

Figure S1: Overview map of Karlsruhe: (a) the average content of dissolved oxygen of the multiple measurements [mg/l]; (b) contaminated sites of the soil protection and contaminated site register (Bodenschutz- und Altlastenkataster) of Karlsruhe (modified after Stadt Karlsruhe, 2006; Kühlers et al., 2012; Wickert et al., 2006); (c) average nitrate concentration [mg/l] of the repeated measurements; (d) iron concentration [mg/l] of the repeated measurements and (e) the phosphate concentration [mg/l] of the repeated measurements at the bottom of the measurement wells.

## Groundwater Fauna Index (GFI)

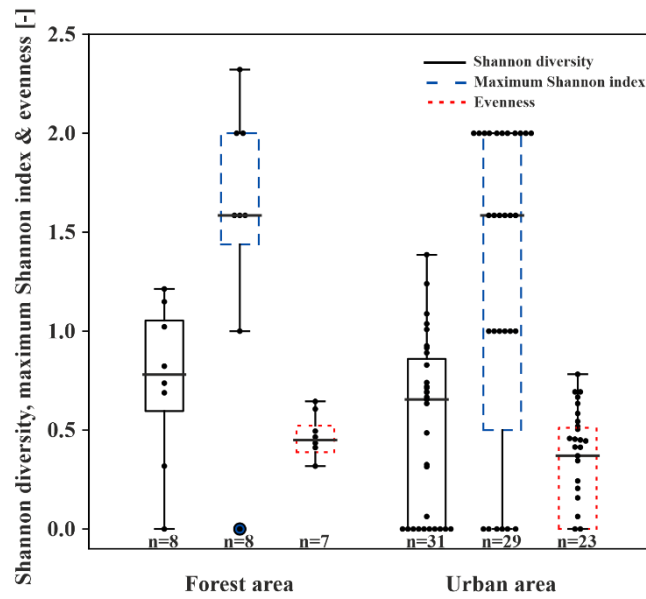
The Groundwater-Fauna-Index (GFI), introduced by Hahn (2006), quantifies the ecological relevant conditions in the groundwater as a result of hydrological exchange between surface and groundwater. It incorporates ecologically important groundwater parameters such as relative amount of detritus, variation of groundwater temperature and concentration of dissolved oxygen (Hahn, 2006) and is calculated by using Equation 1:

$$\text{GW Fauna Index} = \sqrt{\text{Dissolved Oxygen} \left(\frac{\text{mg}}{\text{l}}\right)} \times \sqrt{\text{Relative Amount of Detritus}} \times \text{Standard deviation Temperature} \quad (1)$$

The determined average GFI of all sampled wells is  $6.0 \pm 2.8$  with a total variation between 0 and 14 and a heterogeneous distribution of the GFI-values. High GFI values ( $> 10$ , Type III), indicating hydrological exchange with the surface (Hahn, 2006), were only found in three wells, which share a high standard deviation of GWT (2.6 to 3.5 °C), higher dissolved oxygen (5.5 to 5.8 mg/l) as well as nitrate concentrations (7.7 up to 12 mg/l). These specific well locations have mainly no or minor sealed surfaces. Overall, 82 % of the measurement wells showed meso-alimonic conditions (GFI  $> 2$ -10, Type II) and therefore indicate a medium level of surface influence, at diverse urban and rural locations. Only four wells in this study were well insulated from surface influences (GFI  $< 2$ ), with three wells located in densely built-up surroundings with sealed surfaces. Moreover, the average GFI in the forest area is  $4.5 \pm 1.9$  and in the urban area  $6.2 \pm 2.7$ .

## Shannon diversity index

The Shannon-Index, introduced by Shannon and Weaver (1949) is an established standard method to quantify the ecological diversity of e.g. bacterial or faunistic communities. The index describes the diversity by including the number of species and the relative frequency of individuals. The sampled wells in the forest area show the highest balance (median EH = 0.47) and Shannon diversity index (median HS = 0.74). The maximum diversity (median  $H_{\max} = 1.58$ ) is the same in both the forest and the urban area. The balance (median EH = 0.42) and Shannon diversity index (median HS = 0.52) are only a little bit lower in the urban area. These results are comparable with the study of Brielmann et al. (2009), where the Shannon diversity index of an anthropogenically influenced groundwater of an aquifer downstream of an industrial facility varies between 0.20 and 1.45. Nevertheless, no clear distribution pattern according to faunal diversity is recognizable. Thus, the Shannon diversity index was not considered further.



**Figure S2. Boxplots of the Shannon diversity index, maximum Shannon index and evenness, divided in forest and urban area (n = number of wells, or number of wells at which the evaluation is applicable).**

### 35 Urban impacts on groundwater quality

Urban impacts on groundwater systems can be manifold, such as increasing temperatures (urban heat islands (Menberg et al., 2013)), contaminants (Kuroda and Fukushi, 2008), changes in the precipitation discharge due to sealing, falling water levels due to groundwater withdrawal (Foster, 1990). In our study we intend to provide a first impression of the situation in Karlsruhe and therefore focus on the standard parameters. A first overview is given by the LUBW continuous monitoring program of groundwater wells (Landesanstalt für Umwelt Messungen und Naturschutz Baden-Württemberg, 2020), which provides profound groundwater analysis in Karlsruhe. Some of the considered measurement wells are close to the measurement wells of this study. Assessing the evaluation period of this study (2011-2014), most of the wells of the monitoring program show values within the range of the local background or below the thresholds of the drinking water ordinance of Germany and therefore no contamination.

45 One exception is a measurement well in the Kapellen-Street (next to T105), which shows higher ammonium (average: 0.55 mg/l, threshold drinking water ordinance: 0.5 mg/l), iron (5.1 mg/l, threshold value of the German drinking water ordinance: 0.2 mg/l) and manganese concentrations (0.55 mg/l, threshold drinking water ordinance: 0.05 mg/l). Moreover, this well has a noticeable concentration of arsenic (8.7 µg/l, threshold drinking water ordinance: 10 µg/l) and of the herbicide CGA 369873 (0.1 µg/l, threshold: 0.1 µg/l). This well is at the margin of one of the largest contaminated site in Karlsruhe, the former gas plant.

Three other wells, which contain contaminants are in the Kaiserallee, Mathy-Street (next to T124) and near the municipal hospital. They showed noticeable concentrations of volatile hydrocarbons of up to 13 µg/l during the evaluation period (in detail at the hospital: 3-6 µg/l; Kaiserallee: 5-8 µg/l; Mathy Street: about 3 µg/l). In comparison, the German threshold value of the drinking water ordinance is 20 µg/l.

- 55 The groundwater of one measurement well in the Hardtwald (next to SWM-005/SOM-020) has a different chemical composition than the wells in the urban area. It shows lower concentrations of boron (30-45 µg/l, compared to the other wells: 50-98 µg/l), calcium (100-110 mg/l, compared to the other wells of up to 150 mg/l), chloride (25.5 mg/l in 2014 compared to the other wells: > 50 mg/l), potassium (3.2 mg/l) and sodium (11.3 mg/l). Furthermore, the content of dissolved oxygen is higher than in the wells of the urban area (average with 4.8 mg/l).
- 60 This overview indicates that beside one larger and two smaller contaminations, the groundwater beneath Karlsruhe contains only minor pollution. Groundwater fauna can usually cope well with short-term changes of chemical-physical parameters (Griebler et al., 2016). Previous studies showed that some species can even benefit from pollutants (Matzke, 2006; Zuurbier et al., 2013). Thus, the main documented impacts on groundwater quality in the study area are related to groundwater temperature, oxygen and nitrate concentration.

65 Table S1: Well locations, information, sampled properties and result of the evaluation (GWT=groundwater temperature, \*sampling 2011-2012: 6 times, † sampling 2014: 3 times)

Measuring point	Location	Area classification	Depth [m]	Average GWT [°C]	SD GWT [-]	Relative amount of detritus [-]	Average dissolved oxygen [mg/l]	Average GFI [-]	Amount crustaceans (acc. to Griebler et al. (2014)) [%]	Amount oligochaetes (acc. to Griebler et al. (2014)) [%]	Total amount of individuals [-]	Numbers of taxa [-]	Ecological condition (acc. to Griebler et al. (2014))
T101	Lammstr. No.7	* Urban area	39.0	14.4	0.05	3	0.97	0	0	0	0	0	Faunistic evaluation not possible
T102	Tulla Bad	* Urban area	10.0	14.0	2.99	2	1.45	5	100	0	4	2	Natural
T104	Arbeitsamt - Rankestr.	* Urban area	15.8	12.5	1.28	3	1.07	2	0	0	0	0	Faunistic evaluation not possible
T105	Fritz-Erler-Str. No.21	* Urban area	9.3	14.4	3.29	3	1.29	6	0	100	1	1	Faunistic evaluation not possible
T106	Schloßplatz / Schloßbezirk	* Urban area	11.0	14.2	2.60	3	4.02	9	86	14	7	3	Natural
T123	Sophienstr. - Grillparzerstr.	* Urban area	14.0	12.8	1.65	1	2.18	2	0	100	3	2	Affected
T124	Kaiserplatz	* Urban area	13.0	14.9	1.95	3	1.97	5	0	0	2	1	Affected
T125	Kriegsstr. No.141	* Urban area	11.8	15.0	2.32	1	3.64	4	0	100	103	3	Affected
T128	Sü dendstr. - Brauerstr.	* Urban area	9.5	13.2	3.21	2	5.50	11	0	100	13	2	Affected
T129	Schule Beiertheim	* Urban area	8.5	12.2	3.67	1	2.31	6	91	9	124	4	Natural
T320	Südbeckenstr. No.16	* Urban area	9.0	12.6	3.43	1	2.62	6	0	100	252	1	Affected
T322	Rheinhafenbad	* Urban area	10.0	15.9	2.99	2	3.45	8	0	100	6	2	Affected
T402	Am Fasanengarten - Parkstr.	* Urban area	9.0	12.4	3.43	2	3.68	9	50	50	4	4	Affected
T411	Gewann Blösse	* Urban area	10.9	11.3	2.64	3	5.74	11	0	100	34	2	Affected
T412	Theodor- Heuss - Allee	* Urban area	10.0	11.4	2.99	1	4.47	6	100	0	6	4	Natural
T517	Auer Str. - Reichenbachstr.	* Urban area	9.0	12.8	3.43	2	2.84	8	100	0	5	1	Natural
T524	Dornwaldstr.	* Urban area	9.0	11.5	3.43	2	1.77	6	99	1	275	2	Natural
T401	Area next to the Wildpark-Stadion	† Urban area	11.0	14.2	2.60	2	8.90	10	0	100	8	1	Affected
T109	Erzbergerstr.	† Urban area	13.7	14.1	1.76	1	4.86	4	92	8	38	4	Natural
T108	Edgar-von-Gierke-Str. - Siegfried-Kühn-Str.	† Urban area	12.0	14.9	2.26	2	6.12	8	79	21	25	4	Affected
T114	Allotment garden at the Alb	† Urban area	12.8	15.4	2.01	1	8.25	6	13	88	171	4	Affected

T115	Sonnenstr. – Zietenstr.	† Urban area	13.5	14.8	1.81	1	4.83	4	89	11	23	4	Natural
T117	Sonnenstr. – Zietenstr.	† Urban area	13.0	17.0	1.95	3	6.24	8	92	8	76	5	Natural
T118	Schoemperlenstr.	† Urban area	13.7	16.1	1.76	1	8.45	6	38	63	11	4	Affected
T112	Wattstr. – Annweilerstr.	† Urban area	12.0	14.5	2.26	2	6.87	8	100	0	204	4	Natural
T111	Field near Kaiserslauterner-Str.	† Urban area	8.9	13.4	3.48	3	5.75	14	77	23	96	4	Affected
T113	Hertzstr. – St. Barbara-Weg	† Urban area	11.0	17.5	2.60	1	3.35	5	0	100	1	1	Affected
3Kalmitw	Kalmitweg No.3	† Urban area	15.5	15.3	1.34	1	6.44	3	77	23	13	3	Affected
2Windhor	Wilhelm-Windhorststr. - Schänzle	† Urban area	15.2	15.8	1.34	2	8.64	6	20	80	353	4	Affected
1F-Lust-	Franz-Lust-Str. – Kußmaulstr.	† Urban area	15.2	17.3	1.34	2	5.95	5	65	35	630	3	Affected
T107	Molkestr. – Willy-Brandt-Allee	† Urban area	10.1	16.2	2.95	1	4.90	7	66	34	130	3	Affected
NOM-011		† Forest area	14.9	10.7	1.47	1	3.42	3	100	0	15	1	Natural
NOM-017		† Forest area	15.0	10.9	1.45	3	7.20	7	97	3	506	6	Natural
SOM-020		† Forest area	15.0	10.7	1.45	1	5.81	3	50	50	9	4	Affected
SOM-018		† Forest area	27.0	10.3	0.26	3	12.75	2	90	10	31	2	Natural
SWM-005	Hardtwald	† Forest area	15.5	10.5	1.34	2	8.72	6	26	74	358	3	Affected
NWM-009		† Forest area	15.0	10.8	1.45	2	10.69	7	43	57	90	4	Affected
NWM-006		† Forest area	14.8	10.7	1.49	1	5.00	3	86	14	16	3	Natural
NOM-014		† Forest area	15.0	10.5	1.45	1	9.92	5	67	33	23	3	Affected

75 **Table S2: Taxa-site matrix of the invertebrate fauna of each water gauge.**

Official designation of the water gauges	T101	T102	T104	T105	T106	T123	T124	T125	T128	T129	T320	T322	T402	T411	T412	T517	T524	Number of individuals	Percentage	T401	T109	T108
<i>Amphipoda</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	2	0	0	6	0
<i>Cyclopoida</i>	0	0	0	0	5	0	0	0	0	76	0	0	1	0	0	5	0	87	10	0	27	14
<i>Harpacticoida</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>Parastenocaris</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0
<i>Bathynelleacea</i>	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	272	274	33	0	0	1
<i>Nauplia</i>	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	2	0	0	0	0
Amount Crustacea	0	2	0	0	6	0	0	0	0	77	0	0	1	0	3	5	272	366	44	0	33	15
Amount Crustacea %	0	50	0	0	86	0	0	0	0	62	0	0	25	0	50	100	99			0	87	60
Amount Amphipoda %	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	33.3	0.0	0.0			0.0	15.8	0.0
Amount Cyclopoida %	0.0	0.0	0.0	0.0	71.4	0.0	0.0	0.0	0.0	61.3	0.0	0.0	25.0	0.0	0.0	100.0	0.0			0.0	71.1	56.0
Amount Harpacticoida %	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0			0.0	0.0	0.0
Amount Parastenocaris %	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	16.7	0.0	0.0			0.0	0.0	0.0
Amount Bathynelleacea %	0.0	50.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	98.9			0.0	0.0	4.0
Amount Nauplia %	0.0	0.0	0.0	0.0	14.3	0.0	0.0	0.0	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0			0.0	0.0	0.0
<i>Nematoda</i>	0	2	0	0	0	0	2	65	5	0	0	0	1	0	1	0	0	76	9	0	2	6
<i>Oligochaeta</i>	0	0	0	1	1	2	0	37	8	8	252	3	1	33	0	0	3	349	42	8	3	4
<i>Acari</i>	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	2	0	0	0	0
<i>Mikroturbellaria</i>	0	0	0	0	0	0	0	1	0	39	0	3	0	1	2	0	0	46	5	0	0	0
Amount others	0	2	0	1	1	3	2	103	13	47	252	6	3	34	3	0	3	473	56	8	5	10
Total amount	0	4	0	1	7	3	2	103	13	124	252	6	4	34	6	5	275	839	100	8	38	25
Amount Oligochaeta %	0.0	0.0	0.0	100.0	14.3	66.7	0.0	35.9	61.5	6.5	100.0	50.0	25.0	97.1	0.0	0.0	1.1			100.0	7.9	16
Amount Nematoda %	0.0	50.0	0.0	0.0	0.0	0.0	100.0	63.1	38.5	0.0	0.0	0.0	25.0	0.0	16.7	0.0	0.0			0.0	5.3	24
Amount Acari %	0.0	0.0	0.0	0.0	0.0	33.3	0.0	0.0	0.0	0.0	0.0	0.0	25.0	0.0	0.0	0.0	0.0			0.0	0.0	0
Amount Mikroturbellaria %	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	31.5	0.0	50.0	0.0	2.9	33.3	0.0	0.0			0.0	0.0	0

Official designation of the water gauges	T114	T115	T117	T118	T112	T111	T113	3Kalm itw	2Wind hor	1F- Lust-	T107	NOM- 011	NOM- 017	SOM- 020	SOM- 018	SWM- 005	NWM- 009	NWM- 006	NOM- 014	Number of individuals	Percentage	Number of all individuals	Percentage of all
<i>Amphipoda</i>	2	0	0	0	0	0	0	0	0	10	0	0	41	3	0	0	2	0	0	64	2.3	66	1.8
<i>Cyclopoida</i>	6	15	64	2	171	0	0	8	19	0	84	15	299	1	28	76	36	12	12	889	31.4	976	26.6
<i>Harpacticoida</i>	0	0	2	1	0	0	0	0	0	0	0	0	30	0	0	0	0	0	0	33	1.2	33	0.9
<i>Parastenocaris</i>	0	0	0	0	0	11	0	2	48	402	0	0	119	0	0	16	0	0	0	598	21.2	599	16.3
<i>Bathynelleacea</i>	0	2	1	0	31	62	0	0	0	0	0	0	0	0	0	0	0	0	0	97	3.4	371	10.1
<i>Nauplia</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	2	0.1
Amount Crustacea	8	17	67	3	202	73	0	10	67	412	84	15	489	4	28	92	38	12	12	1681	59.5	2047	55.8
Amount Crustacea %	5	74	88	27	99	76	0	77	19	65	65	100	97	44	90	26	42	75	52				
Amount Amphipoda %	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.6	0.0	0.0	8.1	33.3	0.0	0.0	2.2	0.0	0.0				
Amount Cyclopoida %	3.5	65.2	84.2	18.2	83.8	0.0	0.0	61.5	5.4	0.0	64.6	100.0	59.1	11.1	90.3	21.2	40.0	75.0	52.2				
Amount Harpacticoida %	0.0	0.0	2.6	9.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.9	0.0	0.0	0.0	0.0	0.0	0.0				
Amount Parastenocaris %	0.0	0.0	0.0	0.0	0.0	11.5	0.0	15.4	13.6	63.8	0.0	0.0	23.5	0.0	0.0	4.5	0.0	0.0	0.0				
Amount Bathynelleacea %	0.0	8.7	13	0.0	15.2	64.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0				
Amount Nauplia %	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0				
<i>Nematoda</i>	107	4	3	3	1	1	0	0	12	0	2	0	2	1	0	0	1	2	5	152	5.4	228	6.2
<i>Oligochaeta</i>	56	2	6	5	1	22	1	3	274	218	44	0	15	4	3	266	51	2	6	994	35.2	1343	36.6
<i>Acari</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	2	0.1
<i>Mikrobellaria</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	46	1.3
Amount others	163	6	9	8	2	23	1	3	286	218	46	0	17	5	3	266	52	4	11	1146	40.5	1619	44.2
Total amount	171	23	76	11	204	96	1	13	353	630	130	15	506	9	31	358	90	16	23	2827	100.0	3666	100
Amount Oligochaeta %	32.7	8.7	7.9	45.5	0.5	22.9	100.0	23.1	77.6	34.6	33.8	0.0	3.0	44.4	9.7	74.3	56.7	12.5	26.1				
Amount Nematoda %	62.6	17.4	3.9	27.3	0.5	1.0	0.0	0.0	3.4	0.0	1.5	0.0	0.4	11.1	0.0	0.0	1.1	12.5	21.7				
Amount Acari %	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
Amount Microturbellaria %	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00				



## References

- 80 Brielmann, H., Griebler, C., Schmidt, S. I., Michel, R. and Lueders, T.: Effects of thermal energy discharge on shallow groundwater ecosystems, *FEMS Microbiol. Ecol.*, 68(3), 273–286, doi:10.1111/j.1574-6941.2009.00674.x, 2009.
- Foster, S. S. D.: Impacts of urbanization on groundwater, *Hydrol. Process. Water Manag. Urban Areas (Proceedings Duisb. Symp. 1988)*, 198(198), 209–216 [online] Available from: [https://www.researchgate.net/profile/Stephen\\_Foster11/publication/237480481\\_Impacts\\_of\\_urbanisation\\_on\\_groundwater/links/55b4d97508ae092e96557248/Impacts-of-urbanisation-on-groundwater.pdf](https://www.researchgate.net/profile/Stephen_Foster11/publication/237480481_Impacts_of_urbanisation_on_groundwater/links/55b4d97508ae092e96557248/Impacts-of-urbanisation-on-groundwater.pdf), 1990.
- 85 Griebler, C., Brielmann, H., Haberer, C. M., Kaschuba, S., Kellermann, C., Stumpp, C., Hegler, F., Kuntz, D., Walker-Hertkorn, S. and Lueders, T.: Potential impacts of geothermal energy use and storage of heat on groundwater quality, biodiversity, and ecosystem processes, *Environ. Earth Sci.*, 75(20), 1–18, doi:10.1007/s12665-016-6207-z, 2016.
- Hahn, H. J.: A first approach to a quantitative ecological assessment of groundwater habitats: The GW-Fauna-Index, *Limnologica*, 36(2), 119–137, 2006.
- 90 Kühlers, D., Maier, M. and Roth, K.: Sanierung im Verborgenen, *TerraTech Sanierungspraxis*, 3, 14–16, 2012.
- Kuroda, K. and Fukushi, T.: Groundwater Management in Asian Cities, *Groundw. Manag. Asian Cities*, (September 2014), 334, doi:10.1007/978-4-431-78399-2, 2008.
- Landesanstalt für Umwelt Messungen und Naturschutz Baden-Württemberg: Jahresdatenkatlog Grundwasser, [online] Available from: <http://jdkgw.lubw.baden-wuerttemberg.de/servlet/is/200/>, 2020.
- 95 Matzke, D.: Untersuchungen zum Verhalten von Grundwasserfauna in Altlastflächen mit vorangegangenem Vergleich unterschiedlicher Sammeltechniken., 2006.
- Menberg, K., Bayer, P., Zosseder, K., Rumohr, S. and Blum, P.: Subsurface urban heat islands in German cities, *Sci. Total Environ.*, 442, 123–133, doi:10.1016/j.scitotenv.2012.10.043, 2013.
- Shannon, C. E. and Weaver, W.: *The mathematical theory of communication*, The University of Illinois Press., 1949.
- 100 Stadt Karlsruhe: Bodenschutz- und Altlastenkataster der Stadt Karlsruhe, [online] Available from: [https://www.karlsruhe.de/b3/natur\\_und\\_umwelt/umweltschutz/altlasten.de](https://www.karlsruhe.de/b3/natur_und_umwelt/umweltschutz/altlasten.de) (Accessed 23 October 2019), 2006.
- Wickert, F., Muller, A., Schäfer, W. and Tiehm, A.: Vergleich hochauflösender Grundwasserprobennahmeverfahren zur Charakterisierung der vertikalen LCKW-Verteilung im Grundwasserleiter, *Altlastenspektrum*, 01, 29–35, 2006.
- Zuurbier, K. G., Hartog, N., Valstar, J., Post, V. E. A. and Van Breukelen, B. M.: The impact of low-temperature seasonal aquifer thermal energy storage (SATES) systems on chlorinated solvent contaminated groundwater: Modeling of spreading and degradation, *J. Contam. Hydrol.*, 147, 1–13, doi:10.1016/j.jconhyd.2013.01.002, 2013.
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