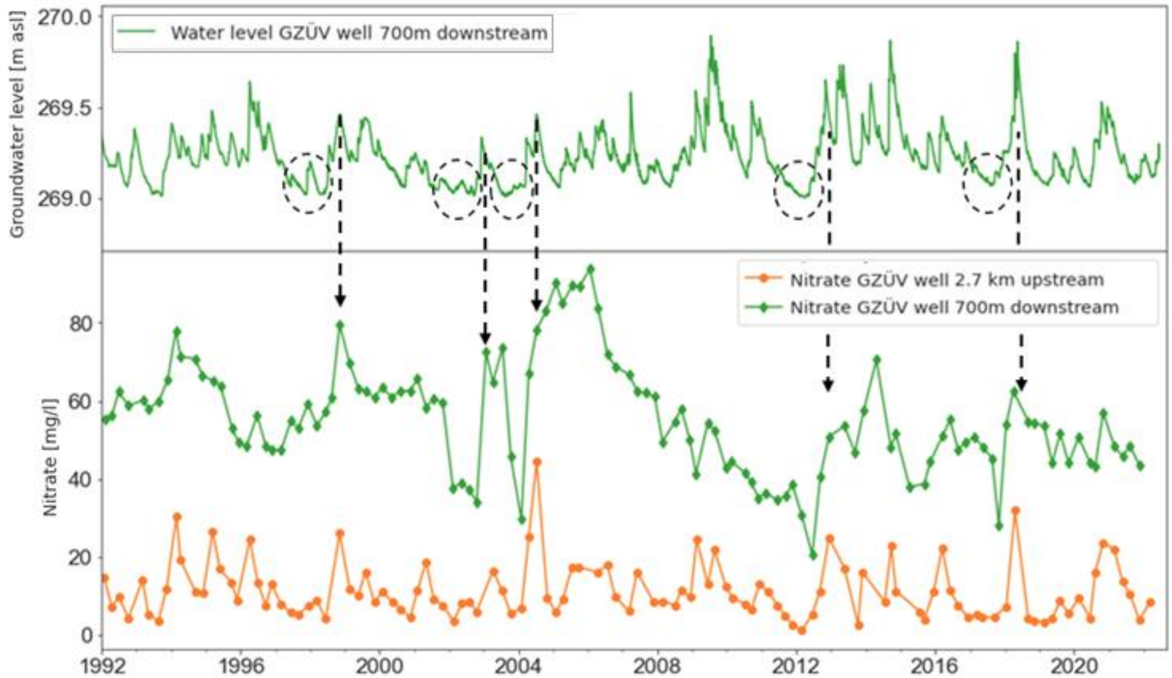

Figure 13: Groundwater levels and nitrate concentrations in observation wells from the existing long-term monitoring in LF, upstream and downstream from the observation well used for the high-resolution monitoring in LF (see Figs. 12 and 14).

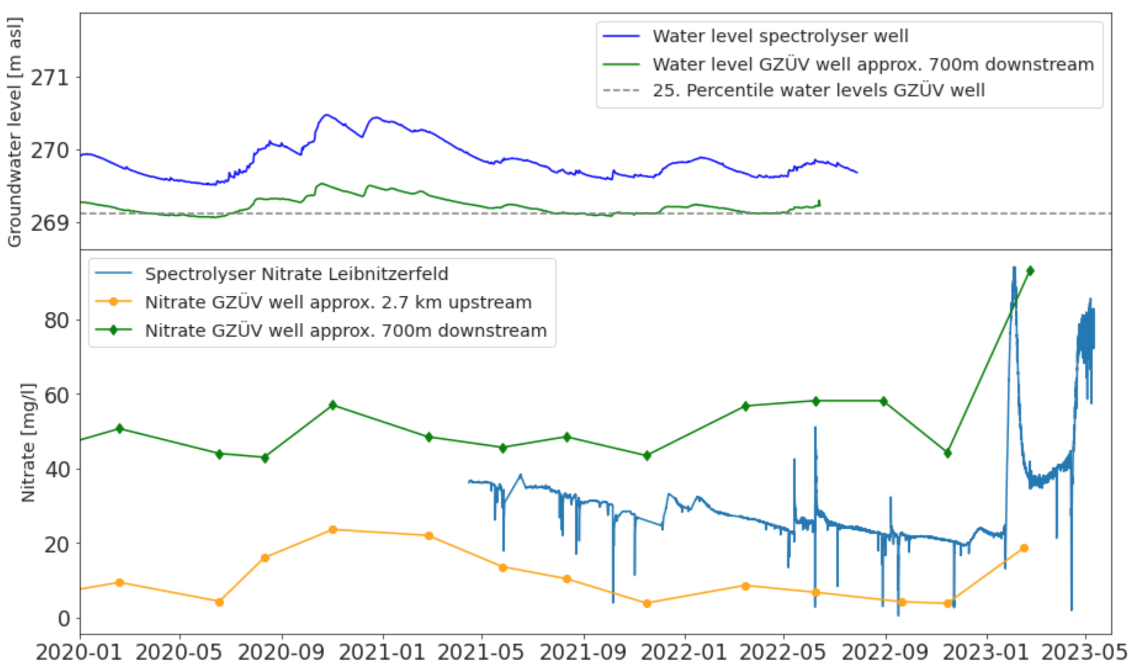

Figure 14: Most recent high-resolution nitrate data from the observation well in LF compared with long-term monitoring data from nearby observation wells.

Indicators and recommendations for groundwater monitoring

Several indicators for water-quantity and (hydrochemical) water-quality monitoring have been in use in science and practice. Drought indices enable the identification and spatiotemporal comparison of hydrological anomalies and their propagation through different components of the water cycle (e.g., Haas and Birk, 2017). Likewise, hydrochemical parameters, such as the wastewater indicator or nitrate concentrations discussed in the previous sections, can be used as water-quality indicators. Yet, the example of high-frequency fluctuations in nitrate concentrations suggests that impacts of extreme events might be overlooked or at least not adequately understood if only sparse monitoring data is available, and in any case the assessment of impacts remains limited to the specific choice of hydrochemical parameters. Thus, there is a need to complement the existing indicators by a holistic assessment of groundwater systems that accounts for the status and functioning of the groundwater as an ecosystem.

For this purpose, a simple and sensitive microbial status index (Griebler et al. 2018) was applied, evaluated and further developed within this project. The B-A-E index evaluates the microbiological-ecological quality of groundwater based on prokaryotic cell counts (B = biomass), microbial activity measurements (A = ATP), and optionally the qualitative characterization of dissolved organic carbon (E = Energy). The purpose of our research in the frame of this project, firstly, was to evaluate if a microbiological-ecological assessment provides additional information besides traditional hydrochemical groundwater quality analysis. This included different ways of application of the B-A-(E) index. For the first time, we tested an extension of the B-A-(E) index by including measurements of dissolved organic matter quality (DOM) derived from fluorescence spectroscopy as additional variables to supplement the analysis of microbial cell density and activity levels. Secondly, we evaluated how the definition of an appropriate reference status for a 'good' microbiological-ecological state can improve the analysis and allow for a more sensitive and accurate detection of impacts on groundwater ecosystems. For these purposes, we made use of the recent data set (n= 61) from the Mur valley produced in early summer and late autumn 2020. In addition, we followed the total prokaryotic cells counts (B) and ATP (A) at three different sampling sites over a period of several months to one year.

Following the Mur valley from its source in the high mountains to the Austrian border, we see a consecutive trend of an increasing number of prokaryotic cells and microbial activity in river water and groundwater (Fig. 15). A B-A plot (Fig. 15) typically shows clean and undisturbed groundwater to contain only few bacterial and archaeal cells (10^6-10^7 cells L^{-1}) with only a low microbial activity (intracellular ATP concentration of ≤ 10 pM) (Fig. 15). The more downstream the more active cells we observe. In Figure 15 we see that the B-A values of the 'cleanest' river water (from the river upper reaches) plots close to the 'dirtiest' and highest productive groundwater samples (from the Leibnitzer Feld and the Lower Mur Valley). Already the two parameters B and A provide us with valuable information in terms of microbial productivity, and thus water quality.

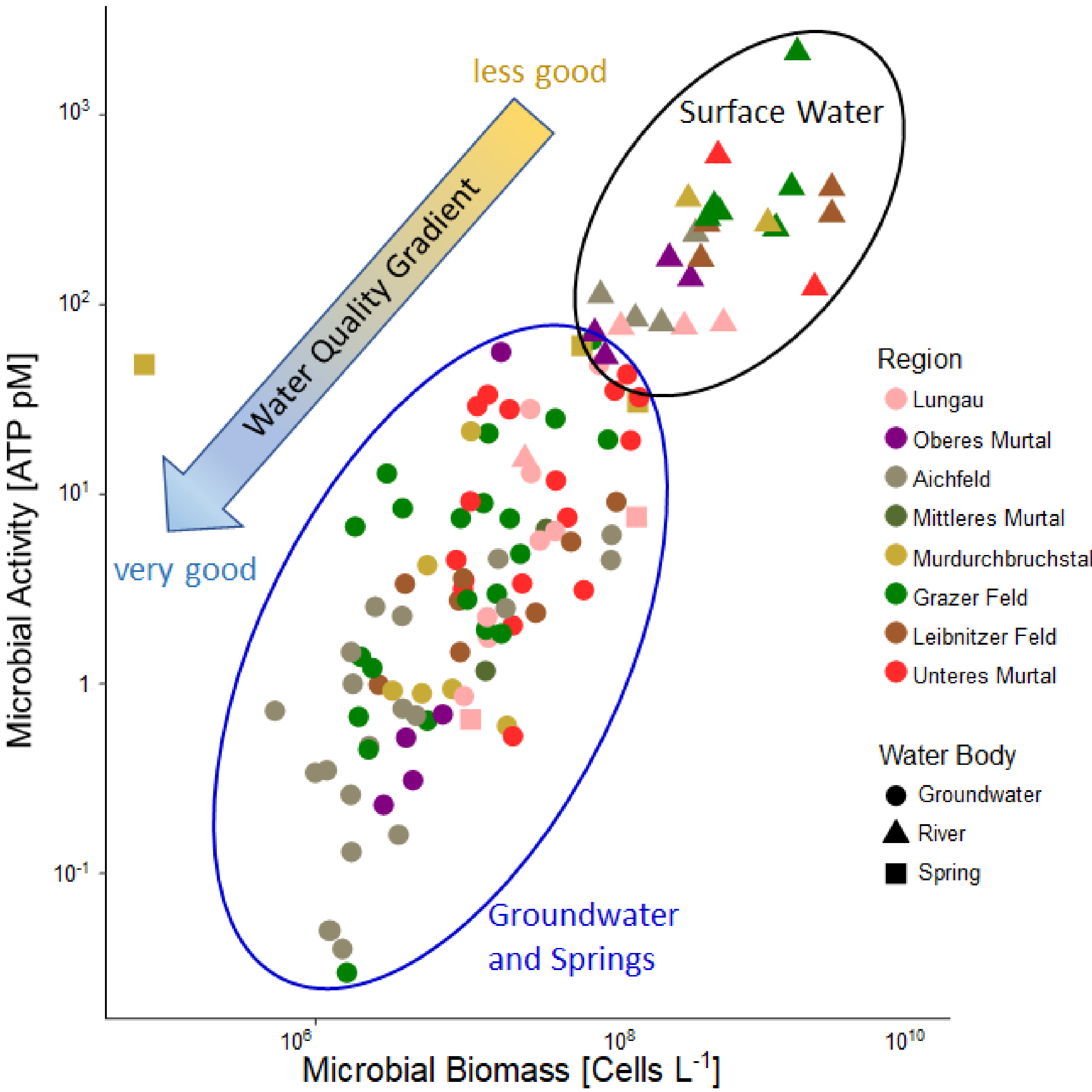

Figure 15: Bivariate plot of internal ATP and microbial cell counts for the groundwater bodies of the Mur valley.

If the B (prokaryotic cell counts) and A (ATP concentrations) values are used to calculate the B-A index (for details, see Griebler et al. 2018; Retter et al. 2021) without consideration of a 'reference data group' (this approach is termed 'uninformed' index analysis), the B-A outlier test is very conservative, defining only the middle and low-reach river samples as outliers (Fig. 16, middle chart). Only one groundwater sample is classified an outlier. Including two DOM quality indices from fluorescence spectroscopy, i.e. the HIX (Humification Index) and the BIX (Biological Index), a much better separation of surface waters and groundwaters was achieved (Fig. 16, right chart). In fact, all surface waters, spring waters, and a significant number of groundwater samples were classified outliers, i.e., not having the expected microbiological-ecological water quality.

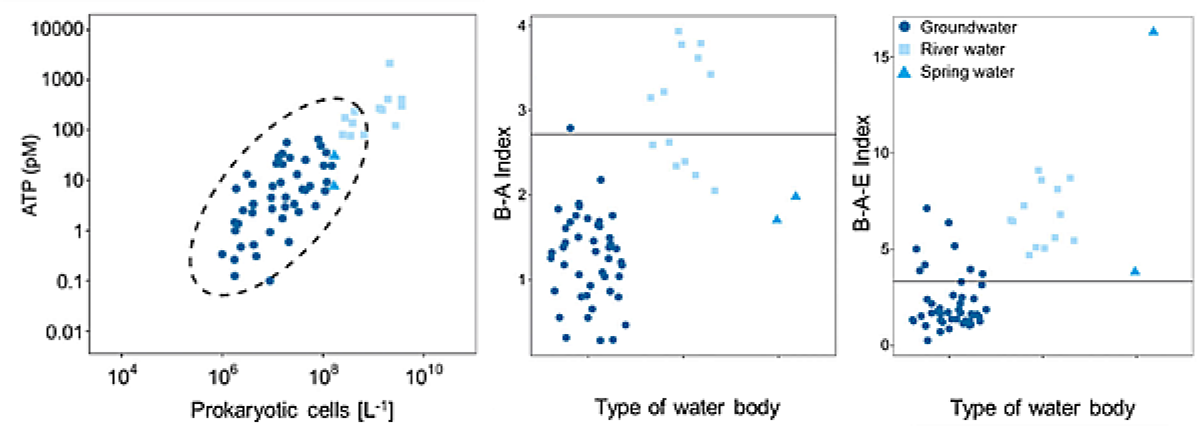

Figure 16: Bivariate plots of internal ATP,and microbial cell counts showing the respective type of waterbody and depicting the mean values of the random variation within the groundwater dataset as a black, dashed 0.975 confidence ellipses (left); the plots in the middle and on the right show the B-A and B-A-E index computed without prior knowledge, mean and covariance based on the groundwater data set, but calculated for all samples. The solid black horizontal line depicts the critical value of the chi-squared distribution with a confidence level of 0.975 and two degrees of freedom(B-A) and four degrees of freedom(B-A-E) (Retter et al., 2021).

In a second approach, we excluded all river and spring water samples from the analysis and did an 'informed' calculation of the B-A and B-A-E indices, using the deep groundwater samples from the Aichfeld as reference group, being aware that this is the extreme opposite of having no reference at all. The deep Aichfeld groundwater samples are the 'cleanest' in terms of B and A, and hardly representative for all other subregions. Moreover, we distinguished groundwater samples with respect to the subregions they originated from and with respect to the land use above. This exercise (see also Retter et al., 2021) shows that based on the B-A Index in 5 out of 7 subregions individual groundwater samples are qualified as outliers. Complementing B and A with E (HIX and BIX), strikingly increases the number of outliers (Fig. 17). Now, there is outliers in all subregions. A similar picture is obtained when groundwater samples are distinguished by the three land use categories, i.e. forests and semi-natural areas, agricultural areas, and urban areas. In conclusion, the addition of further parameters, like DOM quality indices, has the power to increase the sensitivity of the assessment of the microbiological-ecological quality of groundwater. However, currently we are in an evaluation process that targets the most suitable DOM quality measures testing further indices (e.g., Freshness Index). Moreover, as said above, the groundwater reference group selected for this exercise is not appropriate considering that most groundwater samples were collected from ≤ 15 m b.s.l., and the heterogeneity present in our subregions. This is work in progress. Based on our results, we advocate that the analysis be performed by making use of expert knowledge for the definition of reference sites to which target sites are to be compared. Partnerships with non-university experts and stakeholders, who need to be involved in this ongoing work, have been established throughout this project.

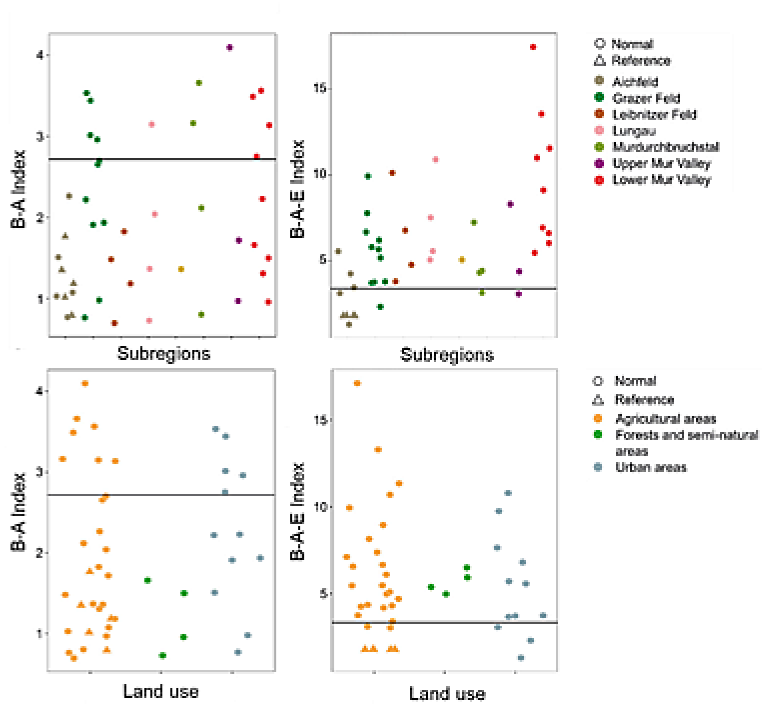

Figure 17: B-A index and B-A-E index computed for groundwater samples in reference to their sub-regions (top) and land use (bottom).

Transdisciplinary process and ESS groundwater cluster

Non-university experts and stakeholders from different fields were involved at all stages of this project in various ways. The most intense collaboration took place with the experts involved in the existing water-quantity and water-quality monitoring of the relevant provincial authorities (Province of Styria, Province of Salzburg) and the Environment Agency Austria, who were already involved in the project proposal and later contributed to the project throughout all its stages.

The identification and integration of other stakeholders was strongly supported by the collaboration within the “ESS groundwater cluster”. The groundwater cluster brought together the following four projects:

- *ClimGrassHydro* investigated the effects of drought events under different climate scenarios on the water balance and productivity of managed grassland in worldwide unique experiment.
- *RechAUT* determined groundwater recharge rates, projected their future changes, and assessed resulting consequences for land use and water management in Austria.
- *Integrative Groundwater Assessment* (this project) investigated the effects of extreme hydrological events on the hydrological, hydrochemical, and ecological status of groundwater bodies.
- *Flowcast* developed new methods to characterize the structure, capacity, and sensitivity of karst aquifers.

Thus, the projects of the groundwater cluster addressed different topics related to soil water and groundwater in mountainous regions. It was therefore to be expected that the stakeholders' interest in the projects would differ. For example, the productivity of grassland, addressed by *ClimaGrassHydro*, obviously attracted stakeholders from agriculture, while the relevance of our project (*Integrative Groundwater Assessment*) was more obvious to stakeholders from water resources management. Yet, for our project (and similarly for the others), the involvement of a wide range of stakeholders was important because groundwater quantity and quality are potentially affected by activities of different stakeholders and groundwater may become increasingly important to them under changing climate conditions (e.g., irrigation in agriculture). In this regard, the implementation of two joint stakeholder workshops was very beneficial for all projects, as it enabled the involvement of stakeholders who would not have been addressed by one project alone.

The first of the stakeholder workshops took place within the first year of the projects (February 2020) and was accompanied by a science-to-public publication introducing all four projects (Birk at al., 2020). To enable targeted communication, the stakeholders were invited to identify the topics that were of major interest to them and to contribute their knowledge in interactive discussions within working groups. From these discussions several relevant topics emerged, some of which were at the interfaces between the projects. For example, in terms of water quantity, particularly the interrelation between soil water (agriculture) and groundwater (water resources) appeared to be of interest, for example, how changes in climate and land use will affect groundwater recharge, but also the opportunities and challenges arising from increased irrigation. Likewise, water quality issues were found to be interlinked across the spheres and thus the projects. In this context, it was noted that nitrate emissions from agriculture and the resulting contamination of groundwater is an issue of great interest. As a result, additional joint activities emerged. For example, members of the project teams of *Integrative Groundwater Assessment* and *RechAUT*, contributed to the factsheet initiated by *ClimGrassHydro*.

For this project, one benefit of the first stakeholder workshop was that it facilitated the establishment of an advisory board consisting of stakeholders who were willing to monitor the progress of the project and provide their feedback. The advisory board met twice (March 2021 and July 2022), but additional consultations with individual members of the board took place at other times as needed. In particular, members of the project team were also invited to contribute to workshops or meetings organized by stakeholders, for example, a meeting of the experts responsible for the water-quality monitoring in the different provinces of Austria. Such meetings, on the one hand, revealed a great interest in several aspects of the project, such as the high-resolution water-quality monitoring or the sampling of groundwater fauna, but on the other hand also showed the need for ongoing communication and collaboration with regard to the development of indicators for the assessment of the ecological status of groundwater bodies. The second joint stakeholder workshop held in September 2022, which again brought together the project teams of the groundwater cluster and a wide range of stakeholders, thus not served to provide an overview of the project outcomes, but also to strengthen and continue the partnerships that have been developed during the project period.

Summary of key findings and recommendations

An integrative interdisciplinary approach has been proposed for the assessment of groundwater systems in alpine and prealpine environments and how they respond to hydrological extremes such as droughts and floods in terms of water quantity, hydrochemical quality, and ecological status. The approach is aimed at improving the understanding of the interaction between physical, chemical, and biological processes in groundwater responses to extreme events. For this purpose, observation wells of the existing state hydrographic monitoring net have been selected within the Austrian part of the Mur valley, stretching from the alpine origin to the national border in the foreland. Using long-term records of hydrological and hydrochemical data as well as data obtained from sampling campaigns conducted in this project, drivers controlling water quantity and quality were identified. Our results demonstrate a deterioration of water quality from the alpine source area towards the foreland, corresponding to the more intense agricultural and urban land use in the foreland. Linkages between water quantity and water quality particularly result from the recharge mechanisms (direct recharge from precipitation vs. indirect recharge through infiltration of surface waters) and their spatiotemporal dynamics, as illustrated by the examples of agricultural and wastewater impacts on groundwater.

To achieve a more holistic assessment of groundwater systems that accounts for their ecosystem nature, we suggest that existing hydrological and hydrochemical indices should be complemented by a microbiological indicator. The B-A-(E) index has been found to be easily applicable for this purpose. However, the size of the data set as well as the distribution of undisturbed and disturbed samples in the data group strongly influence the outcome of the analysis. Without consideration of spatial heterogeneities and temporal variabilities as well as without the availability of a well-defined reference data set, the index cannot classify the microbiological-ecological status into different categories such as 'good' or 'bad'. The consideration of local and regional particularities, such as hydrogeological conditions, increase the discrimination power of the index significantly. However, a reliable separation of groundwater that exhibits a natural or close-to-natural ecological status and groundwater that shows signs of an ecological disturbance is only possible with a reference data set in hand. The delineation of a reference data set is challenging and requires, besides further scientific investigations, the knowledge of local experts and stakeholders. A more detailed discussion and suggestions on the definition of reference conditions are provided by Retter et al. (2021).

Acknowledgements

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Dissemination and transdisciplinary activites

Publications

Publications in peer-reviewed journals and books

Retter, A., Haas, J. C., Birk, S., Stumpp, C., Hausmann, B., Griebler, C., Karwautz, C. (2023): From the Mountain to the Valley: Drivers of Groundwater Prokaryotic Communities along an Alpine River Corridor. Microorganisms 11 (3), art. no. 779. doi: 10.3390/microorganisms11030779

Haas, J., Retter, A., Kornfeind, L., Wagner, C., Griebler, C., Birk, S. (2023): High-resolution monitoring of groundwater quality in unconsolidated aquifers using UV-Vis spectrometry. Grundwasser 28: 53-66. doi: 10.1007/s00767-022-00540-3

Retter, A., Nawaz, A. (2022): The groundwater mycobiome: fungal diversity in terrestrial aquifers. In Encyclopedia of Inland Waters (Mehner, T. & Tockner, K., eds.), 2nd edition, Elsevier, pp. 385-396.

Schweichhart, J.S., Pleyer, D., Winter, C., Retter, A., Griebler, C. (2022): Presence and role of prokaryotic viruses in groundwater environments. In Encyclopedia of Inland Waters (Mehner, T. & Tockner, K., eds.), 2nd edition, Elsevier, pp. 373-384.

Retter, A., Griebler, C., Haas, J., Birk, S., Stumpp, C., Brielmann, H., Fillinger, L. (2021): Application of the D-A-(C) index as a simple tool for microbial-ecological characterization and assessment of groundwater ecosystems—a case study of the Mur River Valley, Austria. Österreichische Wasser- und Abfallwirtschaft 73: 455-467. doi:10.1007/s00506-021-00799-5

Retter, A., Karwautz, C. & Griebler, C. (2020): Groundwater microbial communities in times of climate change. Curr. Issues Mol. Biol. 41: 509-537.

Peer-reviewed publications in preparation

Birk, S., Haas, J., Brielmann, H., Stumpp, C., Griebler, C. (in prep.): Controls on groundwater quantity and quality in the transition from mountains to forelands: The case of the Mur valley (Austria). In preparation for submission to Hydrogeology Journal.

Englisch, C., Retter, A., Karwautz, C., Rasch, G., Fillinger, L., Veits, R., Junker, R., Gaviria, S., Fuchs, A., Scharhauser, F., Eisendle-Flöckner, U., Steger, J., Greilhuber, M., Pfingstl, T., Baumann, J., Griebler, C. (in prep.): Die Grundwasserfauna der Steiermark.

Griebler, C., Retter, A., Haas, J. C., Stumpp, C., Birk, S. (in prep.): Groundwater quality assessment by means of multiple abiotic and biotic indicators – the River Mur valley as a case study.

Retter, A., Haas, J. C., Hausmann, B., Baltar, F., Breyer, E. Birk, S., Stumpp, C., Griebler, C., Karwautz, C. (in prep.): Fungal communities in shallow groundwater along an alpine river corridor.

Retter, A., Haas, J. C., Hausmann, B., Baltar, F., Breyer, E. Birk, S., Stumpp, C., Griebler, C., Karwautz, C. (in prep.): Origin and dynamics of fungal communities in shallow groundwater of a river valley subject to different land use.

Other publications (including science-to-public and science-to-professionals)

Brielmann, H., Haas, J., Birk, S., Roll, M., Kulcsar, S., Zieritz, I., Eisenkölb, G., Rosmann, T. (in prep.): ÖAW-Projekt "Integrative Groundwater Assessment" – Ergebnisse des Indikatorentests für kommunale Verunreinigungen. Report, Umwelbundesamt, Wien.

Birk, S. (2022): Auswirkungen von Dürren auf den Boden- und Grundwasserhaushalt. In: 22. Alpenländisches Expertenforum - Trockenheit als neue Herausforderung der Grünlandbewirtschaftung, 08. November 2022, HBLFA Raumberg-Gumpenstein: 13-15.

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Conference abstracts

Haas, J. C., Retter, A., Birk, S., Brielmann, H., Stumpp, C. (2023): River influence on groundwater – head changes vs. chemical changes, EGU General Assembly 2023, Vienna, Austria, 24–28 Apr 2023, EGU23-12983, doi.org/10.5194/egusphere-egu23-12983

Haas, J., Birk, S., Retter, A., Griebler, C. (2022): Ein integrativer Überblick über die Grundwasserqualität im Murtal: Von der Quelle bis zur slowenischen Grenze. In: Berichte der Geologischen Bundesanstalt, 143: 62.

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Birk, S. (2021): Assessment of climate change impacts on groundwater: Crossing the boundaries of hydrogeology. In: D. Ducci, V. Allocca, A. Corniello, P. De Vita, S. Fabbrocino, G. Forte (eds.): 5th Edition of FLOWPATH - the National Meeting on Hydrogeology, Napoli, 1-3 December 2021, Conference Proceedings Book: 2.

Haas, J. C., Retter, A., Birk, S., Griebler, C. (2021): Selection of representative groundwater monitoring wells – A compromise between site characteristics, data history, stakeholder interests and technological limitations. EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-12895, doi.org/10.5194/egusphere-egu21-12895

Birk, S., Haas, J., Retter, A., Collenteur, R., Brielmann, H., Stumpp, C., Griebler, C. (2021): Integrative hydrogeo-ecological assessment of the quantitative and qualitative response of groundwater to hydrological extremes. EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-13111, https://doi.org/10.5194/egusphere-egu21-13111

Birk, S., Collenteur, R. (2020): Reviewing our options: How can we address climate change impacts in hydrogeological studies? EGU General Assembly 2020, Online, 4–8 May 2020, EGU2020-16143. doi: 10.5194/egusphere-egu2020-16143

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Birk, S., Haas, J. (2019): Drivers of changes in Austrian groundwater levels – climate vs. water use. In: Gómez Hernández, J. J., Andreo Navarro, B. (Hg.): Groundwater Managementand Governance - Coping with Uncertainty. Barcelona. Asociación Internacional de Hidrogeólogos – Grupo Español. 2019: 176.

Theses

Retter, A. (in prep.) Groundwater microbial biodiversity along an alpine river catchment and its link to hydro-meteorological extremes. Doctoral thesis, University of Vienna.

Wegscheider, L. (in prep.): Estimating groundwater recharge – a comparison of methods using time series of groundwater. Master's thesis, University of Graz.

Onatt, M. (2022) Verteilung der Grundwasserfauna entlang der Mur in Österreich'. Bachelor Thesis, University of Vienna.

Salzmann, J. (2022): Estimation of groundwater recharge at selected sites in Austria: comparing conceptual and physically-based models. Master's thesis, University of Graz. (In collaboration with ESS groundwater cluster project RechAUT)

Englisch, C. (2021) Distribution patterns of the groundwater fauna in the River Mur Valley, Austria. Master Thesis, University of Wien.

Gollner, M. (2021): Kleinräumige Charakterisierung der Strömungsverhältnisse und Chloridbelastung des Grundwassers im Bereich der Autobahnabfahrt Kalsdorf. Bachelor's thesis, University of Graz.

Transdisciplinary activities and invited talks

Presentations and lecture series

Birk, S.: Groundwater resources in Austria. Invited talk, Meteorological-Geophysical Colloquium, University of Vienna, 23.5.2023

Griebler, C.: Groundwater Ecology research at the UniVIE - Current activities and future visions. Invited talk at the Institute of Limnology, Mondsee, Austria, 11. Jan 2023.

Birk, S.: Auswirkungen von Dürren auf den Boden- und Grundwasserhaushalt. Alpenländisches Expertenforum, Irdning. 08.11.2022.

Griebler, C.: Grundwasserökologie - Stand der Forschung in Österreich – Grundlagen und Anwendung. Invited talk, ÖWAV Seminar, Vienna, Austria, 19. Oct. 2022.

Griebler, C.: The B-A-(E) index as a simple tool for microbial-ecological characterization and assessment of groundwater ecosystems. Invited talk, Alpflow Conference at Bad Ischl, Austria. 20. May 2022.

Griebler, C.: Grundwasser - Biodiversität & Schutz. Invited talk at the ZooBot Seminar Series 15. Dec 2021

Birk, S.: Integrative Groundwater Assessment - Impact of extreme hydrological events on the quantity and quality of groundwater in alpine regions – multiple-index application for an integrative hydrogeo-ecological assessment. Presentation at GZÜV-Bund-Bundesländersitzung Graz, 30.09.2021

Griebler, C.: Sonderuntersuchung Mikrobiologie GW – der B-A-E Index als mikrobiologisch-ökologisches Konzept zur Überwachung des Grundwassers. Presentation at GZÜV-Bund-Bundesländersitzung Graz, 29.09.2021

Griebler, C.: Warum gelangt Nitrat ins Grundwasser & wer badet das aus? Invited talk at University of Münster, Germany, 22. Jun 2021.

Griebler, C.: Carbon transformation and cycling in groundwater - Current research activities & future plans. Invited talk at University of Jena – Project AquaDiva 18. May 2021.

Birk, S., Ludescher, M.: Organisation of a lecture series "Vita Activa - Was wir zum Leben brauchen: Wasser als Ressource" (5 lecture days). Graz. 05.03.2019 - 07.05.2019.

Birk, S.: Grundwasser im Wasserkreislauf. Presentation at lecture series “Vita Activa - Was wir zum Leben brauchen: Wasser als Ressource” Graz. 06.03.2019.

Advisory board (Projektbeirat)

Advisory board meeting, online, 11.3.2021

Advisory board meeting, online, 8.7.2022

Stakeholder workshops

Stakeholderworkshop Wasserressourcen im Klimawandel: Konsequenzen für Wasser-, Energie- und Landwirtschaft, Graz, 7.2.2020.

Stakeholderworkshop Wasserressourcen im Klimawandel: Konsequenzen für Wasser-, Energie- und Landwirtschaft, Wien, 27.9.2022

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