

Supporting Information for

# Long Term Evolution of Anthropogenic Heat Fluxes into a Subsurface Urban Heat Island

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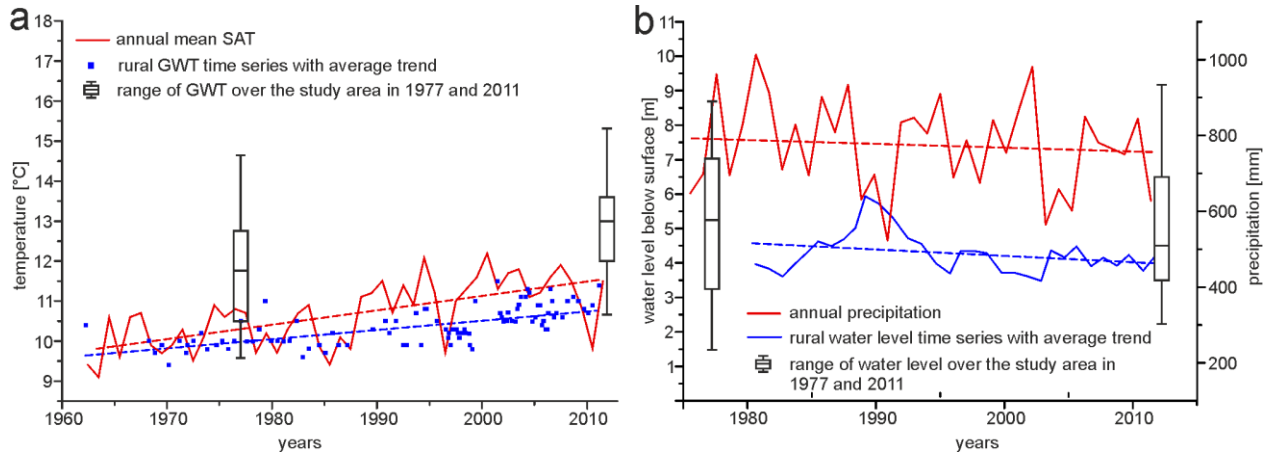
1 Table

2 Figures

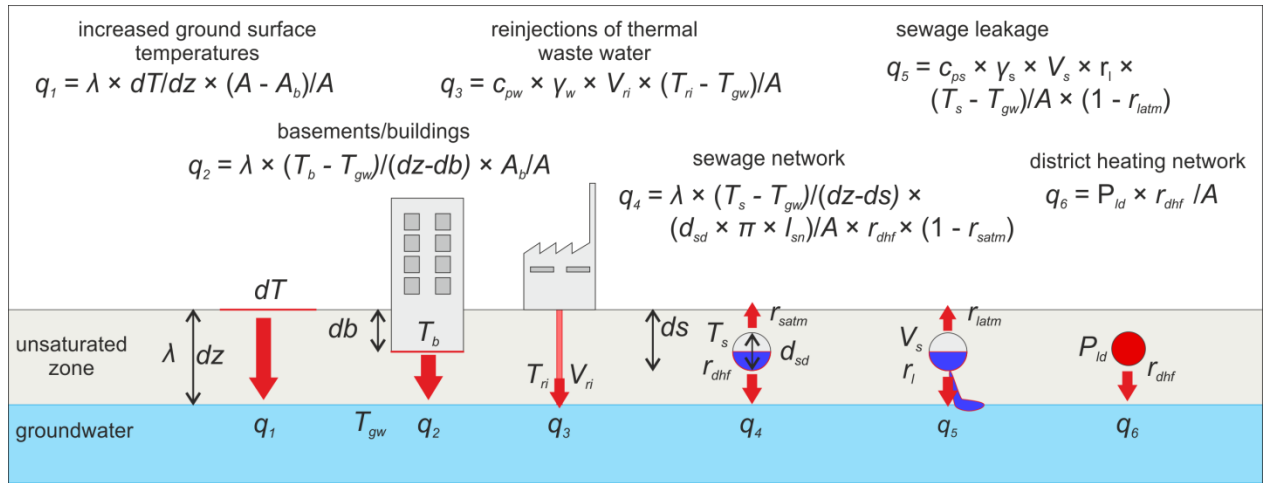
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**Figure S1.** a) Long term development of air and groundwater temperatures in the study area; b) Long term development of water level and precipitation rate in the study area. The boxplots show the spatial distribution of the parameters in the compared years. The background values for GWT and water level were taken from two different wells in a forest outside the city of Karlsruhe.



**Figure S2.** Conceptual sketch of the developed urban heat flux model with heat flux equations and input parameters.

**Description of the assumed parameter ranges.** In the following paragraphs, the assumptions for the model parameters (Table 1) are discussed in detail.

For the thermal conductivity,  $\lambda$ , of the unsaturated zone we use literature values<sup>1,2</sup>, which correspond to partly saturated sand and gravel deposits typical for the study area<sup>3</sup>. Thus, the assumed range also accounts for changes in the moisture content of the sediments. The lowest  $\lambda$  was set to 0.3 W/mK for dry gravel; the highest value, 1.8 W/mK, represents completely saturated sandy material.

The difference in local GST and GWT,  $dT$ , is assumed to range between 0 and 5 K. In long-term steady-state examinations mean annual GST and shallow GWT are usually assumed to equal each other (e.g. Taylor and Stefan, 2009)<sup>4</sup> with no heat flux occurring into the subsurface. Alteration of the surface cover leads to a change in GST. Changes from vegetated surfaces to bare soil were found to cause an increase in annual mean GST between 0.3-1 K, while concrete and asphalt surfaces show a GST that is 2–5 K higher than at a grass or forest site<sup>4,5</sup>. The percentages of different surface types in the study area were estimated based on a land use plan, similar to the approach by Taylor and Stefan (2009)<sup>4</sup>. According to the land use plan of Karlsruhe, approx. 20% of the study area are covered by buildings and the rest is characterized by different kinds of vegetation (approx. 56%) and artificial surface covers (approx. 24%). Due to this distribution and the fact that the GWT below the urban area is already elevated compared to the undisturbed background the mode value for  $dT$  is set to 1 K. As the annual mean SAT in 2011 was 0.8 K higher than in 1977<sup>6</sup> this value was added to the triangular distribution, given that GST usually track SAT in long-term trends<sup>7</sup>.

For the groundwater temperature,  $T_{gw}$ , and the depth of water table,  $dz$ , measured data in the study area was interpolated using kriging in GIS (ESRI® ArcInfo™ 10.0) (Figure 1). Raster data

sets, with a spatial resolution of  $15 \times 15 \text{ m}^2$  were created, and the individual pixel values were then used for the Monte Carlo simulation. Likewise, the area covered by buildings,  $A_b$ , in 2011 was derived from GIS by evaluating a municipal land-use plan. The actual building density of the individual built-up polygons in GIS was estimated with Google Earth and an uncertainty of  $\pm 5\%$  was assigned. For the year 1977, no detailed land-use plan was available. Instead, the map from 2011 was revised by excluding newly built residential and industrial areas and reducing the overall building density for the remaining built-up polygons by 10% based on statistical data on city development<sup>8</sup>. For each building polygon, a respective basement depth,  $db$ , was also assigned. The standard basement depth of residential buildings in Germany is approx.  $2.5 \text{ m}$ <sup>9</sup>. Greater depths were assumed for certain areas, for example with underground parking lots or shopping malls, lesser depths or no basements were assigned to industrial areas with large industrial halls. The relevant distance for the heat flux can then be calculated by subtracting the basement depth from the water table level. For basements with contact to the groundwater, we assume a minimal distance of  $0.3 \text{ m}$ , which represents the typical thickness of a concrete slab<sup>10</sup>. The  $\lambda$  in heat flux  $q_2$  thus, accounts for the subsurface and the slab material. As typical thermal conductivities of different concrete types ranges between  $0.45$  and  $1.8 \text{ W/mK}$ <sup>11,12</sup> and the fraction of the slab to the distance ( $dz-db$ ) is rather small, the same  $\lambda$  as for  $q_1$  is taken for  $q_2$ .

For the reinjections of thermal wastewater, data on the reinjected water volume,  $V_{ri}$ , and temperature,  $T_{ri}$ , was provided by the environmental department of the city of Karlsruhe for 2011. For 1977 this data was taken from the study by Makurat (1980)<sup>13</sup>. However, both data sets represent mostly licensed values for  $V_{ri}$  and  $T_{ri}$ , which are usually not confirmed by in situ measurements. Measurements on 8 reinjection sites in 1977 showed that between 80% and 100% of licensed temperature and water amount are actually utilized. Thus, we assume that on average,

90% of the licensed temperature and water amount are utilized, and we account for uncertainty by assigning a range of  $\pm 10\%$ .

The data to describe the sewage network ( $ds$ ,  $l_s$ ,  $V_s$ ) was provided by the municipal water supplier of Karlsruhe for 2011, and for the year 1977 values were again taken from Makurat (1980)<sup>13</sup>. The minimum sewage temperature,  $T_s$ , is defined by the annual temperature measured at the outlet of the sewers at the treatment plant by the public works service Karlsruhe. The mode and maximum of  $T_s$  are based on an estimation of the average domestic waste water temperature by Makurat (1980)<sup>13</sup>. For the diameter of the sewage pipes,  $d_{sd}$ , and the leakage rate,  $r_l$ , a range of values from studies in other German cities was applied<sup>14,15</sup>. The values for the percentage of upward and downward directed heat flux, ( $r_{satm}$ ,  $r_{latm}$ ,  $r_{dhf}$ ) are assumed based on the geometry of the pipes. The heat capacity and density of wastewater are assumed to be slightly higher than of pure water due to solid contents<sup>13</sup>.

### Contribution to variance analysis.

**Table S1.** Results of the contribution to variance analysis. Spearman's rank correlation coefficients for the total heat flux result and all parameters with the 95% confidence interval determined by bootstrapping.

Parameter	Spearman's rho 1977	95% confidence interval		Spearman's rho 2011	95% confidence interval	
		min	max		min	max
GST difference urban - rural	0.4629	0.4583	0.4687	0.2631	0.2602	0.2663
depth of water table	-0.4050	-0.4100	-0.4001	-0.6271	-0.6293	-0.6250
depth of basements	-0.3523	-0.3575	-0.3461	-0.7464	-0.7480	-0.7450
groundwater temperature	-0.2988	-0.3031	-0.2936	-0.3644	-0.3676	-0.3615
thermal conductivity	0.2578	0.2527	0.2625	0.2085	0.2053	0.2123
sewage temperature	0.1094	0.1048	0.1147	0.0503	0.0469	0.0531
leakage rate	0.0493	0.0440	0.0551	0.0204	0.0168	0.0240
reinjection temperature	0.0412	0.0367	0.0482	0.0087	0.0050	0.0134
percentage of downward directed heat flux	0.0332	0.0260	0.0376	0.0158	0.0131	0.0198
reinjection volume	0.0196	0.0131	0.0256	0.0007	-0.0026	0.0055
diameter of sewage drains	0.0192	0.0133	0.0242	0.0132	0.0087	0.0171
percentage of heat flux to atmosphere (rlatm)	-0.0139	-0.0193	-0.0087	-0.0023	-0.0064	0.0012
heat loss from district heating pipes	0.0105	0.0055	0.0160	0.0061	0.0028	0.0101
depth of sewage drains	-0.0079	-0.0124	-0.0032	0.0007	-0.0042	0.0026
density of waste water	0.0099	0.0019	0.0145	0.0028	0.0000	0.0064
heat capacity of waste water	0.0061	0.0014	0.0107	0.0023	-0.0056	0.0023
sewage volume	0.0117	0.0075	0.0167	0.0013	-0.0021	0.0050

percentage of heat flux to atmosphere (rsatm)	-0.0034	-0.0097	0.0016	-0.0038	-0.0078	-0.0008
area covered by buildings	-0.0015	-0.0055	0.0035	-0.0025	-0.0070	-0.0012
temperature of basements	-0.0048	-0.0103	0.0004	0.1968	0.1924	0.2001
length of sewage network	0.0011	-0.0030	0.0076	0.0029	-0.0003	0.0075

## References.

- (1) Menberg, K.; Steger, H.; Zorn, R.; Reuss, M.; Proell, M.; Bayer, P.; Blum, P. Bestimmung der Wärmeleitfähigkeit im Untergrund durch Labor- und Feldversuche und anhand theoretischer Modelle (Determination of thermal conductivity in the subsurface using laboratory and field experiments and theoretical models). *Grundwasser* **2013**, *18* (2), 103–116.
- (2) Verein Deutscher Ingenieure. VDI 4640-1: Thermische Nutzung des Untergrundes – Grundlagen, Genehmigungen, Umweltaspekte (Thermal use of the underground – Fundamentals, approvals, environmental aspects), Beuth Verlag GmbH: Berlin, 2010.
- (3) Geyer, O. F.; Gwinner, M. P. *Geologie von Baden-Württemberg*; Schweizerbart: Stuttgart, Germany, 2011.
- (4) Taylor, C. A.; Stefan, H. G. Shallow groundwater temperature response to climate change and urbanization. *J. Hydrol.* **2009**, *375*, 601–612.
- (5) Dědeček, P.; Šafanda, J.; Rajver, D. Detection and quantification of local anthropogenic and regional climatic transient signals in temperature logs from Czechia and Slovenia. *Climatic Change* **2012**, *113*, 787–801.
- (6) Deutscher Wetterdienst: Web-based Weather Request and Distribution System. <http://www.dwd.de/> (accessed March 20, 2013).
- (7) Smerdon, J. E.; Pollack, H.; Cermak, V.; Enz, J. W.; Kresl, M.; Safanda, J.; Wehmiller, J. F. Air-ground temperature coupling and subsurface propagation of annual temperature signals. *J. Geophys. Res.* **2004**, *109* (21), D21107.



(8) Stadt Karlsruhe. Stadtgebiet und Flächennutzung. <http://www1.karlsruhe.de/Stadtentwicklung/siska/sgt/sgt01050.htm>. (accessed March 7, 2013).

(9) Landesamt für Geologie, Rohstoffe und Bergbau Baden-Württemberg. Informationen 11: *Anwendung geowissenschaftlicher Informationssysteme am Landesamt für Geologie, Rohstoffe und Bergbau Baden-Württemberg*. [http://www.lgrb.uni-freiburg.de/lgrb/Produkte/schriften/online-publikationen/informationen\\_11/pdf\\_pool/info11.pdf](http://www.lgrb.uni-freiburg.de/lgrb/Produkte/schriften/online-publikationen/informationen_11/pdf_pool/info11.pdf) (accessed January 18, 2013).

(10) Adjali, M. H.; Davies, M.; Littler, J. G. Earth-contact heat flows: Review and application of design guidance predictions. *Build. Serv. Eng. Res. T.* **1998**, *19* (3), 111–121.

(11) Deutsches Institut für Normung e.V. DIN EN ISO 10456: Baustoffe und Bauprodukte – Wärme- und feuchtetechnische Eigenschaften (Building materials and products – Hygrothermal properties), Beuth Verlag GmbH: Berlin, 2010.

(12) Deutsches Institut für Normung e.V. DIN V 4108-4: Wärmeschutz und Energie-Einsparung in Gebäuden – Teil 4: Wärme- und feuchteschutztechnische Bemessungswerte (Thermal insulation and energy economy in buildings – Part 4: Hygrothermal design values), Beuth Verlag GmbH: Berlin, 2007.

(13) Makurat, A. Analyse der Temperaturschwankungen des Grundwassers im Stadtgebiet von Karlsruhe. Diploma thesis, Universität Karlsruhe (TH), Karlsruhe, 1980.

(14) Eiswirth, M.; Held, I.; Hötzl, H.; Wolf, L. *Abwasser im urbanen Grundwasserleiter: Stoffeintrag, Umsetzungen und Gefährdungspotential*. In Progress Report „Forschergruppe Kanalleckage: Gefährdungspotential von Abwasser aus undichten Kanälen für Boden und Grundwasser“: Universität Karlsruhe, Germany, 2002.

(15) Klinger, J. Beschreibung der Wasser- und Stoffflüsse in einem urbanem Raum unter besonderer Berücksichtigung von Kanalleckagen. Ph.D. Dissertation, Universität Karlsruhe (TH), Karlsruhe, 2007.