

Article

Behaviour of PPCP Substances in a Fluvial Aquifer after Infiltration of Treated Wastewater

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Abstract: One of the reasons for the still prevailing concerns about the recycling of treated wastewater is the low efficiency of current Waste Water Treatment Plant (WWTP) technologies for removing Pharmaceuticals and Personal Care Products (PPCP) substances, especially pharmaceuticals. The goal of this investigation was to verify the behaviour of these substances after infiltration into the fluvial aquifer. During an experiment, this water (containing 45 PPCP substances) was infiltrated using a 10 m deep well for a period of one month. The whole process of infiltration was intensified by pumping at a well in a distance of 52 m. In the surrounding monitoring wells, 113 PPCP substances were monitored at three-day intervals with a detection limit in the order of tens of ng/L. The results showed that 32 PPCP substances were already present in the fluvial aquifer before the start of the infiltration experiment and thus represent “background” values. These substances are the result of river water seepage. The influence of infiltration was manifested by changes in the chemistry of the monitoring wells 8–12 days after the beginning of the experiment. The experiment demonstrated the high natural attenuation capacity of the fluvial aquifer, which eliminated a wide range of PPCP substances to a level below the detection limit.

Keywords: pharmaceuticals; waste water; fluvial aquifer

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1. Introduction, Motivation of the Experiment

In the last decade, Central Europe, including the Czech Republic, has increasingly been faced with the negative effects of drought [1–3]. In some regions, long-term drought has caused in extreme cases the drying up of rivers and a long-term drop in groundwater levels [4,5]. The related water management problems are manifested mainly in agriculture, but also in the supply of drinking water to the population [6].

One of the partial solutions is an approach used in Greece, Malta, Portugal, Italy, and Spain, where the share of reused urban effluent ranges between 1 and 12% [7]. Analysis carried out in preparation for the Water Reuse Regulation expected a provision cost for the reclaimed water of less than EUR 0.5 per m³ [8]. The current, relatively restrained attitude towards the reuse of treated waste water in Europe might be gradually mitigated [9]. The European Commission included wastewater in the circular economy action plan and set itself the goal of facilitating water reuse, especially in the field of irrigation [10]. Cleaned wastewater used for irrigation of crops that are not intended for direct human consumption can thus become an important tool for reducing demands on water resources in European agriculture.

The annual production of all WWTPs in the Czech Republic is 23 m³/s, i.e., 738 Million m³/year [11]. These water currently leave the territory of the state without any use in a short period of time. A more meaningful use of this water, for example by its infiltration

and subsequent reuse, is prevented by current legislation. Primarily, waste water treatment plants must discharge their production into the receiving water in the river in the Czech Republic. Only in exceptional cases treated wastewater can be infiltrated into an aquifer, never directly into the saturated zone, but always through the soil layer.

One of the main reasons why today's European public is so cautious about treated wastewater is the fear of discharging PPCPs into the groundwater. Today's waste water cleaning technologies mostly remove these substances only with problematic efficiency [12–14]. The published results suggest that many PPCPs are released into the rivers in nanograms to micrograms per liter concentrations [15–17].

The main goal of the project was to provide expert documents that would confirm or, on the contrary, remove objections against the infiltration of treated wastewater into the fluvial quaternary and its possible reuse. The work focused primarily on clarifying the behavior of different types of PPCP substances, the speed of their spread and the possibility of natural attenuation. The tool for solving these questions was an experiment consisting in the infiltration of 2366 m³ of treated wastewater over into a fluvial sand-gravel and monitoring the behavior of 113 monitored PPCP substances at the test site Kojetín in South Moravia (Figure 1).

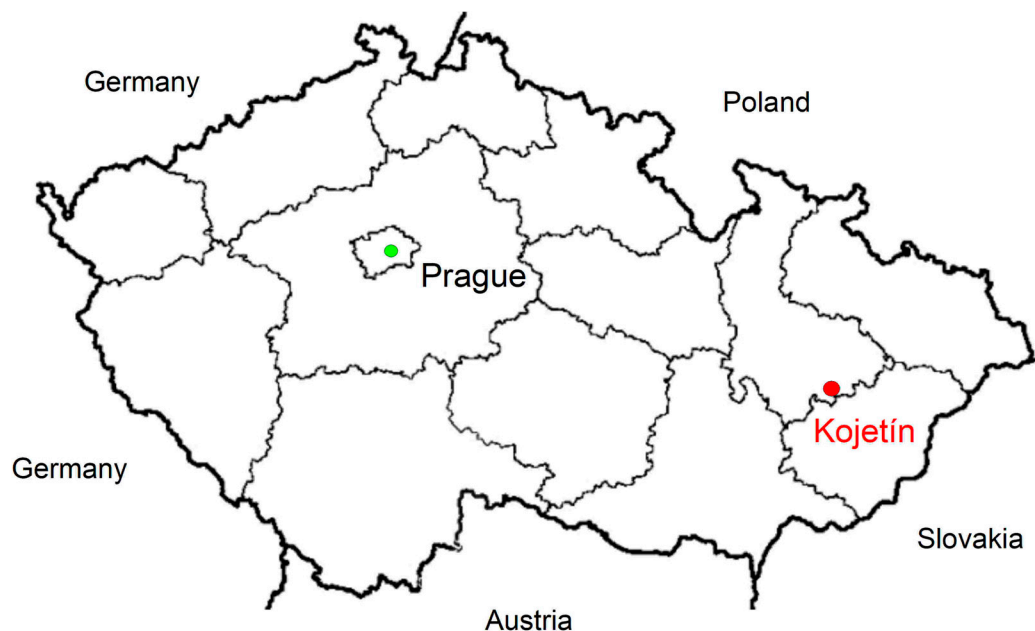


Figure 1. Location of the experimental site.

2. Natural Characteristics of the Experimental Site

The Kojetín area is located 220 km east of the capital of the Czech Republic, Prague. Climatically, the area is slightly warmer and drier than the national average (average annual temperature in Kojetín (1961–2019) is 8.9 °C, in the Czech Republic 7.8 °C; average precipitation in Kojetín is 660 mm, in the Czech Republic 675 mm). Over the past 60 years, the average annual temperature in the Czech Republic has risen by 2 °C. Regarding precipitation, no significant trends have been observed. The nationwide long-term average of precipitation over the last sixty years is stable, only the course of precipitation changes during the year. Increased temperatures, especially in the summer months, result in high evapotranspiration, which is manifested by a decrease in river flows [18,19].

Kojetín experimental site is located on the right bank of the most important water-course in the eastern part of the Republic, the Morava River. In 2022, only 45% of the long-term monthly flow (which is ca. 47 m³/s) flowed through the Morava River in Kojetín.

Morphologically, the Kojetín area is part of a floodplain with an altitude of around 190 m a.s.l. Geological and hydrogeological conditions are relatively simple. The uppermost zone is represented by flood clays with low permeability, causing the artesian regime of the underlying Quaternary aquifer. This aquifer of fluvial gravel-sands have a thickness of 2.6 to 6 m, and is characterized by an average hydraulic conductivity value of 7.8×10^{-4} m/s and is in close hydraulic connection with the adjacent watercourse of the Morava River. The subsoil of the fluvial Quaternary is represented by Tertiary clays, which form an lower impermeable layer.

3. Experimental Setup and Performance

The area of interest was equipped with observation wells PZ1, PZ5, and CP1 (Figure 2). A well VSK was used for infiltration of treated wastewater from the local WWTP. All wells penetrated the entire thickness of the aquifer. The depth of the wells was between 8 and 10 m, depending on the thickness of the fluvial Quaternary. The casing diameter of pumping/infiltration wells CP1, CP5 and VSK was 425 mm, in the case of monitoring wells PZ1 and PZ13 the diameter was 273 mm. Length of casing again depended on local lithological conditions and was most often in the range of 2–7 m.

Special attention was paid to monitoring the expected clogging of the VSK infiltration well, which was equipped with a casing observation probe Solinst for this purpose. The probe worked on the principle of measuring barometric pressure and was placed in a pipe in the filter material of the well.

The level in the Morava River is maintained by manipulation at the weir at 190.9 m a.s.l. The levels in the wells VSK, CP1, PZ1 in the original artesian regime are at the level of 190.6 m a.s.l.

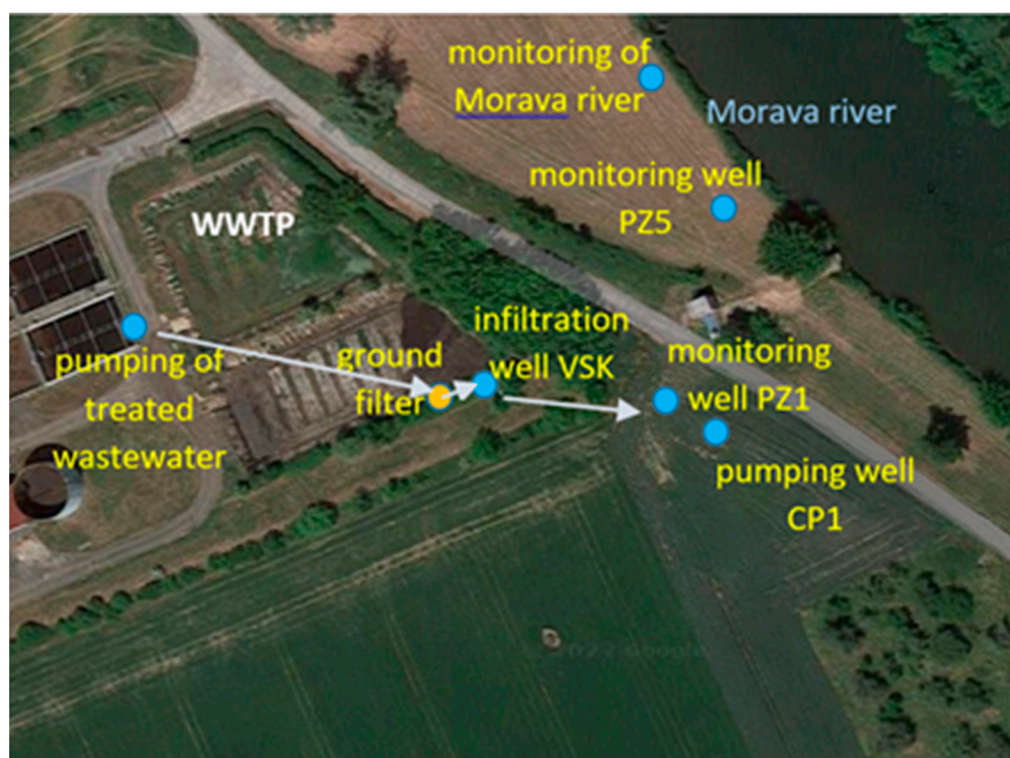


Figure 2. Location of pumping (CP1), monitoring (PZ1 and PZ5), and infiltration wells (VSK) at the Kojetín experimental site (blue points—wells, yellow point—ground filter)

Czech legislation does not allow the discharge of wastewater into groundwater, but always through the unsaturated zone. Therefore, a container with a volume of 1 m³ filled with fine-grained sand (its granulometry was very similar to the unsaturated zone) was placed between the outlet of the WWTP and the infiltration VSK well.

A slug test was performed before the major infiltration experiment conducted with clean water. The goal was to specify the infiltration rate into the VSK well. The water level measurement took 5.5 h. At one time, the borehole was filled with 212 L of water and the decrease in its level over time was measured. The test was evaluated using the Jacob-Lohman method [20].

The initial amount of infiltrated wastewater was set at 2 L/s and then adjusted so that the level in the VSK well was constant. Due to clogging, the infiltration rate in VSK well gradually decreased from 1.8 L/s to 0.7 L/s.

The infiltration was intensified by pumping from adjacent well CP1. The withdrawal from well CP1 was therefore maintained systematic greater than the infiltration rate. The pumped volume of groundwater from CP1 well ranged from 2.9 L/s to 1.6 L/s. During the experiment, 2366 m³ of treated wastewater was infiltrated into VSK well, and 4332 m³ of groundwater was pumped from CP1 well.

Water samples were taken at scheduled intervals from five monitoring points—the inlet into VSK well with treated wastewater, CP1 well, PZ5 and PZ1 wells, and Morava River for a period of 36 days. A total of 113 PPCP substances were analyzed.

4. Results

4.1. Evaluation of Qualitative Changes

Table 1 provides a complete overview of the occurrence of PPCP substances at the monitoring points in the period before and during the infiltration experiment. For substances that were analyzed in more detail, the mean and median content values are also given.

A comparison of both recipients of PPCPs (i.e., treated wastewater from the WWTP and water in the Morava River) reveals their similarity in terms of the range of detected components. Upstream from the Kojetín site, many other wastewater treatment plants are connected to Morava River. A total of 80 PPCP substances with values above the detection limit appeared in at least one sample on the monitored objects.

The permanent occurrence (that is, they were detected in all samples) exhibited 45 PPCP substances concerning treated wastewater and 32 substances concerning water in the Morava River. At the beginning of the VSK infiltration experiment (7 November 2022), well PZ5 already contained 29 PPCP substances, whilst wells CP1 and PZ1 contained 13 resp. 12 substances. The PZ5 well is located in the proximity of the Morava River (Figure 2). It follows that the river water negatively affects the adjacent fluvial aquifer and a non-negligible set of PPCP substances is “naturally” present in the groundwater unaffected by the infiltration experiment. During floods and due to the dam cascade, influent conditions exist occasionally or permanently in some of areas between the aquifer and the Morava River. This causes the PPCP to transport from the river into fluvial sediments.

Table 1. Information on the presence of PPCP substances at monitoring objects (black fields—values above the detection limit, white fields of values below the detection limit, green period “background” data before the experiment, yellow period data during the experiment).

DATE OF SAMPLING	20 November 2021	7 November 2022	20 November 2022	24 November 2022	30 November 2022	8 December 2022	2022/12/12	Average	Median	20 November 2021	7 November 2022	20 November 2022	24 November 2022	30 November 2022	8 December 2022	12 December 2022	Average	Median	20 November 2021	7 November 2022	20 November 2022	24 November 2022	30 November 2022	8 December 2022	12 December 2022	Average	Median	20 November 2021	7 November 2022	20 November 2022	24 November 2022	30 November 2022	8 December 2022	12 December 2022	Average	Median													
	ng/L										ng/L										ng/L										ng/L										ng/L								
No	PPCP	WWTP OUTFLOW						MORAVA RIVER						PZ1						CP1						PZ5																							
1	Carbamazepine							274	273								42	44								29	22							28	22			38	37										
2	4-formylaminoantipyr							289	261								158	151								55	61							70	76			84	84										
3	Valsartan acid							1166	1280								190	195								157	135							174	154			217	220										
4	Acesulfame							128	119								242	220								214	217							177	179			179	160										
5	Gabapentin							690	680								218	209								127	82							102	72														
6	Lamotrigine							1050	921								114	109																					40	38									
7	Diclofenac							1651	1580								139	140								127	57													32	30								
8	Telmisartan							7250	7060								494	492																						31	31								
9	Valsartan							38	33								35	28																						14	14								
10	Tramadol							1673	1380								109	103																						32	31								
11	Oxypurinol							13903	13400								1911	1960																	491	204			395	390									
12	Benzotriazol							4834	5620								563	498																	124	63			156	150									
13	Benzotriazol 5-methy							475	474								170	153																						86	85								
14	Sulfapyridin							264	269								23	22																	24	17					13	14							
15	Hydrochlorothiazide							1553	1600								117	104																															
16	Metoprolol							794	789								59	54																															
17	Clarithromycin							303	281								42	42																															
18	Acebutolol							169	191								14	13																															
19	Venlafaxine							222	225								23	21																															
20	Sulfamethoxazol							968	1050								59	57																															
21	Celiprolol							268	284								14	15																															
22	Fexofenadine							60	59								22	22																															
23	Fluconazole							79	65								21	21																															
24	Irbesartan							109	127								25	24																															
25	Sotalol							289	189								46	49																															
26	Metformin							652	147								635	551																															

[illegible]

[illegible]

The presence of more or less similar PPCP substances both in the river and in the outlet from the WWTP is not surprising; especially in times of low flows, inflows from treatment plants represent a non-negligible part of the flow of watercourses in Europe. This fact is documented by comparing the contents of PPCP substances in some Central European (CE) rivers (see Table 2). The water quality in the Morava River in terms of the range of detected PPCP substances fits very well into this regional context; in absolute values the contents of some substances are even significantly higher (e.g., Oxypurinol, Iopromide, Telmisartan).

Table 2. PPCPs occurrence in six watercourses in CE region (The colour indicates the frequency of occurrence: red in all rivers; orange—the substance was missing in one of the streams; yellow—the substance was missing in two streams; green—the substance was missing in three rivers [21]).

PPCP SUBSTANCES	LABE	ISAR	JIZERA	PO	SAVA	BRYNICA	MORAVA
	ng/L						
Metformin	501	94	479	257	104	21	635
DEET	26	26	44	10	10	63	24
Telmisartan	195	53	223	36	10	191	494
Valsartan	16	98	20	26	21	376	35
Valsartan acid	65	38	45	44	10	15	190
Benzotriazol methyl	97	160	42	48	26	152	170
Diclofenac	20	78	25	10	10	10	139
Iopromide	25	25	25	68	160	5	585
Irbesartan	5	34	10	16	24	25	25
Paracetamol		5	11	5	17	76	25
Gabapentin	119	82	110	35	9		218
Benzotriazol	256	348	210	93	45		563
Caffeine	141	155	120	50	50		
Iohecol	25	206	25	25		5	50
Oxypurinol	526	370	362	204	25		1911
Acesulfam	164	66	284	85	25		242
Lamotrigine	39	58	38	5	5		114
Saccharin	76	25	74	25	25		145
Paraxanthine	145	50	160	50	50		
Iomeprol	233	182	123	104	140		289
Ibuprofen	10	10	26	10			81
Clarithromycin	5	5	5		5		42
4-formylaminoantipyr	73	114	53		27		158
Peniciline G	5	5	5			57	
Tramadol	37	21	41			49	109
Carbamazepine	21	23	23	5			42
Metoprolol	23	43	17			5	59
PFOS	5	3	12		3		
Fexofenadine	5	30		5	5		22
Hydrochlorothiazide	25	75	25		25		117
Bisphenol S	25	25			25		
Carbamazepine-DHH		23		5		5	
Erythromycin		5	5			79	
Celiprolol	10		11			29	14
Cotinine	10	10	10				
Iopamidol		25		941		170	

Methylparaben	50	15	43	
Primidone	5	5	17	33
Venlafaxine	13	24	5	23
Venlafaxine O-desmethyl	29	59		97
Sulfamethoxazole	16	23	17	59

Despite the presence of more or less identical substances, large quantitative differences occur between the outlet of WWTP and the Morava River. The highest average concentration in treated wastewater was exhibited by Oxypurinol (13,903 ng/L; Table 1). However, such high difference in content are not always usual. For the other eight substances, average content was higher than 1 µg/L; these were Valsartan acid, Lamotrigine, Diclofenac, Telmisartan, Tramadol, Benzotriazole, Hydrochlorothiazide, and Sucralose. All these substances can also be found in river water, but in lower orders of magnitude—due to the dilution, degradation, or gradual transformation into others. However, such high differences in content are not always a general rule. In Table 1, the group of substances occur where the differences in PPCP content are smaller, or negligible, between the WWTP outlet and river Morava. These are, for example, 4-formylaminoantipyrine, Gabapentin, or Valsartan; the content of Metformin is more or less equal, with Acesulfame even more in the river water than in the WWTP discharge.

The data from Table 1 also shows the significant role of infiltrated water from the Morava River: the adjacent well PZ5 contained a significantly more varied range of PPCP substances before the start of the infiltration experiment than wells CP1 and PZ1 further from the river. The effect of the infiltration of treated wastewater in the VSK well was evidently not manifested in the PZ5 well.

4.2. Cluster Analysis

Changes in groundwater chemistry in wells PZ1 and CP1 due to the infiltration of treated groundwater into the VSK well was confirmed by statistical processing using cluster analysis. Cluster analysis is one of the methods that deal with investigating the similarity of multidimensional objects and classifying them into classes. It allows assessment of the relationships between individual clusters.

In the case of the implemented experiment, 30 chemical analyzes of water for PPCP substances were available, each of these contained a determination of the content of 113 substances (matrix of 30 × 113 elements). Cluster analysis focused on:

1. the number of clusters of PPCP substances—i.e., substances belonging to one set;
2. a measurable degree of difference in the occurrence of pharmaceuticals between individual observation objects.

The graphical output of this analysis is a dendrogram which allows measurable evaluation of the difference in the framework of the entire data matrix. The differences between groundwater, Morava river water, and infiltrated water during the whole experiment are documented in Figure 3. The difference of individual clusters is determined by the so-called inter-cluster distance. The measure expressing the probability of agreement of the created distribution of objects into individual groups is the cophenetics correlation coefficient (CP). The value of cophenetics coefficient was CP = 0.906.

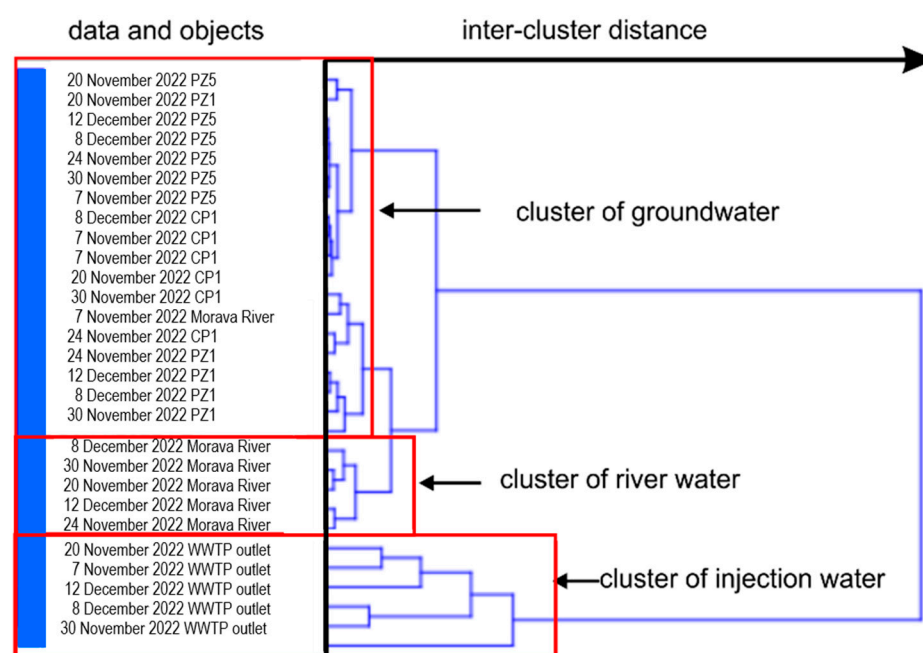


Figure 3. Results of cluster analysis documenting the relationships between monitored parameters.

The results showed that the groundwater in wells PZ1, CP1, and PZ5 was significantly different from the output from the WWTP and mostly from the Morava River throughout the experiment. The water in Morava River is significantly more “related” to groundwater than water from the WWTP. As a result of infiltration into the VSK well, the difference between the infiltrated water from the WWTP and groundwater has decreased. This statistically confirmed the change in groundwater quality due to infiltrated water originating from the WWTP.

4.3. Characterization of the Transport Process

The transport of PPCPs from the VSK infiltration well to the PZ1, CP1, or PZ5 boreholes can be demonstrated based on increases in the content of PPCP substances. Temporal changes in content enable the approximate assessment of transport rates. The most obvious markers are potentially those substances which did not occur in monitoring wells at the beginning of the experiment, but appeared later. The focus was on substances that could be used as tracers due to their physical and chemical properties. Such non-degrading and non-sorbing substances migrate in the rock environment at the same speed as groundwater flows—i.e., without retardation. Oxypurinol and Benzotriazole were supposed to be in this category.

A comparison of both substances reveals that their content are significantly higher in treated wastewater than in the Morava river (Tables 3 and 4). In well PZ5, the content of both pharmaceuticals were already present before the start of the infiltration experiment and remained more or less stable during the entire test, or there was no fundamental fluctuation. Neither Benzotriazole nor Oxypurinol was present in the CP1 and PZ1 boreholes before the start of the infiltration test. Both substances appeared in these objects with a delay of 8–12 days from the start of the experiment and had an upward trend. The values given correspond to velocities of 6.6–4.4 m/day. The distance between VSK and CP1 wells is 52.5 m. In the context of objectivity, it is necessary to emphasize that the calculated mentioned transport rates are not natural, but influenced by pumping in well CP1.

Table 3. Time development of Benzotriazole content at monitored objects.

Date of Sampling	CONCENTRATION OF BENZOTRIAZOL IN ng/L				
	WWTP	MORAVA RIVER	CP1 WELL	PZ1 WELL	PZ5 WELL
7 November 2022	4390	657	<20	<20	159
20 November 2022	6640	459	<20	<20	155
24 November 2022	6610	606	93	<20	173
30 November 2022	6290	471	196	62	124
8 December 2022	5620	838	analysis error	167	168
12 December 2022	2140	498	420	187	155
AVERAGE	5282	588	236	69	156
MEDIAN	5955	552	93	31	157

Table 4. Time development of Oxypurinol content at monitored objects.

Date of Sampling	CONCENTRATION OF OXYPURINOL IN ng/L				
	WWTP	MORAVA RIVER	CP1 WELL	PZ1 WELL	PZ5 WELL
7 November 2022	10200	729	<50	<50	270
20 November 2022	13400	2350	<50	<50	540
24 November 2022	17100	1960	338	<50	438
30 November 2022	21800	2270	849	299	328
8 December 2022	14700	3050	analysis error	811	427
12 December 2022	12300	1600	1690	1070	366
AVERAGE	14917	1993	550	363	395
MEDIAN	14050	2115	379	150	400

4.4. Evaluation of Groundwater Flow Velocities and Clogging

All the hydraulic experiments conducted at Kojetín experimental site, including several pumping tests and VSK infiltration, were analysed using MODFLOW-USG software [22]. Inflow tests were carried out in the period 26 October 2021–16 December 2021 (length 52 days). The CP wells and the VSK well are 50 and 80 m from Morava, respectively. After the completion of the pumping of the CP1 and CP2 wells and at the end of the period, short recovery tests were carried out. The maximum withdrawal reached in the final phase of inflow tests, when pumping the VSK well, was 4 L/s. For well CP1, the value of hydraulic conductivity k_f was determined in the range of 1.3×10^{-3} – 1.8×10^{-3} m/s, for well CP2 in the range of 1.3×10^{-3} – 1.8×10^{-3} m/s and for well VSK in the range of 9.1×10^{-4} – 1.2×10^{-3} m/s.

The model simulations described the period of inflow tests at wells CP1, CP2 and VSK. Model calibration consisted in optimizing the agreement between measured and simulated groundwater levels. The agreement of the model and measurements was achieved by a combination of manual and semi-automatic tuning of selected hydraulic parameters of the model. The model simulation faithfully affected the observed development of the levels, including the tested wells. The withdrawals were simulated using the Neuman boundary condition (the pumped amount of groundwater was entered) and the groundwater level in the pumped wells was calculated by the model (see example Figure 4).

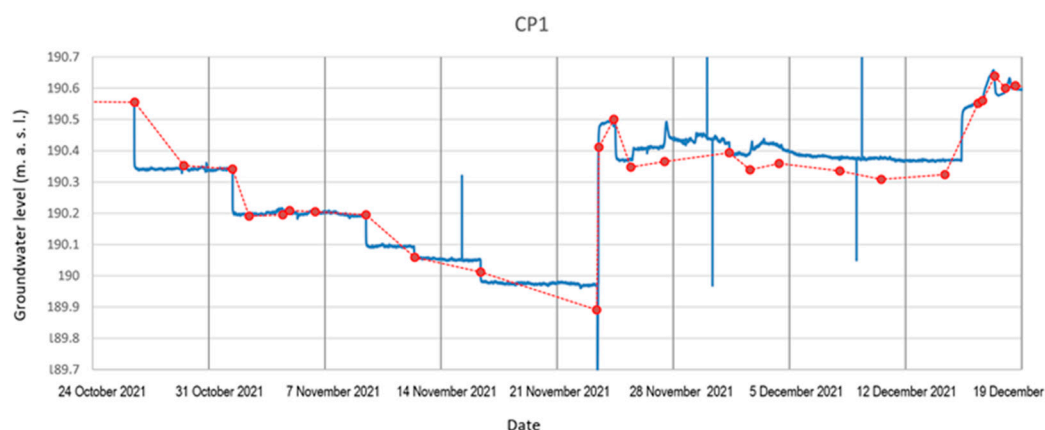


Figure 4. Comparison of measured and modeled groundwater levels, pumped borehole CP1. blue line—measured data, red points and line—simulated data.

The transport of non-sorbing, non-reacting PPCPs from VSK well was simulated too. Figure 5 demonstrate the example of simulation of Sucralose content.

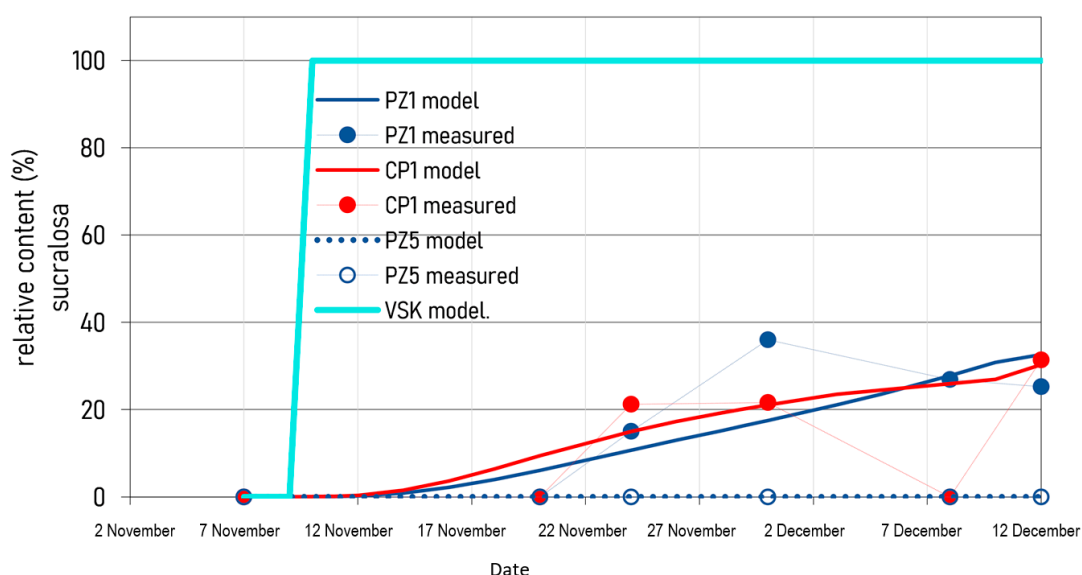


Figure 5. Measured and modelled content of Sucralose in 2022, relative values.

The best agreement between measurement and model result was achieved with the aquifer porosity of 15%, which is the expected value when considering a fluvial aquifer. In accordance with the measurement, the model also predicted that the locality of the PZ5 well remained unaffected by transport from the VSK well.

Model calculated breakthrough time (3–5 days) is shorter than observed (8–12 days), even though the model longitudinal dispersivity was reduced to 1 m to minimise dispersion. This suggests that during the initial phase of the transport process, sucralose was degraded. The same process probably took place which caused the initial content of this substance to be zero. We repeated the same experiments and calculations for oxypurinol and benzotriazole with practically identical results.

Clogging of the VSK borehole was manifested by a huge difference in groundwater level response during the pumping and infiltration period. Throughout the proceeding pumping test, the water level in the VSK well decreased by 1 m, when 4 L/s were abstracted. The infiltration experiment was finished with the recharge rate of approximately

0.7 L/s and the water level increased by 4 m. The level difference between the VSK bore-hole and the casing observation probe increased too. The reason is the position of the observation probe in a pipe in the filter material of the well.

The persistently relatively small level difference between the infiltration well and the casing probe proves that the hydraulic resistance against infiltration arose only at the filter pack/aquifer interface. It is likely that physico-chemical processes caused by the seepage of oxygenated water into the originally anoxic environment, in combination with microbiological processes and sorption to precipitated Fe^{3+} compounds, contributed significantly to the clogging. It is evident from the obtained data that the artificial recharge of wastewater using the technology of infiltration wells will bring technical problems associated with a decrease in yield.

4.5. Generalization of PPCP Substance Behaviour

The results of the infiltration experiment at the Kojetín site enable PPCP substances to be divided into four groups

- Substances with random occurrence in very low concentrations and therefore with an undetectable origin.

At the WWTP outlet, the substances of this group often had concentrations below the detection limit, so the infiltration experiment could not affect the concentrations of these substances in the monitoring wells PZ1, CP1 and PZ5. Nevertheless, they were analyzed in low concentrations at irregular intervals in some samples. An example of this group of substances is caffeine, which was detected in well PZ1 in the sample from 20 November and in well CP1 in the sample from 30 November. However, during the entire experiment, caffeine was not detected in the WWTP water samples. A similar result can be observed with other substances such as Bisphenol S, Methylparaben, Paracetamol, Paraxanthine, Propylparaben, and Saccharin. The problem with these substances is their general presence in various components of the environment, including practically all watercourses, so their origin is difficult to unambiguously detect.

- Substances, the contents of which increased in the Quaternary aquifer after the infiltration experiment.

Substances of this group are characterized by a high concentration in treated wastewater, which was later manifested in the occurrence in wells PZ1 and CP1. It is important that these substances were not present in the wells before the start of the experiment. The resulting content of these substances in the wells remain lower than at the WWTP outlet. Characteristic representatives of this group are oxypurinol, Sucralose, Hydrochlorothiazide, Diclofenac-4-hydroxy, and Benzotriazole. But all the substances which systematically occurred during the infiltration experiment should be included (Table 2). Absence of these substances at the beginning of the experiment reveals that they are degrading at some rate in the groundwater.

- Substances persistent, apparently without significant WWTP influence

Substances in this group are characterized by a higher concentration in wells than in treated wastewater. They usually occurred in the groundwater from the beginning of the infiltration experiment. The water in the observed wells was therefore more similar to water from the Morava River than to the WWTP. A typical representative is Acesulfame, whose concentrations in the river exceeded twice the average values of the water leaving the WWTP. This group also includes DEET and Sulfamethazine, which are all persistent substances that are not subject to degradation either in the Morava River or in the rock environment of the gravel sands of the experimental site.

- Substances with a high natural attenuation capacity.

Substances in this group are characterized by concentrations above the detection limit in the water leaving the WWTP, possibly also in the Morava River. Nevertheless, these substances were not detected in the observation wells. It can be assumed that these

substances have a good sorption/degradation capability in the rock environment. This is a relatively large group of substances that includes Acebutolol, Atenolol, Azithromycin, Benzotriazole 1-methyl, Bisoprolol, Celiprolol, Cetirizine, Citalopram, Clarithromycin, Climbazole, Clindamycin, Cyclophosphamide, Erythromycin, Fexofenadine, Fluconazole, Irbesartan, Carbamazepine-2-hydr., Carbamazepine-DHH, Carbamazepine-E, Lamotrigine, Losartan, Metoprolol, Mirtazapine, Naproxen, Naproxen-O-desmeth, Oxcarbazepine, PFOS, Sertraline, Sitagliptin, Sotalol, Sulfamethoxazole, Telmisartan, Tramadol, Trimethoprim, Venlafaxine, Venlafaxine O-desmet, Verapamil, and Warfarin.

5. Conclusions

- An experiment consisting of the gradual infiltration of 2366 m³ of treated wastewater over a period of 36 days into a fluvial sand-gravel aquifer demonstrated a diverse influence on the quality of groundwater. Of the 113 monitored PPCP substances, 80 were detected at the experimental site, of which 69 were in the WWTP discharge.
- Groundwater contained a non-negligible range of PPCP substances even before the start of the experiment (PZ1 12 substances, CP1 11 substances and PZ5 17 substances), which represent “background” values. The source of these, mainly pharmaceuticals, is bank infiltration from the Morava River. River water contains a similar range of PPCP substances as WWTP discharge, although mostly in much lower concentrations.
- The influence of infiltration into the VSK infiltration well was manifested by changes in chemistry about 50 m away with a delay of 8–12 days.
- Of the monitored PPCP substances present in WWTP discharge, roughly half did not appear in the groundwater at all. It shows the selectively high degree of natural attenuation of the fluvial gravel sand sediments for some substances.
- On the other hand, a group of substances such as Oxypurinol or Benzotriazole, which are often contained in treated wastewater in concentrations of the order of thousands of ng/L, migrated with groundwater, despite the fact that they were not detected as background values. Probably some degree of degradation of these occurred in the aquifer.
- Due to the lack of long-term medical studies that would document the possible negative impact of the detected substances on human health, the only option is to use the precautionary principle. Until a more efficient wastewater treatment technology is applied, it is clear that, despite the very good attenuation capacity of the rock environment for some substances, the infiltration of treated wastewater remains a problematic issue.
- However, this depends on the purpose for which the infiltration technology would be used. Both surface and shallow groundwater (in some places) in Central Europe already contain a non-negligible amount of PPCP substances. Therefore, in regions suffering from a lack of water for agricultural purposes, it would be possible potentially to infiltrate WWTP output into groundwater in accordance with current Czech legislation. After purification, these newly generated sources of groundwater could be used for irrigation in the event of a lack of another water source.

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