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Abiotic Drivers of Groundwater Fauna Across Aquifer Types and Urban–Rural Gradients in the City of Halle (Saale), Germany

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ABSTRACT

Subterranean ecosystems in urban environments are exposed to multiple anthropogenic stressors that compromise groundwater quality and biodiversity. Rising groundwater temperatures, oxygen depletion, hydraulic disturbance and chemical contamination are among the main pressures. Complex geological settings further modulate subsurface conditions and habitat suitability. Yet the combined effects of urban and geological factors on groundwater fauna remain poorly understood. This study examines the relationships between environmental conditions and the diversity and abundance of major faunal groups along gradients of urbanisation and geological gradients in 91 monitoring wells of the city of Halle (Germany) and its surroundings. Repeated measurements revealed an urban–rural gradient with rising groundwater temperature and dissolved organic carbon (DOC) concentrations towards more urbanised areas. Despite generally low dissolved oxygen (DO) levels, fauna occurred even under hypoxic conditions. Faunal abundance and diversity were primarily governed by redox-sensitive variables. Groundwater from wells lacking fauna showed elevated DOC concentrations, increased groundwater temperature, greater depth to the groundwater table and lower DO concentrations. Urbanisation indicators, that is, elevated DOC, temperature and potassium, are negatively correlated with faunal metrics, particularly under the combined effects of stressors. The aquifer type alone exerts only a minor influence. All major taxonomic groups were present in both porous and fractured aquifers. Spatial variability in faunal composition was more pronounced between eastern and western sectors than along the urban–rural gradient, highlighting complex interactions between geological and urban factors in shaping groundwater biodiversity.

1 | Introduction

Groundwater fulfils a number of essential purposes. One of them is supporting human well-being with a significant economic value by serving as a vital source of drinking water, irrigation water and a geothermal energy source (Bayer et al. 2019; Job 2021; Mammola et al. 2026). Beyond its resource character, it harbours a biodiverse ecosystem where microbes as well as microfauna, meiofauna and macrofauna interact with each other (Saccò et al. 2022). These biological

interactions are an essential contribution to the natural purification processes within groundwater systems (Griebler and Avramov 2015; Herrmann and Taubert 2022). Microbial communities steer and control important biogeochemical processes and, in the form of biomass, provide an important food source for stygofauna (true groundwater fauna). Spending their entire lifespan in the groundwater realm, stygofauna, represented by a diverse community of invertebrates, in turn stimulate microbial activities (Mermillod-Blondin et al. 2023) and can improve hydraulic properties of the aquifer (Hose

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and Stumpp 2019). By grazing biofilms formed by microbes, feeding on detritus and through bioturbation, they prevent the pores from clogging and contribute to the formation of new hydraulic pathways (Schmidt et al. 2017). Furthermore, stygofauna contributes significantly to the carbon cycle via retardation and decomposition of particulate organic matter (Griebler and Avramov 2015).

As stygofauna is highly adapted to their dark, low temperature (in Central Europe) and physicochemical rather stable subterranean environments, the occurrence and diversity of groundwater fauna are strongly affected by shifts in abiotic conditions, such as water temperature or dissolved oxygen (DO) availability (Englisch et al. 2024). Most stygofauna can withstand low oxygen levels ($< 3.0 \text{ mg L}^{-1}$ DO) typically found in groundwater (Malard and Hervant 1999), though hypoxic ($0.5\text{--}1 \text{ mg L}^{-1}$ DO) and oxygen-deficient environments are a limiting factor for groundwater fauna to persist (Griebler et al. 2014; Hahn 2006).

Depending on the respective land use, the vulnerable subterranean ecosystem is exposed to various stressors affecting groundwater quality, especially in urban settings (Kaminsky et al. 2025; Knüsel et al. 2024). These include increased groundwater temperatures (Menberg et al. 2013; Ngarambe et al. 2025; Noethen et al. 2024), oxygen depletion, enhanced local hydraulic fluctuations and chemical pollution (Becher et al. 2022). There is evidence that elevated groundwater temperatures in urban areas lead to a decline in groundwater quality and biodiversity and vice versa (Blum et al. 2021; Hahn et al. 2013; Koch et al. 2021).

The hydrogeological setting is considered as another significant driving force on the quality of groundwater habitats, with lithological characteristics (permeability and pore space) shaping physicochemical conditions, both affecting the composition of the fauna (Hahn and Fuchs 2009; Weitowitz et al. 2017).

The precise impact of drivers like urbanisation and the geological setting on the groundwater ecosystem remains to be thoroughly investigated, and the influence of abiotic gradients in shaping stygofaunal diversity is not yet fully elucidated. In order to identify key driving factors and their effect on groundwater fauna, studies have been conducted on various scales, that is, at the continental scale (Eme et al. 2015; Zagmajster et al. 2014, 2018), at the province scale in Baden-Württemberg (Koch et al. 2024) and Saxony-Anhalt, Germany (Matzke et al. 2009). Nonetheless, these studies could not consider smaller spatial heterogeneities. In recent years, additional studies have therefore been conducted to investigate the urban influence on groundwater fauna at a local to regional scale. Studies in cities such as Krakow, Poland (Dumnicka et al. 2025), and Berlin, Germany (Hahn et al. 2013), concluded that wells inhabited by groundwater fauna tend to be shallower, have a moderate to high oxygen content and exhibit lower temperatures and lower ionic concentrations compared to wells without fauna. Koch et al. (2021) revealed noticeable differences between the groundwater ecosystems in the urban area and those in the surrounding forests of the city of Karlsruhe, Germany.

As urban ecosystems are multifaceted and shaped by diverse overlapping factors, further research is necessary to ensure that groundwater ecological aspects are taken into account in future

urban planning and geothermal use (Brielmann et al. 2011; Saccò et al. 2023). The diverse shallow aquifers of the city of Halle offer an ideal benchmark to investigate drivers of spatial patterns in subsurface biodiversity. This setting allows for disentangling the influence of geology-related versus urban-driven factors in shaping the community composition of groundwater fauna. This study aims to assess abiotic groundwater quality together with the abundance and diversity of major taxonomic groups of groundwater fauna across gradients of urban impacts as well as different geological units and aquifer types.

2 | Material and Methods

2.1 | Study Site

Located in central Germany, the city district of Halle (Saale) covers 135 km^2 and has about 230,000 inhabitants, whereas the surrounding rural district of Saalekreis spans 1434 km^2 and counts approximately 183,000 residents (Statistisches Landesamt Sachsen-Anhalt 2024a, 2024b). The river Saale and its tributary, the Elster, provide the city area with waterways and green space in the floodplain. As the groundwater and the groundwater level within the floodplain are heavily influenced by the Saale, a 3.5-km-long series of wells was built along the eastern bank of the Saale in order to permanently lower the groundwater level to prevent flooding by rising seepage water in the residential district Halle Neustadt (Lauer et al. 1998).

The city of Halle and surroundings offer a diverse geology, with rocks of different ages emerging at the surface. Tectonic movements during the Cretaceous formed NW-SE directed faults leading to individual faulted blocks. The major fault resulting from this phase, the so-called Halle Fault, crosses the city centre separating conglomerates and porphyritic volcanites of the Rotliegend in the north from the salt sequence of the Zechstein in the city centre and borders Triassic rocks (Bunter sandstone and Muschelkalk) in the south of the city. After an erosion phase from the Jurassic to the Middle Eocene, Tertiary and Quaternary layers were deposited (Krumbiegel and Schwab 1974).

Hydrogeologically, the area can be distinguished into a lower main aquifer formation, which comprises the confined rock aquifers of the Bunter sandstone, Muschelkalk, Zechstein and the Rotliegend, and an upper main aquifer formation, consisting of aquifers of unconsolidated rocks of the Quaternary and Tertiary (Lauer et al. 1998). The Quaternary valley aquifer extends along the Saale in the form of Holocene floodplain gravel and divides the area into a western and an eastern plateau. In the east, the Saalian-glacial main terrace extends from south to north as a 6- to 12-km-wide gravel deposit and is overlain by till and Saalian-glaciofluvial sands, whereas in the west, confined rock aquifers as well as Tertiary aquifers predominate (G.E.O.S 1998). Due to the Halle Fault and its parallel and transverse faults, hydraulic connections can occur between the aquifers. Though the Zechstein layer is located at greater depths ($> 400 \text{ m}$, Lauer et al. 1998), rising, saline deep waters can cause a strongly fluctuating groundwater chemistry in the shallow Quaternary layers (Pretschold 1998). Elevated sulphate contents are characteristic of influences from the saltwater aquifer (HYDOR 2017).

2.2 | Sampling and Laboratory Analysis

In the period from June 2022 to July 2023, samples were repeatedly collected at 91 monitoring wells in five field campaigns covering the four seasons. Sixty of these wells are located within the city limits, 31 in the surrounding rural area. The sampling aimed to achieve an equal distribution across all lithological units (Figure 1). To minimise a depth-related bias (Fuchs 2008; Hose et al. 2015; Fuchs et al. 2024), the selected sampling sites were restricted to a maximum well depth of 23 m. The monitoring wells sampled are maintained by the City of Halle and the State Agency for Flood Protection in Saxony-Anhalt, Germany (LHW).

The following key physicochemical in situ parameters were recorded for each well as a depth profile using a multiparameter probe (KLL-Q-2 with MPS-D8, SEBA, Kaufbeuren, Germany): temperature (T), electric conductivity (EC), pH, redox potential (Eh) and DO. Water samples representing well water were collected using a bailer (aqua sampler; Cole-Parmer) within the filter section wherever possible. Otherwise, samples were taken from the middle of the water column. The values of the physicochemical parameters utilised for statistical analysis are consistent with the depth at which the sample was collected. An additional sample of fresh groundwater was collected after replacing twice the well volume using a Grundfos submersible MP1 pump (Eijkelkamp). Key physical-chemical parameters (T, EC, DO and Eh) have been recorded subsequent to their stabilisation. If the well ran dry because of insufficient yield before the intended extraction of groundwater was completed, water that subsequently refilled the well was used for analysis.

In general, hydrochemical analyses were conducted for both the well water and pumped groundwater. This analysis included the measurement of major ions by ion chromatography (Metrohm AG, Herisau, Schweiz) and the measurement of dissolved organic carbon (DOC) concentration by using a total organic carbon analyser (N/C 3300, Analytik Jena GmbH, Jena, Germany). Samples for DOC analysis were filtered on site using 0.45- μ m PVDF syringe filters. Further, groundwater fauna was collected from the bottom of the monitoring wells using a modified phreatobiological Cvetkov net (Jäger and Hahn 2022). Although the sampling procedure without purging described by Hahn and Fuchs (2009) only provides a distorted image of the surrounding aquifer (Hahn and Gutjahr 2014; Hahn and Matzke 2005; Korbel et al. 2017), this method was chosen because it is a common method that allows comparability with other studies. Combined with multiple sampling events over time, as done in this study, this method is appropriate for assessing stygofauna diversity according to Korbel et al. (2017). Samples were preserved with ethanol (> 70% final concentration) and later sorted into major taxonomic groups using a stereo microscope.

2.3 | Data Evaluation

The analysis of faunal abundance and richness was carried out at major taxonomic group level (Table S1). In order to recognise faunal patterns, respective groups were visualised in similar colours according to their demands on the environment. This distinction was made on the basis of the classification scheme for groundwater ecosystems by Griebler

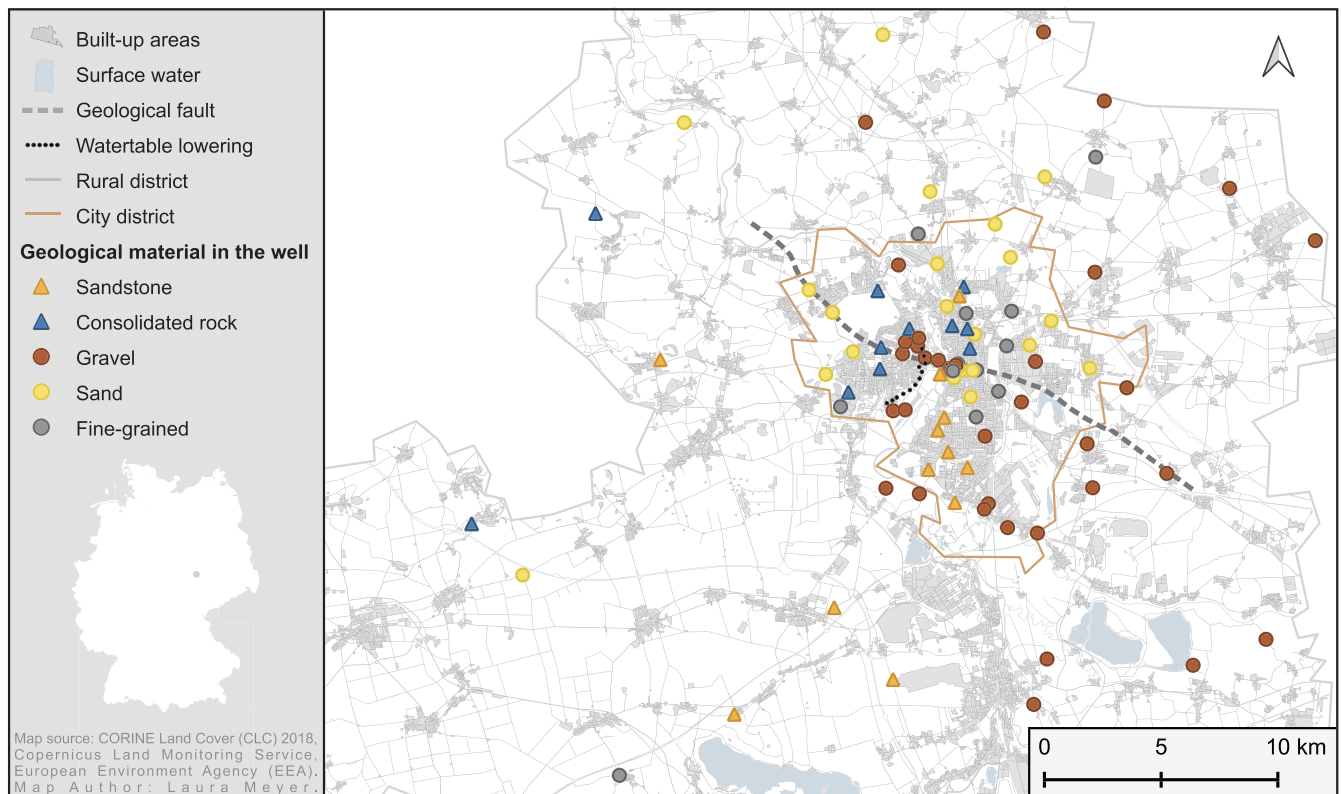


FIGURE 1 | Overview of sampling wells across the study area. Each point represents a monitoring well, with information on the predominant geological material at the screened section.

et al. (2014), where a high proportion (> 70%) of Crustacea is an indicator of a good groundwater ecological status, whereas a high proportion of Oligochaeta (> 20%) indicates a disturbed system. The latter and Nematoda appear to be more tolerant towards pollution and oxygen deficiency compared to certain groups of Crustacea, which were found to be more sensitive (Mösslacher 1998). To quantify the community composition based on the mentioned assessment scheme (Griebler et al. 2014), a coefficient $C_{Cr/Ol}$, ranging from -1 to +1, was calculated to indicate the ratio of Crustacea (Cr) to Oligochaeta (Ol). $C_{Cr/Ol} > 0$ indicates a dominance of Crustacea and thus indicate a better water quality, and $C_{Cr/Ol} < 0$ indicates a dominance of Oligochaeta and presumably a poorer water quality. A value of 0 indicates that neither group is present. The coefficient was calculated as follows:

$$C_{Cr/Ol} = \begin{cases} \frac{Cr - Ol}{Cr + Ol}, & Cr + Ol > 0 \\ 0, & Cr + Ol = 0 \end{cases}$$

Pie charts illustrating the spatial distribution of fauna were generated using a presence-based approach. For each campaign, the detection of a major taxonomic group was counted as 1, regardless of its abundance. This approach was chosen to prevent certain groups from becoming overrepresented in the well water compared to the surrounding aquifer (Hahn and Matzke 2005; Korbel et al. 2017). Sporadic mass occurrences of faunal groups like Platyhelminthes and Cyclopoida observed in some samples indicated this to be the case (Table S1).

A dataset of 426 samples was analysed following a preliminary selection. As the fauna samples were collected from the bottom of the monitoring wells, the analysis was linked to the values from physicochemical analyses of well water (Table S2).

In order to quantify the geological environment, the borehole profiles recorded by the State Office for Geology and Mining Saxony-Anhalt (LAGB 2024) were evaluated. The aquifer material in the screened section was assigned a hydraulic conductivity value for each lithological unit, reflecting the available pore space and hydrodynamics. These values are based on those determined for the corresponding hydrogeological units in the groundwater pollution register for Halle's urban area (G.E.O.S 1998). As a previous study by Hahn and Fuchs (2009) indicated that the aquifer type with its available pore space primarily shapes the community structure of the groundwater fauna rather than the mineralogy, the various hydrogeological units were assigned to one of the two aquifer types: (a) fractured aquifers including Bunter sandstone, Muschelkalk and Rotliegend and (b) porous aquifers including Quaternary and Tertiary sediments. For the geological analysis, only observation wells were considered where the aquifer material within the screened section could be clearly classified as either (a) or (b).

To analyse correlations between the fauna and the abiotic parameters, nonparametric univariate and bivariate statistical tests were applied. The Kolmogorov-Smirnov test was used to evaluate the normal distribution of the physicochemical data. As all parameters were found to be nonnormally distributed,

Spearman's rank correlation coefficient was employed to test correlations between faunal and abiotic parameters. A significance level of $p < 0.05$ was used for all statistical tests (Leyer and Wesche 2008). To test differences between groups and to assess their statistical significance, the nonparametric rank tests of Kruskal-Wallis (H test) and of Mann-Whitney (U test) were applied. For parameters with significant group differences, median values and median absolute deviation (MAD) were subsequently calculated. In the analysis of community composition, samples without faunal records were included as a separate category (no fauna) alongside the major taxonomic groups, ensuring comprehensive comparisons across all sample types.

In order to incorporate the temporal variability of oxygen concentration into the analysis, which is associated with fluctuations in the groundwater level, the wells were divided into three categories. Wells with constantly (i) low concentrations of $< 0.5 \text{ mg DO L}^{-1}$, (ii) high concentrations of $> 1 \text{ mg DO L}^{-1}$ or (iii) variable values during all measurement campaigns.

Using the digital atlas of Germany from the CORINE Land Cover database (European Environment Agency 2019), different land use classes were calculated using Python. Land use within a 100-m radius around each groundwater monitoring well was assessed and assigned according to the dominant category. The 27 initial groups were merged into five categories: (i) industrial, commercial and comparable; (ii) urban green areas and sport leisure facilities; (iii) open and natural surfaces; (iv) residential; and (v) roads and railways. In order to further quantify the urban gradient, building density was recorded based on imperviousness density data (European Environment Agency 2020) within a radius of 100m around the monitoring well.

3 | Results and Discussion

3.1 | Faunal Distribution

Across all sampling campaigns, 9954 animals were collected in total, with fauna absent in 47.9% of the samples. Fifteen percent of the wells were found unpopulated, and 62% infrequently populated, whereas 23% of the sampling sites delivered fauna in all five campaigns. Invertebrates found in groundwater samples from the study area were assigned to the following major taxonomic groups: Rotifera, Platyhelminthes, Oligochaeta, Polychaeta, Nematoda, Cyclopoida, Nauplia, Harpacticoida, Cladocera, Amphipoda, Bathynellacea and Acari (Figure 2c). Other taxonomic groups commonly found in groundwater, such as Isopoda, Mollusca and Gastropoda, were not observed. Most individuals collected belong to the Platyhelminthes and Cyclopoida. The high population density and abundance of Platyhelminthes in the study area are surprising, as a study by Matzke et al. (2009), which examined groundwater biocoenoses in uncontaminated areas of the surrounding region of Saxony-Anhalt, reported only a few findings of these taxa (Microturbellaria).

Regional differences in the composition of the fauna hint at the dominance of specific taxonomic groups in certain

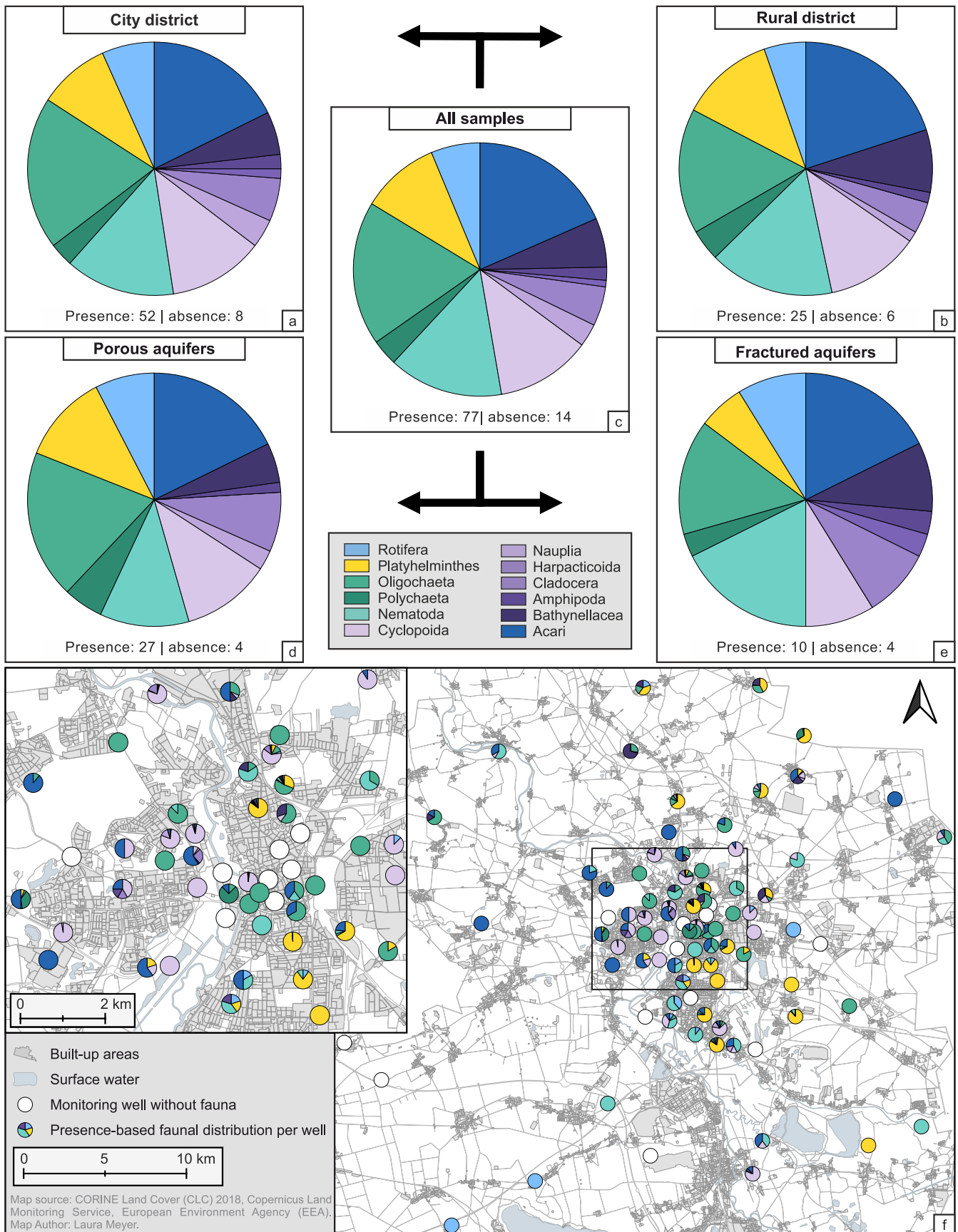


FIGURE 2 | Presence-based distribution of major taxonomic groups per well across the five sampling campaigns of (c) all taxa collected. Subsequent charts differentiate between (a) city and (b) rural district as well as (d) porous and (e) fractured aquifers including only clearly assignable wells. (f) Map of faunal distribution indicating spatial patterns in faunal composition.

areas (Figure 2f). Worms including Oligochaeta, Polychaeta, Nematoda and Platyhelminthes were prevalent in the eastern and southeastern part of the study area, whereas Crustacea and Acari were predominantly found in the west. Oligochaeta and Nematoda dominated the city centre but were also present at individual wells in the surrounding rural areas. Platyhelminthes were prevalent in both the central and peripheral areas of the southeastern region, as well as in rural parts in the northeast. Crustaceans were observed primarily in the central-western area, specifically within the Halle Neustadt residential district. This phenomenon may be attributed to the impact of artificial groundwater lowering (Lauer et al. 1998), which results in the creation of hydraulic dynamics in this region. Acari were prevalent in groundwater of the western suburbs, at a greater distance from the city centre.

As there was a strong and significant correlation between the number of major taxonomic groups and the abundance of animals per sample ($r=0.96$, $p=1.35\text{e}-232$), the number of major taxonomic groups (richness) was primarily used as the unit to quantify faunal occurrence and diversity. Environmental factors that significantly correlated with the stygofauna richness were redox-sensitive variables (DO, Eh, NH_4^+ , NO_3^- and DOC) as well as groundwater temperature, concentration of selected cations (Ca^{2+} and K^+) and well depth (Table S3).

3.2 | Dissolved Oxygen

The concentration of DO in the groundwater within the study area revealed a median value of $0.70 \pm 0.62 \text{ mg L}^{-1}$, with a maximum value of 9.3 mg L^{-1} and minimum values of $<0.1 \text{ mg L}^{-1}$. The oxygen content in groundwater can be influenced by multiple factors and reflects underground conditions like organic matter content, groundwater temperature, in combination with biological activity. A multitude of interacting factors, including seasonal dynamics, geological characteristics and land use categories, potentially impact oxygen concentrations (Becher et al. 2022; Malard and Hervant 1999; Rose and Long 1988). This was reflected in the data, which show significant variations in DO content across measurement campaigns, degree of urbanisation, and aquifer types (H test; see Tables S4–S8). No discernible pattern emerged from the distribution and variability of DO in the study area (Figure 3a). Constantly moderate to high oxygen concentrations $>1 \text{ mg L}^{-1}$, which represent favourable conditions for groundwater fauna, occurred both in the city centre and in the surrounding area.

The expectation of a geological influence on oxygen concentration, as described by Dole-Olivier et al. (2009), was evident in the data through a negative correlation between DO and hydraulic conductivity ($r=-0.15$, $p=2.5\text{e}-03$). Furthermore, median DO concentrations in fractured aquifers ($1.3 \pm 1.07 \text{ mg L}^{-1}$) were significantly higher than porous aquifers ($0.51 \pm 0.44 \text{ mg L}^{-1}$). This is consistent with previous studies (HYDOR 2017). No correlation between DO and building density was obtained. However, significant differences were found between groundwater DO median values in the city district ($0.48 \pm 0.4 \text{ mg L}^{-1}$) and the rural district ($1.4 \pm 1.28 \text{ mg L}^{-1}$). Finally, a positive correlation was found between DO and nitrate concentration, which is

explained by the dependence of nitrate reduction on hypoxic to anoxic conditions (Rivett et al. 2008).

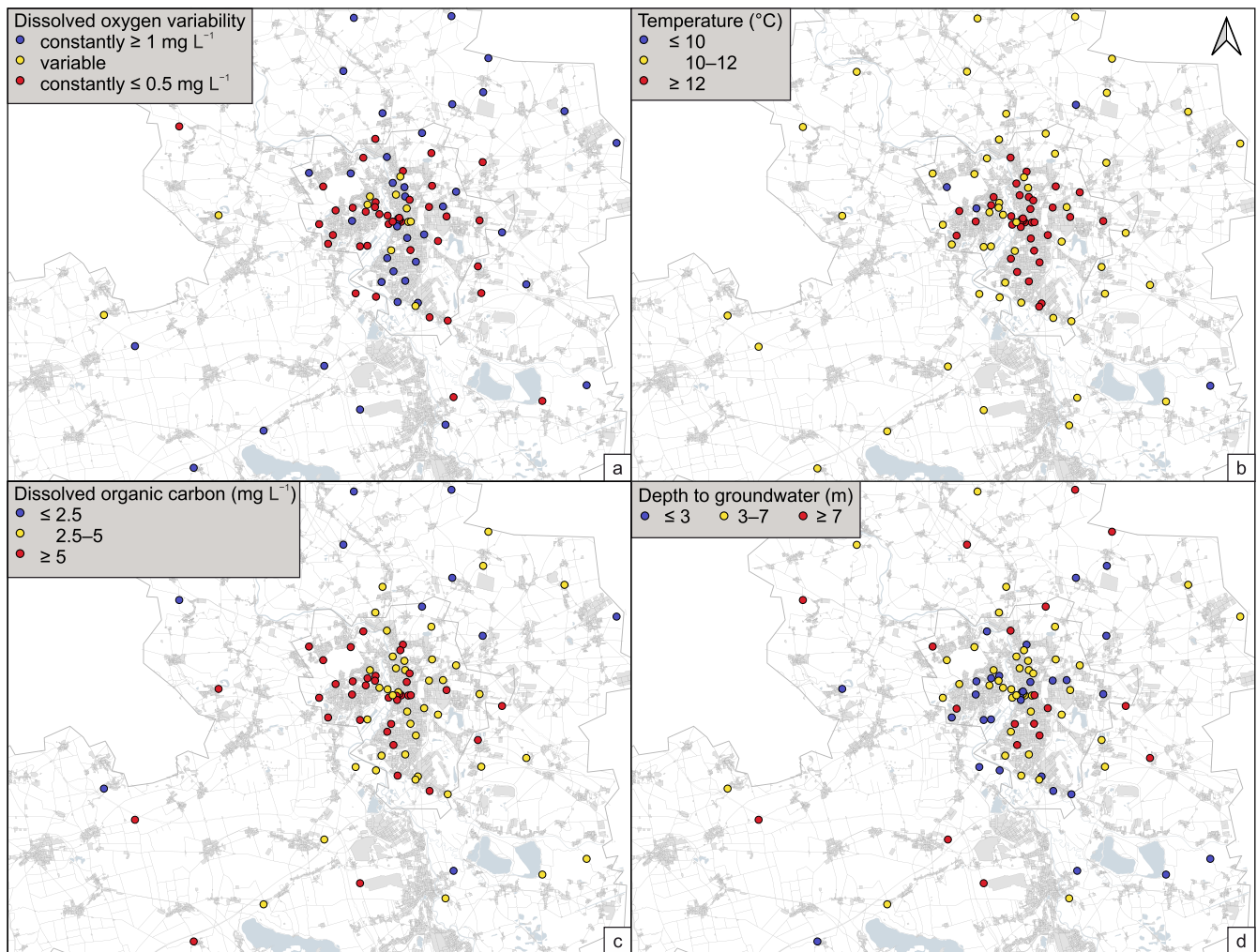
When considering the influence of oxygen availability on groundwater fauna, it is remarkable that a considerable number of invertebrates (28% of individuals) were found in unfavourable conditions with $\text{DO} < 0.5 \text{ mg L}^{-1}$. Nevertheless, a significant but weak positive correlation was found between oxygen concentration and number of major taxonomic groups ($r=0.15$, $p=1.9\text{e}-03$) and was found even more pronounced in pumped groundwater ($r=0.26$, $p=1.6\text{e}-07$). The correlations between faunal parameters and other redox-sensitive parameters, such as ammonium, nitrate, DOC and Eh, were even stronger. The influence of oxygen on the occurrence of groundwater fauna is further underlined by the fact that wells that did not exhibit the presence of fauna had lower median DO compared to those with fauna (Figure 4a). Additionally, unpopulated wells showed signs of reduced conditions and/or anthropogenic pollution such as elevated DOC values (Figure 4c) and low nitrate levels (Figure 4d).

Differing median DO values and corresponding standard deviations across major taxonomic groups indicate an influence of oxygen availability on community composition (Figure 4f). This provides evidence that the respective groups and/or species varied in their tolerance to low oxygen conditions. In contrast to the assumption that crustaceans prefer to occur under favourable living conditions (Griebler et al. 2014), copepods were found in samples with a low dissolved oxygen concentration $<1 \text{ mg L}^{-1}$ (see Table S9). Interestingly, plathelminths were found in conditions with higher oxygen levels ($1.68 \pm 1.23 \text{ mg L}^{-1}$; see Table S9), contradicting the observations of Hahn et al. (2013) and Koch et al. (2021), who found microturbellarians at unfavourable living conditions.

The abundance of Cyclopoida was found to show a negative correlation with DO content ($r=-0.10$, $p=4.1\text{e}-02$). The fact that different taxonomic groups reacted differently to the availability of oxygen could be one reason for the low correlation between overall faunal parameters and DO.

3.3 | Temperature and Urban Influence

The parameters that exhibited the most significant disparities (U test) between the categories rural and urban districts were groundwater temperature, building density, DOC concentration (see Section 3.4), EC and DO (see Section 3.2). Representing the degree of urbanisation, the building density showed a high positive correlation with groundwater temperature ($r=0.69$, $p=1.1\text{e}-60$), pointing to a suburban heat island effect towards the centre of study area (Menberg et al. 2013; Ngarambe et al. 2025; Noethen et al. 2024). In Figure 3b, this phenomenon is illustrated by the fact that temperatures above 12°C occurred exclusively in the city centre, whereas temperatures below 12°C were most present in the rural area. The groundwater temperature ranged from as low as 8.9°C in April 2023 to 17.0°C in October 2022. The highest annual median temperature per site was found at a monitoring well in the city centre close to the marketplace ($15.8^\circ\text{C} \pm 0.4$) and the lowest at a well downstream



Map source: CORINE Land Cover (CLC) 2018, Copernicus Land, Monitoring Service, European Environment Agency (EEA). Map Author: Laura Meyer.

FIGURE 3 | Spatial distribution of selected abiotic parameters (median values across all campaigns). Each map displays one environmental variable, with colours indicating habitat suitability for groundwater fauna: red represents more hostile conditions, yellow indicates intermediate suitability and blue corresponds to favourable conditions. Built-up areas are shown in grey and surface water bodies in blue, derived from CORINE Land Cover 2018 (European Environment Agency 2019).

of the Heide Forest area ($9.6^{\circ}\text{C} \pm 0.4$) in the northwest of the city district.

Temperature differences across major taxonomic groups were found to be nonsignificant. As shown in Figure 4g, the corresponding boxplots illustrate that most faunal groups occurred within a wide temperature range, with minor differences in median values between the individual groups. A comparison of urban (Figure 2d) and rural (Figure 2e) districts shows that all major taxonomic groups found in the study area were present in both the city centre and in the rural area. The major group Cladocera was the only exception, as it was not found in the rural area. This may be because this group was poorly represented and only found twice.

Because laboratory experiments have shown that some stygobiont species are sensitive to elevated temperatures (Briellmann et al. 2011), a negative correlation between groundwater temperature and abundance and biodiversity was expected. Based on our data set, this assumption is supported by the fact that wells without fauna across all campaigns showed a higher

median temperature (Figure 4b). Additionally, there was a significant but weak negative correlation between temperature and stygofauna richness ($r = -0.11$, $p = 1.8 \times 10^{-2}$). When considering the group of wells with oxygen concentrations consistently below 0.5 mg L^{-1} as an additional stress factor (Figure 5a), it becomes apparent that temperature exhibited an even stronger negative correlation ($r = -0.47$, $p = 2.9 \times 10^{-6}$). Another parameter that may indicate anthropogenic influence and that correlated with building density is potassium ($r = 0.35$, $p = 6.5 \times 10^{-14}$). This parameter also exhibited a negative correlation with the number of major taxonomic groups ($r = -0.11$, $p = 3.1 \times 10^{-2}$).

3.4 | Dissolved Organic Carbon

The median DOC concentration in the study area was $4.1 \pm 1.55 \text{ mg L}^{-1}$. Values ranged from 1.4 mg L^{-1} to an exceptionally high value of 165.6 mg L^{-1} at a well located close to the geological fault in the city centre. Low values ($< 2.5 \text{ mg L}^{-1}$) occurred primarily in the northern rural area. Moderate DOC levels ($2.5\text{--}5 \text{ mg L}^{-1}$) were more common in the east, both in the

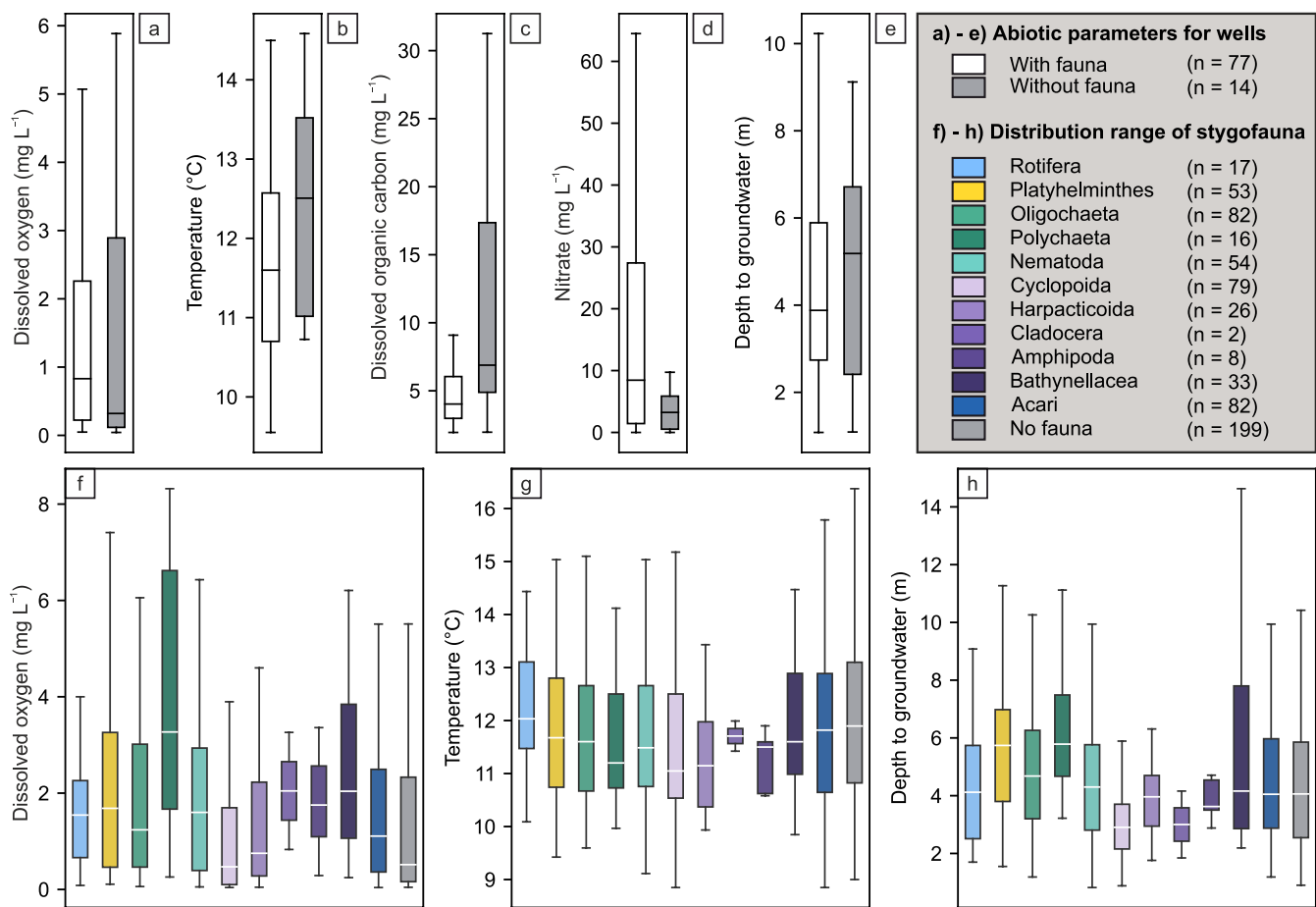


FIGURE 4 | Abiotic groundwater parameters during the observation period, displayed separately for wells with or without fauna (a–e; n = wells) and distribution range of stygofauna in response to different environmental parameters (f–h; n = samples). Boxes show the interquartile range (25th–75th percentile), the central line the median and whiskers the data range excluding outliers.

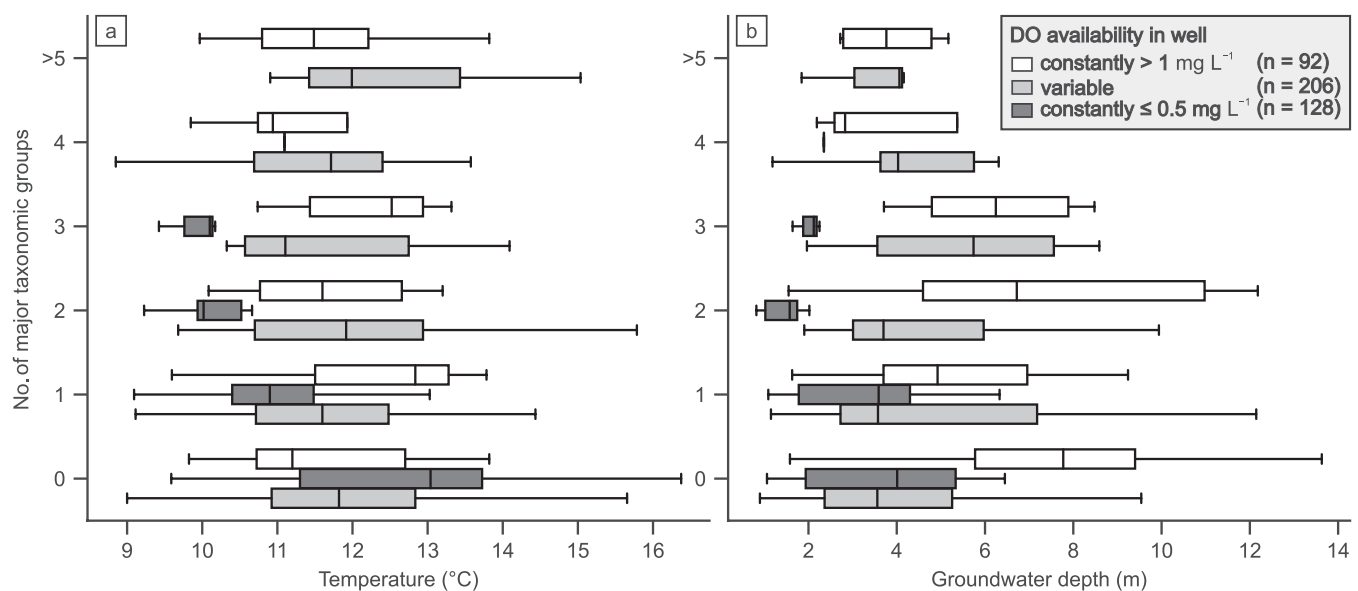


FIGURE 5 | Boxplots showing the number of major taxonomic groups in relation to (a) temperature and (b) depth to groundwater. Samples were assigned to three groups based on the dissolved oxygen (DO) availability of the respective wells over the entire monitoring period. The boxplots summarise all individual samples within each DO availability group. Boxes show the interquartile range (25th–75th percentile), the central line the median and whiskers the data range excluding outliers.

centre and in the rural areas, whereas high values ($> 5 \text{ mg L}^{-1}$) occurred mainly in the western city centre and surrounding (Figure 3c). The spatial variations could be explained by differences in land use and geological background. The DOC content correlated with building density ($r = 0.28$, $p = 3.9 \times 10^{-9}$) and was significantly higher in the urban district ($5.08 \pm 1.83 \text{ mg L}^{-1}$) than in the rural district ($2.82 \pm 0.68 \text{ mg L}^{-1}$), indicating reduced water quality and significant anthropogenic impacts downtown.

Furthermore, the discovery of a significant negative correlation between hydraulic conductivity and DOC ($r = -0.25$, $p = 1.1 \times 10^{-7}$) indicates a geological impact. Median DOC value per lithological unit (Table S8) additionally revealed that the DOC content increases with an increase in fine sediments. DOC in gravel ($3.45 \pm 1.0 \text{ mg L}^{-1}$) was significantly lower compared to sand ($3.87 \pm 1.77 \text{ mg L}^{-1}$) and silt/clay-dominated substrate ($4.15 \pm 0.98 \text{ mg L}^{-1}$). This is due to the fact that clay minerals act as an important absorbent (Chapelle 2022).

Although DOC serves as an energy source for microorganisms and consequently groundwater fauna (Saccò et al. 2022; Venarsky et al. 2023), a significant negative correlation was found between DOC concentration and the number of major taxonomic groups ($r = -0.16$, $p = 8.1 \times 10^{-4}$). DOC is often only weakly correlated with invertebrate abundance across moderate DOC gradients (Korbel and Hose 2011), whereas stronger relationships have been reported under conditions of substantial DOC enrichment (Masciopinto et al. 2006). In fact, the data demonstrate a negative correlation between DO and DOC ($r = -0.18$, $p = 3.0 \times 10^{-4}$), thus reflecting the finding that elevated DOC concentrations indicate reducing conditions and therefore unfavourable living conditions for the fauna (Kunkel et al. 2004; McDonough et al. 2020).

3.5 | Hydrogeology

No significant differences were found between fractured and porous aquifers regarding stygofauna richness. These findings contrast with previous studies, which reported an influence of aquifer type on groundwater biodiversity (Hahn and Fuchs 2009), as well as with the previously documented hydrogeological effects on DO (see Section 3.2) and DOC (see Section 3.4), both of which are key drivers for stygofauna richness.

Although previous studies have observed a correlation between groundwater biodiversity and hydraulic conductivity (Dole-Olivier et al. 2009), our study could not confirm that. However, significant differences were observed between the lithological groups in terms of total abundance, stygofauna richness and the abundance of polychaetes, cyclopoids and platyhelminthes. Lowest abundances were found in the fine-grained substrate category, which was also the group that contained the least amount of oxygen and the highest concentration of DOC. This is in line with the general assumption that fine-grained material is considered rather unfavourable for colonisation (Hahn 1996). As laboratory studies have shown, copepods (Harpacticoida and Cyclopoida) and amphipods prefer to colonise sand and gravel rather than clay (Korbel et al. 2019).

A comparison of faunal community composition in fractured aquifers with those in porous aquifers reveals only minor differences regarding the proportion of major taxonomic groups. Members of all taxonomic groups occurred in both aquifer types (Figure 2d,e). These findings are consistent with the results of Matzke et al. (2009), who did not find significant differences between faunal communities in fractured and porous aquifers of Saxony-Anhalt either.

Looking at individual groups, it was found that the proportion of crustaceans in fractured rocks exceeded that in porous aquifers. This observation is corroborated with statistical tests (U test), which also revealed significant differences with polychaetes and platyhelminthes, with higher abundances observed in the porous aquifer. Furthermore, a positive correlation was found between $C_{Cr/ol}$ and hydraulic conductivity ($r = 0.21$, $p = 1.3 \times 10^{-5}$). High conductivity is therefore associated with a more dominant occurrence of Crustaceans compared to Oligochaetes. Significant differences were obtained also regarding hydraulic conductivity and stygofauna richness. Accordingly, invertebrates like Amphipoda and Copepoda were found in wells with higher hydraulic conductivity (1.50×10^{-3} to $1.00 \times 10^{-4} \text{ m s}^{-1}$) and therefore larger available pore space. Worms like Annelida and Platyhelminthes were found in wells with lower average hydraulic conductivity ($5.00 \times 10^{-5} \text{ m s}^{-1}$).

Although our results provide a first overview of relationships between hydrogeological and faunistic data, a potential bias in the selection of wells cannot be excluded. In fact, the two aquifer types differed in terms of groundwater temperature and building density. Additionally, land use classes varied with respect to hydraulic conductivity. Moreover, a weak correlation existed between hydraulic conductivity and well depth ($r = -0.20$, $p = 4.7 \times 10^{-5}$). High hydraulic conductivities were mainly found in the Saale gravels near the surface in the floodplain area, while consolidated aquifers occurred at greater depths.

Examining the spatial distribution pattern of groundwater fauna in terms of composition revealed differences between the west and east. This could be due to the large-scale distribution of hydrogeological units, particularly the eastern and western plateaus, where the three Quaternary units differed from each other. Subdividing the geology into aquifer types, as Hahn and Fuchs (2009) proposed, did not allow these trends to be verified, which suggests that this approach is not sufficient in this case. In order to further decipher the distribution pattern of the fauna, a detailed examination of the aquifer material, flow conditions and confinement conditions should be included in the evaluation. A hydrogeological classification of the wells might be more effective on a larger scale and should be considered in future analyses. Additionally, information about the specific faunal species will provide deeper insights into the faunal composition within the different lithological groups.

3.6 | Depth to Groundwater

As nutrient and DO availability decreases with increasing depth, groundwater fauna usually varies accordingly (Hose et al. 2015). To rule out any potential impact on fauna related to depth, the selection of wells was limited to the shallow aquifer

zones (less than 23 m) with depths to groundwater table being generally low (Figure 3d). Still, groundwater in wells where no fauna was found was discovered to be at greater depths than in wells where fauna was found (Figure 4e). This finding is consistent with comparable studies conducted in Berlin (Hahn et al. 2013) and Warsaw (Dumnicka et al. 2025). However, no significant negative correlation could be obtained between depth to groundwater and the number of major taxonomic groups. This correlation becomes significant though, when decoupled from oxygen availability (Figure 5b). The number of major taxonomic groups decreased at greater depths to groundwater in both permanently low-oxygen ($r = -0.29$, $p = 5.7e-03$) and high-oxygen wells ($r = -0.29$, $p = 5.6e-03$).

Previous studies have shown that taxonomic assemblages vary along vertical gradients (Dumnicka et al. 2017; Fišer et al. 2014). In our data, this became evident by a significant correlation between $C_{Cr/Ol}$ and the depth to groundwater ($r = -0.25$, $p = 1.6e-07$), indicating a more dominant occurrence of Oligochaeta compared to Crustacea as the depth to groundwater increases. Furthermore, depth to groundwater is significantly different between faunal groups (H test). Among all major taxonomic groups, Rotifera and many Crustacea groups including Cyclopoida, Cladocera and Amphipoda occurred in wells with lower median depth of the groundwater table (<4 m), whereas worms (Oligochaeta, Polychaeta and Platyhelminthes) were found mainly in wells with a deeper median groundwater table (Figure 4h).

4 | Conclusion

This study addressed urban stressors and geological settings in its influence on groundwater fauna abundance and diversity in the shallow aquifers of the city of Halle, Germany. The faunal composition indicated spatial patterns neither reflected by the aquifer type nor by the degree of urbanisation alone. By examining the relationship between abiotic and biotic conditions, we discovered that stygofauna was substantially controlled by redox-sensitive variables but also by the distance to the groundwater table and the hydraulic conductivity. Parameters associated with an urban environment, such as elevated DOC levels, increased groundwater temperature and potassium values, showed a weak, albeit significant, negative correlation. Negative effects of elevated temperature were even more pronounced when occurring simultaneously with other stressors. Our results suggest that urban groundwater ecosystems are shaped by a complex combination of interacting factors, which should be considered in future assessments and urban planning.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available in the Supporting Information.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Data S1:** Supporting Information.