The thermal footprint of urbanization: Linking high-density basement structures to groundwater heat contamination

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Abstract: The thermal influence of urban infrastructure on groundwater resources is a growing concern in hydrogeological studies, particularly in the context of urban heat islands. This research presents a novel approach to quantifying this influence using building density as a proxy for estimating groundwater temperatures (GWT) in urban areas. Using a GIS-based methodology, we constructed circular buffers with a radius of 600 meters centred on groundwater monitoring wells to calculate urban density. Our model demonstrated a strong correlation between building density and GWT, with a correlation coefficient (R^2) of 0.94, indicating a substantial thermal impact of urban structures within this range. The precision of our model was highlighted by the average deviation of 0.34 °C between predicted and measured groundwater temperatures, and a maximum error of 0.79 °C. A case study in Bratislava city validated the model's effectiveness, showing an almost perfect correlation between urban density and GWT. The findings suggest that our approach provides a reliable and simplified method for predicting GWT in urban environments. However, to generalize our model, further research is recommended that incorporates data from various cities and considers additional variables such as groundwater flow. This study contributes to the field of urban hydrogeology by offering a methodological advancement for the assessment and management of groundwater resources in densely built environments.

Key words: Urban hydrogeology, groundwater temperature, building density, GIS buffer, urban heat island

1. INTRODUCTION

The rapid pace of urbanization, characterized by the construction of high-density basement structures, has led to a discernible thermal footprint on urban groundwater resources. The phenomenon of urban heat islands, typically associated with increased atmospheric temperatures in urban areas relative to rural areas, extends below the surface and affects the thermal regime of groundwater systems (Zhu et al., 2010; Menberg et al. 2013). Although the thermal effects of subsurface structures have been increasingly studied, the specific contribution of heated building structures to groundwater heat contamination has not been as thoroughly examined (Dahlem, 2000; Benz et al., 2015).

In Europe, groundwater temperature management has gained attention, resulting in the development of regulations that often impose restrictions on temperature changes attributable to anthropogenic activities (Haehnlein et al., 2010). Accurate monitoring and prediction of groundwater temperatures are essential for the effective management of these resources, particularly in urban settings where the thermal influence of human activities is most pronounced (Florides & Kalogirou, 2007; Shi et al., 2008; Pouloupatis et al., 2011).

In Basel, Switzerland, the thermal impact of urbanization on groundwater was studied. Basel's diverse array of subsurface structures, including tunnels, sheet pile walls, and building foundations that penetrate the aquifer, provides a unique opportunity to analyze these effects (Epting et al., 2008; Epting & Huggenberger, 2013). The extensive monitoring networks of the city and the availability of calibrated numerical models facilitate a comprehensive assessment of the thermal disturbances caused by the urban infrastructure.

By integrating field investigations, monitoring data and synthetic local process-scale heat-transport models, the study by Epting et al. (2017a) aims to quantify the thermal impacts of subsurface structures on groundwater regimes. The application of a Geographic Information System enables the upscaling of localized heat loads to estimate their overall influence on the urban scale, thus improving our understanding of the interplay between natural and anthropogenic factors that shape the thermal landscape of urban groundwater.

This research aims to underscore the significance of anthropogenic heat contributions to groundwater temperature anomalies and inform the development of strategies to mitigate the thermal impacts of urbanization on subsurface water resources.

2. METHODS

The buffers in Geographic Information Systems (GIS) are a critical tool used in spatial analysis. They are essentially zones around a map feature measured in units of distance or time. A buffer is useful for proximity analysis, as it helps to visualize the data concerning to what is nearby.

In hydrogeology, buffers are often used to identify areas that are within a certain distance of a specific feature, such as a river or a well. For example, a buffer might be created around a well to identify a protection zone where certain activities, such as the use of pesticides, are restricted to prevent contamination of groundwater.

In terms of mathematical application, buffers in GIS are created using Euclidean geometry principles. The process involves calculating the distance from each location in the data set to

Manuscript received 2023-12-5
Revised version accepted 2023-12-20

the features of interest. The result is a new polygon layer that represents the buffer zone.

Buffers can be of two types: uniform, where the distance from the feature of interest is the same in all directions, and nonuniform, where the distance varies based on other factors, such as the direction of groundwater flow or the slope of the terrain.

In GIS, buffers are used not only to represent proximity, but also to perform spatial queries and analyses. For example, they can be used to determine the number of certain features within a specified distance from another feature or to identify areas that meet multiple criteria, such as being within a certain distance from a river, but also on a certain type of soil.

In conclusion, buffers are versatile tools in GIS that allow for a wide range of spatial analyses, making them invaluable in fields like hydrogeology.

To assess the influence of building density on groundwater temperature within an urban environment, we first delineated zones of interest around predefined points using the buffer tool in ArcGIS. These points represent locations where groundwater temperature data was collected in observation wells. The buffer tool creates a new layer of polygons at specified distances around the input points, effectively defining the areas within which the density of the building would be evaluated.

The following steps were taken to construct the buffers:
1. The point feature layer containing the groundwater temperature monitoring locations was loaded into ArcGIS.
2. The buffer tool, found under the Analysis Tools toolbox in the proximity toolbox, was selected.
3. The point layer was set as the input feature for the buffer operation.
4. A fixed buffer distance was specified, which was determined based on of the expected range of influence of the subsurface structures on the surrounding groundwater temperatures.
5. The buffer distance unit was set (e.g., meters or feet), consistent with the coordinate system of the input data.
6. The output feature class was named and saved to the desired location.
7. The tool was executed to create the buffer polygons.

Once the buffers were created, the building density was calculated within each buffer zone. The density of the building was defined as the total footprint of the building divided by the total buffer area. This was accomplished using the following steps:
1. The building footprint layer, which contains polygons representing the footprints of the buildings, was loaded into ArcGIS.
2. The 'Intersect' tool, found under 'Analysis Tools' in the 'Overlay' toolbox, was used to identify the portions of building footprints that fell within each buffer zone.
3. The intersected building footprints and the buffer polygons were used as the 'Input Features'.
4. The output feature class was named and saved to the desired location.
5. The tool was executed to create a new layer containing only the building footprints within the buffer zones.
6. The 'Calculate Geometry' function was used to compute the area of each building footprint within the new layer.
7. The sum of all building footprint areas within each buffer was calculated using the 'Summary Statistics' tool, with 'SUM' as the statistic type and the buffer identifiers as the 'case field'.
8. The total area of each buffer zone was calculated using the Calculate Geometry function.
9. The density of the buildings for each buffer was determined by dividing the sum of the building footprint areas by the total buffer area.
10. The building density values were then recorded in the buffer layer attribute table for further analysis.

Then, a linear regression analysis in Excel was done to evaluate the relationship between groundwater temperature and building density.
1. Groundwater temperature data and building density data were entered into adjacent columns.
2. A scatter plot of the data was created.
3. A linear trendline was added to the scatter plot, and the R-squared value was displayed on the graph.
4. For detailed regression analysis, the Excel Data Analysis tool was used.

By following these steps, we have statistically evaluated the fit between groundwater temperature and building density using the built-in statistical tools of Excel.

These methods allowed for a spatially explicit assessment of the relationship between building density and groundwater temperature variations within the urban environment of Bratislava, Slovakia. The results provide insight into the extent to which urban development patterns contribute to the thermal footprint observed in urban groundwater systems.

3. RESULTS AND DISCUSSION

In our investigation of the spatial relationship between urban infrastructure and groundwater temperature, we initially employed a square-grid (or grid-based) buffering approach. This method involved the creation of a square grid overlay with each side measuring 1000 meters. The grid was superimposed onto a map detailing the urban landscape, which included buildings and roads. For each square of the grid, we calculate the percentage coverage of these characteristics relative to the total area of the square, thus quantifying the urban density within the grid in percentage terms (Fig. 1).

Subsequently, we conducted a comparative analysis between the urban density computed and the average groundwater temperatures recorded at the wells that corresponded spatially to each square of the grid. A notable limitation of the square-grid buffer approach emerged from the spatial distribution of the wells. Rather than being centrally located within each square, the wells were frequently positioned near the grid boundaries, introducing a potential bias in the density values attributed to each well and, by extension, affected the precision of our analysis.

Despite this limitation, the square grid buffer method yielded a correlation coefficient (R2) of 0.81, indicating a strong relationship between urban density and groundwater temperature (Fig.

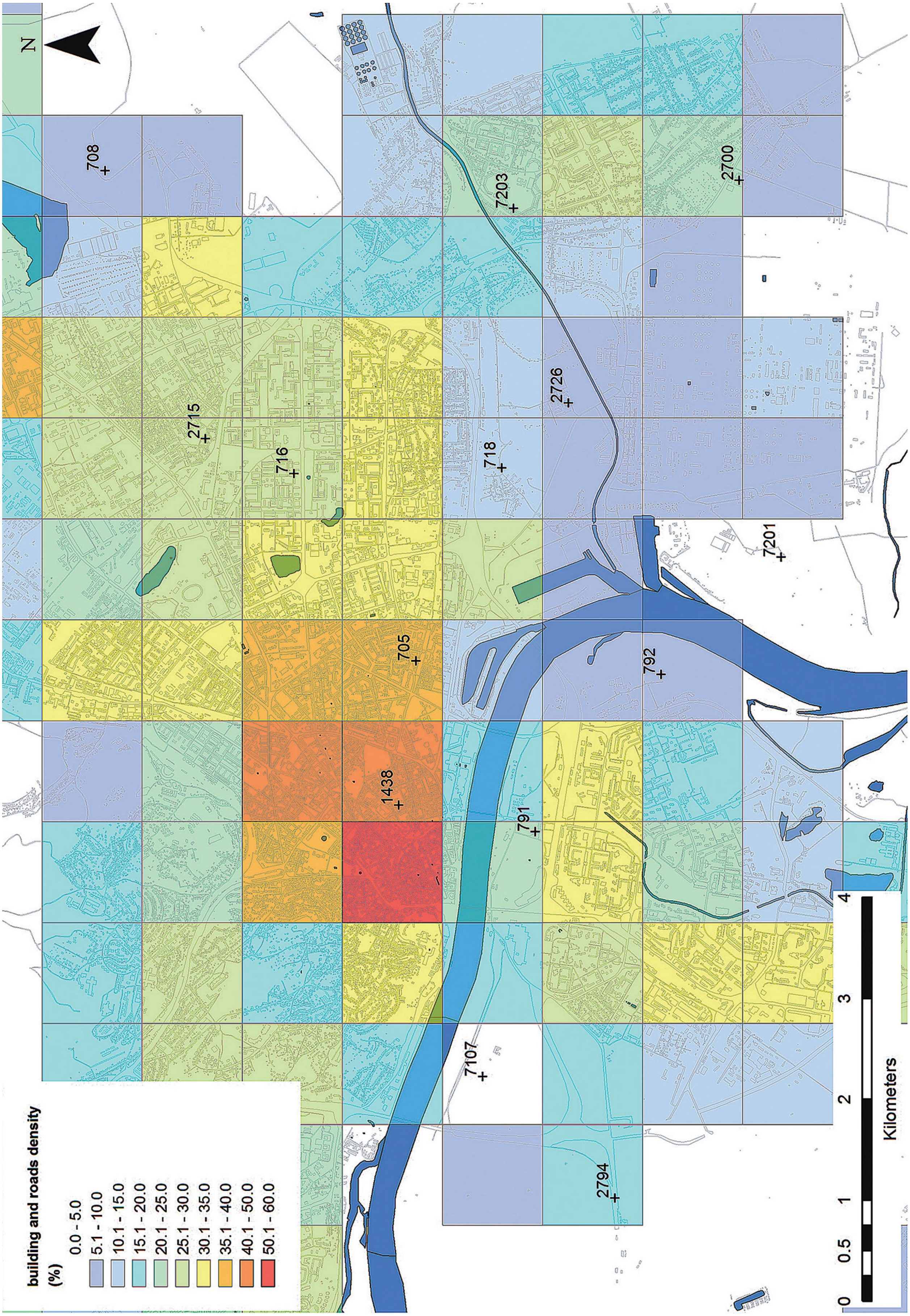

Fig. 1: Square buffer 1000 x 1000 m displaying building and roads density (all figures are from Bratislava city)

2). However, to refine our analysis, we explored an alternative buffering technique using circular buffers.

The circular buffer approach proved to be more advantageous for our study. In this method, each well served as the centroid of a circular buffer (Fig. 3), improving the precision of urban density measurements in the vicinity of the well, with a better correlation coefficient (R2) = 0.91 (Fig. 4). The primary challenge with this approach was determining the optimal radius for the buffers, which conceptually represents the extent to which urban structures influence the thermal characteristics of groundwater at each well site.

To address this, we constructed multiple circular buffers with varying radii and performed correlation analyzes between urban density (buildings plus roads) and groundwater temperature for each buffer size (Fig. 5). Through iterative calculations in Excel, we determined the correlation coefficients (R2) for each scenario. Our analysis revealed the strongest correlation at a buffer radius of 600 meters (Fig. 5), with an R2 value of 0.92, suggesting a significant thermal influence of urban structures within this range.

A further examination of the data involved isolating the effect of roads (including parking lots) on groundwater temperature. When considering only the density of the buildings within the 600-meter radius buffers, the correlation coefficient increased marginally to R2=0.94 (Fig. 6-7). This finding underscores the substantial impact of building density on the thermal regime of the subsurface environment.

The case of well 1438, located in Kamenné námestie, a central urban area with a high concentration of impervious surfaces such as asphalt and concrete, demonstrated an almost perfect correlation (R2 nearly 1) when including both buildings and roads in density calculations. However, the correlation weakened when considering buildings alone, highlighting the importance of road density in areas with extensive paved surfaces.

For circular buffers with a radius of 600 meters, we derived a correlation line equation that related the density of the building to the temperature of the groundwater. Using this model, we estimated groundwater temperatures based on building density data and compared these values with actual temperature measurements (Tab. 1).

The analysis revealed that the mean discrepancy between the temperatures predicted by our model and the actual measured groundwater temperatures was 0.34 degrees Celsius, while the

Tab. 1: Comparison of average measured temperature (for period 2010–2014) and estimated temperatures in observation wells (SHMU).

SHMU	average temp	estimated temp	del=(avg-est)
705	14.42	14.60	−0.18
708	11.90	11.11	0.79
716	14.06	13.55	0.51
718	11.71	11.71	0.00
791	11.49	12.11	−0.62
792	11.28	11.74	−0.46
1438	16.56	17.11	−0.55
2700	12.25	12.35	−0.10
2715	13.69	13.59	0.10
2726	11.55	11.61	−0.06
2794	11.45	11.06	0.39
7107	10.61	11.03	−0.42
7201	11.17	11.14	0.03
7203	13.42	12.85	0.57

max err: 0.79; avg err: 0.34

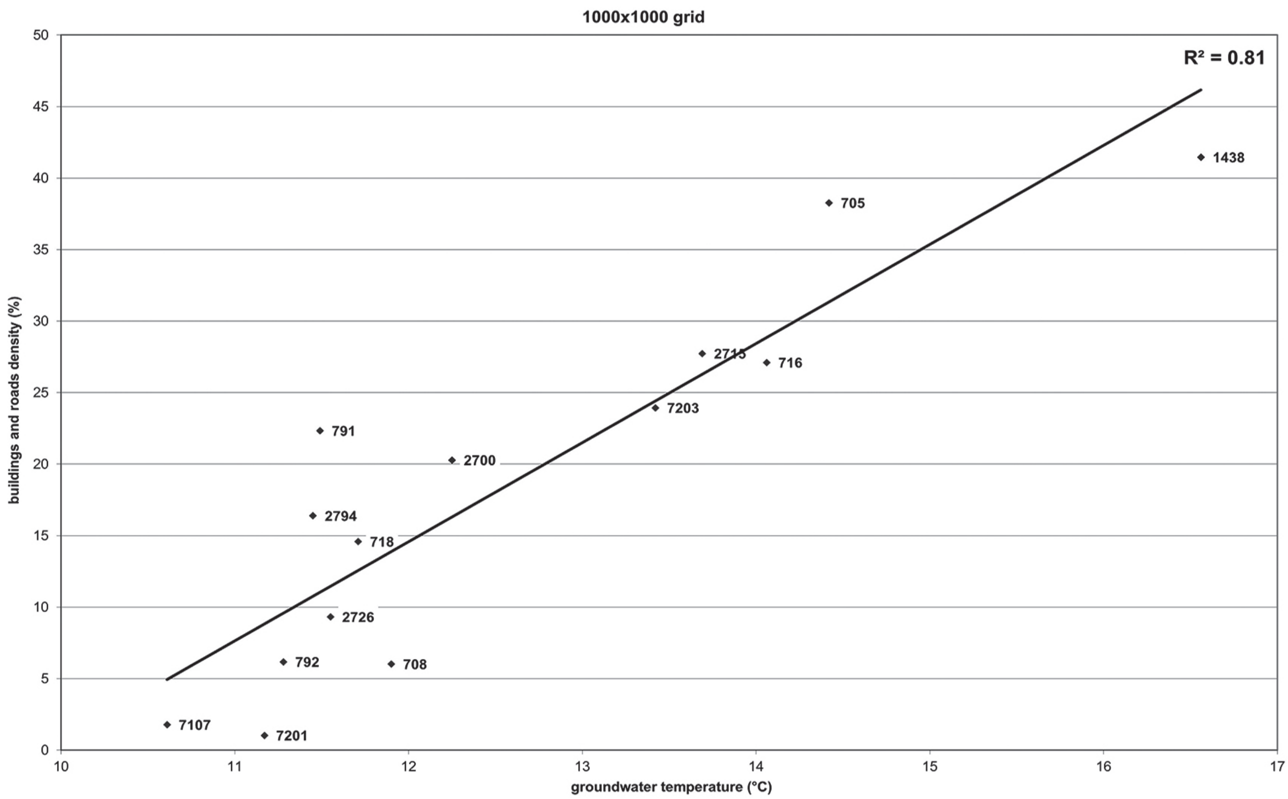

Fig. 2: Relation between groundwater temperature and building and road density using a 1000 x 1000 m square buffer

Fig. 3: Circular buffer with diameter 1000 m that shows the density of buildings and roads

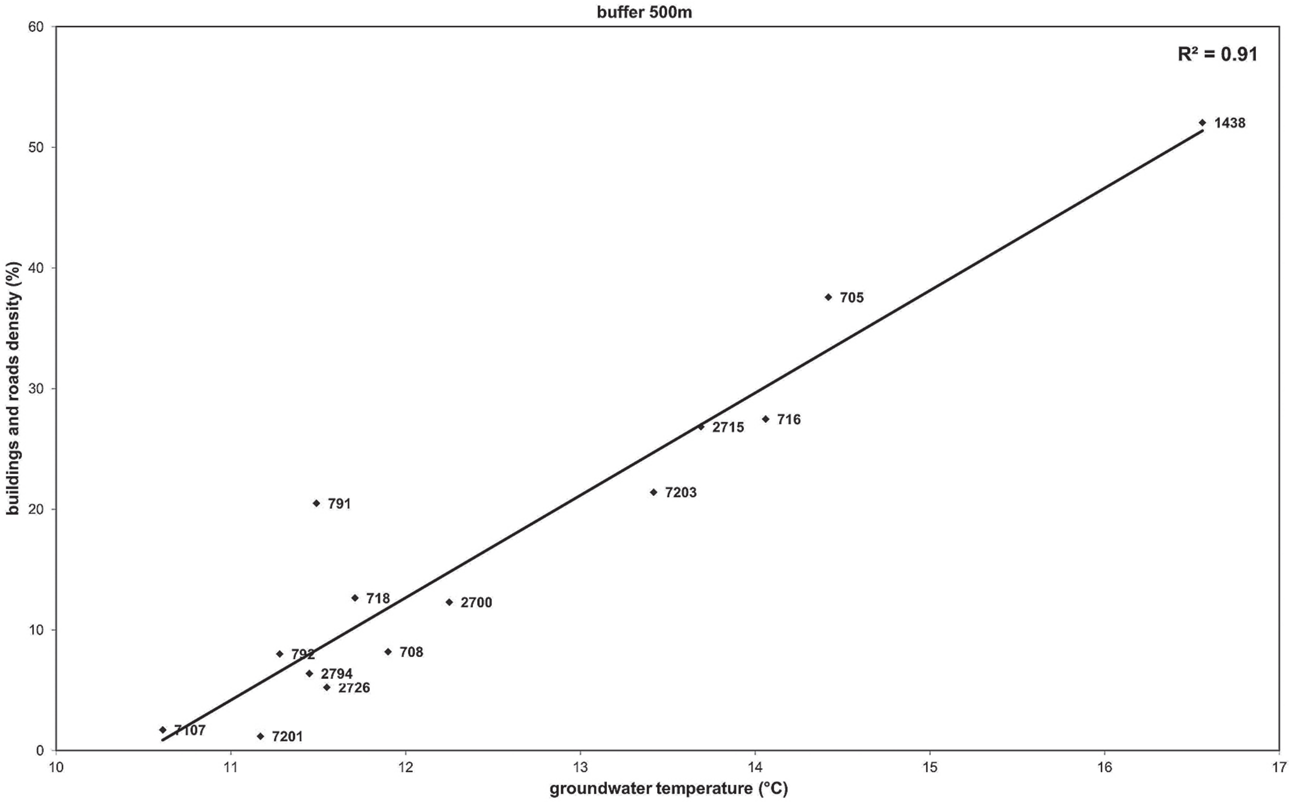

Fig. 4: Relation between groundwater temperature and building and road density using circular buffer with radius 500 m (diameter 1000 m)

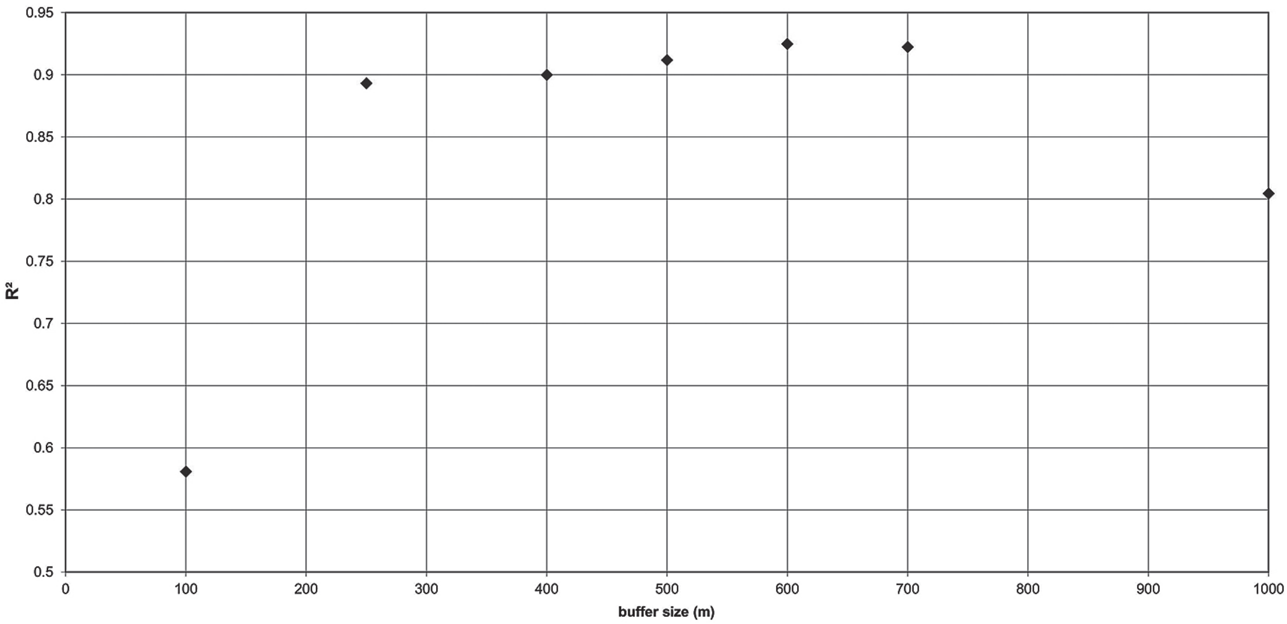

Fig. 5: Relation between buffer size and correlation coefficient R2

largest observed error was 0.79 degrees Celsius. The errors are randomly distributed around a zero value, showing a good fit to the model (Fig. 8). This level of precision is in line with the findings of Benz et al. (2016), who developed a method for estimating groundwater temperatures by integrating land surface temperatures with basement temperatures, achieving a mean absolute error of 0.9 Kelvin. In particular, their research indicated that reliance on land surface temperatures alone tended to underestimate groundwater temperatures by 1.5 Kelvin. On the contrary, our methodology, which uses building density as the sole predictor, appears to provide an even more accurate estimate of groundwater temperatures. However, to substantiate the reliability and generalizability of our approach, additional data from diverse urban contexts are required.

These results suggest that our model can reliably predict groundwater temperatures based on urban density metrics,

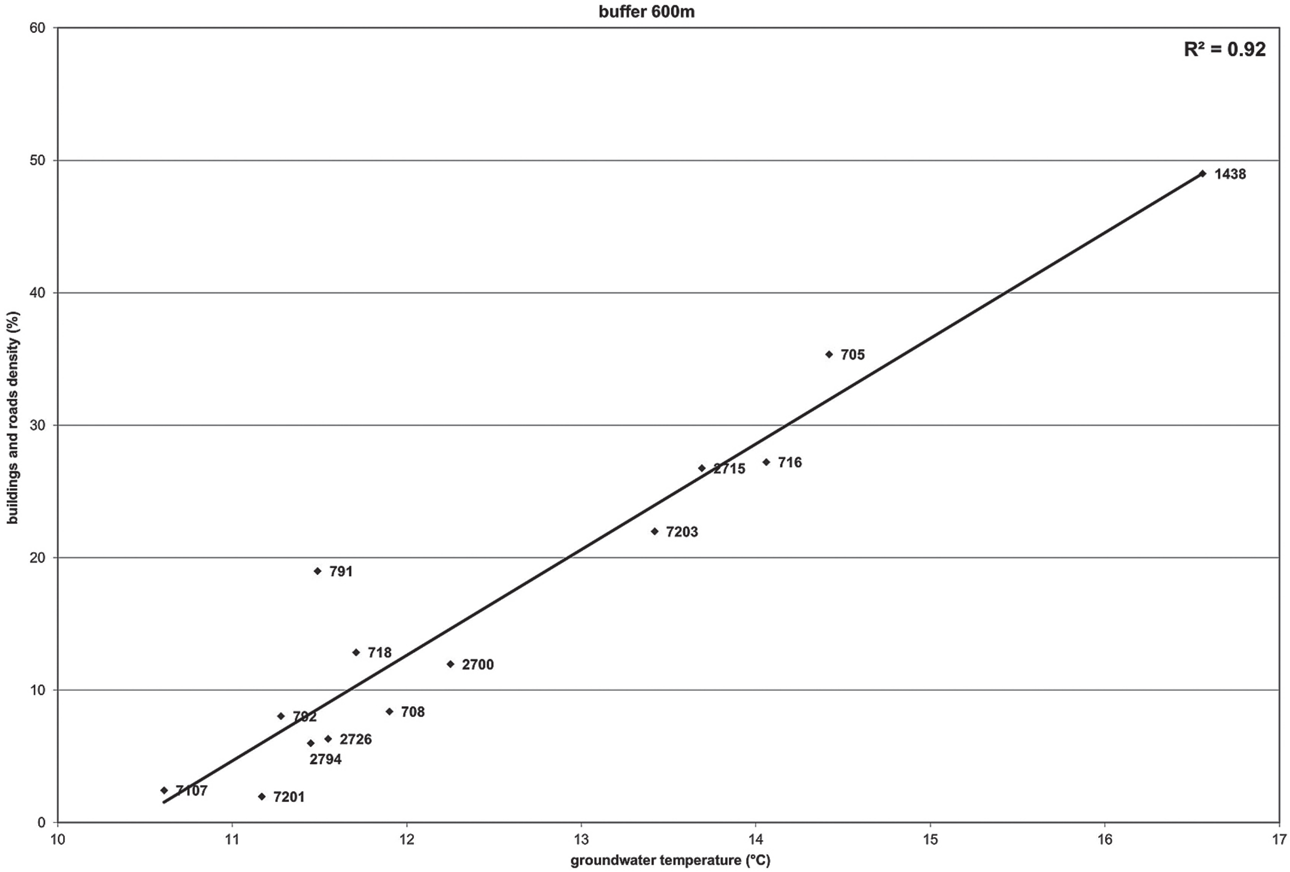

Fig. 6: Relation between groundwater temperature and building and road density using circular buffer with radius 600 m

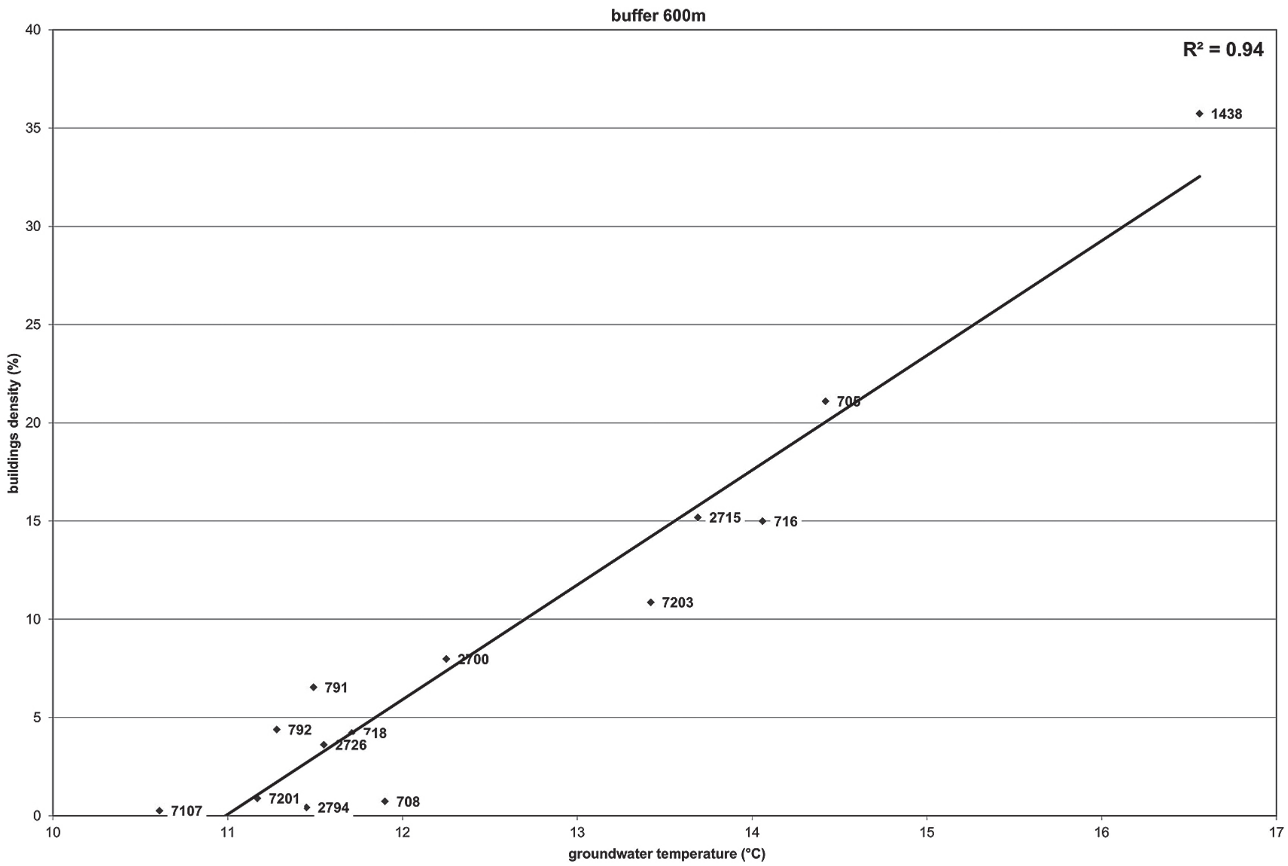

Fig. 7: Relation between groundwater temperature and building density only using circular buffer with radius 600 m

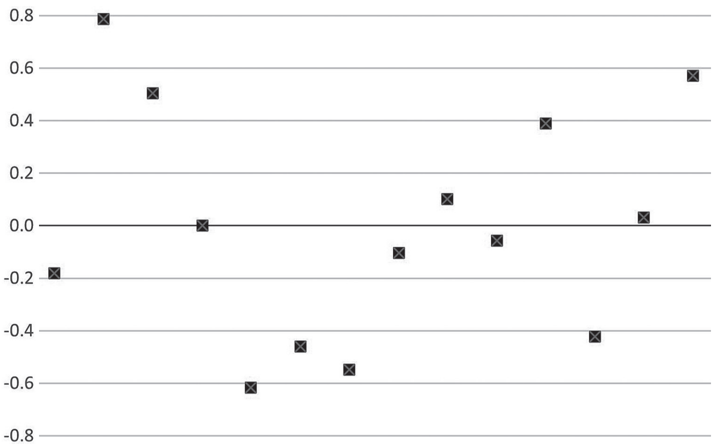

Fig. 8: Distribution of error (del=avg-est; see Table 1)

within a reasonable margin of error. However, to enhance the robustness of our findings, future studies should incorporate the dynamics of groundwater flow. Adjusting the position of the circular buffers in relation to the direction of groundwater flow may potentially refine the correlation further. Epting et al. (2017b) demonstrate that with increasing groundwater flow velocities, the heat load from building structures increases. In addition, the influence of other types of land use on groundwater temperature warrants investigation to provide a more comprehensive understanding of the thermal impact of urban buildings on the subsurface environment.

4. SUMMARY

Our study has demonstrated a robust method for predicting groundwater temperatures in urban environments using building density as a primary indicator. The results of our analysis have shown a high degree of accuracy, with an average deviation of only 0.34 degrees Celsius between the model-predicted temperatures and the actual measurements, and a maximum error of 0.79 degrees Celsius. This precision exceeds the mean absolute error of 0.9 Kelvin reported by Benz et al. (2016), who estimated groundwater temperatures using a combination of land surface and basement temperatures.

Our approach, which relies solely on building density data to estimate groundwater temperatures, not only simplifies the predictive process, but also provides a more precise estimate than methods based solely on land surface temperatures. The latter has been shown to underestimate groundwater temperatures by as much as 1.5 kelvin.

Innovative use of circular buffers with a radius of 600 meters around monitoring wells has proven to be particularly effective in capturing the thermal influence of urban structures. This technique has produced a strong correlation coefficient (R2=0.94), indicating a significant relationship between the density of urban development and the thermal state of the subsurface environment.

Although our findings are promising, they highlight the need for further research to validate the model in different urban settings. Expanding the data set to include a variety of cities with diverse characteristics will enhance the robustness of our predictive model and confirm its applicability on a broader scale. Furthermore, future studies could explore the impact of other variables, such as groundwater flow dynamics and different types of land use, to refine our understanding of the factors that influence urban groundwater temperatures.

Acknowledgements: This research was funded by the Slovak Research and Development Agency under contract No. APVV–14–0174, as well as the Ministry of Education, Science, Research and Sport of the Slovak Republic under contract No. VEGA 1/0302/21.

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