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Sources, intensities, and implications of subsurface warming in times of climate change

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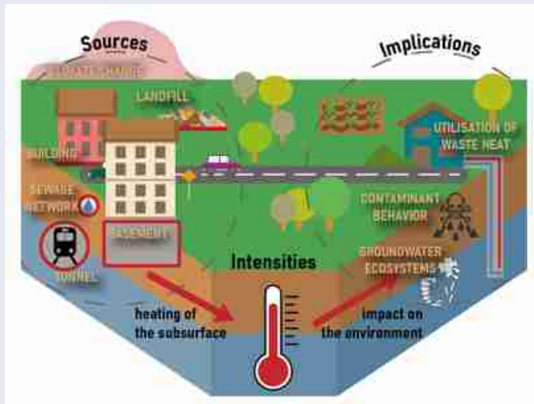
ABSTRACT

Anthropogenic warming of the atmosphere is one if not the most pressing challenge we face in the 21st century. While our state of knowledge on human drivers of atmospheric warming is advancing rapidly, little so can be said if we turn our view toward the Earth's interior. Intensifying land use and atmospheric climate change condition the changing thermal state of the subsurface at different scales and intensities. Temperature is proven to be a driving factor for the quality of our largest freshwater resource: groundwater. But there is only insufficient knowledge on which sources of heat exist underground, how they relate in their intensity of subsurface warming, and which consequences this warming implies on associated environments, ecosystems and resources. In this review, we propose a differentiated classification based on (1) the geometry of the heat source, (2) the scale at which the subsurface is heated, (3) the process that generates the heat, and (4) the intention of heat release. Furthermore, we discuss the intensities of subsurface warming, the density of induced heat fluxes, as well as their abundance, and draw implications for depending processes and ecosystems in the subsurface and the potential of recycling this waste heat with geothermal installations.



KEYWORDS Climate change; geothermics; groundwater quality; subsurface temperature; thermal environment; waste heat

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1. Introduction

Enhanced greenhouse gas emissions yield an imbalance in Earth's energy budget. Due to their great impact on climate change, priority is set on their effect on atmospheric global warming. Only around 5% of the excess heat is taken up by land (von Schuckmann et al., 2020) which manifests in trailing in-situ underground warming when compared to temperature trends in the atmosphere (Arias et al., 2021). Without surface warming, the thermal regime in shallow ground would be equilibrated and only respond to the seasonal oscillation in surface temperature in the top few meters (Taylor & Stefan, 2009). Meanwhile, the effects of global warming manifest down to depths of up to 100 m (Harris & Chapman, 1997; Lachenbruch & Marshall, 1986). Subsurface warming in response to atmospheric climate change is superimposed by human encroachment that changes the energy balance at the land surface. Especially in densely populated areas the

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thermal impact of direct anthropogenic land use is often more pronounced than the warming in response to climate change (Eggleston & McCoy, 2015). This has been measured worldwide in boreholes and groundwater wells, revealing a highly heterogeneous picture of man-made spatial and temporal temperature variations that chiefly represent interferences of multiple coexisting heat sources (Benz et al., 2017). Local heat accumulation in the ground can be magnitudes higher than in the atmosphere, but is transferred at much lower rates. As a consequence, recent anthropogenic warming imprints as a persistent signature in the subsurface (Pollack et al., 1998). Beneath many cities, the agglomeration of a multitude of anthropogenic heat sources evolved so-called subsurface urban heat islands, with higher intensity and temperature stability than the far better-known surface and atmospheric urban heat islands (Ferguson & Woodbury, 2007; Menberg, Bayer, et al., 2013; Oke, 1973; among others).

Knowledge of ground temperature and heat transport processes of individual heat sources is necessary to quantify energy flows in urbanized areas and for understanding the functioning of the ground as a heat sink and source (Bayer et al., 2019). Characterizing environmental impacts of subsurface warming, such as changes in microbial community compositions, possible deterioration of groundwater quality or contaminant behavior, is a pressing topic in environmental research. For example, heated ground cannot buffer hot summer days well and enhances heat waves in cities (Founda & Santamouris, 2017; Li & Bou-Zeid, 2013). Moreover, due to the high heat density of ground and groundwater, shallow geothermal energy is gaining attention as a renewable source for integrated heat and cold supply systems (Benz et al., 2015; Kammen & Sunter, 2016). We can consider heated ground not only as a resource but also as natural laboratories of the conditions to be expected in the future. Unchanged global warming will continue to increase the previously long-term stable temperature of the shallow ground by several degrees during the next decades (Arias et al., 2021; Figura et al., 2015; Gunawardhana & Kazama, 2011). Permanent direct anthropogenic heat release, as it has been occurring especially in urbanized areas since at least a century, has generated modified environments that project the conditions in non-urban areas in the next century.

The objective of this study is to characterize the diversity of different anthropogenic sources that yield local ground heating, which is fundamental for understanding their interaction in areas that are heavily altered. We discuss different classification schemes and review source types, the degree and consequences of anthropogenic ground heating. Special focus is set on thermal alteration of shallow groundwater due to its vital role as the largest resource of freshwater on earth, as a widely unexploited energy resource, and as an important environmental variable in subterranean and groundwater dependent ecosystems.

2. Classification of anthropogenic heat sources

Anthropogenic heat sources are defined by changing the natural thermal conditions in the subsurface. To our knowledge, there exists no classification of such sources, yet. This is surprising considering many common features, causes and effects, as well as their global appearance. We propose a classification based on the following four main characteristics:

1. The **scale** and size of the thermally affected zone of the heat source. The scale can be attributed to be either of global, regional, or local dimension. The local extent comprises thermal diameters of the size of centimeters (e.g. power cables) to a couple of hundred meters (e.g. infiltration). Regional scale phenomena appear over the extent of several kilometers and are typically very large alterations of the thermal natural state induced by mining, extensive shallow geothermal applications, or altered microclimatic conditions, as often found in cities. We consider climate change as the only global heat source under which the shallow subsurface is heated by recent ground surface and atmospheric temperature rise.

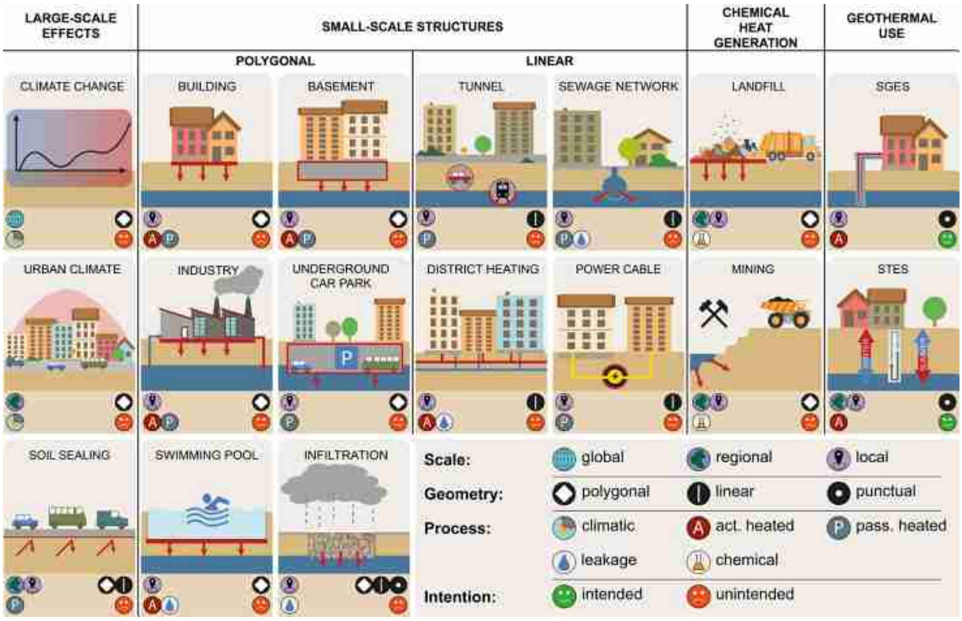

Figure 1. Graphical overview of anthropogenic heat sources. SGES: Shallow Geothermal Energy Systems, STES: Seasonal Thermal Energy Storage.

2. The **geometry** of the heat source: We define the geometry as seen from the aerial perspective into polygonal, linear, and punctual. The geometry is particularly important for implementation of heat sources in numerical and analytical models. While most heat sources have a polygonal shape (e.g. buildings), there also exist multiple linear geometries which are typically associated to networks of pipes. Punctual geometries are found around boreholes of, for example, geothermal systems, when the projected shape is considered.
3. The **process** that generates or emits the heat: the processes defined in this study are long-term responses to atmospheric climate, heat release from actively heated structures (e.g. basements) and passively heated structures (e.g. trains in subway tunnels), influx of a heated fluid (leak), or (bio)chemical in-situ heat generation. Some sources are associated with different processes.
4. Further, we distinct by the **intention** of the heat release: Thermal alteration of the subsurface is usually only intended by application of geothermal facilities. For all other sources, the thermal change is unintended.

To introduce a comprehensible classification of primary heat sources, we decided to order them by their characteristics into large-scale effects, small-scale structures, chemical heat generation, and geothermal use as seen in Figure 1. To stay as concise as possible, we did not include the dimensions depth and time. We introduce the geometry as seen in map view perspective for easier implementation and to reduce the level of complexity in the description. Information on 3D geometries and the depth of thermal interaction with the environment is discussed individually for each heat source. The temporal resolution of the thermal interaction can be seasonally dependent both on the heat source itself as well as on ambient ground temperature in the seasonally affected zone. Seasonal variations of the heat source are especially relevant for shallow geothermal units, where seasonal heating or cooling is applied. However, most heat sources emit heat throughout the year. With the chosen classification, allocation in classes is not unequivocal. For example, the geometry of infiltration structures can be polygonal, linear, and even punctual.

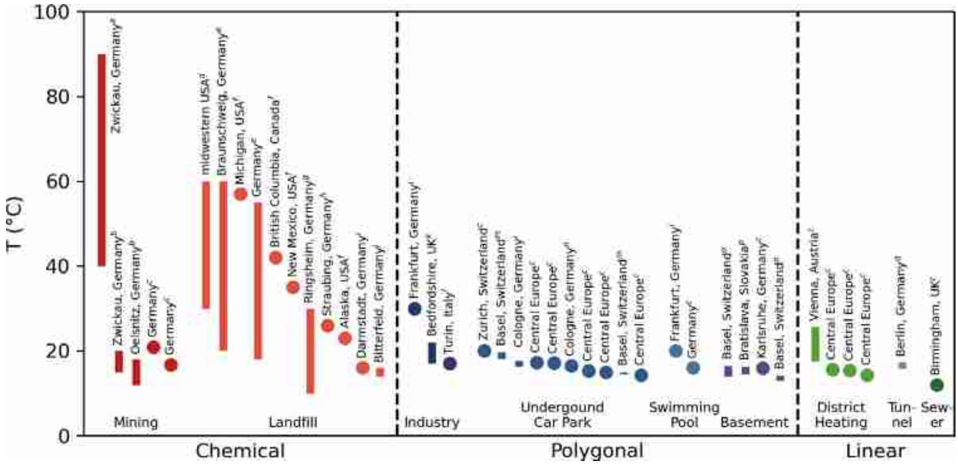

Figure 2. Cases of unintended anthropogenic groundwater heating. This overview provides examples of anthropogenic structures heating groundwater. Note that the comparability of these examples is limited due to different local conditions, measurement techniques, and distances to the heat source.
[a]Willscher et al. (2010).
[b]Felix et al. (2009).
[c]Tissen et al. (2019).
[d]Yeşiller & Hanson (2003).
[e]Dernbach (1982).
[f]Yeşiller et al. (2005).
[g]Wiemer (1982).
[h]Tidden & Scharrer (2017).
[i]This study.
[j]Menberg, Bayer, et al. (2013).
[k]Westaway et al. (2015).
[l]Bucci et al. (2017).
[m]Becker & Epting (2021).
[n]Zhu (2013).
[o]Epting, Scheidler, et al. (2017).
[p]Krcmar et al. (2020).
[q]Henning (2016).
[r]Ford & Tellam (1994).

3. Determination of the thermal impact

Investigating the thermal impact of a heat source requires in-situ measurement of soil or groundwater temperature. Observations from wells should be in close vicinity of only one heat source to avoid the influence and thermal overlapping of other sources. In practice, observation wells are typically scarce and heat sources are rarely found as separate isolated structures, and thus interpretation of anomalous temperatures and their sources is often not straightforward. Examples of altered groundwater temperatures by different heat sources are given in Figure 2. Despite varying local conditions, measurement techniques and distances to the heat source, many of the polygonal and linear structures are in a comparable range of low subsurface temperature (12–30 °C). Geochemical heat sources, on the other hand, induce higher temperatures of 12–90 °C.

To evaluate the intensity of subsurface warming, the definition of a natural state (or background temperature), which is usually determined by the annually averaged conditions in unaffected rural surroundings (Epting & Huggenberger, 2013), is needed. Although the rural surrounding is not uniformly defined, values are often taken from agricultural or forest areas. This, however, already ignores potential anthropogenic impacts on temperature as caused by modifications of natural vegetation and groundwater level. Alternatively, the undisturbed shallow groundwater temperature can be approximated by the mean air temperature of a region, evapotranspiration and snow cover period (Benz et al., 2017).

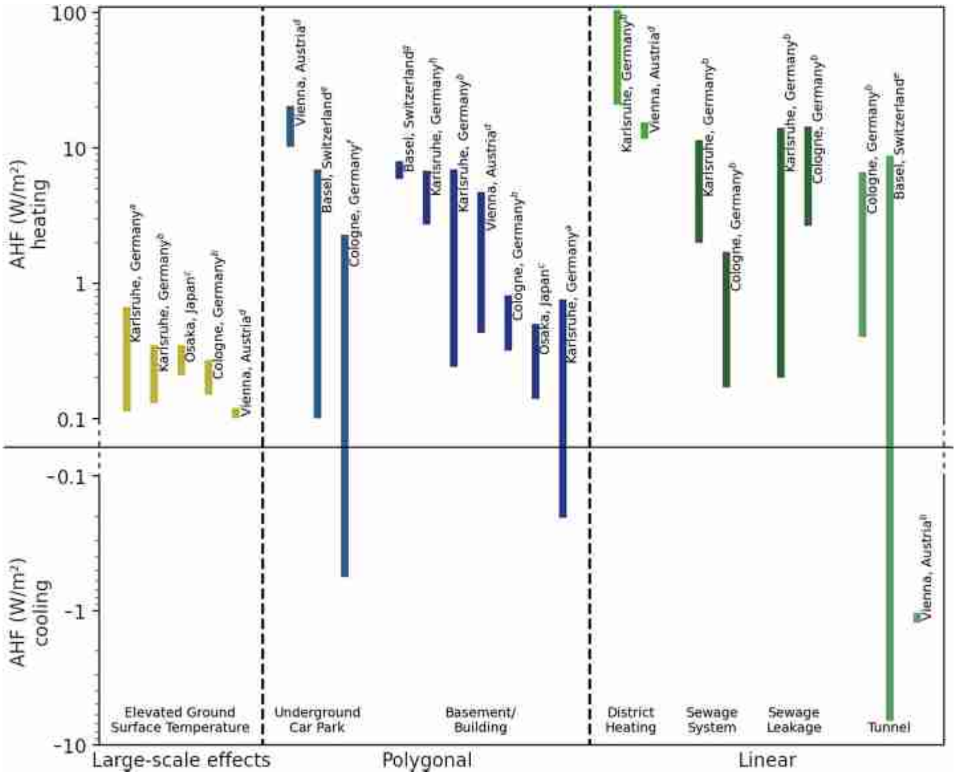

Figure 3. Literature examples of the Anthropogenic Heat Flux (AHF) for different heat sources. Note that different methods were used to calculate the AHF and some studies give the average AHF of a heat source, while others give the AHF of single structures. The "heating" values describe a heat flux into the subsurface and the "cooling" values vice versa.
[a]Menberg, Blum, et al. (2013).
[b]Benz et al. (2015).
[c]Benz, Bayer, Blum, et al. (2018).
[d]Tissen et al. (2021).
[e]Becker & Epting (2021).
[f]This study.
[g]Mueller et al. (2018).
[h]Lofi (1977).

When natural thermal conditions are known, the anthropogenic thermal impact can be quantified as anthropogenic heat intensity (AHI), which is determined by subtracting the median natural background temperatures from individual temperatures (Tissen et al., 2019). Further, the calculation of the anthropogenic heat flux (AHF) is possible. Different approaches have been applied that most often use analytical solutions and less frequently apply numerical models. Typically, they are based on Fourier's law of heat conduction to quantify vertical heat flux, considering parameters such as groundwater flow, ground thermal conductivity, and heat source type-specific insulation or leakage. Calculated AHFs for several heat sources and cities are compared in Figure 3. The large ranges of the AHFs result from high uncertainties in subsurface parametrisation and methodological deviations. Most studies found strictly positive heat fluxes, indicating a warming of the subsurface. Only few studies reveal cases of reversed vertical heat fluxes, meaning a net cooling of the subsurface. Thermal coupling of soil and atmospheric temperatures causes an interplay of seasonal ground heat accumulation and loss. Heat sources with seasonally varying temperatures, such as tunnels or underground car parks, have the same effect. However, detailed investigations on the effect of anthropogenic structures on the seasonal temperature oscillation in the subsurface are scarce.

4. Sources of subsurface warming

4.1. Large-scale effects

The most acknowledged and largest source of subsurface warming is **climate change** (Arias et al., 2021). The thermal signal of atmospheric and land surface warming slowly propagates downward and changes the thermal conditions of the underground (Bense et al., 2020). It can be detected by analysis and inversion of borehole temperature profiles (Harris & Chapman, 1997; Pollack et al., 1998). Similarly, time series analysis of long-term temperature records logged at fixed depths reveals warming (Menberg et al., 2014). When time series of different depths are compared, time shifting of the thermal signal and attenuation with depth can be observed (Čermák et al., 2014; Hemmerle & Bayer, 2020).

A number of studies in the northern hemisphere recently focused on the thermal impact of climate change on groundwater in comparison to soil and atmosphere. Those that state a temperature lapse rate are summarized in Figure 4. The depicted comparison with the mean air temperature change does not account for regional variability of climate change. Aside from this, measurement depths are not consistent and potential local sources of subsurface warming are not further detailed. Still, clear trends are revealed. Studies conducted in cities report higher temperature increase, which is attributed to super-positioning of local heat sources and anthropogenic effects such as land use change and urban climate (Eggleston & McCoy, 2015). Climate change effects are often difficult to isolate, and are ideally identified in areas with minimal other anthropogenic influences. Also, single well measurements are barely representative. Instead, to mitigate the influence of local hydrogeological conditions such as groundwater depth, flow, and distance, elaborate probing in a significant number of wells at high spatial and temporal resolution is favorable (Benz, Bayer, Winkler, et al., 2018).

The studies summarized in Figure 4 show the evident link between air and subsurface temperature warming in the recent past. This trend is believed to continue according to the rise of air temperature (Blum et al., 2021). Figura et al. (2015) predicted an increase in groundwater temperature in Swiss aquifers of 1.1–3.8 K by the end of the century, extrapolating a linear regression model for data between 1980 and 2009, while Gunawardhana and Kazama (2012) projected an aquifer warming of 1.0–4.3 K for the Sendai Plain in Japan in this period of time, depending on the applied climate scenario.

At the regional scale, the role of **urban climate** was described by Oke (1973) as an urban heat island (UHI) for air temperature. This regional rise in air temperature induces an increase in groundwater temperature beneath cities due to the coupling of air and soil temperatures (Henning & Limberg, 2012). Additional to this direct effect, there are numerous anthropogenic heat sources accumulated in cities that lead to a subsurface UHI. This regional phenomenon of elevated groundwater temperature in urban environments was extensively described in the past decades (Bucci et al., 2017; Taniguchi & Uemura, 2005)—accompanied by the emerging questions of utilizing and managing this resource (Attard et al., 2020; Mueller et al., 2018). However, most studies lack a detailed analysis on individual heat sources that cause local anomalies and agglomerate into subsurface UHIs.

A main driver of large-scale urban subsurface heat accumulation is **soil sealing** (Benz, Bayer, Blum, et al., 2018). The heating effect of anthropogenic surfaces depends on several factors like material, albedo, emissivity, roughness, and the angle to the sun (Henning & Limberg, 2012; Scalenghe & Marsan, 2009), and hence differs strongly. Although material properties have been studied (Popiel & Wojtkowiak, 2013), as well as the soil sealing effect on the urban climate (Murata & Kawai, 2018), the large scale impact on underground temperature is difficult to distinguish from other heat sources and has not been sufficiently investigated to date. However, several studies include elevated ground surface temperatures in the estimation of subsurface temperatures (Benz et al., 2015; Hemmerle et al., 2019; Menberg, Blum, et al., 2013; Tissen et al., 2021).

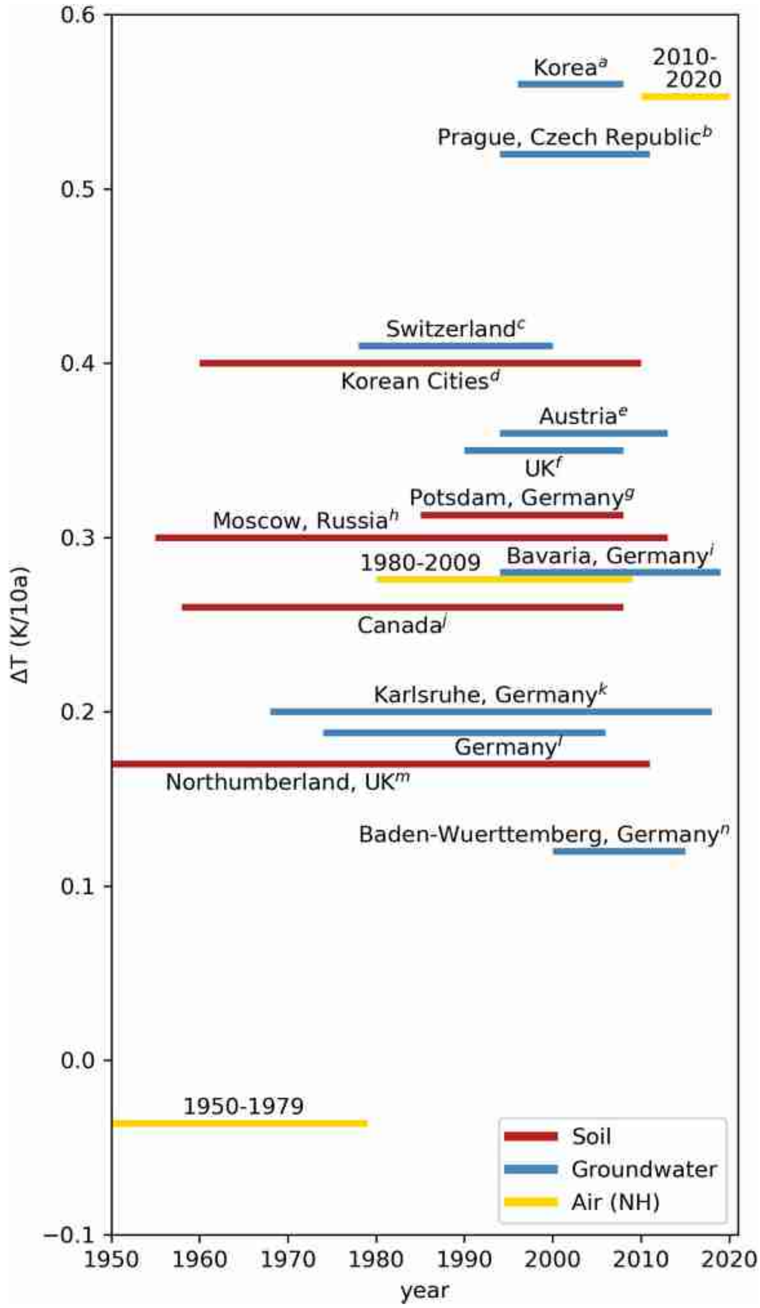

Figure 4. Summary of studies showing temperature change in the subsurface per decade. The historical data for the northern hemisphere (NH) air temperature is taken from Osborn et al. (2021). Note that the study from Northumberland, UK, includes data from 1907 to 2011.

[a]Park et al. (2011).
[b]Čermák et al. (2014).
[c]Figura et al. (2011).
[d]Cheon et al. (2014).
[e]Benz, Bayer, Winkler, et al. (2018).
[f]Bloomfield et al. (2013).
[g]Henning & Limberg (2012).
[h]Korneva & Lokoshchenko (2015).
[i]Hemmerle & Bayer (2020).
[j]Qian et al. (2011).
[k]Blum et al. (2021).
[l]Menberg et al. (2014).
[m]Luo & Asproudi (2015).
[n]Riedel (2019).

Asphalt has been highlighted in the past as the material storing most solar energy (O'Malley et al., 2015), inducing the highest soil temperatures beneath it (Čermák et al., 2017). In comparison to a grass surface, asphalt can become almost 20 K hotter (LeBleu et al., 2019). In addition, surface sealing prevents air exchange between soil and atmosphere and mitigates latent heat fluxes by evapotranspiration and hereby further increases heat accumulation in the subsurface (Scalenghe & Marsan, 2009).

As shown in Figure 3, several studies have calculated the AHF of elevated ground surface temperatures. The ground surface temperature is not considered as a heat source itself but is influenced by soil sealing and urban climate. Hence, the ground surface temperature gives indirect information about anthropogenically elevated heat fluxes into the subsurface. The cited studies report values between 0.1 and 0.7 W/m^2. In comparison to many other heat sources, these heat fluxes are at the lower end. However, the regional thermal impact of elevated ground surface temperatures is high due to its large spatial extent.

4.2. Small-scale structures

The anthropogenic heat sources that can be traced back to structures above or below the surface can generally be divided by the geometry in polygonal and linear structures. This characterization is especially useful for implementation of heat sources in models. Many of these heat sources share similar characteristics and are often summarized, for example, as "underground structures" (Attard, Rossier, et al., 2016). Nevertheless, a closer look reveals features that are unique to each type and condition the specific heat transfer.

4.2.1. Polygonal structures

The most common anthropogenic surface structures are **buildings** without basements. They transmit heat via the ground slab to the subsurface. Although the influence of a single structure is often hardly observable, the large number of heated buildings makes them an important source of subsurface heating. Previous work in this context focused mainly on heat loss or "ground heat transfer" reduction in the field of civil engineering (Rees et al., 2000). Field tests and simulations have shown that the highest heat loss occurs at the slab edges (Thomas & Rees, 1998). Further studies have shown a strong influence of soil moisture and groundwater flow rate on the heat transfer (Janssen et al., 2004). Heat losses are highest for uninsulated buildings during the heating season (Adjali et al., 2000). Seasonal heating can be identified in temperature signals below buildings, which are rarely measured and difficult to access (Thomas & Rees, 1998).

Industrial buildings, such as factories or power plants, deserve special attention as they can have a large extent, strong local effects, and high indoor temperatures (Brinks et al., 2014). Also, reinjection of industrial cooling water directly into aquifers or cooling lakes can generate an additional heat input (Menberg, Bayer, et al., 2013). Elevated groundwater temperatures caused by heat release from industrial buildings have been observed in particular in Europe (see Figure 2) (Bucci et al., 2017; Menberg, Bayer, et al., 2013; Westaway et al., 2015).

Similar to buildings, heat loss from **basements** is of special interest in the field of civil engineering (Medved & Černe, 2002). Additional to the slab, here, heat is also transferred through the basement walls. Generally, the smaller the distance to the groundwater table and the higher the groundwater flow rate, the higher the heat losses are (Bidarmaghz et al., 2019; Epting, Scheidler, et al., 2017). The heat flux drastically increases when the basement reaches into the saturated zone (Attard, Rossier, et al., 2016; Epting et al., 2013). The thermal plume induced by basements was reported for a heated shopping center (Krcmar et al., 2020) and in different modeling studies (Attard, Rossier, et al., 2016; Ferguson & Woodbury, 2004). Epting, Scheidler, et al. (2017) observed heat plumes reaching 16.5 °C in Basel, Switzerland, downstream of basements, and

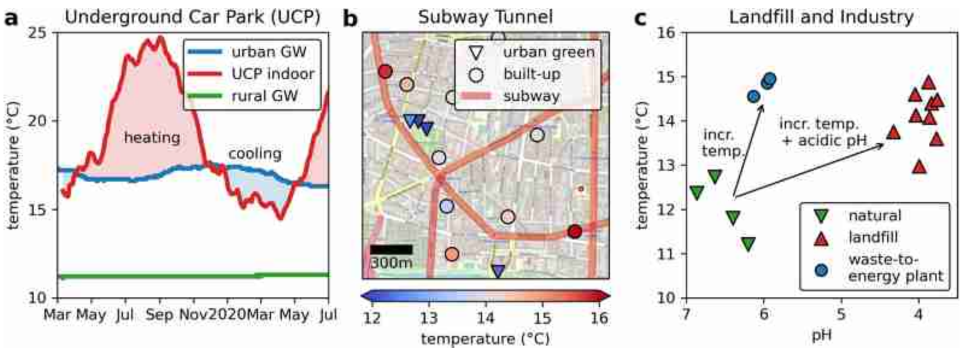

Figure 5. (a) Time series of the groundwater temperature (urban GW) in a well 10 m next to an underground car park (UCP) and the indoor temperature at the lowest level. Additionally, the groundwater temperature of an undisturbed well outside of Cologne is plotted to show the rural background in the regarded time span. (b) Map of Berlin Wilmersdorf, Germany, showing the groundwater temperature at 15 m depth in 2016 as well as the location of subway tunnels. A strong thermal anomaly was detected in the close vicinity of a subway tunnel. Data from Henning (2016). Note that this map only shows the relevant section of the study area. Basemap: OpenStreetMap. (c) Scatter plot of groundwater temperature and pH in Bitterfeld, Germany. Wells downstream of a landfill and a waste-to-energy plant show elevated temperatures, while the groundwater downstream of the landfill is also acidic. Mean values of 16 wells between 2017 and 2021 were provided by local authorities (LHW, 2021).

applied groundwater heat transport models to determine the influence of aquifer properties and building settings.

AHFs have been calculated in previous studies typically for both buildings and basements together, and heat losses through basement walls are not resolved in large-scale studies. The findings vary between −0.2 and 16 W/m^2. Only Menberg, Blum, et al. (2013) show partly negative values, caused by spatial variability in groundwater temperature.

Underground car parks (UCP) have the same characteristics as basements, but they are typically larger and buried deeper in the subsurface. Therefore, the local thermal anomaly in the subsurface is generally higher as reported for several cities (Figure 2). Studies regarding UCPs have been dedicated to the role of the groundwater flow regime (Attard, Winiarski, et al., 2016) and the integration in urban underground management (Sartirana et al., 2020). For instance, Becker and Epting (2021) scrutinized the thermal impact of five UCPs in Basel, Switzerland, and found that the released heat strongly depends on UCP indoor temperatures and contact area with groundwater. The groundwater temperature measured downstream was increased by up to 2.7 K.

As a further example, we chose a 10 m deep UCP in the city center of Cologne, Germany (Figure 5a). The groundwater temperature is monitored at a well located in a distance of 10 m next to the UCP by a permanently installed datalogger. Additionally, we monitored the indoor temperature of the lowest floor at around 8 m depth. The groundwater table is deeper than the UCP at around 14 m, but the well shows an elevated groundwater temperature throughout the year. As background temperature of undisturbed conditions at the same depth, we refer to a well in the rural surroundings of Cologne, which has a temperature of around 11 °C. Therefore, the AHI of this well reaches 5–6.5 K in the studied period. During the summer months, the indoor temperature of the UCP is highest, mostly caused by high traffic of heated vehicles (Becker & Epting, 2021) and ventilation. The yearly peak in groundwater temperature at 17 m depth (17.7 °C) is shifted several months due to the depth distance of 4 m between UCP basis and groundwater. Although the influence of other heat sources can be expected, the elevated indoor temperature in the summer months indicates a strong heat flux rate into the surrounding soil and hence a local hotspot in subsurface temperature. Interestingly, from May to November, the indoor temperature is even below the groundwater temperature, thus inducing a reversed heat flow into the UCP. To put this in numbers, we calculated the AHF into the aquifer by Fourier's law, assuming a thermal conductivity of 1 W/(m K) for the soil. The results show seasonally varying values between −0.6 and 2.3 W/m^2. Other case studies, as shown in Figure 3, report higher AHF values, but no seasonally negative heat flux.

As containers of heated water, **swimming pools** have many similarities to structures for thermal energy storage like water-based closed seasonal thermal energy storage systems (Bott et al., 2019). However, their thermal impact depends even more on season, water temperature, and possible boiler rooms in the basement (Li et al., 2020). When it comes to heat losses of swimming pools, leakage has to be considered as well (Chapuis, 2010). Only few studies have observed elevated subsurface temperature in connection to swimming pools (Figure 2).

In times of increased groundwater scarcity, artificial recharge of groundwater by **infiltration** gains importance. Infiltration, which can be achieved in many different ways such as by basins (polygonal), trenches (linear), or injection wells (punctual), is generally summarized as *managed aquifer recharge* and has been applied for decades (Dillon et al., 2019). The infiltration of stormwater can have an impact on groundwater quality (Fischer et al., 2003) and temperature (Foulquier et al., 2009). Comparable to shallow karst systems, stormwater infiltration accelerates the recharge of groundwater and therefore increases the seasonal effect on groundwater temperature, whereas the long-term heating of groundwater is considered moderate (Foulquier et al., 2009). The greatest impact is to be expected in urban areas, where stormwater runoff is heated by artificial surfaces (LeBleu et al., 2019). Also, aquifer storage and recovery of stormwater yields an impact on groundwater quality, including the temperature (Page et al., 2017). However, the thermal impact of artificial groundwater recharge is commonly neglected.

4.2.2. Linear structures

Tunnels are one of the widest, deepest and most abundant linear heat sources in the subsurface. Barla and Di Donna (2018) classified tunnels according to their thermal conditions, which can be either cold all year round (approx. 15 °C) in street tunnels and less frequently used railway tunnels, or hot (up to 30 °C in summer) in subway and deep mountain tunnels. Extreme temperatures of 35–40 °C, mainly heated by braking trains and passengers (Mortada et al., 2015), are observed in subway tunnels in several cities worldwide (Mortada, 2019). As with many other heat sources, groundwater flow strongly enhances heat exchange with the ground (Barla & Di Donna, 2018; Di Donna et al., 2021). Since these structures obstruct the natural flow of groundwater, the flow is often led through culvert pipes that further increase heat exchange (Epting, Baralis, et al., 2020). Tunnels warming the ambient ground are a well-known phenomenon (Bidarmaghz et al., 2020), but are difficult to study as their main application in dense urban areas leads to an overlap with other heat sources. When considering the AHF of tunnels (Figure 3), car tunnels can both gain and lose heat seasonally depending on the atmospheric air temperature with the highest variations of indoor temperatures close to the exits (Becker & Epting, 2021). Case studies of car tunnels in Basel (Becker & Epting, 2021) and Vienna (Tissen et al., 2021) show net negative heat fluxes. This implies that car tunnels can cool down the subsurface, especially in urban space where the underground temperature is already elevated by anthropogenic use. Contrary to car tunnels, a case study of the subway tunnel system in Cologne (Benz et al., 2015) reports positive heat fluxes all year round, implying that subway tunnels are warm enough during all seasons to release heat into the subsurface.

Henning (2016) investigated the subsurface temperature in the vicinity of subway tunnels in Berlin, Germany, to evaluate the magnitude of the induced temperature change. Additional to historical data from 1989 to 2014, groundwater temperature was measured in 23 observation wells, of which 14 are shown in the section, in the district Wilmersdorf in 2016 (Figure 5b). Only two wells show the thermal influence of the subway tunnel unequivocally. These two wells have the highest groundwater temperatures (17.4 and 15.8 °C) and the shortest distance (10 m, 30 m). The case study further illustrates the variety and superpositioning of heat sources in a city. The thermal anomaly caused by the tunnels is local and attenuated in the adjacent Preußenpark.

Here, lower temperatures (11.4–12.6 °C), which are typically under urban green areas, were found.

Sewers have been identified as major heat source in the subsurface of cities (Menberg, Blum, et al., 2013; Tissen et al., 2021). Additionally to the conductive heat transport, leakage of wastewater yields a noticeable heat input (Benz et al., 2015; Ford & Tellam, 1994). Leakages of sewer pipes are challenging to detect and quantify and are strongly varying regionally (Peche, 2019). While the temperature of wastewater depends on several factors (Kretschmer et al., 2016), for Central European cities it is generally around 12–22 °C (Benz et al., 2015; Cipolla & Maglionico, 2014; Schmid, 2008; Tissen et al., 2021). The AHF of sewage systems has been calculated by Benz et al. (2015) for the cities of Karlsruhe and Cologne (Figure 3). In both cities, the average AHF from leakages is higher than the conductive heat loss of the conduits in the network.

District heating pipes are also buried shallow in the ground. Apart from a similar depth and linear shape, district heating pipes carry hot water of typically 60–120 °C and are usually well insulated. For economic reasons, heat losses are monitored and kept as low as possible, with typical values of 11–14% in Germany (Helbig & Weidlich, 2018). However, these numbers do not indicate whether heat loss is evenly distributed or local. Local hot spots can be caused by leakage and have been proven to be detectible by airborne thermography (Zhou et al., 2018). The effect of district heating networks on subsurface temperature can be considerable (Figure 2), and can for instance, result in snow melt at the ground surface (Arola & Korkka-Niemi, 2014). In Vienna, Tissen et al. (2019) detected groundwater temperatures of up to 25 °C (equalling an AHI of 13 K) in an observation well in 3.5 m distance to a district heating pipe. Relatively high AHFs of 11.8–104.7 W/m^2 are reported for Vienna and Karlsruhe (Figure 3). Such AHFs of district heating pipes can be calculated if heat loss values are accessible from public authorities. In order to reduce the consumption of fossil fuels, modern low exergy district heating systems (LowEx) utilize the different energy level needs and integrate renewable energy sources as well as waste heat from industry (Hepbasli, 2012). Because of the use of decentralized heat pumps, the supply temperatures can be kept below 45 °C (Schmidt et al., 2017). LowEx district heating systems generally have lower heat losses compared to district heating networks and therefore, the impact on subsurface temperature is reduced as well (Dolna & Mikielewicz, 2020).

Another linear heat source type is underground **power cables**. Conducting electricity warms the power cables up to 60 °C (Stegner, 2016). Numerical studies show the heat dissipation in the surrounding soil (Ocłoń et al., 2015) depending on the bedding material (Stegner et al., 2017), whereas research about the overall impact on subsurface temperature is still lacking. Power cables are typically buried at shallow depth of a few meters (Stegner, 2016) to not interfere with groundwater; however, soil moisture and percolating water can significantly enhance the heat transfer (Kroener et al., 2014). In the course of ongoing energy transition and an accompanied rise in the electricity demand in many countries, there will be a broader use of high voltage power cables in the future and therefore, a growing impact on subsurface temperatures.

4.3. Chemical heat generation

Some anthropogenic sources lead to (bio)chemical reactions that generate heat in or at the (sub)-surface. Often found in the proximity of cities, municipal solid waste **landfills** are typical sources of in-situ underground heating. The generation of heat by biochemical decomposition processes is well studied (Yeşiller et al., 2005) and includes sequential aerobic and anaerobic phases over a period of several decades (Grillo, 2014). Yeşiller and Hanson (2003) monitored the temperature development in a landfill in the midwestern USA and found a warming rate of 2.6–4.0 °C/a depending on the waste age, while the rate of temperature increase is higher for newly deposited waste. Typically, a temperature of 30–60 °C is reached within landfills (Figure 2) (Coccia et al., 2013; Yeşiller & Hanson, 2003), even though 90 °C or higher can occur (Grillo, 2014). The lateral extent of the thermal anomaly of landfills can be substantial. For example, Mahmood et al. (2016) have observed a thermally affected zone of averagely 800 m radius using a remote sensing approach. Similar processes of biochemical decomposition can be observed at the aerobic fringe of contamination plumes (Tuxen et al., 2006). Warren and Bekins (2018) studied the heat generation at a crude oil-contaminated site with an AHI of up to 4.2 K in surrounding soil, where half of the heat is attributed to biodegradation while the other half originates from the oil pipeline itself, which is estimated to be 24 °C warm. The contamination is a source of chemical in-situ heat generation of polygonal geometry, whereas the pipeline acts as a passively heated, linear heat source.

As an example of a thermal anomaly caused by chemical heat generation, we present a landfill in Bitterfeld, Germany. This landfill is located in a coal mining area and is hosted in a former open pit mine that was filled with a mixture of overburden and industrial waste. The base of the landfill reaches into the groundwater saturated zone and causes a contamination of the groundwater downstream. Additional to the landfill as a heat source, a waste-to-energy plant was constructed in close vicinity. These two heat sources induce roughly the same temperature in the subsurface with an AHI of around 3 K, but also have a distinct chemical signature. The groundwater downstream the landfill has a higher acidity (pH below 4.5) compared to the ones downstream the waste-water plant, that show no or only a minor change in pH toward the upstream groundwater with pH values above 6 (Figure 5c). This exemplifies that the thermal anomaly of landfills can be correlated to exothermal processes, as illustrated in Figure 1. The waste-to-power plant represents an industrial building source with active heat generation.

Geochemical processes induced by **mining** can also generate heat. Especially coal mining has considerable effects on the in-situ thermal conditions. The effects are not restricted to the subsurface, but are also observed at heaps, where tailings and overburden are deposited above ground (Willscher et al., 2010). Aerobic conditions lead to the oxidation of sulfur by microbiological and particularly geochemical processes. By these, a temperature of up to 90 °C is induced in the center of heaps (Felix et al., 2009; Willscher et al., 2010). Furthermore, extreme subsurface temperatures of several hundred degrees can be reached by coal seam fires in open pit coal mines (He et al., 2020).

4.4. Geothermal systems

The thermal impact of geothermal systems on groundwater is well studied, as their efficiency and sustainability depend on the initial as well as altered thermal conditions (Rivera et al., 2015). Since geothermal systems rely on heat exchange, the interference within the natural thermal regime is classified as both active and intended. While supplying heat for buildings is the standard application of geothermal heat pumps, the demand of geothermal energy for cooling applications is increasing (Ampofo et al., 2006) in response to global climate change (Epting, García-Gil, et al., 2017). There is a growing focus on solutions with sustainability and longevity, both to store and to extract thermal energy depending on the seasonal demand (García-Gil et al., 2020). Therefore, geothermal systems can show high variability in the thermal impact throughout the year. Overall, the continuously rising number of geothermal systems and energy geostructures has an increasing impact, especially in densely populated areas (Epting, García-Gil, et al., 2017; Epting et al., 2013; Menberg, Bayer, et al., 2013).

The most popular application of shallow geothermal energy systems (**SGES**) are ground source heat pumps. A heat carrier fluid is pumped in a closed-loop through heat exchanger tubes installed in vertical (borehole heat exchanger) or horizontal (ground heat exchanger) direction. In contrast, open-loop systems, are dependent on productive aquifers because of the direct utilization of groundwater as heat carrier fluid and are called groundwater heat pumps for this reason (Bayer et al., 2019). Such systems usually are operated with an extraction well and injection well.

The thermal impact of SGES is determined by several factors like the number and depth of the boreholes, the induced temperature reduction or rise (heating or cooling), the groundwater pumping rate and the local geological and hydrogeological conditions. By knowing operating conditions and effective subsurface parameters, the induced thermal impact can be estimated. Some works monitored the thermal impact of closed-loop systems (Vienken et al., 2019) or open-loop systems (García-Gil et al., 2020; Mueller et al., 2018). Unlike other heat-emitting anthropogenic structures, geothermal systems underlie regulations and laws regarding the induced change of the thermal conditions. Hähnlein et al. (2010) compiled the legal status of shallow geothermal energy use in 60 countries worldwide and found that most countries have no regulations for absolute temperature thresholds, while these countries, which have a legal framework, permit a maximum induced temperature change between ±3 and ±11 K relative to the initial groundwater temperature.

Ground-based seasonal thermal energy storages (**STES**) are operated as closed systems like boreholes, pits, tanks, caverns, or as open systems directly in the aquifer (ATES) (Bott et al., 2019). Even if lateral heat loss is mitigated by insulation for the closed STES systems, local warming of the ambient subsurface can often be observed. The thermal impact of STES systems varies strongly and is dependent on a number of factors like the type, dimensions, temperature difference to the surrounding environment, possible insulation, and the local geological and hydrogeological conditions. 99% of all ATES systems worldwide are operated at low storage temperatures below 25 °C, while well depths strongly vary between 20 and 1,200 m (Fleuchaus et al., 2018). Numerical simulation of low-temperature borehole TES shows a temperature rise of 2 K in 100 m distance after 30 years of operation (Mielke et al., 2014). For pit and tank TES, the heat losses are dependent on the geometry, dimension and insulation of the storage facility. Here, operating temperatures can be as high as 80 °C (Bott et al., 2019). The thermal impact of pit and tank TES systems are rarely monitored, however, Bauer et al. (2008) observed more than 40 °C at 4.3 m below a storage after 10 years of operation, and Bodmann and Fisch (2004) report 30 °C at 4 m depth next to a storage. Bai et al. (2020) validated numerical models of predicted heat dissipation in the ground by an experimental study. The results show a good accordance between experimental and numerical study and furthermore, a storage efficiency of 62%, with a 70% fraction of the heat losses to the surrounding soil.

5. Implications

5.1. Environmental impact

It is known that thermal alteration of the subsurface poses numerous environmental threats on ecosystems hosted in the soil water, the unsaturated, and the saturated zone, as well as on groundwater dependent ecosystems (Brielmann et al., 2009; Griebler et al., 2016). Temperature also is known to control bacterial activity and contaminant behavior and can hereby affect the quality and usability for the freshwater supply of groundwater, world's largest drinking water resource (Bonte et al., 2011). Environmental research is mainly focused on the impact of geothermal systems, while only few studies have considered the impact of unintended heat sources so far. However, findings from the field of geothermal energy are generally applicable to other heat sources, as long as the thermal change is comparably low, for example, for ATES, and the heat transferring process is similar, for example, conduction and advection.

Healthy **groundwater ecosystems** are generally the driving factor of groundwater quality. Their microbiological communities are adapted to constant conditions, where a change in temperature will cause shifts in community composition and microbial diversity (Brielmann et al., 2009; Griebler et al., 2016; Retter et al., 2021). Another issue of groundwater quality is the abundance of prokaryotic cells, which may increase along with a rise in temperature (Lienen et al., 2017). However, Brielmann et al. (2009) underlined that while a temperature increase stimulates metabolism, bacteria require energy to grow, which is limited in clean and oligotrophic groundwater systems. Also, Hartog et al. (2013) did not observe any correlation between bacteria quantities and temperature at a monitored ATES site (11–35 °C), while García-Gil, Gasco-Cavero, et al. (2018) even revealed a decrease in waterborne pathogenic bacteria in relation to shallow GWHP systems, possibly due to a heat shock inflicted by the heat pumps. With groundwater fauna, a negative relationship was regularly observed between water temperature and biodiversity (Brielmann et al., 2009; Spengler & Hahn, 2018) as well as the activity of individual species of crustaceans (Brielmann et al., 2011).

Increasing subsurface temperature especially in the urban environment leads to higher temperatures in **drinking water distribution systems** (DWDS) (Müller et al., 2014). Although most countries have no legal standards for drinking water temperature, some countries recommend temperature limits of 20 or 25 °C at the tap to avoid extensive bacteria growth (Agudelo-Vera et al., 2020). In particular, *Legionella* infection poses a threat to drinking water safety, when the temperature exceeds into the growth range of 25–50 °C (Bartram et al., 2007). Therefore, it is important to monitor shallow ground temperatures in proximity of DWDS and mitigate the anthropogenic thermal impact if necessary. Besides soil sealing, linear heat sources, such as district heating networks, yield an increased impact on DWDS temperature because of the often close and parallel implementation in the shallow ground (van den Bos, 2020). In the future, the threshold of 25 °C is expected to be exceeded more often due to global warming in combination with local thermal anomalies (Agudelo-Vera et al., 2017).

The identified environmental impacts of groundwater temperature change include effects on **contaminant behavior**. Possible effects are enhanced dissolution, transport ,and degradation of contaminants (Beyer et al., 2016). Furthermore, increased concentrations of arsenic (Bonte et al., 2013) as well as pharmaceuticals and personal care products (García-Gil, Schneider, et al., 2018) have been detected in connection with elevated groundwater temperatures.

Despite the known effects of thermal alteration, a moderate rise of groundwater temperature (5–10 K) is considered as a minor impact on groundwater quality (Griebler et al., 2016). However, in the future, this rate will be able to be exceeded more easily when the superposition of different heat sources, as well as climate change, amplify hotspots in subsurface temperature. In urban environments, such local hotspots can become patches more often, eventually forming a pronounced subsurface UHI and thereby, affecting groundwater quality at a regional scale. Koch et al. (2021) investigated the groundwater ecosystem status in the urban area of Karlsruhe (Germany) and found that only 35% of the wells meet the criteria for very good and good ecological conditions.

5.2. Utilization of subsurface waste heat

Another important implication of anthropogenic heat in the subsurface is an elevated geothermal potential for heating (Epting, Böttcher, et al., 2020). Rivera et al. (2017) found that the technically usable potential in urban areas can be 40% higher than in rural areas. On the other hand, geothermal applications for cooling loose efficiency in an anthropogenically heated environment (Di Donna et al., 2021). Therefore, the recovery of waste heat in cities is widely discussed (Bayer et al., 2019). With continuously increasing numbers of SGES in cities, there will be an emerging need for management of this resource by municipal authorities (Epting, García-Gil, et al., 2017) to avoid interferences of the geothermal systems (Attard et al., 2020).

Beside common geothermal systems, there also are direct utilisations of the waste heat of earth-contact structures. These are known as energy geostructures (Brandl, 2006). Such applications not only allow to combine existing structures with geothermal systems, but can also take advantage of anthropogenically generated waste heat. Typically, energy geostructures are equipped with heat exchanger pipes, which lead to a heat pump. The hereby extracted heat can, for example, supply buildings. These closed-loop systems allow for an easier integration in structures. Energy piles, the most common of these technologies, are thermoactive foundations to stabilize and heat (or cool) buildings simultaneously (Sani et al., 2019) and are proven applicable (Zito et al., 2021). Energy tunnels have the heat exchange pipes installed in tunnel linings, while the energy is mostly utilized for local facilities such as schools (Adam & Markiewicz, 2009; Barla & Di Donna, 2018). The research focus is mainly on subway tunnels due to their high energy potential in the urban environment (Epting, Baralis, et al., 2020). Energy walls are thermoactive retaining walls of buildings, including diaphragm and sheet pile walls (Rammal et al., 2020). The thermoactive energy slabs are similar to energy walls but have only one side with earth contact and thus, are less effective (Lee et al., 2021). Energy anchors are thermoactive piles, driven into soil or rock to stabilize structures, for example, tunnels or retaining walls (Adam & Markiewicz, 2009; Brandl, 2006). Recovery of sewage heat is possible with energy sewer pipes (Cipolla & Maglionico, 2014). They can either be equipped with heat exchange pipes at the base of the sewage pipe (Adam & Markiewicz, 2009) or an external heat exchanger is installed (Schmid, 2008). However, high variations in sewage temperature are a challenge for this technology (Kretschmer et al., 2016). For landfill waste heat recovery, conventional shallow geothermal systems are applied (Coccia et al., 2013; Tidden & Scharrer, 2017). Although closed-loop systems are the most common application, there also is the possibility to extract the heat with open-loop systems (Grillo, 2014). This, however, might cause problems if the groundwater is contaminated. The geothermal potential in landfills is typically high, but longevity limitations result from the decomposition period. A further overview of energy geostructures and in-situ examples is given by Loveridge et al. (2020).

6. Conclusions

This review paper highlights the importance of single anthropogenic heat sources to subsurface warming. Currently, there is no consistent classification of anthropogenic heat sources that covers the variability and diversity of characteristics described in this study. Such a classification is the basis for defining guidelines and a legal framework for heat sources of the same characteristics. Different kinds of thermal impacts will require different legal thresholds. Actively heated sources could be governed by a maximum induced temperature difference in the surrounding subsurface and sources that passively emit heat could require a statutory insulation. Further, it is helpful for designing and quantifying thermal boundary conditions in model parametrisation. The environmental impacts caused by increasing subsurface temperature are hardly researched so far despite their crucial importance to groundwater ecosystems and resources. In this work, we provide a holistic overview of the known anthropogenic sources of subsurface warming and their characteristics. In this regard, we propose four main characteristics to classify anthropogenic heat sources.

The first characteristic, the scale, orders heat sources by the extent of the thermally affected zone. Heat sources are classified into *local, regional*, and even *global* (climate change). Secondly, the geometry allows us to classify the heat sources by their shape, which is especially handy when heat sources are to be implemented in models as boundary conditions. We defined three geometries based on the aerial perspective: *polygonal, linear*, and *punctual*. The third classification applies to the process of heat generation. Process types can be *climatic* for above local scale heat sources that warm the underground from the surface, direct *active* (e.g. swimming pools) or *passive heating* (e.g. basements) of the subsurface, *leakage* of a fluid with elevated temperature, or heat that is generated in-situ by a *chemical* process. The fourth characteristic, the intention, particularly shows that besides *intended* geothermal applications, all anthropogenic sources heat the subsurface *unintended*.

However, none of the introduced approaches is unambiguous in all cases—hence, we proposed a classification by outstanding characteristics. The subsequent review of anthropogenic heat sources follows this classification in order to give a consistent and easily accessible structure. The analysis of the relevant literature on the one hand shows the magnitude of the thermal impact of the different heat sources, but on the other hand also reveals a significant research gap regarding the thermal impact of individual heat sources, as well as the implications of the elevated ground(-water) temperature. Ultimately, the discovered knowledge gaps revealed several topics that need to be addressed by future works:

1. To date, studies investigating anthropogenic subsurface warming are performed almost exclusively at district or city scale and integrate local heat sources only as agglomerations or undifferentiated bulk effects. The thermal impact of singular heat sources, however, is typically not considered specifically due to sparse density of measurement points. Filling this gap gives insight into the emitted heat at individual locations but also allows to calculate overall contributions to subsurface warming in general. In fact, some potential heat sources remain to be proven as contributors to subsurface heating like soil heating (agriculture and sport), thermally activated traffic areas, or electrical substations.
2. In this study, we introduced a classification by the process of heat generation. This is only a fraction of the mechanisms and factors that play a role in the underground emission of heat. Therefore, process understanding is another key component to disentangle anthropogenic subsurface warming. Detailed case studies are needed to ascertain the quantitative and qualitative relevance of single parameters like depth to groundwater or insulation.
3. Little is known about the impact thermal change has on subsurface ecosystems. Groundwater, as one of our most valuable resources, is well worth protecting from any possible threat—including thermal alteration. Open questions include temperature thresholds for groundwater ecosystems, changes of hydrogeochemical conditions as well as the establishment of thermal protection zones. Other environmental implications like the influence on DWDS or contaminant behavior remain to be studied more thoroughly.
4. The huge geothermal potential created by waste heat has already been topic of research in the past years. Still, there is a need for research regarding the application of geothermal systems in connection with heat sources, as well as the regulation in densely populated areas in order to maximize the recovery of emitted waste heat. Smart solutions like energy geostructures need to go hand in hand with shallow subsurface management by local authorities for an efficient and sustainable operation of geothermal installations.

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