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Urban Hydrogeology of Vienna – Current state of knowledge

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8 Text-Figures, 10 Tables

Österreichische Karte 1:50.000
BMN / UTM
40 Stockerau / NM 33-12-19 Tulln an der Donau
41 Deutsch Wagram / NM 33-12-20 Wien
58 Baden / NM 33-12-25 Baden
59 Wien / NM 33-12-26 Schwechat

aquifer properties
land use
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groundwater chemistry

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Abstract

This study describes the current knowledge of the hydrogeology of Vienna, Austria. It covers information on land use, conditions for groundwater recharge, geology, aquifer types as well as on the occurrence, yield and use of groundwater in the city. For each hydrogeological unit, it summarizes the available data on depth-to-groundwater, aquifer thickness, hydraulic conductivities, dynamics, residence times and groundwater chemistry. The study is based on data from online government portals, unpublished project reports as well as publicly available literature and identifies knowledge gaps for ongoing and future research.

Hydrogeological units in Vienna comprise the easternmost parts of the Austrian Calcareous Alps, the Flysch units of the Vienna Woods, Neogene marine sediments and Quaternary fluvial deposits. With regard to the hydrogeological properties of these units, information density is highest for fluvial deposits in the eastern half of the city area and decreases towards older units situated more to the west and/or at greater depth. In view of potential water supply backup systems and their protection, it is recommended to include those units known to a lesser extent, as for example coarse-grained Neogene sediments underlying the fluvial deposits, or karst aquifers at depth, in future monitoring and sampling networks.

Zur Hydrogeologie der Stadt Wien – gegenwärtiger Wissensstand

Zusammenfassung

Der Beitrag stellt den derzeitigen Wissensstand über die Hydrogeologie der Stadt Wien (Österreich) dar. Es werden Informationen über Landnutzung, Grundwasserneubildung, Geologie, Grundwasserleiter sowie über Grundwasservorkommen, Grundwasserergiebigkeit und Grundwassernutzung innerhalb des Stadtgebietes zusammengetragen. Für jede hydrogeologische Einheit werden verfügbare Daten zu Flurabstand, Grundwassermächtigkeit, hydraulische Durchlässigkeit, Grundwasserdynamik, Grundwasserverweilzeiten und Grundwasserchemie zusammengefasst. Die Basis bilden Daten von Onlineportalen, unveröffentlichten Projektberichten und veröffentlichter Literatur. Es werden Wissenslücken und mögliche zukünftige Forschungsthemen beschrieben.

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Die hydrogeologischen Einheiten in Wien umfassen die östlichen Ausläufer der Kalkalpen, die Flyschzone im Wienerwald, Neogene marine Sedimente und quartäre Flussablagerungen. Bezüglich der hydrogeologischen Eigenschaften dieser Einheiten ist die Informationsdichte für die postglazialen Flussablagerungen der Donau in der östlichen Stadthälfte am höchsten, während sie für ältere Einheiten gegen Westen und in der Tiefe abnimmt. Im Hinblick auf mögliche Wasserversorgungsgebiete und deren Schutz wird empfohlen, bei zukünftigen Monitoring- und Beprobungskampagnen diese weniger gut erforschten Einheiten, wie zum Beispiel grobkörnige neogene Sedimente unterhalb quartärer Ablagerungen oder Karstaquifere in größerer Tiefe, mit zu berücksichtigen.

Introduction

The city of Vienna does not depend on urban groundwater for its drinking water supply. Since 1837, Vienna's drinking water is provided mainly by Alpine karst springs captured up to 120 km southwest of the city. Nonetheless, groundwater within the city area is widely used for irrigation, geothermal heat extraction and, to a lesser extent, for industrial and drinking water purposes. According to the Austrian Water Act, groundwater has to be protected to the extent that drinking water quality is ensured (BMNT, 2018, Wasserrechtsgesetz 1959 idgF.). Information on urban groundwater in Vienna is therefore important not only to secure a sustainable supply but also to protect its quality.

Numerous studies describe single aspects of Vienna's groundwater or cover parts of the city area or individual aquifers (e.g. Götzinger, 1951; Schuch, 1980; Schügerl et al., 1988; Erhart-Schippek & Niederbacher, 1995; Donauconsult, 1997; Grupe, 2011, 2012, 2013; Grupe & Payer, 2009, 2010, 2014, 2015, 2017, 2018; Grupe et al., 2016). A brief overview of hydrogeological units within the entire city area is given by the Municipal Department of Water Management (https://www.wien.gv.at/umwelt/gewaesser/schutz/hydrografie/grundwasser/hydrogeologie.html). However, detailed investigations including all aspects of urban hydrogeology and covering the entire city area date back to the 1980s (Lebeth at al., 1988; Lebeth, 1989).

The present review compiles hydrogeological data available from online government portals, unpublished project reports as well as from publicly available literature. It covers all relevant aspects of hydrogeology such as land use, conditions for groundwater recharge, geology, aquifer types as well as the occurrence, yield, use and quality of groundwater in the city. By collecting and analysing data on depth-to-groundwater, aquifer thickness, hydraulic conductivities, dynamics, residence times and groundwater chemistry separately for each hydrogeological unit, the paper takes an encompassing, holistic approach to, and presents the current knowledge of, Vienna's urban hydrogeology.

Data sources

Land use data for the city area of Vienna are available online as part of the EU Copernicus Urban Atlas (http://www.eea.europa.eu/data-and-maps/data/urban-atlas; EU Copernicus, 2016). This data set is based on a classification of multispectral satellite imagery with a 2.5 m spatial resolution and was published by the Copernicus Land Monitoring Service in 2012. Land use classes include urban fabric (five density classes), forests, parks, agricultural, industrial and traffic areas, and water bodies. A second data source constitutes the multi-purpose, digital city map issued as open government data by Vienna's Surveyors Department (https://www.wien.gv.at/stadtentwicklung/stadtvermessung/geodaten/mzk/index.html; MA 41, 2019). It is based on triangulation measurements with centimetre accuracy and distinguishes 51 land use classes. This data set was most recently updated in 2016. Both data sets allow for identification of sealed areas, which prevent rainwater infiltration, and, together with geological maps, to describe groundwater recharge.

Geological and lithological information was obtained from maps published by the Geological Survey of Austria at a scale of 1:200,000 (Schnabel et al., 2002) and 1:50,000 (Hofmann & Pfleiderer, 2003). Lithological descriptions of geological units were interpreted in terms of aquifer type. For maps and figures, the network of streams and rivers was downloaded as open government data from Vienna's Surveyors Department (https://www.wien.gv.at/ma41datenviewer/public).

The register of groundwater extraction licences, maintained by the Municipal Department of Water Management, was accessed in order to compile well location, types of groundwater use and abstraction limits. The latter were used to estimate groundwater yield of each hydrogeological unit. For deep aquifers, the depth information contained in the Water Rights Register was combined with a 3D geological model of Vienna's subsurface (Pfleiderer & Hofmann, 2004) to estimate groundwater yield. The register currently contains data for 3,127 extraction sites, however, no data exist within the area of the Calcareous Alps.

The depth-to-groundwater was obtained by querying the online data portal of the Hydrological Service (https://ehyd.gv.at). This portal contains the location of Austria's official groundwater monitoring stations and allows the download of time series of absolute heights of the uppermost water table including statistical parameters such as yearly maximum or minimum levels. The time series used here covered the period between 1996 and 2015. 38 monitoring stations were queried, all lying within Neogene and Quaternary sediment units. Together with the digital elevation model, provided by Vienna's Surveyors Department (https://www.wien.gv.at/ma41datenviewer/public), depth-to-groundwater was calculated. Combining the base level of aquifers, provided by the 3D geological model, with water table data enabled the calculation of groundwater thickness, albeit only for Quaternary deposits.

For Neogene and Quaternary sediments, 169 hydraulic conductivity data were derived by Pfleiderer & Hofmann (2004) using grain size distribution data (Beyer & Schweiger, 1969). In addition, 70 pumping test results were compiled from reports included in the Water Rights Register. Hydraulic gradients were extracted from groundwater table maps and groundwater flow velocities were calculated using the Darcy formula. Such groundwater table maps however only exist in the area east of the river Danube, and between the Danube River and the Danube canal (Blaschke et al., 1992; Pfleiderer & Hofmann, 2004; Gruppe Wasser, 2005; Pöyry, 2011).

Groundwater dynamics in porous aquifers were described by water table variations between 1996 and 2015 using 38 monitoring stations included in the data portal of the Hydrological Service. In fractured and karst aquifers, the ratio of maximum to minimum groundwater discharge of 12 springs monitored monthly during one year (Pfleiderer et al., 2010), were used to describe groundwater dynamics.

Groundwater residence times are published online by the Environment Agency Austria through an interactive map, which includes the results of all groundwater isotope studies performed in Austria (https://secure.umweltbundesamt.at/webgis-portal/isotopen/map.xhtml; Kralik et al., 2015). However, within Vienna's city area information on residence times is available only at 13 locations in the Danube plain and in younger terraces, and at one location for the deep thermal aquifers of the Calcareous Alps (Oberlaa).

Hydrochemical data were compiled for all hydrogeological units using three data sources. (1) Regular monitoring of groundwater quality is performed twice a year by the Municipal Department of Water Management at monitoring stations in the Danube plain, in alluvial deposits of tributary rivers and in younger terraces. Data can be viewed online via a portal hosted by the Environment Agency Austria (https://wasser.umweltbundesamt.at/h2odb). For this study, analyses of major ion and trace element concentrations, taken at 50 wells between 2015 and 2018, were used. (2) For the Flysch zone and the Calcareous Alps, hydrochemical analyses of major ion and trace element concentrations were sourced from a study commissioned by the Municipal Department of Water Management, which sampled 12 springs in monthly intervals during a period between October 2009 and September 2010 (Pfleiderer et al., 2010). (3) The archives of the Geological Survey of Austria contain additional hydrochemical analyses of groundwater samples from all hydrogeological units, taken between 1961 and 1994 and only include major ion concentrations. 42 of these analyses were considered reliable to describe groundwater chemistry.

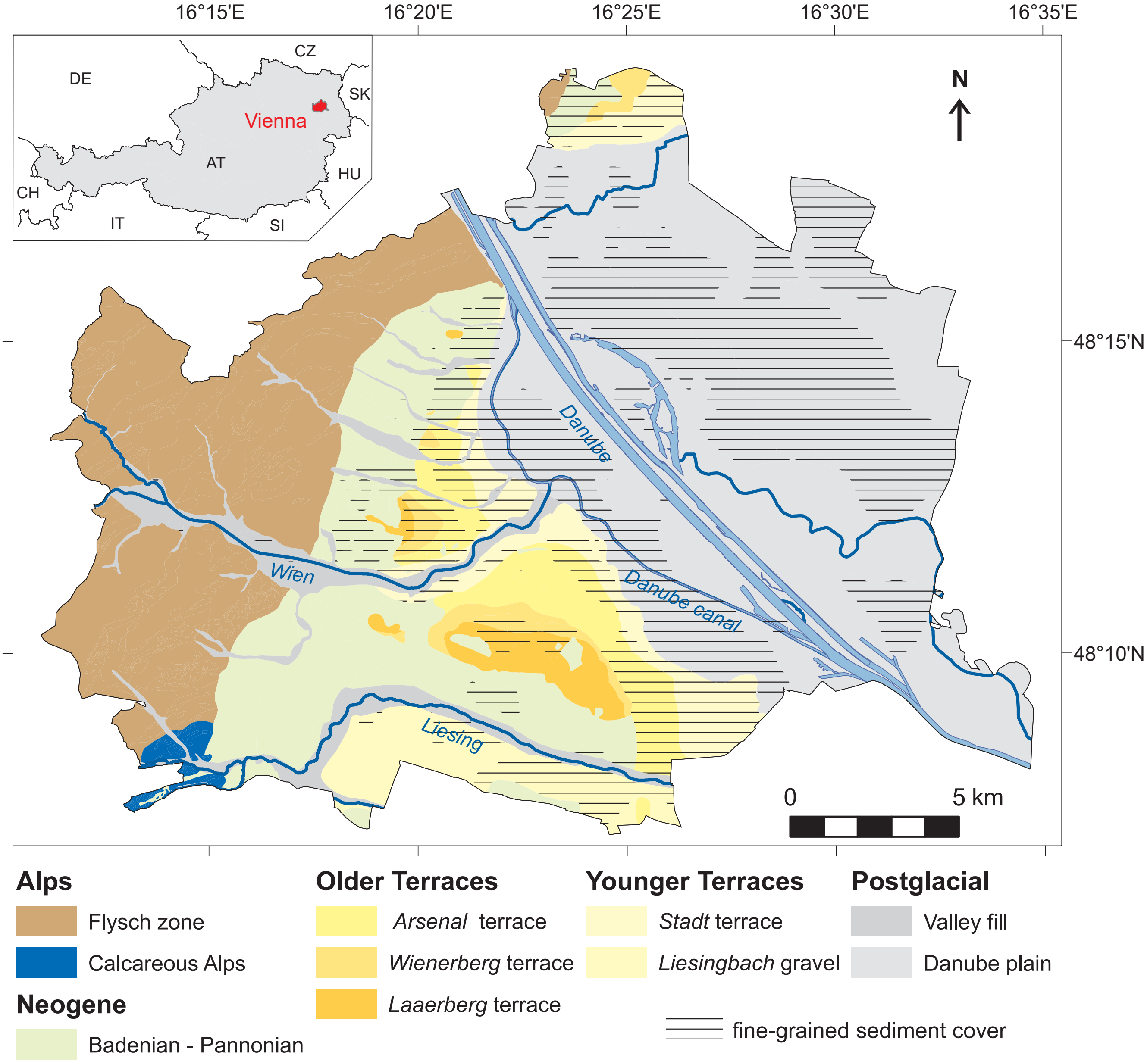
Characteristics of hydrogeological units

The geological map 1:50,000 (Hofmann & Pfleiderer, 2003) forms the basis for identifying hydrogeological units. Geological units of this map were aggregated based on similar hydrological properties and aquifer type. Seven hydrogeological units were identified (Text-Fig. 1).

- The Calcareous Alps in the Southwest are made of limestones and dolomites and constitute karst aquifers.
- The Flysch zone in the western part of the city is made of sandstones, claystones and marlstones. Of these, the sandstone units yield groundwater in separate, partially confined, fractured aquifers.
- The Neogene sediments represent predominantly marine silt and clay deposits with sand and gravel intercalations. In particular near the Flysch zone (Badenian, Sarmatian), and in the Danube plain (Upper Pannonian), sandy gravel deposits are present. These form several, partially connected and partially artesian, porous aquifers. Locally, calcarenites occur within the Badenian and sandstones within the Sarmatian. These occurrences however do not constitute relevant groundwater bodies.
- Among the Pleistocene fluvial sediments, the older terraces (*Laaerberg*, *Wienerberg* and *Arsenal* terraces) represent sandy gravel deposits with a significant portion of sand and silt intercalations. Gravel components comprise rounded pebbles, predominantly consisting of quartz, crystalline and carbonate components, as well as platy sandstone pebbles. These terraces were deposited by the river Danube and constitute local, unconfined aquifers, partially covered by loess. Groundwater flows intermittently along subsurface channels prescribed by the morphology of the impermeable Neogene base.
- The younger Pleistocene sediments (*Stadt* terrace and *Liesingbach* gravel) also represent sandy gravel deposits, but with fewer sand and silt intercalations which form thin beds, sometimes of wide lateral extent. Gravel components comprise rounded pebbles, predominantly consisting of quartz, crystalline and carbonate components, as well as platy sandstone pebbles. The local, unconfined aquifers are partially covered by loess and hydraulically linked to the Danube plain aquifer.
- Postglacial sediments in the Danube plain consist of sandy gravel (rounded pebbles, predominantly consisting of quartz, crystalline and carbonate components) with thin silt intercalations of limited lateral extent. Locally, fine-grained flood plain deposits cover these sediments. Groundwater in the continuous, unconfined aquifer flows parallel to the Danube River. Where the underlying Pannonian sediments are fine-grained, these form the impermeable base of the aquifer. Where Pannonian sand or gravel deposits form the top of the Neogene, they are part of the Danube plain aquifer.
- Valley fill deposits along the tributary rivers from the West (e.g. the rivers Wien and Liesing) represent silt, sand and gravel (predominantly platy sandstone pebbles) deposits. Groundwater is linked, and flows parallel to these streams. Within the central part of the city area, the rivers are mostly channelled and flow underground.

Aquifer properties

Characteristic values for depth-to-groundwater are given for Neogene and Quaternary units in Table 1. In general, the interquartile ranges amount to 4–6 m, but can reach up to 11 m and 19 m within older terraces and the *Stadt* terrace, respectively. For Quaternary units, Table 1 also includes the interquartile range of values for groundwater thickness, ranging between 0.5 m and 2 m in older terraces and tributary valleys, and between 3 m and 10 m in younger terraces and in the Danube plain. The location of



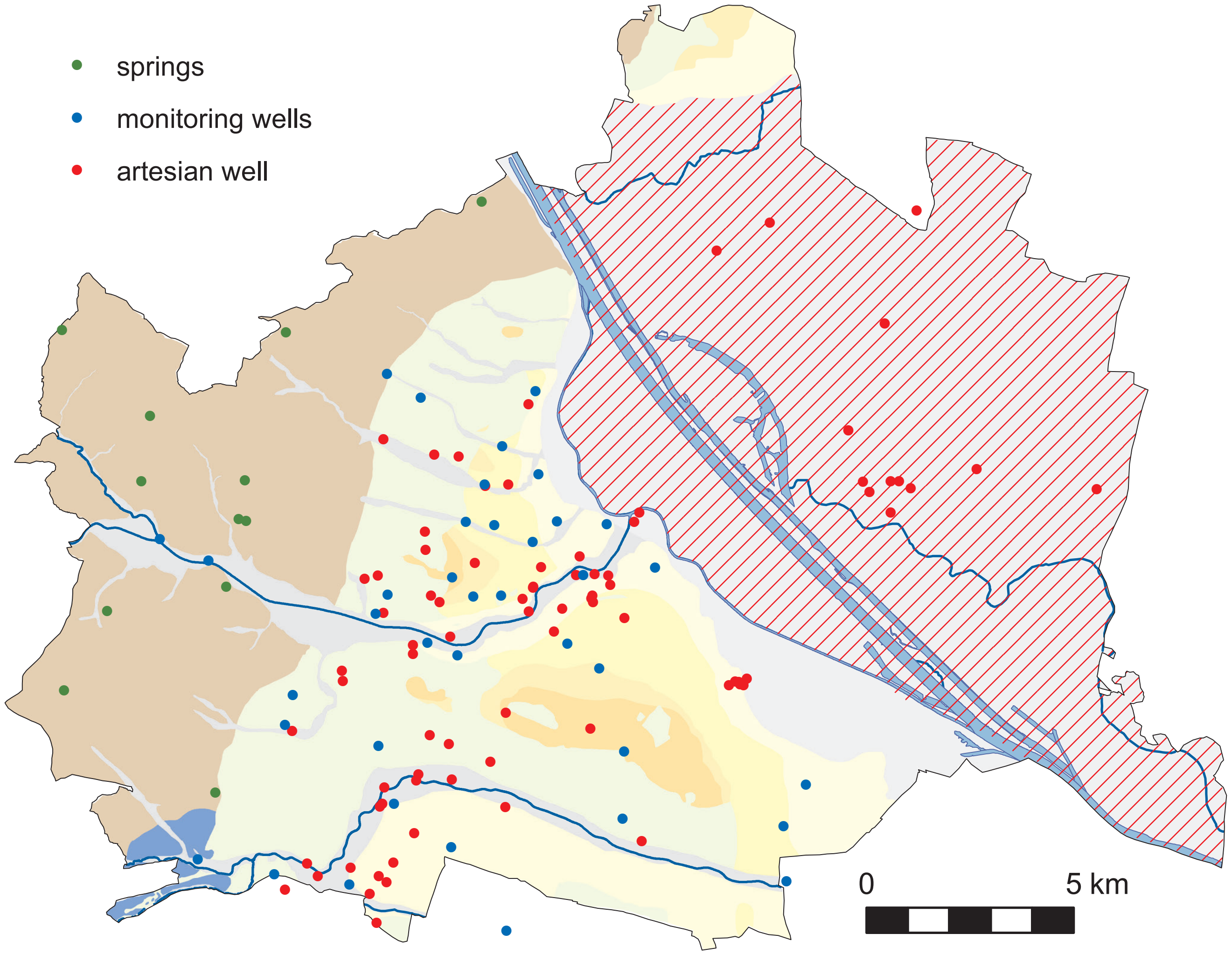
Text-Fig. 1.
Simplified geological map of Vienna (after Hofmann & Pfleiderer, 2003).

monitoring wells used to derive this information west of the Danube Canal is shown in Text-Figure 2. East of the Danube, and between the Danube River and the Danube canal, the information (Tabs. 1, 2) was derived from mean groundwater table maps (Gruppe Wasser, 2005; Pöyry, 2011).

The values cited for Neogene aquifers in Table 1 are representative for unconfined aquifers observed in wells where Neogene sediments appear at the surface east of the Flysch zone. For confined aquifers, no detailed information on hydraulic heads is publicly available. It is however known, that hydraulic heads often lie above ground (Schubert, 2015). Text-Figure 2 shows the location of 80 artesian wells, compiled by Schubert (2015). They represent groundwater levels in deeper layers of Neogene sediments, often overlain by Quaternary deposits. Concerning the groundwater thickness in Neogene sediments, information is available from cross-sections such as the one shown in Text-Figure 7 (Nowy et al., 2001), and from well

	Neogene (9)	older terraces (10)	younger terraces (7)	Danube plain (derived from maps)	valley fill (11)
depth-to-groundwater	4–6	5–11	*Stadt* terrace: 11–19 *Liesingbach* gravel: 5	4–6	4–5
groundwater thickness	no information	0.5–1.5	*Stadt* terrace: 3–6	4–10	1–2

Tab. 1.
Depth-to-groundwater and groundwater thickness of porous aquifers in Vienna (q_{25}–q_{75}) in Meter. Data count in brackets.



Text-Fig. 2.
Wells and springs used to derive depth-to-groundwater, groundwater thickness and dynamics; artesian wells in Vienna (Schubert, 2015). Areas where mean groundwater table maps were used, are hatched in red.

logs. Niederbacher et al. (1995) estimate the cumulative thickness of coarse-grained layers within the top 300 m of the Neogene in the Danube plain to be 80 m.

In porous aquifers, the water table variations over time give an indication of groundwater dynamics (Tab. 2). Interquartile ranges generally lie between 0.1 m and 1 m and show no significant differences between hydrogeological units. In the Danube plain east of the Danube River, the groundwater table is hydraulically linked to the river level, while the groundwater table between the Danube River and the Danube canal is uncoupled from the river and artificially controlled (Dreher & Gunatilaka, 2008). In the other hydrogeological units, the groundwater table is free to vary according to recharge from precipitation.

To express the dynamics in fractured aquifers of the Flysch zone and in karst aquifers of the Calcareous Alps, the ratio of maximum to minimum groundwater discharge is listed in Table 2. The location of springs used to derive this information is shown in Text-Figure 2. A distinct difference is present between highly dynamic springs in the Flysch zone and more constant discharge of springs in the Calcareous Alps.

Characteristic values for hydraulic conductivities in the older terraces and the Danube plain (postglacial gravel and Neogene coarse-grained deposits, are listed in Table 3. For the Danube plain, the values agree with results from pumping test performed in previous studies (Schuch, 1980; Schügerl et al., 1988; Fürnkranz, 1990; van Husen,

	Calcareous Alps (1)	**Flysch zone (11)**	**Neogene (9)**	**older terraces (10)**	**younger terraces (7)**	**Danube plain (derived from maps)**	**valley fill (11)**
water table variation (m)			0.2–0.7	0.2–0.5	*Stadt* terrace: 0.1–0.5 *Liesingbach* gravel: 0.4–0.9	0.5–1	0.2–1
max/min groundwater discharge	4	13–39					

Tab. 2.
Groundwater dynamics of aquifers in Vienna (q_{25}–q_{75}). Data count in brackets.

	Neogene underlying Quaternary sediments	Danube plain
hydraulic conductivity (m/s) derived from grain size	5×10^{-5}–2×10^{-4}, 1×10^{-3} (120)	1×10^{-4}–1×10^{-3}, 2×10^{-3} (48)
hydraulic conductivity (m/s) derived from pumping test	6×10^{-5}–2×10^{-4}, 4×10^{-4} (4)	2×10^{-3}–8×10^{-3}, 7×10^{-2} (66)
groundwater flow velocity (m/day)		0.01–0.3, 4.6

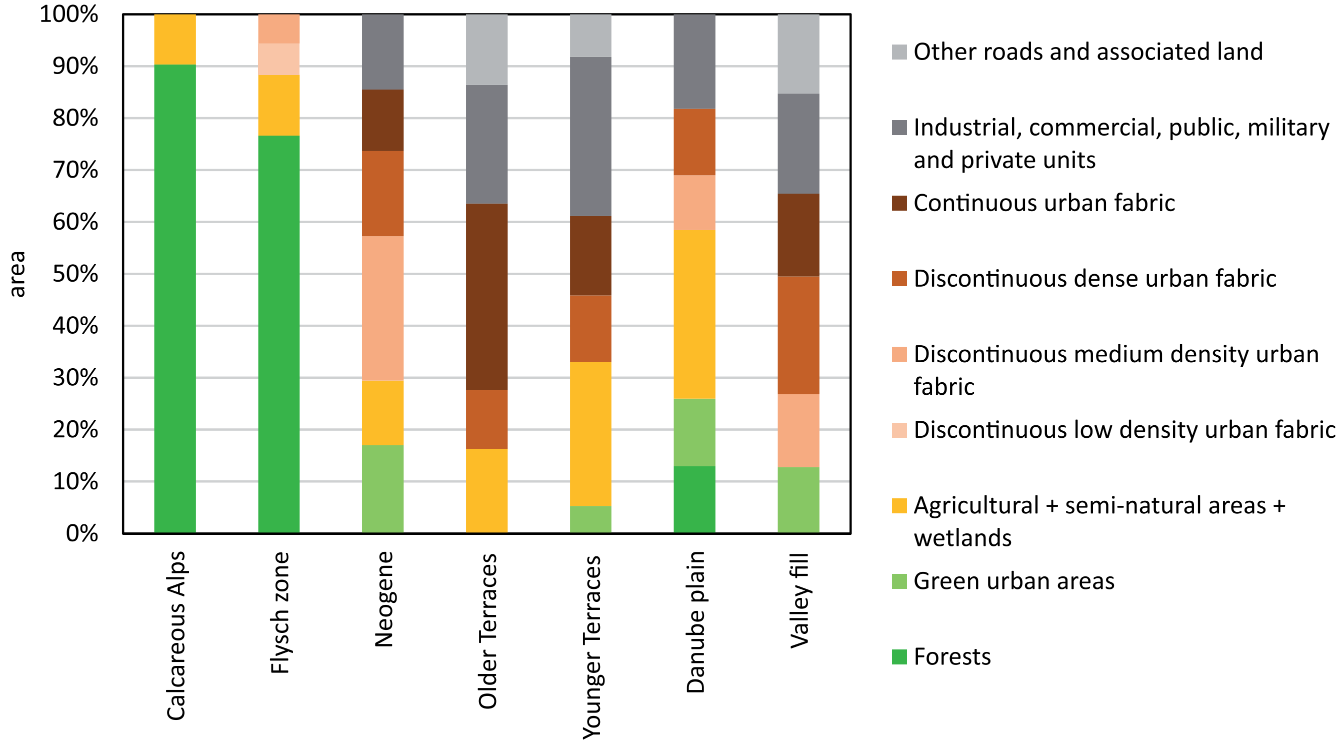
Tab. 3.
Hydraulic conductivities and flow velocities of porous aquifers in Vienna (q_{25}–q_{75}, maximum). Data count in brackets.

1990). For Neogene, coarse-grained layers underlying Quaternary sediments, median hydraulic conductivity values are lower than Danube plain gravel by a factor of 40.

In the Danube plain, hydraulic gradients were derived from groundwater table maps. These gradients range from 0.4 ‰ to 0.8 ‰ and groundwater flow velocities were calculated to lie between 0.01 m/day and 0.3 m/day, with a maximum of 4.6 m/day (Tab. 3).

Land use

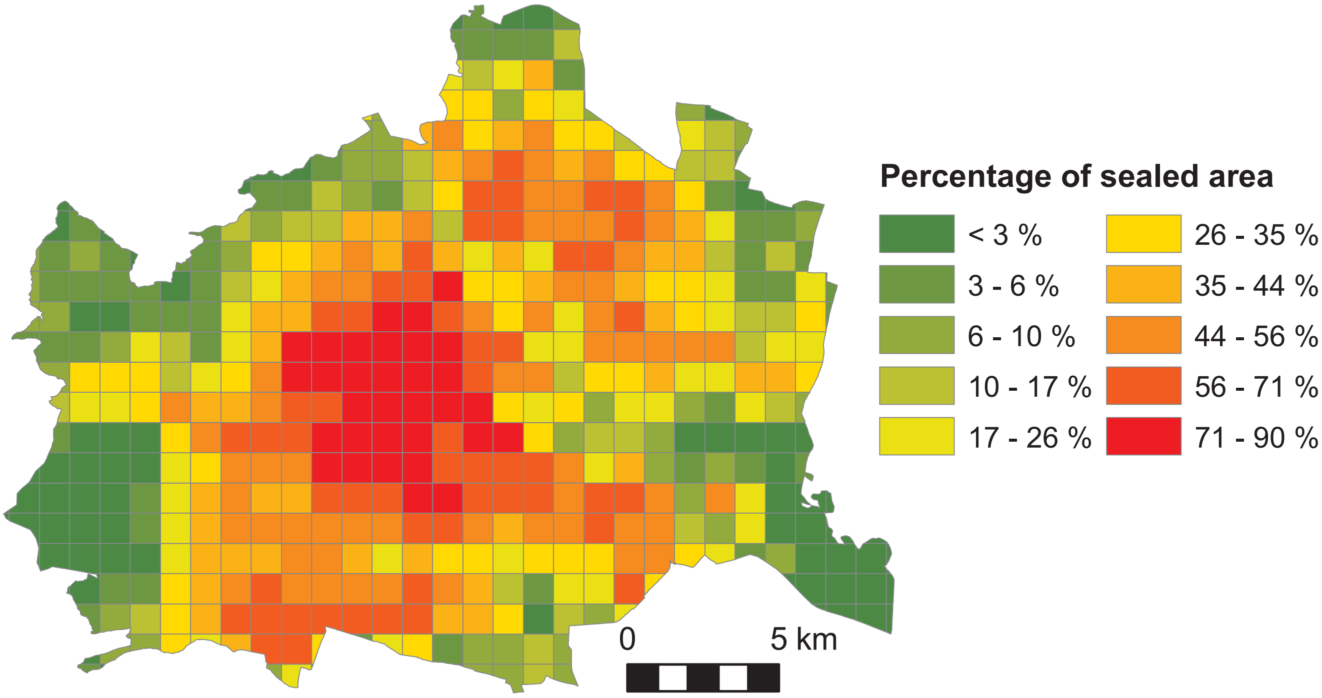
Due to their geographic position within the city area, the hydrogeological units display different percentages of land use classes according to the EU Copernicus Urban Atlas (Text-Fig. 3). While the Calcareous Alps and the Flysch zone in the West are covered mostly by forest, urban fabric dominates within the Neogene, the Pleistocene terraces and the valleys of tributary streams. In contrast, the Danube plain is characterised by large agricultural areas.



Text-Fig. 3.
Land use within hydrogeological units according to the Urban Atlas (EU Copernicus, 2016).

Hydrogeological unit	Recharge conditions	Percentage of sealed area
valley fill	Strongly reduced recharge due to sealing, possible infiltration from leaky sewage systems.	53
Danube plain	Reduced recharge due to sealing and loam cover, river filtrate of the Danube River east of the Danube, artificial infiltration of Danube River water into the groundwater between the Danube River and the Danube canal.	31
younger terraces	Strongly reduced recharge due to sealing and loess cover, possible infiltration from leaky sewage systems.	48
older terraces	Strongly reduced recharge due to sealing and loess cover, possible infiltration from leaky sewage systems.	56
Neogene	Strongly reduced recharge due to sealing and loess cover, possible infiltration from leaky sewage systems.	43
Flysch zone	High infiltration rates in sandstones, strongly reduced recharge in clay- and marlstones.	10
Calcareous Alps	High infiltration rates.	5

Tab. 4.
Conditions for groundwater recharge within hydrogeological units.



Text-Fig. 4.
Percentages of area sealed against rainwater infiltration as derived from Vienna's multi-purpose city map (MA 41, 2019).

The regional distribution of land use classes has implications not only for possible contamination sources for, but also for the recharge rate of, groundwater. The degree of sealing was derived from the multi-purpose city map by calculating percentages within regular cells of 1 x 1 km (Text-Fig. 4). Forest and agricultural areas located in the West and East show < 10 % sealed area, while in the city centre values increase up to 90 %. In the Neogene, the Pleistocene terraces and the valleys fill units, sealed areas amount to 44–57 % (Tab. 4).

In addition to surface sealing through infrastructure, fine-grained sediments such as loess or loam partially cover some of the hydrogeological units and restrict rainwater infiltration (Text-Fig. 1). On the other hand, some artificial groundwater recharge is assumed to take place through leaky sewage pipes and channels. With the currently available data sets, groundwater recharge rates cannot be calculated, nevertheless, Table 4 describes the condition for groundwater recharge within hydrogeological units.

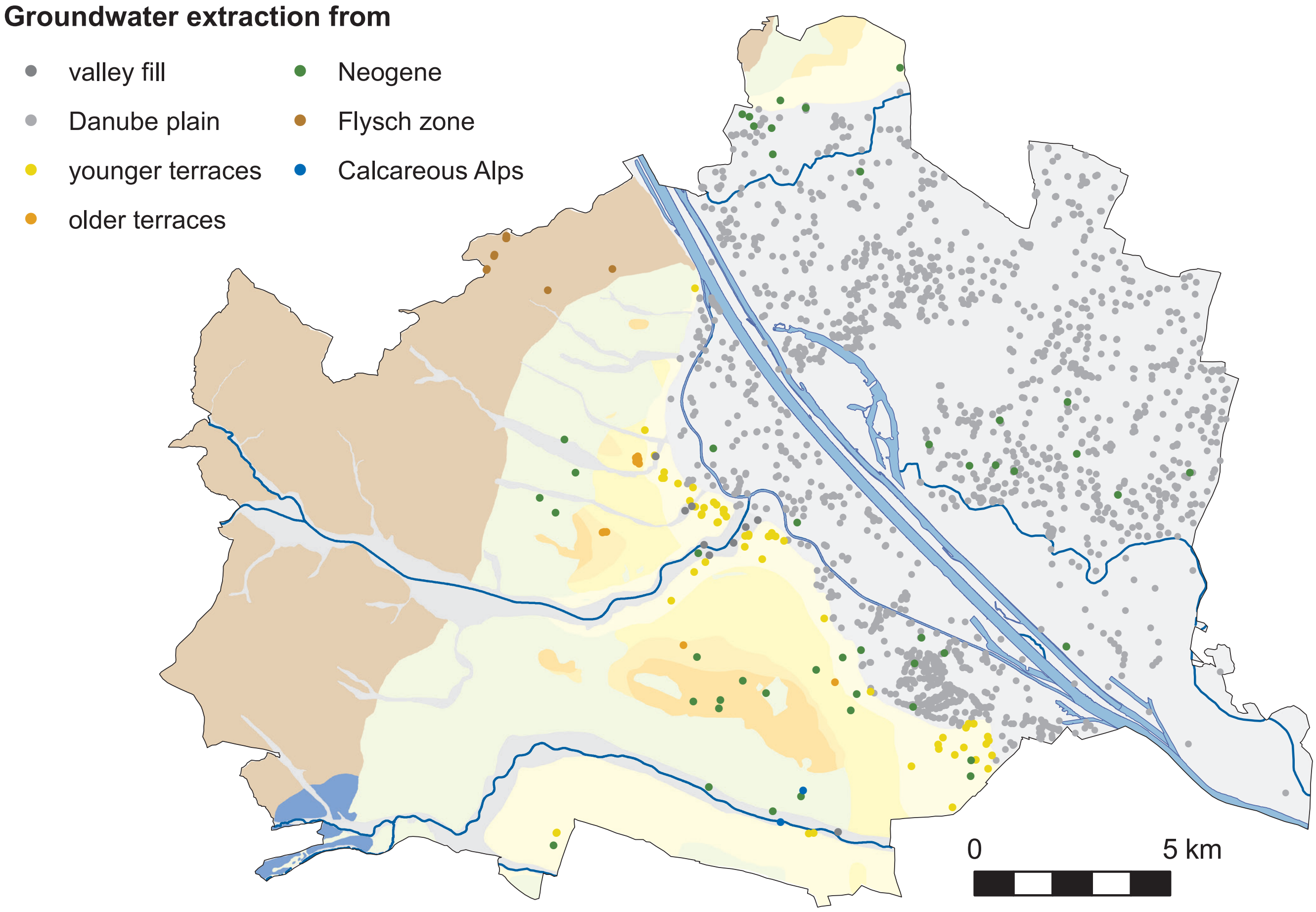
Groundwater use

The most intensive use of groundwater takes place in postglacial gravel sediments of the Danube plain. In Vienna's Water Rights Register, 1,777 groundwater extraction sites are currently registered within this unit. The younger terraces (mostly the *Stadt* terrace) and the Neogene sediments (mostly Pannonian deposits underlying postglacial sediments in the Danube plain) are used at 57 and 46 sites, respectively. Distinctly less used is the groundwater in the Flysch zone, the older terraces and in valley fills (9, 10 and 8 sites, respectively). From carbonate aquifers of the Calcareous Alps, deep thermal groundwater is extracted at 2 wells for thermal use (spa Oberlaa). Text-Figure 5 shows the location, Text-Figure 6 the number of extraction sites for each hydrogeological unit, specifying the types of groundwater use.

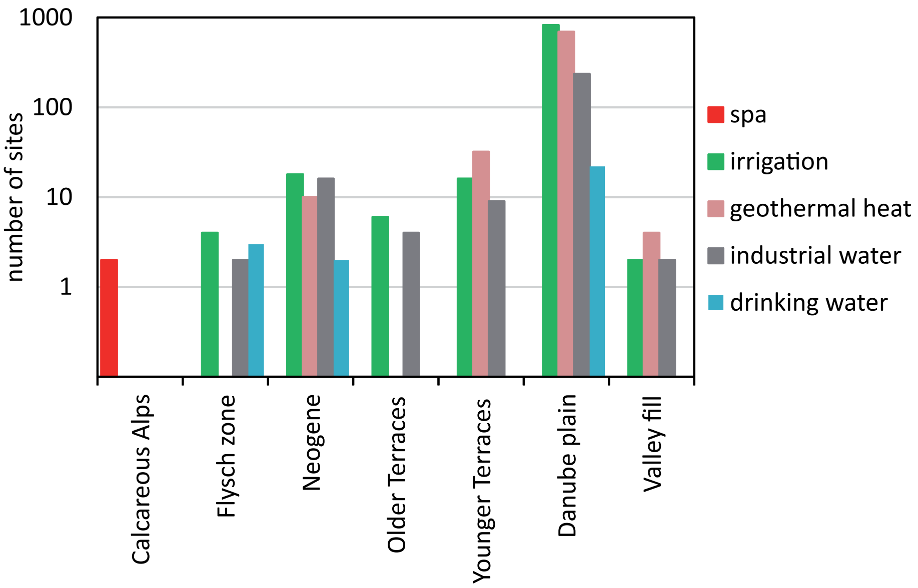
Table 5 compares the abstraction limits, giving interquartile ranges and maxima of all wells within hydrogeological units. A clear grouping emerges with postglacial sediments of the Danube plain displaying the highest values (max. 16.9 m^3/s), followed by Neogene (particularly the Upper Pannonian and Sarmatian) layers underlying these

Flysch zone	Neogene	older terraces	younger terraces	Danube plain	valley fill
0.8–3, 3 (9)	Sarmatian: 1–2, 2.5 (4) Badenian: 5 (1)	23–25, 25 (10)	*Stadt* terrace: 2–6, 27 (53) *Liesingbach* gravel: 1 (4)	1–11, 16,948 (1,822)	2–8, 11 (9)
Calcareous Alps (deep geothermal aquifer)		**Neogene underlying Quaternary sediments**			
62 (2)		Upper Pannonian: 3–12, 81 (22) Middle Pannonian: 0.5–2, 6 (12) Sarmatian: 2–7, 40 (6) Badenian: 1–4, 7 (3)			

Tab. 5.
Abstraction limits of groundwater wells grouped by hydrogeological unit (q_{25}–q_{75}, maximum) in l/s. Data count in brackets.



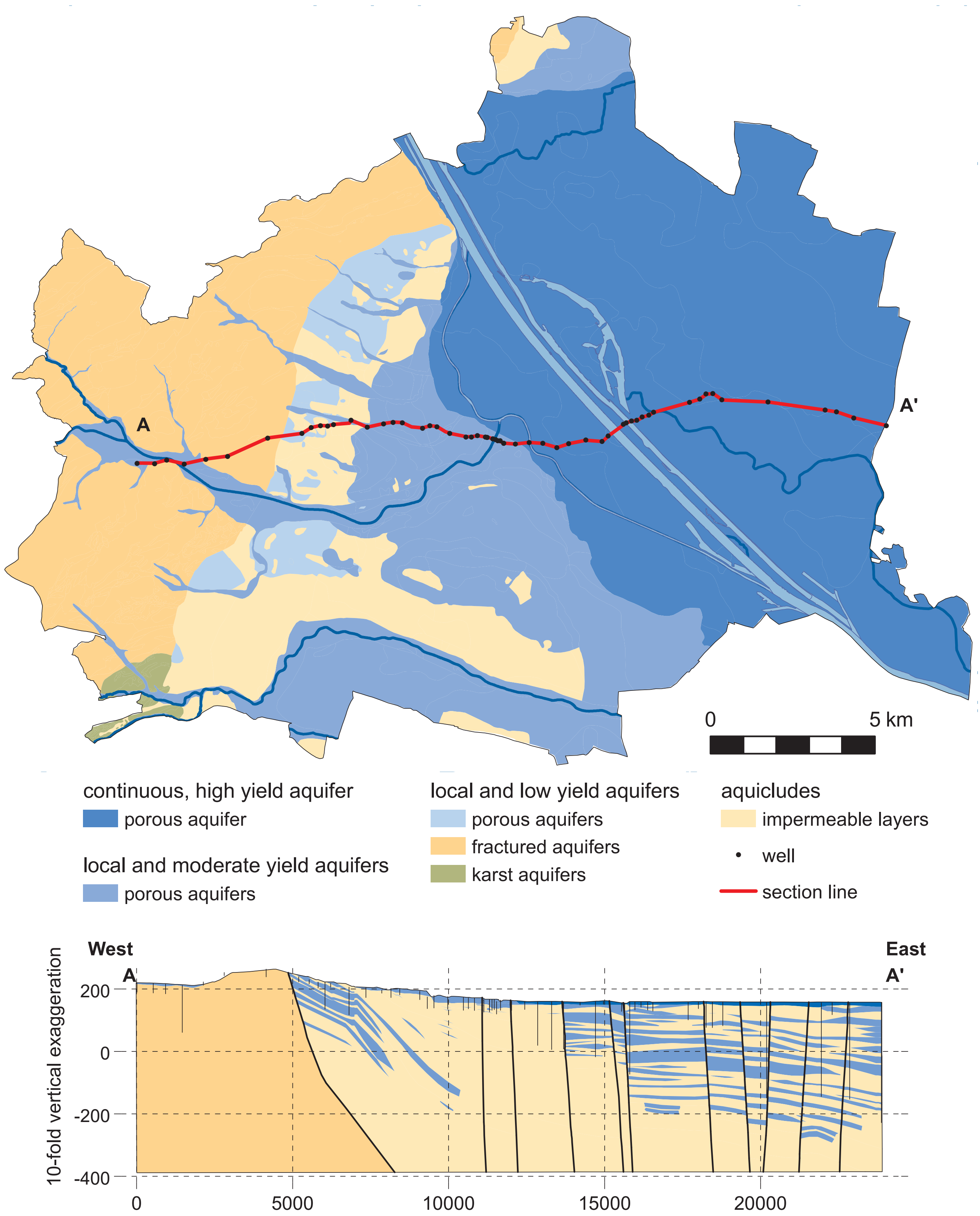
Text-Fig. 5.
Location of groundwater extraction sites grouped by hydrogeological unit.



Text-Fig. 6.
Number of groundwater extraction sites and types of groundwater use, grouped by hydrogeological unit.

sediments in the Danube plain (max. 81 l/s). The terraces and valley fill take third place (max. 27 l/s and 11 l/s, respectively). Abstraction limits in the Flysch zone only reach a maximum of 3 l/s. As a special case, a total of 62 l/s are permitted to be extracted from 2 wells in the deep thermal carbonate aquifers at Oberlaa (Elster et al., 2016).

Although abstraction limits do not directly reflect groundwater yield, the data were used here as indicators to group aquifers according to their potential yield (Text-Fig. 7). At the surface, the Danube plain aquifer represents the only continuous, high yield, porous aquifer in Vienna. Discontinuous, porous aquifers with moderate yield include the younger and older terraces and the valley fill sediments. Even less yield is to be expected from Neogene units east of the Flysch zone although some important water supply sites here extract groundwater from coarse-grained lay-



Text-Fig. 7.
Aquifer types in Vienna, grouped by relative yield, and cross-section (Nowy et al., 2001).

ers. Among the low yield aquifers, fractured aquifers of the Flysch zone and karst aquifers of the Calcareous Alps form separate groups due to their aquifer type. Text-Figure 7 includes a hydrogeological cross-section (modified from Nowy et al., 2001) showing coarse-grained layers within the Neogene which represent moderate to high yield, porous aquifers at depth.

Calcareous Alps (deep geothermal aquifer) (1)	younger terraces (3)	Danube plain (10)
> 10,000 years	< 5 years	< 5 years

Tab. 6.
Groundwater residence times in hydrogeological units (Kralik et al., 2015; Eichinger, 2009). Data count in brackets.

Groundwater residence times

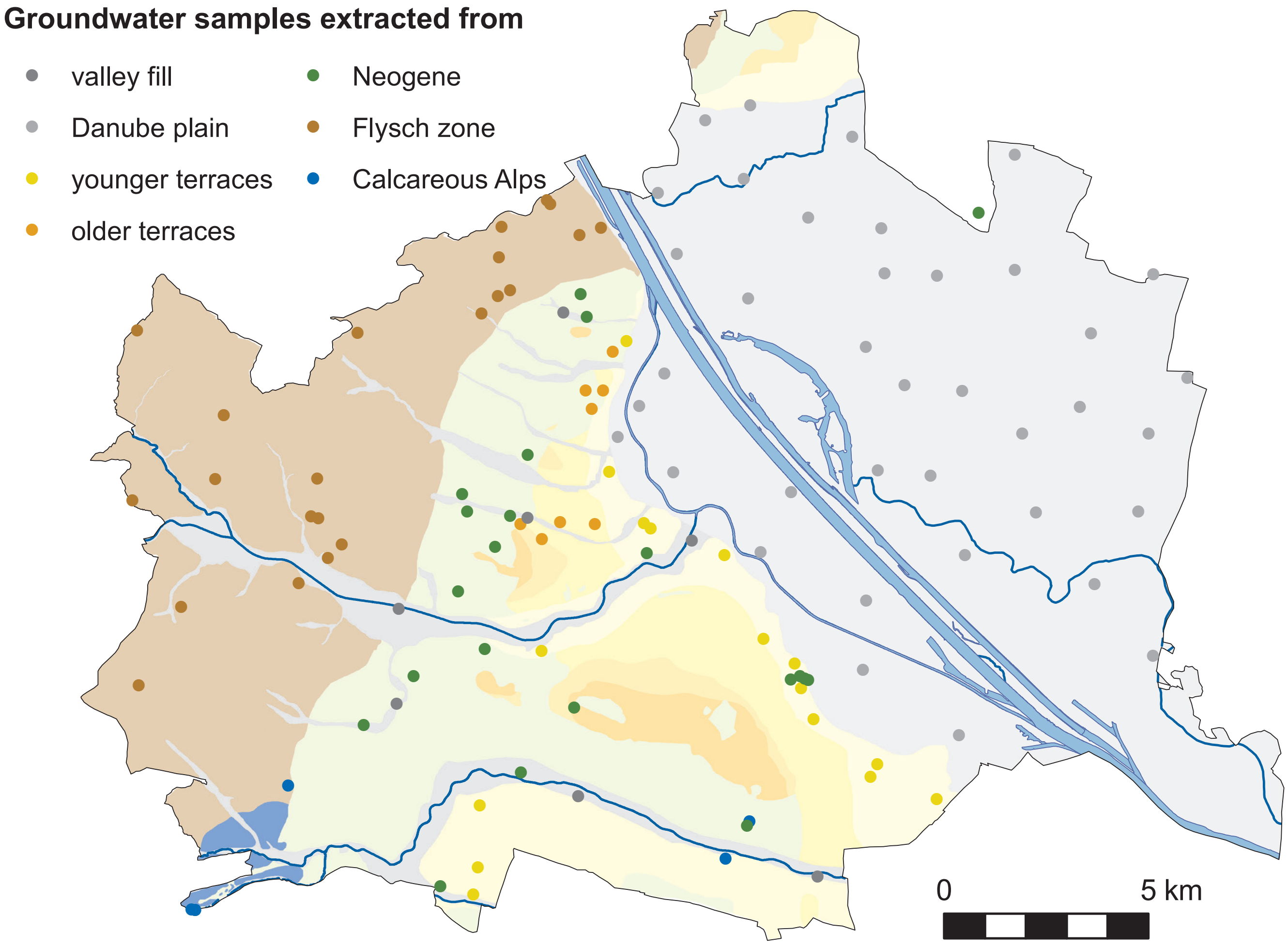
Table 6 lists groundwater residence times derived from ^3H isotope data and published in the Austrian Water Isotope Map (Kralik et al., 2015). The analyses in the Danube plain and in younger terraces show that the groundwater here infiltrated into the aquifer less than five years ago. This is not surprising in the light of high flow velocities, Danube river water infiltration and groundwater recharge through precipitation. The thermal groundwater at Oberlaa contains no tritium suggesting a residence time of > 60 years. The circulation system of this deep aquifer was explained by Wessely (1983). According to Eichinger et al. (2009), the thermal water entered the underground circulation system during the last ice age (> 10,000 years ago).

Groundwater chemistry

Text-Figure 8 shows the location of groundwater samples, Table 7 lists median values of major ion concentration in the samples, grouped by hydrogeological unit. In general, values are highest in the groundwater of postglacial deposits and decrease towards the Pleistocene and Neogene deposits, the Flysch zone and the Calcareous Alps, which show the lowest concentrations.

Some samples contain elevated concentrations of Fe, Mn, NO_2, NO_3 or SO_4. Table 8 shows the percentages of samples exceeding the Austrian National Guideline values for drinking water (Trinkwasserverordnung 2001 idgF.). For example, 20 % of groundwater samples in the Flysch zone exceed Mn concentrations of 50 µg/l. These samples also show sporadically high Fe concentrations (> 200 µg/l). The natural chemical composition of Flysch rocks is the most likely cause for this (Pfleiderer et al., 2010). The frequent exceedance of Fe, Mn and Na concentrations in groundwater within Neogene units may also have natural causes, as samples here were taken at great depth (100 m below ground on average) and are thus more highly mineralised.

On the other hand, 25 % of groundwater samples in the Danube plain, and 50 % of groundwater samples in the



Text-Fig. 8.
Location of samples used for the description of groundwater chemistry.

Parameter	valley fill	Danube plain	younger terraces	older terraces	Neogene	Flysch zone	Calcareous Alps	Calcareous Alps (deep geothermal aquifer)
Number of analyses	2	284	57	6	18	129	13	3
Ca (mg/l)	165.1	116.5	112.25	112.21	96	143.84	92.288	446.6
Cl (mg/l)	40	100.745	51.9175	40	26	13.73	14.373	840
Fe (mg/l)	0.07	0.005	0.0075		0.135	0.014	0.025	< 0.015
H_2SiO_3 (mg/l)						18.36	8.955	42.9
HCO_3 (mg/l)	452	392	399.5	385.5	422	407	328.92	263.5
K (mg/l)		9.7175	6.515		2	2.3275	2.01	23.8
Mg (mg/l)	48.55	41.7	65.995	60.61	30.16	24.62	21.015	133
Mn (mg/l)	0.03	0.0015	0.0015		0.1	0.0023	0.0007	< 0.015
Na (mg/l)		48.825	51.5		27.56	11.245	9.01	531
NH_4((mg/l)		0.005	0.005		1	0.03	0.0275	1.31
NO_2 (mg/l)		0.0025	0.0025			0.011	0.0068	
NO_3 (mg/l)		39.805	28.835		0.5	12.453	4.53	< 0.35
PO_4 (mg/l)		0.0295	0.0325			0.08	0.1	
SO_4 (mg/l)	175	112.5	151.6	152	93.5	80	33.065	1302
Sr (mg/l)						1.385	0.565	13.9
TDS (mg/l)	881	856	951	770	738	727	483	3,700.89
Total hardness (dGH)	33.6	26.1	31.3	32.0	20.3	25.5	22.1	
Carbonate hardness	18.0	18.0	19.6	17.7	19.4	18.7	15.8	

Tab. 7.
Median values of major ion concentrations in groundwater, grouped by hydrogeological unit.

Parameter	valley fill	Danube plain	younger terraces	older terraces	Neogene	Flysch zone	Calcareous Alps
Cl	0	0	0	0	6	0	0
Fe	0	4	2	0	40	3	0
Mn	0	6	2	0	47	20	0
Na	0	0	0	0	13	0	0
NO_2	0	4	0	0	0	0	0
NO_3	0	25	50	0	0	0	0
SO_4	0	1	9	0	0	2	0

Tab. 8.
Percentages of groundwater samples exceeding Austrian National Drinking Water Guideline values.

younger terraces, exceed NO_3 concentrations of 50 mg/l. Here, anthropogenic activities, such as fertilization of agricultural land, are assumed to be the cause. Two springs in the Flysch zone consistently exhibit elevated Na and Cl concentrations, albeit not exceeding the Guideline values. The location of these springs' catchment areas near high traffic roads suggests road salt as the likely cause (Pfleiderer et al., 2010).

Analytical results from the deep geothermal aquifer at Oberlaa (Elster, 2016) are not compared to the guideline values as these waters are not considered as drinking water.

Within the Danube plain, the regional distribution of individual major ion concentrations shows a distinct pattern. Values for Ca, Mg, Na, SO_4, Cl and NO_3 are generally low near the Danube River and increase towards the East and West. In the East, this is due to river filtrate from the Danube, which is less mineralised and dilutes the groundwater near the river. In the West, the groundwater is artificially recharged with Danube river water, also diluting ion concentrations.

Median values of trace element concentrations in groundwater samples are grouped by hydrogeological unit in Table 9. None of the analyses shows concentrations in excess of National Guideline values. For groundwater in Quaternary units, maximum concentrations of Al, As, Cd, Cr, Cu, Hg, Ni, Pb and Zn are 2–50 times lower than the guideline values, in the Flysch zone and the Calcareous Alps even 6–104 times lower. Again, analytical results from the deep geothermal aquifer at Oberlaa are not compared to the guideline values, as these waters are not considered as drinking water.

Parameter	valley fill	Danube plain	younger terraces	Flysch zone	Calcareous Alps	Calcareous Alps (deep geothermal aquifer)
Number of analyses	2	145	26	114	12	1
Al (µg/l)		3.5	3.5	7.45	6.6	< 20
As (µg/l)	0.5	0.875	0.5	0.45	0.28	7
Cd (µg/l)	0.05	0.04	0.04		0.1	< 0.3
Cr (µg/l)	1	0.3	1.275	0.2	0.2	< 5
Cu (µg/l)		2.3	2.5	3.8	5.7	< 5
Hg (µg/l)	0.25	0.035	0.035			0.19
Ni (µg/l)		0.425	0.35			< 2
Pb (µg/l)	2.5	0.35	0.35	0.45	0.3	3
Zn (µg/l)		8.25	10	13	17.75	< 100

Tab. 9.
Median values of trace element concentrations in groundwater, grouped by hydrogeological unit.

In addition to major ion and trace element concentrations, analyses of groundwater quality performed by the Environment Agency Austria east of the Danube contain concentrations of chlorofluorocarbons, pesticides and their metabolites, per- and polyfluoroalkyl substances, polybrominated diphenyl ethers, polycyclic aromatic hydrocarbons, organotin compounds and mercury. The area east of the Danube is considered a prospective intervention area due to elevated concentrations of nitrate and desethyldesisopropyl atrazine. In 2016, analyses from 36 % of monitoring stations exceeded the alert threshold with respect to nitrate concentrations, 4 % with respect to nitrite, 5 % with respect to atrazine, 9 % with respect to desethyl atrazine and 44 % with respect to desethyldesisopropyl atrazine (Philippitsch & Grath, 2019).

Discussion

The derivation of depth-to-groundwater and groundwater thickness (Tab. 1), and of groundwater dynamics (Tab. 2) west of the Danube canal, rests on few data points, available online via the portal of the Hydrological Service. The values listed in Tables 1 and 2 therefore give only a first approximation. In addition to the wells included in the online portal, 600 more groundwater wells are monitored by Vienna's Municipal Department of Water Management. Ideally, maps of the groundwater table at high, medium and low levels should be used. Within Vienna's city area, such maps are however only available for the Danube plain east of the Danube River, and between the Danube River and the Danube canal. To derive thickness, the aquifer base was extracted from a 3D geological model, which bears uncertainties particularly at greater depths. For confined aquifers within the Neogene sediments, even hydraulic heads are largely unknown.

Hydraulic conductivities (Tab. 3) were derived from grain size distribution curves as well as from pumping tests. Within the Danube gravel, an equally large number of data exists for both methods. Comparing the results of two methods shows that values derived from grain size underestimate conductivities by a factor of 6–33. This is confirmed by pumping tests carried out in the Danube plain east of Vienna (Fürnkranz, 1990).

The quantification of areas sealed against rainwater infiltration (Text-Fig. 4) is based on the land use classes of Vienna's multi-purpose city map. Forests, meadows, parks, vineyards, cemeteries, sports fields, railway lines and gravel pits were considered as not sealed. For other classes, the interpretation in terms of surface sealing is less certain. For example, courtyards or construction sites may or may not be sealed. The surface area of these classes however amounts to 0.8 % of the city area and the uncertainties can be considered as negligible.

To identify the aquifers used for groundwater extraction (Text-Figs. 5, 6, Tab. 5), depth information was taken from well descriptions contained in the Water Rights Register. However, the location of screens is mostly given in meters below the well top, without specifying the height of the well top above ground. A digital elevation model was used for the translation into absolute depth assuming the well top at ground level, which can cause an error of up to approximately 1 m. Uncertainties in the 3D geological model add to the error. The identification of hydrogeological units from which water is extracted may therefore be false for individual sites and the data shown in Text-Figures 5, 6 and in Table 5 only give a general picture of groundwater use.

Abstraction limits are granted by the water authorities partly on the basis of groundwater availability but often on the basis of demand, which may be less than the actual yield. Therefore, abstraction limits can be used only as indicators of groundwater yield. The distinction of high, moderate and low yield in Text-Figure 7, based on maximum abstraction limits, reflects relative groundwater availability of Vienna's hydrogeological units. Yields, however, cannot be quantified with these data.

The median values of major ion concentrations in groundwater samples from older terraces and valley fill (Tab. 7) are based on very few hydrochemical analyses dating from 1961–1962 and are therefore not reliable. However, the high concentrations of Mn (and to a lesser extent Fe) in valley fill groundwater samples (10 times higher than samples from any other unit) agree with the fact that valley fill sediments consist mainly of sandstone components from the Flysch zone where groundwater samples also show high Mn concentrations (Tab. 8).

Ongoing research and knowledge gaps

The hydrogeology team of the Viennese Waters Management, a subsidiary company of the City of Vienna, has been investigating the extent, lithology and the base of Quaternary sediments in Vienna for the last 10 years, analysing > 60,000 drilling profiles in minute detail as a still ongoing project (Grupe, 2011, 2012, 2013; Grupe & Payer, 2009, 2010, 2014, 2015, 2017, 2018; Grupe et al., 2016). From this will emerge an updated geological map, more accurate than the map used here (Hofmann & Pfleiderer, 2003). In addition, a more accurate structural map of the Quaternary base will be produced. With groundwater table maps from the Municipal Department of Water Management, it will possible to develop a 3D model with better information on depth-to-groundwater, groundwater thickness and water table variations of the uppermost Quaternary aquifers. This will allow the revision of data in Tables 1 and 2.

The project “GeoPlasma” provides an online information system for shallow geothermal use of the topmost aquifer east of the Danube (https://portal.geoplasma-ce.eu/webgis/vienna) which includes important hydrogeological information such as aquifer productivity (Steiner et al., 2017).

The project “GeoTief Wien” currently investigates geothermal reservoirs underneath the city of Vienna at 2,500–6,500 m depth (Schreilechner et al., in press). Both Neogene sediments and Triassic carbonates of the Calcareous Alps are studied. Results will include a geological model (3D structures) and a thermal-hydraulic model (reservoir properties).

From the present review and ongoing research, some knowledge gaps emerge (Tab. 10).

Future work could aim at linking the groundwater monitoring wells, residing at Vienna’s Municipal Department of Water Management, and the groundwater extraction sites (Municipal Department of Water Rights) to the register of borehole logs (Municipal Department of Bridge Construction and Foundation Engineering, https://www.wien.gv.at/verkehr/grundbau/kataster.html) on a well-by-well basis. Defining the absolute heights of well screens would allow the correct identification of the aquifers, which are currently monitored for water table variations or used for groundwater extraction. Linked to the borehole logs, the site-specific description of the lithological characteristics of aquifers becomes possible. At the same time, it would allow the identification of areas where future monitoring and sampling sites should be installed to include hydrogeological units known to a lesser extent.

Conclusions

The present study describes the current knowledge of the urban hydrogeology of Vienna, Austria. It defines seven hydrogeological units based on similar geological and aquifer properties. Conditions for groundwater recharge were described on the basis of land use and fine-grained sediment cover. Aquifer type was interpreted from geological maps. Aquifer geometric properties (depth-to-groundwater, groundwater thickness) were derived from data on groundwater tables, from an elevation model and a 3D geological model. Aquifer material properties (hydraulic conductivity), groundwater residence times and groundwater chemistry were compiled from existing data sets. Groundwater use was derived from Vienna’s Water Rights Register. Abstraction limits were used to infer relative groundwater availability, leading to a map of aquifer types grouped by yield.

The present study demonstrates that knowledge is scarce particularly for hydraulic aquifer properties, recharge rates, groundwater residence times and chemistry of aquifers in valley fill sediments and older terraces, for the Neogene confined aquifers and for the deep geothermal aquifer of the Calcareous Alps. Particularly in view of potential water supply backup systems and their protection, future investigations are recommended to focus on Neogene confined aquifers underlying Quaternary sediments in the Danube plain.

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Hydrogeological unit	geometric properties	hydraulic properties	recharge rates	residence times	chemistry
tributary valleys	~	x	x	x	x
Danube plain	~	√	x	√	√
younger terraces	~	x	x	x	√
older terraces	~	x	x	x	x
Neogene	x	x	x	x	x
Flysch zone	x	x	x	x	√
Calcareous Alps	~	~	x	x	x

Tab. 10.
Ongoing research and knowledge gaps (~: currently investigated, x: largely missing, √: largely known); Aquifer geometric properties include structural maps of the top and base of aquifers, of groundwater tables, depth-to-groundwater and groundwater thickness; hydraulic properties include porosity, conductivity, flow velocity, yield and storage.

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