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"Heat Below the City" – City-Wide Groundwater Temperature Measurements Reveal Subsurface Urban Heat Islands in Vienna (Austria)

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ABSTRACT

This study investigates the subsurface urban heat island (SUHI) effect in Vienna, caused by various heat sources. The impact of prolonged and hotter summer periods extends beyond the surface into subterranean layers causing groundwater temperatures to rise continuously. Various subterranean factors, such as sewage systems, district heating, metro lines, tunnels, and underground structures contribute to the temperature amplification. Additionally, surface temperatures, influenced by climate change and sealing, further exacerbate the subterranean heat. The project, "Heat below the City", aims to evaluate and understand causes of existing SUHI in the city of Vienna, to identify future trends and quantify groundwater potential for heating and cooling. To establish a robust data basis, extensive groundwater temperature measurements were conducted across Vienna's aquifers during the annually warmest (October 2021) and coldest (April 2022) periods in more than 800 boreholes. The documented temperatures in the field studies vary between 6.9 °C and 30.6 °C. Unexpectedly, temperatures in April exceed October in some areas, indicating local warming effects. A first quantification of the impact of heat sources revealed that boreholes near district heating pipes, sewage pipes and sealed surfaces show temperatures higher compared to the average expected groundwater temperature in both periods. These results emphasize the need for locally adapted strategies to mitigate SUHI effects and optimize groundwater use for heating and cooling.

1. INTRODUCTION

Summer periods of warm weather become longer and hotter causing "Urban Heat Islands" worldwide in large cities. Rising temperatures do not stop at the surface, but migrate into the underground, where multiple heat sources amplify the temperature increase, generating subsurface urban heat islands (SUHI). Case studies for - Munich (Boettcher and Zosseder, 2022), Amsterdam (Visser et al, 2020), Cologne, (Zhu et al, 2014), Paris (Hemmerle et al 2019), Cardiff (Farr et al, 2017), Turin (Bucci et al, 2017), Bratislava (Marschalko et al, 2018), Virginia Beach (Eggleston and McCoy 2015), Osaka and Bangkok (Taniguchi et al, 2009), Istanbul (Yetemen and Yalcin, 2009) and Moscow (Lokoshchenko and Korneva, 2015) have proven the SUHI effect. Known heat sources in the underground are sewage system, district heating systems, metro lines, tunnels as well as underground buildings like cellars and metro stations (Noethen et al, 2022, Menberg et al, 2013, Epting and Huggenberg, 2013). Additionally, surface temperatures, influenced by climate change, and surface sealing are known to affect temperatures in the underlying groundwater (Boettcher and Zosseder, 2022). Shallow geothermal energy systems have an ambivalent effect. In cooling mode, they also heat the subsurface. Due to this fact, groundwater heat exchangers solely for cooling purposes are usually not permitted anymore in Vienna, Austria. However, if they are used for heating, they cool the underground by returning colder water than extracted. In this way, they can counteract the trend of increasing underground temperatures. The most common type of groundwater heat exchangers in Vienna pump water from a well, extract the heat (or add heat) with a heat exchanger, which then connects to a heat pump. Afterwards, the water is injected into another well to be returned to the aquifer. A temperature difference of +/- 5 K between extraction and injection is currently the maximum value allowed. However, it is unclear whether these regulations hold true in future. This would allow for a higher heating capacity with the same amount of pumped groundwater and therefore increase the potential for heating with groundwater.

One of the goals of the "Heat below the city" project is to identify existing underground urban heat islands and investigate their future development, as well as to quantify the resources for heating and cooling with groundwater in Vienna. In order to achieve this, a sound data basis is necessary. Previous projects focused on the analysis of data from regularly monitored boreholes (Steiner et al, 2021) or small pilot areas with additional measurements (Cypaite et al, 2021 and Steiner et al, 2019). The novelty of this project is, that we measured the groundwater temperature in as many boreholes as possible within a short period. We did this in two weeks to measure the warmest (October 2021) and coldest (April 2022) groundwater conditions. First results of the temperature measurements will be presented here, with the aim to describe the impact of the underground urban heat island effect on the groundwater temperature.

1.1 Hydrogeology of Vienna

in this study groundwater temperature was analyzed in all shallow aquifers within the city of Vienna, Austria. Gravel deposits alongside the river Danube make up the main productive aquifer in the city (Grupe et al, 2021). Their thickness ranges from 6 m to 25 m, with depths below ground to the groundwater level ranging between 4 m to 15 m. They create favourable conditions for groundwater heat exchangers (Steiner et al, 2021). Those Danube gravels cover the entire left side of the Danube and expand parallel to the Danube further west towards the city centre. Older terrace deposits with locally groundwater bearing layers are found in the west of the city centre. Groundwater-bearing and confining layers alternate in the terrace deposits, making a prognosis of groundwater resources difficult. Smaller streams flowing from the Wienerwald at the western border into the city, cut through these terraces. The two slightly larger streams "Wien" and "Liesing" also form smaller gravel deposits, which are still suitable for groundwater heat exchangers.

2. METHODS

A preliminary analysis of groundwater temperature time series in 217 boreholes in Vienna revealed that the highest and lowest temperatures are generally documented in October and April, respectively. To reach the goal of presenting a spatial temperature distribution at a state of maximum and minimum, we selected one week in October 2021 and one in April 2022 for the detailed field campaigns. The duration of one week allowed us to conduct representative water level and temperature measurements in 793 (October) and 812 (April) boreholes, without any external influences distorting the measured values e.g. from rainfall. Groundwater temperature measurements were conducted manually at one-meter intervals in boreholes distributed across the aquifers. For the herein presented analyses and to achieve a comprehensive overview of the entire city, measurements from all aquifers were combined into one dataset for each field campaign.

The impact of multiple heat sources on the groundwater temperature was determined to gain an initial understanding of the heat sources which exerted the most influence and to identify features that might contribute to cooling the groundwater. Spatial data sets encompass all known potential heat sources, such as contaminated sites (CS), district heating system (DH), sewage system (SeS), shallow geothermal energy systems (SGE, borehole heat exchangers – BHE and groundwater heat exchangers – GWHE), underground buildings (UB), surface sealing (SuS) and surface waters (stagnant – SW and flowing FW waters), were utilized. Given the known thermal propagation characteristics of groundwater heat exchangers, the radius for considering their influence was expanded to 100 meters, compared to 50 meters for other heat sources. Boreholes beyond these radii were considered to represent a more natural state (no-UHI), although acknowledging potential influences from large-scale urban heat island effects and climate change. The temperature variations were shown for all heat sources in boxplots.

Further, the citywide temperature distribution was assessed to validate the hypothesis that the urban heat island effect is strongest in the city center, gradually diminishing outwards. This was achieved by plotting mean temperatures of all boreholes against the distance from Stephansplatz (Square of Stephan's Cathedral), symbolizing the city center.

3. RESULTS

Groundwater temperatures in October generally exhibited higher values compared to April. The slow propagation of seasonal variations from air temperature to the underground resulted in a phase shift of around three months, causing warmer temperatures in shallow aquifers during fall and colder temperatures in spring. The recorded temperatures during the study ranged from 6.9 °C to 30.6 °C. Some areas experienced higher temperatures in April than in October, suggesting the presence of local warming effects from anthropogenic heat sources. These variations could also be attributed to factors such as varying depths to the groundwater level or the influence of adjacent surface water bodies, leading to alterations in phase shift and amplitude.

To provide a comprehensive analysis of the impact of various heat sources on groundwater temperatures, boreholes were categorized based on their proximity to these sources. Boreholes adjacent to district heating and sewage pipes, as well as sealed surfaces, consistently exhibited the highest temperatures in both field campaigns (Figure 1). Boreholes categorized as reflecting a more natural state consistently demonstrated lower temperatures. In October, none of the displayed categories had a lower average temperature than the boreholes in their natural state. However, in April, the category of sites influenced by stagnant surface water bodies showed slightly colder temperatures, indicating a cooling effect of around -0.5 K nearby stagnant surface waters. Mean groundwater temperature for a natural state in Vienna was 12.3 °C.

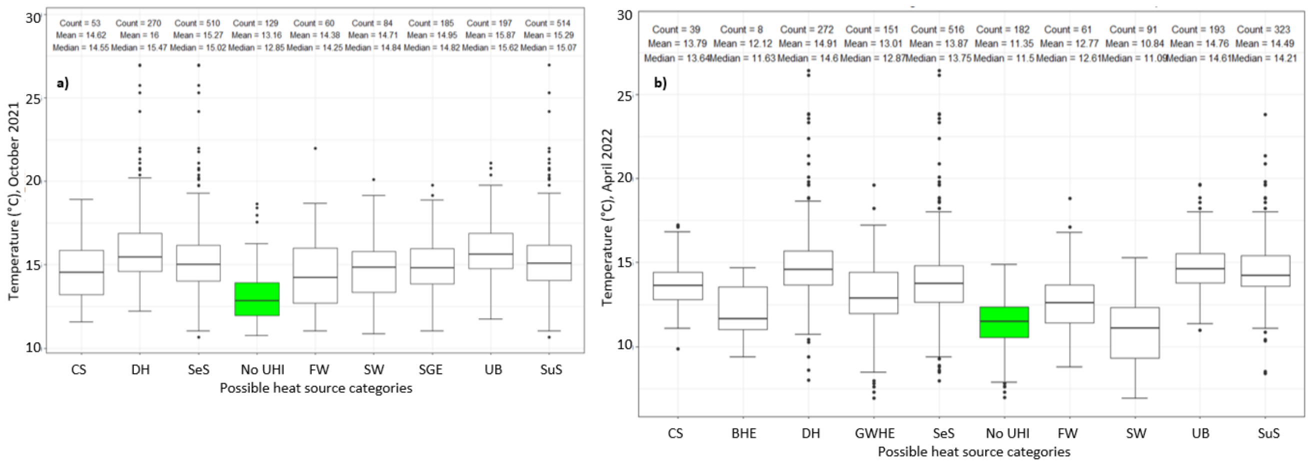

Figure 1: Groundwater temperatures in a) October 2021 and b) April 2022 for boreholes grouped by possible heat sources in a distance of 50 m (100 m for SGE and GWHE). CS – contaminated site, BHE – borehole heat exchanger, DH – district heating system, GWHE – groundwater heat exchanger, SGE – shallow geothermal energy system (comprising BHE and GWHE), SeS – sewage system, No UHI – no possible heat source nearby, FW – flowing surface water, SW – stagnant surface water, UB – underground building, SuS – sealed surface. Count – Number of boreholes, Mean – Mean groundwater temperature, Median – Median groundwater temperature.

Boreholes with the most natural state displayed the lowest temperatures in both field campaigns (Figure 2). Temperatures increased consistently when more than one and up to five heat sources were nearby.

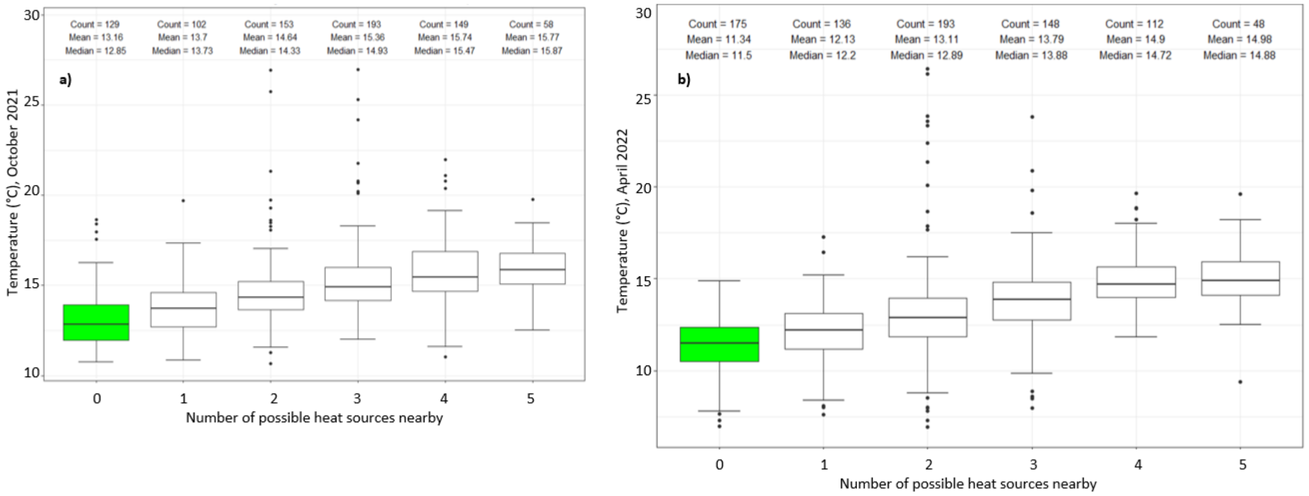

Figure 2: Groundwater temperatures in a) October 2021 and b) April 2022 for boreholes grouped by number of nearby heat sources. Count – Number of boreholes, Mean – Mean groundwater temperature, Median – Median groundwater temperature.

The hypothesis that the warmest temperatures are found in the city center and gradually decrease outward was confirmed and a decrease of 4.5 K over 16 km distance was found between Stephansplatz and the city's outskirts (Figure 3). However, a large temperature variability was found with a scatter of up to 20 K. Intriguingly, the highest mean temperatures were identified between 4 and 6 km away from the city center, challenging the assumption that the larger hotspots are directly in the city center.

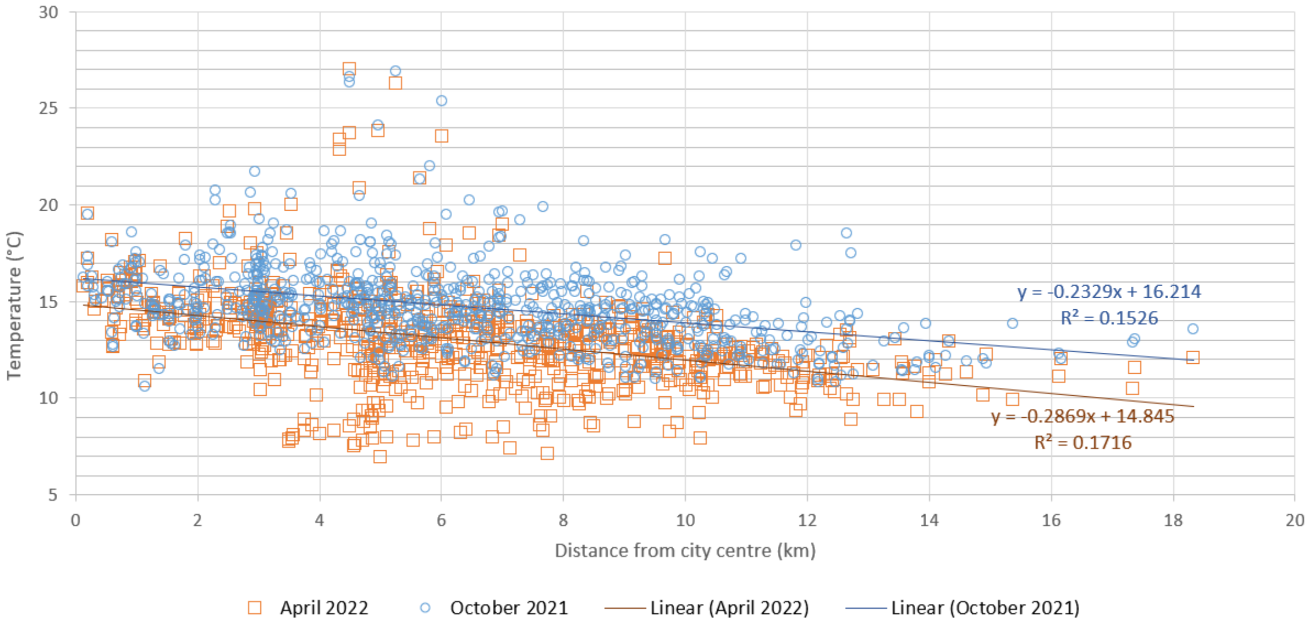

Figure 3: Groundwater temperatures as a function of distance from the city center (Stephansplatz). The lines depict the regression line models with the given equations and the determination coefficient (R²) for the two seasons.

CONCLUSION AND OUTLOOK

These first findings underscore the complex interplay of factors influencing Vienna's groundwater temperatures. The manifestation of SUHI beyond the city center highlights the need for a local understanding of Vienna's thermal dynamics. Groundwater temperatures in October 2021 generally surpassed those in April 2022, with some exceptions, indicating the influence of local warming effects. Boreholes near district heating, sewage pipes, and sealed surfaces consistently exhibited the highest temperatures, emphasizing the impact of anthropogenic heat sources. While the hypothesis of warmer temperatures in the city center, gradually decreasing outward, was partially supported, the highest mean temperatures were identified at 4 to 6 km from the city center. The observed variability in data, with a scatter of up to 20 K, highlights the complexity of Vienna's subsurface thermal dynamics.

Upcoming, temperatures will be mapped for different seasons and depths, and an extensive temperature trend analysis including a temperature prognosis will be done for a better understanding of Vienna's underground thermal landscape. A comprehensive statistical analysis will correlate multiple heat sources with groundwater temperature, considering groundwater flow direction. Additionally, the city-wide chemical and biological state of the groundwater will be evaluated with the aim to gain a fundamental understanding of the relationship between different hydrogeological conditions and urban stressors on the groundwater quality and biodiversity. This is crucial for the development of effective strategies to mitigate the urban heat island effect and optimize a sustainable use of groundwater for heating and cooling purposes.

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