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Spatial resolution of subsurface anthropogenic heat fluxes in cities

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Urban heat islands in the subsurface contain large quantities of energy in the form of elevated groundwater temperatures caused by anthropogenic heat fluxes (AHF_S) into the subsurface. Hence, the objective of this study is to exemplarily quantify these AHF_S and the generated thermal powers in two German cities, Karlsruhe and Cologne. A two-dimensional (2D) statistical analytical model of the vertical subsurface anthropogenic heat fluxes across the unsaturated zone was developed. The model consists of a so-called Local Monte Carlo approach that introduces a spatial representation of the following sources of AHF_S: (1) elevated ground surface temperatures, (2) basements, (3) sewage systems, (4) sewage leakage, (5) subway tunnels, and (6) district heating networks.

The results show that district heating networks induce the largest local AHF_S with values larger than 60 W/m^2 and one order of magnitude higher than the other evaluated heat sources. Only sewage pipes and basements reaching into the groundwater cause equally high heat fluxes, with maximal values of 40.37 W/m^2 and 13.60 W/m^2, respectively. While dominating locally, the district heating network is rather insignificant for the citywide energy budget in both urban subsurfaces. Heat from buildings (1.51 $\pm$ 1.36 PJ/a in Karlsruhe; 0.31 $\pm$ 0.14 PJ/a in Cologne) and elevated GST (0.34 $\pm$ 0.10 PJ/a in Karlsruhe; 0.42 $\pm$ 0.13 PJ/a in Cologne) are dominant contributors to the anthropogenic thermal power of the urban aquifer. In Karlsruhe, buildings are the source of 70% of the annual heat transported into the groundwater, which is mainly caused by basements reaching into the groundwater. A variance analysis confirms these findings: basement depth is the most influential factor to citywide thermal power in the studied cities with high groundwater levels. The spatial distribution of fluxes, however, is mostly influenced by the prevailing thermal gradient across the unsaturated zone. A relatively cold groundwater temperature combined with a high ground surface temperature (GST) and a high groundwater level promote elevated fluxes. Overall, 2.15 $\pm$ 1.42 PJ and 0.99 $\pm$ 0.32 PJ of thermal energy are annually transported into the shallow groundwater of Karlsruhe and Cologne due to AHF_S. This is sufficient to sustainably cover 32% and 9% of the annual residential space heating demand of Karlsruhe and Cologne, respectively. Furthermore, extracting this energy could also keep groundwater temperatures from rising any further.