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Efficiency of micropollutant removal through artificial recharge and riverbank filtration - case studies Kárany, Czech Republic and Dresden-Hosterwitz, Germany

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Abstract

The aim of the study was to compare the efficiency of pharmaceuticals and personal care products (PPCP) removal in the waterworks Káraný (Czech Republic) and Dresden-Hosterwitz (Germany). Both waterworks use a similar technology of drinking water production (combination of bank filtration and artificial recharge) and have similar river water quality (Jizera and Elbe river). A comparison of two-years monitoring results shows a high efficiency of removing PPCP contained in river water. However, at both waterworks there are groups of substances for which natural treatment steps alone are not sufficient. In the case of Káraný it is Benzotriazole, Sulfamethoxazole and Methylparaben, in the Dresden waterworks it is Oxypurinol, Sulfamethoxazole, Carbamazepine and Lamotrigine.

1. Introduction

Groups of micropollutants, which until recently were practically unknown, have come to the forefront of scientific interest. These include pharmaceuticals and personal care products (PPCPs), steroid hormones, industrial chemicals, pesticides and many other emerging compounds. Their study is possible mainly by the rapid development of analytical laboratory procedures [1–3].

Despite the absence of current regulation, concerns have grown due to their potential effects on ecosystems and organisms through long-term exposure. In case of long-term effects of low concentrations antibiotics pose a risk of microbial resistance and therefore a decrease in their effectiveness [4]. The most significant point sources of micropollutants in surface water are wastewater treatment plants (WWTPs) [5–10]. The efficiency of eliminating PPCP substances in WWTPs depends on the technologies used for purification such as oxidation processes [11–13].

It is known that PPCPs are not consistently removed during conventional wastewater treatment processes and therefore are present in surface water, e.g. Carbamazepine, Oxypurinol, Metformin, and Benzotriazole. Published results suggest that many PPCPs are released into rivers in nanograms to micrograms per liter concentrations [14–19]. If surface water is used for drinking water production, PPCPs may be found during water treatment processes [20–23]. Waterworks have to deal with this problem by implementing advanced treatment technologies such as advanced membrane filtration technologies, granular activated carbon or advanced oxidation processes.

The aim of this study is to compare the efficiency of PPCPs removal in two waterworks in the Czech Republic and Germany. Both are located in the Elbe river catchment (Fig. 1). And both use natural pre-treatment techniques - riverbank filtration and artificial recharge, which commonly show high removal efficiencies for PPCPs based on natural attenuation processes.

2. Materials And Methods

2.1. Characteristics of the Czech and German sites of investigation

Káraný waterworks is located in the central part of Bohemia, about 30 km northeast of Prague (Fig. 1). It is one of the suppliers of drinking water for the city of Prague, with more than 1 million inhabitants. The facility uses surface water from the lower reaches of the Jizera river.

The river basin has a mixed characteristic with a balanced representation of forests and farmland. The biggest settlement in the basin is Mladá Boleslav, with 44,000 inhabitants and an important industrial area, including factory and headquarters of the Škoda brand. The site hydrogeology is characterized as a shallow unconfined aquifer situated in terraces of quaternary fluvial sediments. Under natural conditions, the aquifer is recharged by natural groundwater recharge and inflow from the fractured bedrock and drains to the Jizera river. However, intensive extraction of groundwater induces riverbank filtration from the river and in addition the aquifer is artificially recharged via basins by treated river water.

The waterworks at Káraný operates on the principle of combining two independent drinking water treatment technologies (Fig. 2). The first one is a historic, but still operable riverbank filtration well group built between 1906 and 1913. It consists of 685 wells of a depth ranging from 8 - 12 m, spaced 20 - 40 m apart, situated in the sand-gravel fluvial terraces at 250 m distance from the bank of Jizera river. The total capacity of this system is up to 86,400 m^3/d.

Another technology of the waterworks origins in 1968 and relies on artificial recharge. The first step of this process is a simple mechanical treatment of the surface water from the river. The water is treated by sand filtration and pumped into infiltration ponds (Fig. 2) from where it percolates into sandy fluvial sediments with a thickness of 20 m and is recharged into the aquifer. At a distance of approximately 200 m from the infiltration ponds, a system of large-diameter wells with a total capacity of 77,760 m^3/d is located. The extracted water is a mixture of infiltrated surface water and groundwater from the sandy-gravel terrace inflowing from the east towards the Jizera river.

In terms of potential sources of pollution by PPCPs, the greatest risk is municipal wastewater effluent. The town Mladá Boleslav is also a seat of the psychiatric hospital with a 150-year tradition. Only four more towns in the Jizera basin have more than 5,000 inhabitants (Turnov 14,000, Mnichovo Hradiště 8,700, Benátky nad Jizerou 7,000, Bakov nad Jizerou 5,000). All towns are equipped with wastewater treatment plants.

The waterworks Dresden-Hosterwitz is operated by the DREWAG-Stadtwerke GmbH and located on the floodplain of the Elbe river. The Elbe river is a transboundary perennial river and federal waterway. With a length of 1.097 km the Elbe river originates in the Czech Republic and flows northwest into the North Sea [24]. The catchment of the Elbe river as a water resource for Dresden-Hosterwitz waterworks represents practically entire Bohemia region. The Jizera catchment is a subcatchment of Elbe river in Dresden (Fig. 1). Dresden-Hosterwitz is located in a rift valley along the Elbe river, which is mainly filled with glacial deposits. The quaternary aquifer is in hydraulic connection with the Elbe river and groundwater flows from both sides of the valley towards the river. The local aquifer at Dresden-Hosterwitz comprises two stratigraphic units: the quaternary sand and gravel aquifer with a thickness of 9 to 14 m and 1 to 3 m thick overlying holocene clay [24].

The waterworks operates two separate treatment trains, a riverbank filtration treatment train and an artificial recharge treatment train (Fig. 3).

If the production is less than 20,000 m^3/d, riverbank filtration is used before cascade aeration, granular activated carbon filtration (GAC), pH-adjustment and disinfection with chlorine. The production capacity can be increased to 72,000 m^3/d through five open recharge basins supplied with pre-treated Elbe river water (coagulation and open multimedia sand filtration). Water is extracted from the shallow aquifer with 111 siphon wells and two separate well groups consisting of 8 and 28 wells equipped with submersible pumps [24].

In terms of potential sources of pollution by PPCPs Elbe river water is mainly contaminated by wastewater effluents upstream of Dresden-Hosterwitz in Saxony as well as in more distant parts of the basin in Bohemia.

2.2. Monitoring system

Monitoring campaigns were conducted in the years 2019 - 2021. The monitoring system in both waterworks had an identical structure. At quarterly intervals, 116 PPCPs were analysed in the Elbe river and Jizera river, artificial recharge wells and drinking water.

For the waterworks in Káraný a longer time series of PPCP data is available, because all sampling points were monitored at regular monthly intervals in the years 2017–2021. The monitoring network of the waterworks in Káraný also includes samples from the upper course of the Jizera river upstream of the WWTP of the town Mladá Boleslav, the outlet from the WWTP and data of sampling points downstream of the WWTP outlet. The waterworks in Dresden-Hosterwitz, as a member of the AWE (Association of waterworks in the catchment of the Elbe river), has been following its own monitoring program for relevant PPCPs since more than 10 years, focusing on a reduced parameter set compared to the list of substances analysed within the boDEREC-CE project.

2.3. Analytical methods

To ensure the comparability of the results all samples were treated according to a validated procedure in Vltava catchment laboratory.

The analyses of the collected samples of surface and groundwater were carried out according to valid procedures and EPA method 1694 in the Vltava River Basin Authority laboratory. Samples were collected in 60 mL amber glass vials (filled only halfway). The samples were stored in a freezer (in an inclined position). They were defrosted at a maximum temperature of 30 °C on the day of analysis. It was necessary to conduct the analysis immediately after defrosting.

One method was developed for the analysis of PPCPs (LC-MS/MS with combinated ESI+ and ESI- mode). The samples of water were centrifuged in headspace vials for 10 min at about 3500 rpm (Eppendorf 5804, Eppendorf, Germany). Subsequently 1.50 g of each sample were weighed in a 2 mL vial using an analytical balance Denver TB-215D (Denver Instrument GmbH, Germany). Then 1.5 μL of 100 % acetic acid certified for LC-MS (Honeywell) was added to each sample. An isotope dilution was performed in the next step. Deuterized internal standards of d10-Carbamazepine, d6-sulfamethoxazole, d3-iopromide, d3-iopamidol, 13C2-erythromycin, d3-ibuprofen, d4-diclofenac, d3-naproxen, d5-chloramphenicol and others were used.

PPCPs were separated and detected by LC–MS/MS methods based on direct injection of the sample into a chromatograph. A 1290 ultra-high-performance liquid chromatograph (UHPLC) coupled with an Agilent 6495B Triple Quad Mass Spectrometer (MS/MS) of Agilent Technologies, Inc. (Santa Clara, CA, USA) was used.

The separation was carried out on a Waters Xbridge C18 analytical column (100 mm x 4.6 mm, 3.5 μm particle size). The mobile phase consisted of 0-100 % methanol certified for LC-MS (Merck) and 0-100 % ultrapure water (Merck-Millipore) with 0.02 % acetic acid and 0.5 mM ammonium fluoride certified for LC-MS (Merck) as the mobile phase additives. The flow rate was 0.5 mL/min. The injection volume was 0.050 mL.

3. Results And Discussion

3.1. Comparison of the river water quality of the Elbe river and Jizera river

The Elbe river basin on the border with Germany has a catchment of 49,933 km2, length of 371 km and average discharge in Dresden of MQ = 311 m^3/s [26]. The Elbe in Dresden is a unique watercourse, as it drains 63 % of the entire territory of the Czech Republic [27]. Thus, PPCPs analyzed in Dresden may originate from a mixture of sources in the western half of the Czech Republic. The most prominent sources of PPCPs are WWTP effluents. However, due to the extremely large area of the river basin, it is not possible to analyze the impact of individual sources of pollution on the Czech side. The water quality of the Elbe in Dresden must therefore be approached as a result of diffuse, very heterogeneous sources of PPCPs. Another factor, which has to be considered is natural attenuation of PPCPs in surface water. Some substances such as metformin or iomeprol are partly attenuated in surface water, while other substances such as Carbamazepine are more stable.

The length of the Jizera river along its mouth into the Elbe below Káraný is 165 km, the area of its catchment is 2,193 km^2 and average flow 24 m^3/s [28]. The most significant source of contamination by PPCPs is very likely the town Mladá Boleslav, situated 35 km north from the Káraný waterworks, and the local clinic in case of the Jizera river. Given that the Jizera is a sub-basin of the Elbe, it is not surprising that the nature of PPCP contamination is similar in both cases (Fig. 4).

The monitoring of Jizera and Elbe river water focused on a total of 116 PPCPs substances which are regularly found in European surface water bodies [31] of this number, 56 substances were found in the samples. This fact clearly demonstrates an impact of anthropogenic activities.

Ten substances, including Paracetamol and Chloramphenicol were only found in the Jizera river. On the contrary, in the Elbe river ten specific substances were detected, including 5-methyl-1H-benzotriazole, Cyclamate and Venlafaxine O-desmethyl which were not detected above LOQ in the Jizera river. In all other cases, both watercourses contain identical PPCP substances, in most cases at very similar concentrations (Fig. 4). The only exceptions are the almost twice as high levels of Acesulfame in Jizera river and the higher values of Oxypurinol (526 ng/L) and Iomeprol (233 ng/L) in the Elbe river. Also, results from both rivers indicate that concentrations of PPCPs are on average higher in summer months than in winter months. Such seasonal variations are mostly caused by lower discharge in summer months. In case of Acesulfame, higher concentrations in summer months may be also influenced by changes in consumption. Acesulfame is used in the food industry in sugar-free and low-calorie products [29]. As one of the main sweeteners in soft drinks its consumption is probably higher during warm periods [30].

Out of 116 substances monitored, the median concentrations of only ten substances exceeded 100 ng/L (Tab. 1).

Table 1. Concentration of substances in the Elbe river and the Jizera river exceeding the Median of 100 ng/L

The Jizera river and the Elbe river showed the widest and similar spectrum of substances, and at the same time highest concentrations of the detected substances, compared to the Po river, Isar river, Sava river, Brynica river and Cetina river in Europe investigated within the boDEREC-CE project [31]. The homogeneity of the detected PPCP substances in Central European watercourses is an interesting phenomenon in the context in the context of published regional data in the world. The results from major river watersheds in China showed that most frequently detected pharmaceuticals are sulfonamides, macrolides, antiepileptic drugs, anti-inflammatory drugs, and β-blockers. Amongst these, maximum concentrations of Lincomycin, Sulfamethoxazole, Acetaminophen and Paraxanthine were between 44 ng/L and 134 ng/L. Concentrations of most persistent substances, DEET and Carbamazepine, were 0.8-10.2 ng/L and 0.01-3.5 ng/L, respectively [32].

3.2. Impact of Mladá Boleslav WWTP on Jizera river quality

While it is not possible to analyze the individual sources of pollution of the Elbe river due to it is a large catchment area. An analysis in the Jizera catchment is possible. A point source of contamination originates from the municipal WWTP of Mladá Boleslav. The hospital which is situated in the town can be assumed as a significant source of PPCP in municipal waste water. Tab. 2 indicates, that the removal efficiency of PPCPs is not sufficient at the local WWTP. Thus, high concentrations in the range of 5 to 24,000 ng/L are discharged into the river, of which oxypurinol and telmisartan are the substances with the highest concentrations. An increase in concentrations (more than 50 %) in river water caused by WWTP discharge was recorded for iomeprol, diclofenac, oxypurinol, celiprolol, telmisartan, lamotrigine, tramadol, carbamazepine, sulfamethoxazole and metoprolol. It should be noted that these data were collected 2017-2018, when the range of laboratory analysis was limited to a lower number of substances in comparison to the monitoring campaigns 2019-2021. Therefore, the graph in Fig. 4 contains a wider range of substances.

Table 2. Impact of WWTP on Jizera river quality during the years 2017-2018 (median value in ng/l, n= 38)

3.3. Comparison of the elimination efficiency of selected PPCP substances by riverbank filtration and artificial recharge

Natural attenuation processes during artificial recharge and bank filtration show a high removal efficiency in both waterworks (Tab. 3, Tab. 4). A total of 46 substances were detected in river water, but the majority of those were below quantification limits after artificial recharge and bank filtration. At Káraný, pre-treatment by sand filtration of the river water before infiltration did not affect the monitored substances. At Dresden-Hosterwitz, the raw water is pretreated by coagulation and multimedia filtration resulting in some removal of PPCPs before infiltration.

Table 3. Detected PPCPs in the output from artificial recharge and riverbank filtrate in Káraný (x means result under the limit of quantification, empty cell means that at the time of sampling this substance was not included into the monitoring).

From the field data set it remains unclear, whether the attenuation of those substances is based on degradation/metabolization, sorption or dilution. Results in Tab. 3 indicate that riverbank filtration in Káraný is highly effective in removing PPCPs. Out of 46 substances found in surface water, 12 substances were quantified in riverbank filtrate samples at lower concentrations. In comparison, the removal efficiency of artificial recharge is lower for most PPCPs probably due to a shorter residence time (Tab. 3). Acesulfame is repeatedly detected in artificial recharge samples. Its median concentration of 80 ng/L is almost four times higher than those of riverbank filtrate samples (25 ng/L). Also, Carbamazepine as well as Lamotrigine, Sulfamethoxazole and Oxypurinol were detected with a median concentration of 14 ng/L, 22 ng/L, 33 ng/L and 97 ng/L, respectively, from 2017 to 2021. Other substances appear only at random frequency, unsystematically and at low concentrations such as Primidon.

In Dresden-Hosterwitz 43 substances were found in surface water in comparison to 19 substances in riverbank filtrate and 25 in artificial recharge samples (Tab. 4). The concentrations were on average 50 % lower than in surface water. While frequently found in the Elbe river, Acesulfame was detected in only one out of five riverbank filtrate samples above the limit of quantification (50 ng/L). For the same substance in artificial recharge samples two out of six samples showed concentrations above the limit of quantification. Regarding riverbank filtrate and artificial recharge samples median concentrations of Carbamazepine, Sulfamethoxazole, Benzotriazole as well as its metabolite 5- Methyl-1H-benzotriazole, and Telmisartan were found on a regular basis at lower concentrations than in surface water (Tab. 4).

The removal efficiencies of those substances are shown in Tab. 4. In case of Oxypurinol median concentrations were on average 45 and 24 % higher than in surface water. Concentrations above the limit of quantification of other substances were detected in minor concentrations on single occasions.

In past studies Acesulfame was found frequently in groundwater in concentrations up to 34 µg/L [33]. Due to frequent findings in various waterbodies and also because of its physical, chemical as well as biological properties, Acesulfame is considered environmentally persistent and an indicator of wastewater contamination [3,15,34]. Concentrations shown in Table 4 at the sampling points WWTP discharge and Jizera river downstream with an increase of 15 % in comparison to Jizera river upstream confirm this assumption. A former study indicated that Acesulfame is not degraded under aerobic or anaerobic conditions and therefore was proposed as an anthropogenic marker [35]. However, more recent studies revealed Acesulfame is degradable under certain conditions [35–37]. Kahl et al. hypothesized that Acesulfame degrading species evolved during the last few years, e.g. due to horizontal gene transfer [38].

In riverbank filtrate samples of Káraný, often reported PPCPs such as Carbamazepine and Sulfamethoxazole were reduced below the limit of quantification (10 ng/L). In Dresden-Hosterwitz no significant removal was observed either in riverbank filtrate samples as well as artificial recharge samples. The median concentrations of both substances are almost similar to surface water concentrations. The median removal rate of Carbamazepine during artificial recharge in Káraný is 30 %. Carbamazepine is a frequent prescribed antiepileptic drug whose occurrence was widely reported in the literature [28]. Similar to Acesulfame, it has been detected in WWTP effluents, surface waters, groundwater and even drinking water due to its inefficient removal during wastewater treatment as well its persistence in the aquatic environment [30]. In general, Carbamazepine has been often reported to be highly persistent during conventional wastewater treatment and can be also found in recharged groundwater [39–41]. It has been confirmed that soil aquifer treatment alone is not able to remove Carbamazepine, hence lower concentrations measured in Káraný may likely originate from dilution with groundwater [42].

Similar to Carbamazepine, Lamotrigine was detected in Dresden Hosterwitz with a median concentration of 39 ng/L in surface water and 32 ng/L and 26 ng/L in riverbank filtrate and artificial recharge samples, which results in removal efficiencies calculations of 18 % and 33 %. In Káraný Lamotrigine with the limit of quantification of 10 ng/L was detected with a median of 38 ng/L in river water and 22 ng/L in artificial recharge samples, which accounts for 42 % removal. 20 years ago lamotrigine along with Carbamazepine was introduced as mood stabilizing agent, for treatment of bipolar disorder, and is combined with other drugs for the treatment of alcohol withdraw [43]. It is assumed, that it is prescribed nearly as frequently as Carbamazepine [44]. Little is known about the biodegradation and indirect photodegradation in natural waters, but reports on wastewater, groundwater, surface water and even drinking water suggest that it is approximately as recalcitrant as Carbamazepine [3,43,45,46].

As the most widely applied Sulfonamide antibiotic, Sulfamethoxazole was widely found especially in surface waters [47]. It has been proven that this compound has adverse effects on aquatic organisms and therefore needs to be removed from wastewater [47–50]. Various technologies have been studied regarding removal, but until now no existing WWTP treatment train was able to efficiently remove Sulfamethoxazole from wastewater [51,52]. It has been confirmed through various field monitoring studies and column soil experiments that Sulfamethoxazole is preferably degraded under anaerobic conditions [53]. If redox conditions are mostly aerobic and retention times are short, no efficient removal could be expected which would explain the difference in removal rates observed regarding both sides. In Dresden-Hosterwitz, bank filtrate is anoxic, thus the observed 30 % removal could be the result of degradation.

Oxypurinol concentrations were reported above 350 ng/L on a regular basis in surface water in the Elbe river and above 100 ng/L in the Jizera river. Also, artificial recharge samples at both sites show median concentrations of 652 ng/L in Dresden-Hosterwitz and 97 ng/L in Káraný. Median concentrations in bank filtrate samples in Dresden-Hosterwitz are similar to artificial recharge samples (762 ng/L), indicating an increase compared to river water. Oxypurinol is a metabolite of the anti-gout agent Allopurinol, a regular prescribed pharmaceutical in Europe. Despite its widespread use only low concentrations of allopurinol were detected in the aquatic environment because it is mostly (about 90 %) metabolized to Oxypurinol in the human body [54,55]. Because of its high biological persistence and polarity, Oxypurinol is not removed in WWTPs and is present in surface water, groundwater and in some cases in drinking water at concentrations in high ng/L to low µg/L range [56]. An increase durig bank filtration was also observed by Kruć et al. [57]. They associated the increase in concentrations with unrecognized fluctuations in concentrations in the source water. Whether this is the case in Dresden-Hosterwitz needs to be investigated in further monitoring campaigns.

The median removal efficiency from surface water of 1H-benzotriazole in Dresden-Hosterwitz bank filtrate samples is 68 % and 80 % in artificial recharge samples. However, 1H-benzotriazole as well as its metabolite 5-Methyl-1H-benzotriazole were detected in all samples above the limit of quantification (50 ng/L). In general, 1H-benzotriazoles and its derivates are widely used corrosion inhibitors for antifreeze liquids or protecting agents of silverware in dishwashing detergents [26]. Due to its wide usage and environmental persistence, 1H-benzotriazole has been appraised as an ubiquitous environmental contaminant [28]. Former studies however reported considerably lower concentrations in riverbank filtrate and in artificially recharged water [58–60]. When comparing median concentrations of 5-Methyl-1H-benzotriazole and 1H-benzotriazole the metabolite concentrations are considerably higher as for the Elbe river as expected result for degradation processes in the subsurface (Tab. 4). These values indicate a possible degradation of 1H-benzotriazole during aquifer passage. In Káraný the dataset of 1H-benzotriazole and its metabolite is not sufficient to identify such trend.

Regarding sartans, a group of often reported PPCPs in environmental samples, Telmisartan was found in the Jizera river as well as in the Elbe river at concentrations ranging from 97 ng/L to 356 ng/L. In Dresden-Hosterwitz Telmisartan concentrations in riverbank filtrate and artificial recharge samples were significantly lower and ranged from 23 ng/L to 192 ng/L. A similar removal was observed in Káraný, however the concentration was lower than the limit of quantification in 10 out of 10 samples. Telmisartan is a specific angiotensin II receptor (type AT1) antagonist widely prescribed against e.g. hypertension, stroke or cardiac arrest [61]. Degradation studies under various conditions and photo stability have been conducted. The results show that the substance is mainly affected by oxidising conditions, but unaffected by temperature [62]. Nevertheless, due to lack of data about sartans in WWTPs, characterisation of their environmental fate demands further research [62].

Table 4. Detected PPCPs in the output from artificial recharge and riverbank filtration in Dresden-Hosterwitz (x means result under the limit of quantification).

Table 5. Comparison of PPCPs removal efficiency in Dresden-Hosterwitz and Kárany waterworks

(efficiency calculated as the percentage difference between the measured concentrations of the substance in the river and after treatment)

4. Conclusions

This study provides a general insight of PPCPs and their persistence in various components of the aquatic environment at two waterworks sites. However, persistence is a property that is greatly influenced depending on site conditions and travel time [63,64]. The datasets presented in this study prove natural attenuation processes such as riverbank filtration and artificial recharge are equally effective to overall eliminate or at least decrease concentrations of PPCPs from surface water. However, the results also indicate that specific substances known for their persistence such as Acesulfame or Carbamazepine are frequently present in abstracted waters.

Given the fact, that the list of PPCPs found in the environment is constantly expanding, specific compounds need to be priontized with regard to cost-intensive monitoring efforts and risk-asessment. In order to adress this problem a regulatory framework on PPCPs in the environment is urgently needed.

A number of new questions has been raised. Monitoring was based on the "black box" principle. Substances were monitored at the inlet (recharge) and further at the outlet (quality of produced drinking water). But gradual changes taking place along the flowpath have not been investigated. Therefore, the next step of the research will include sampling at monitoring wells between the river or infiltration basin and pumping wells investigating the impact of travel time.

Declarations

Author Contributions: Z.H. and Y.A. prepared the manuscript and all authors read and approved the manuscript, D.R. and Y.A. took part in fieldwork and performed graphical and statistical interpretations. Z.H. and Y.A. interpreted the data, Z.H. and T.G. were responsible for the overall coordination of the research and editing of the manuscript.

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Tables

Tables 1 to 5 are available in the Supplementary Files section

Figures

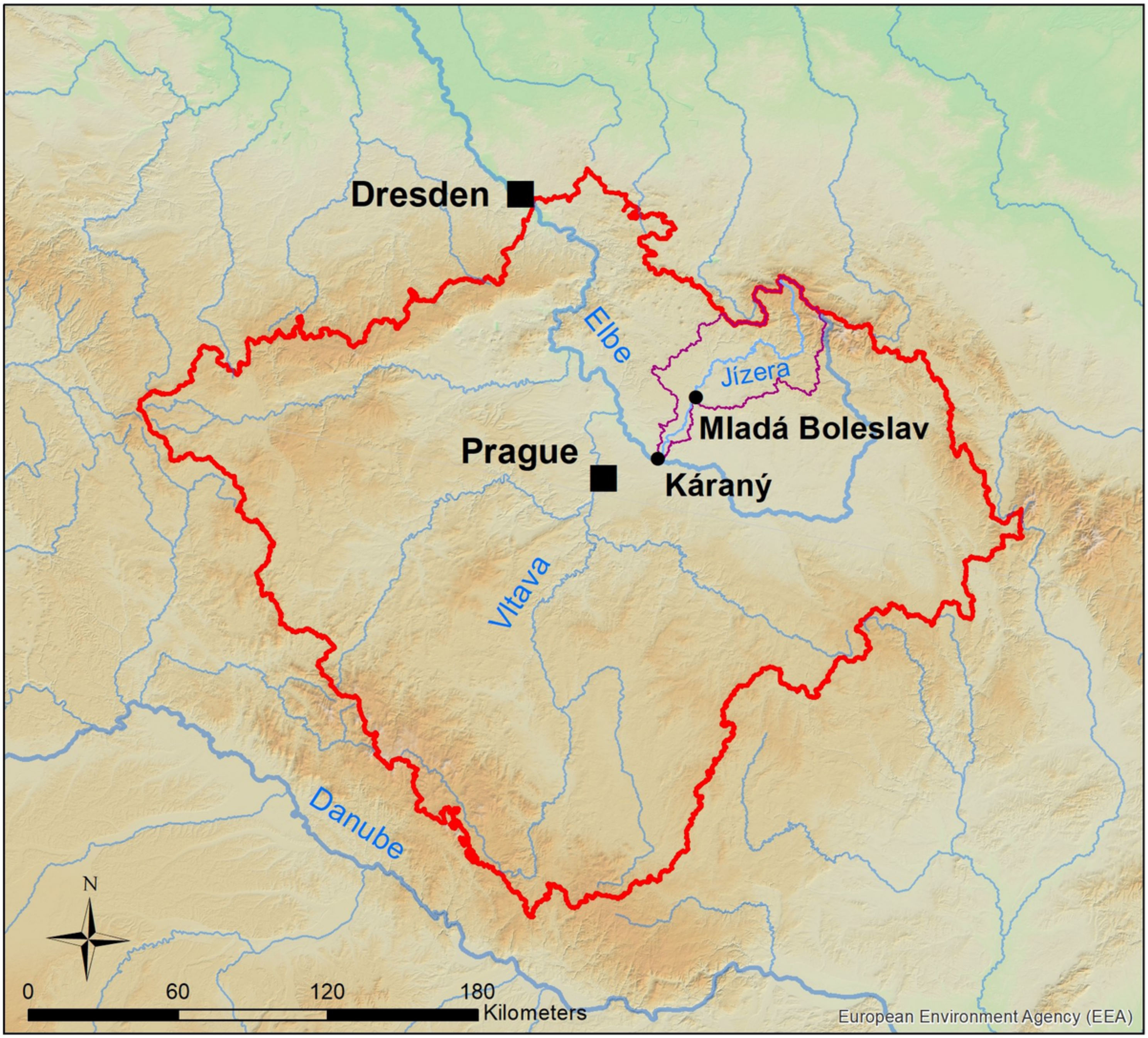

Figure 1

Location of compared waterworks in the Elbe and Jizera river catchmentLocation of compared waterworks in the Elbe and Jizera river catchment

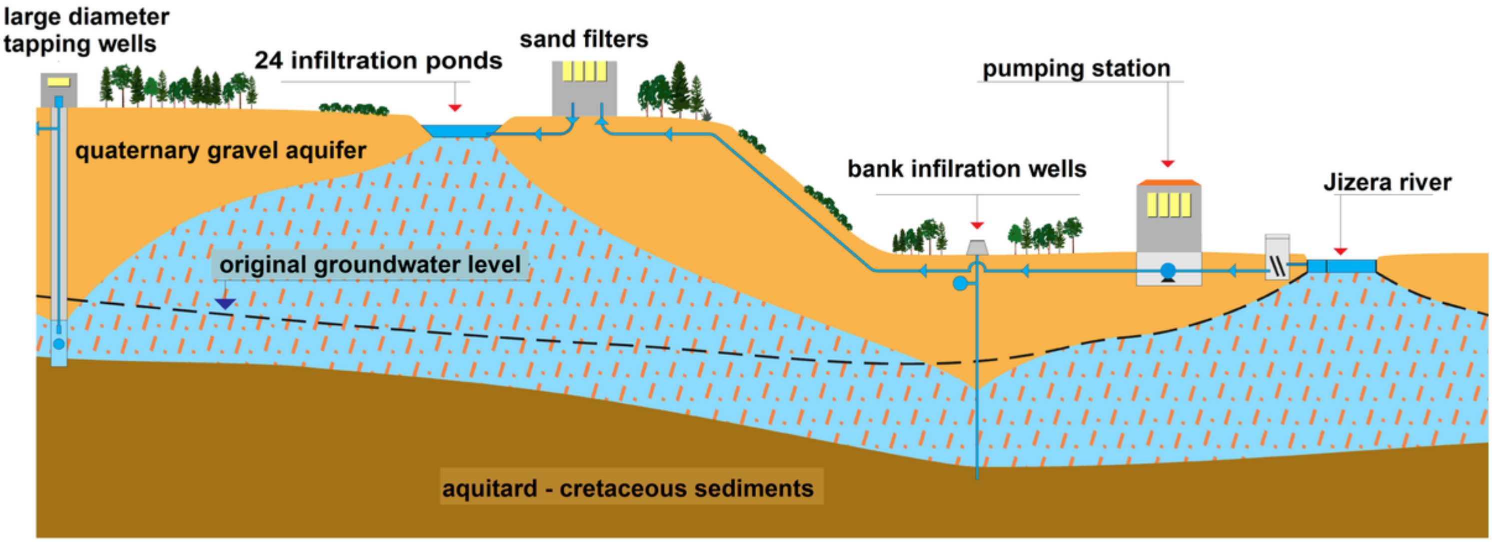

Figure 2

Scheme of Káraný waterworks

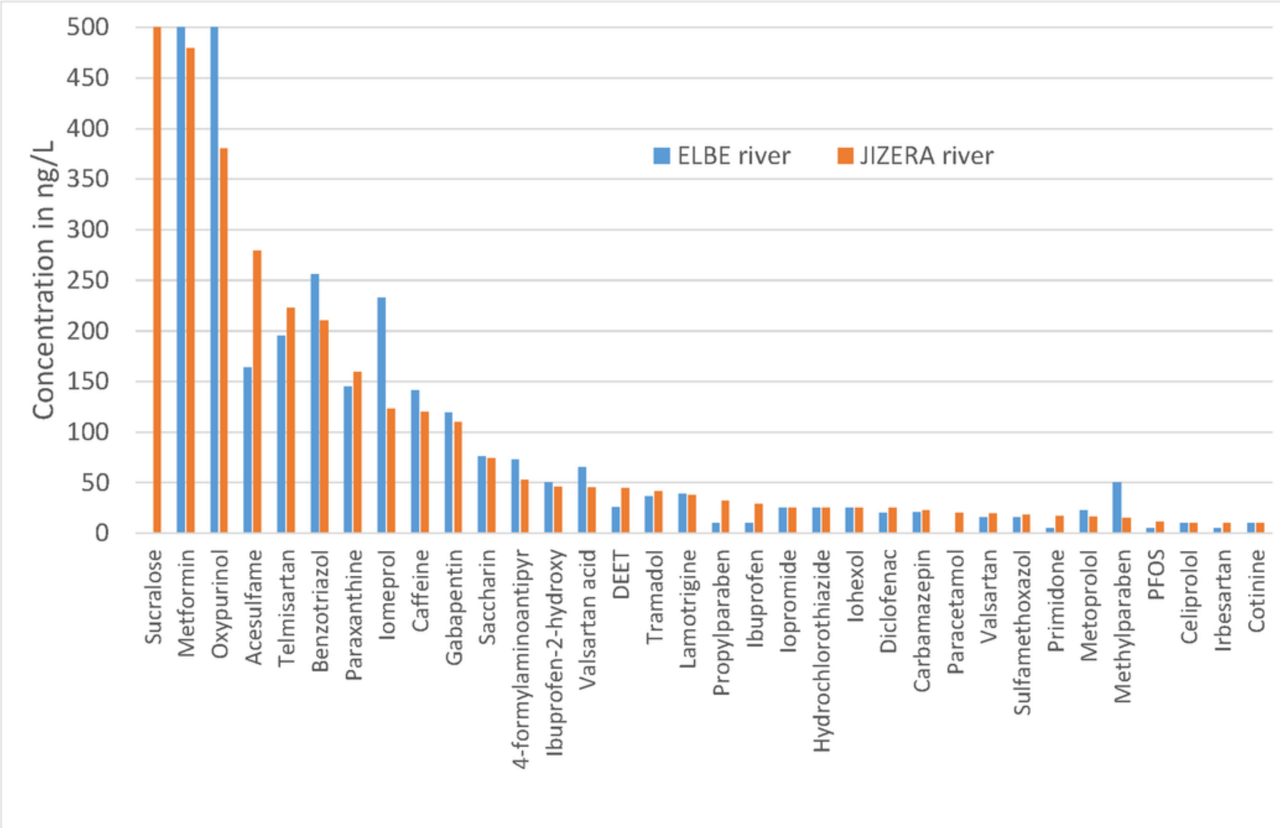

Figure 3

Schematic water treatment, WW Dresden-Hosterwitz [25]

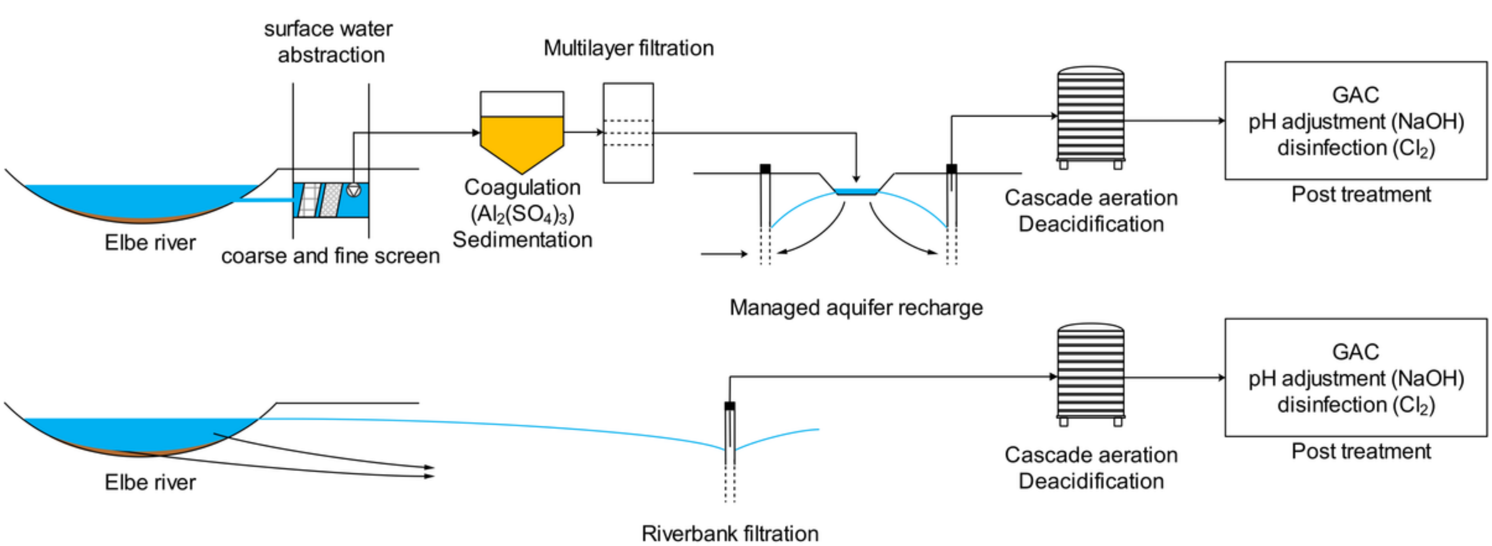

Figure 4

Comparison of PPCPs median concentrations in Jizera (n = 38) and Elbe river water (n = 7), 34 most represented components

Supplementary Files

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