



# The Role of Wastewater Treatment Plants in Pollution Reduction - Evaluated by Grey Water Footprint Indicator

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## Abstract

One of the tools for water use evaluation is the Water Footprint introduced in 2002 by professor Hoekstra. This work assesses the pollution discharged from 251 wastewater treatment plants (WWTPs) throughout the Odra river basin in the Czech Republic. The development of pollution production over a period of 15 years (2004–2018) together with a number of WWTPs in the Odra river basin were analyzed. The Grey Water Footprint of discharged pollution was determined both in terms of individual size categories of WWTPs and in terms of the pollution parameter that most affects the level of pollution. Total phosphorus and ammonium nitrogen were identified as the decisive pollutants that determine the value of the Greywater footprint the most.

**Keywords:** Greywater footprint; Odra river basin; Pollution; Wastewater treatment plant; Water Footprint assessment

## 1 Introduction

The wastewater collection and treatment systems are increasingly centralized. The objective of the Council Directive 91/271/EEC concerning urban wastewater treatment is to protect the environment from the adverse effects of urban wastewater discharges. In December 2019, the European Commission published the Evaluation of the Urban Wastewater Treatment Directive which evaluated whether the existing rules have reached their objectives and whether they still serve their purpose [1]. The assessment confirms that the Directive has proved very effective overall when fully implemented. The reduction of organic matter and other pollution in treated wastewater has improved water quality throughout the European Union. Though implementing the Directive has been expensive, benefits clearly outweigh the costs. In this study, we focused on the evaluation of a 15-year period of intensive construction of new and intensification and modernization of existing wastewater treatment plants. For the evaluation, the Greywater footprint (GWF) methodology was used. The Water Footprint Assessment (WFA) was introduced in 2002 [2] and methodology was standardized by the Water Footprint Network [3]. The Greywater footprint is defined as the volume of fresh water required to assimilate the load of pollutants; based on natural background concentrations and existing ambient water quality standards. The GWF studies are often focused on agriculture, energy sector, industry, organizations, regions or states, river basins, households, etc. The application of the Grey Water Footprint methodology on wastewater treatment plants has so far been limited to a few studies: Shao & Chen [4], Gu et al. [5], Morera et al. [6], Gómez-Llanos et al. [7,8], Johnson & Mehrvar [9], Yapıcıoğlu [10], Stejskalová et al. [11], Ansorge et al. [12,13]. This work assesses the pollution discharged from 251 wastewater treatment plants throughout the Odra river basin in the Czech

Republic. The development of pollution produced and discharged over the period of 15 years (2004–2018) has been assessed, from a point of view of basic monitored pollution parameters reduction.

## 2 Methods

### 2.1 Greywater footprint (GWF)

GWF is a part of the Water Footprint introduced in 2002 [2] and points to the level of pollution. It is defined as the volume of fresh water required to assimilate a load of pollutants to the level of existing ambient water quality standards. The GWF calculation was made in accordance with the Water Footprint Assessment Manual [3]. The calculation is carried out in three steps: for each pollutant (*i*) and discharge point (*j*), the  $GWF_{j,i}$  is calculated according to Equation (1). The pollutant with the highest value of the GWF at the point of *j* then indicates the GWF at *j* (Equation 2). The GWF of a system under assessment is the sum of the GWFs of all pollutant emission points into the aquatic environment (Equation 3).

$$GWF_{j,i} = \frac{L_{j,i}}{C_{max,j,i} - C_{nat,j,i}} \quad (1)$$

$$GWF_j = \max\{GWF_{j,1}, GWF_{j,2}, \dots, GWF_{j,i}\} \quad (2)$$

$$GWF = \sum_{j=1}^n GWF_j \quad (3)$$

where  $GWF_{j,i}$  is GWF of the pollutant *i* released into water at the point *j* [volume/time],  $GWF_j$  is GWF of pollutant at the point *j* [volume/time],  $GWF$  is GWF of the subject [volume/time],  $L_{j,i}$  is quantity of the pollutant *i* being emitted into water at the point *j* [weight/time],  $C_{max,j,i}$  is maximum permissible concentration of the substance *i* in receiving water

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at the point  $j$  [weight/volume],  $C_{nat,i,j}$  is natural concentration of the substance  $i$  in receiving water at the point  $j$ , [weight/volume], and  $n$  is number of discharge points.

## 2.2 Site description - Odra river basin

Two large European rivers have their springs in the central part of Europe, in the Czech Republic - Elbe and Odra. The analysis was carried out for the Odra river basin in the Czech Republic (Figure 1). A share of the Odra River on the total run-off from the Czech Republic is 9,8% and its district occupies about 7% of the total territory of the Czech Republic, with an area of 7,217 km<sup>2</sup>.



Figure 1: Odra river basin district in middle-north Europe (the area of interest is highlighted by hatch pattern)

## 2.3 Data sources

For the purpose of this study, data on all WWTPs listed in the Water Balance Database (Decree 431/2001 on the content of Water Balance, method of its compilation, and data for the Water Balance) were analyzed. The Water Balance Database is a national register of withdrawals and discharges. It orders all subjects discharging wastewater into surface or groundwater in quantities exceeding 6,000 m<sup>3</sup>/year or 500 m<sup>3</sup>/month to forward data on the water quantity and quality. In the Czech part of the Odra river basin, a total of 3,056 records concerning 251 wastewater treatment plants are registered for the period from 2004 to 2018. According to the outflow volume and incoming organic pollution, the WWTPs were divided into 7 size categories (the approximate annual amount of treated wastewater is given in brackets).

- **Cat. I:** for less than 50 PE (< 2,000 m<sup>3</sup>/year)
- **Cat. II:** for 51–200 PE (2,000 – 8,000 m<sup>3</sup>/year)
- **Cat. III:** for 201–500 PE (8,001 – 20,000 m<sup>3</sup>/year)
- **Cat. IV:** for 501–2,000 PE (20,001 – 80,000 m<sup>3</sup>/year)
- **Cat. V:** for 2,001–10,000 PE (80,001 – 400,000 m<sup>3</sup>/year)
- **Cat. VI:** for 10,001–100,000 PE (400,001 – 4,000,000 m<sup>3</sup>/year)
- **Cat. VII:** for more than 100,000 PE (> 4,000,000 m<sup>3</sup>/year)

When evaluating the GWF, special attention must be paid to the selection/setting of the use of concentration limits, as these strongly affect the GWF value [14,15]. Maximum acceptable concentrations ( $C_{max}$ ) of a pollutant in a receiving watercourse are set by the Czech Technical Standard ČSN 75 7221 Water quality - Classification of surface water quality (Class II) [16]. Natural concentration values ( $C_{nat}$ ) are given by the same Standard, Class I. The difference between the values of maximum acceptable concentration ( $C_{max}$ ) and natural concentration ( $C_{nat}$ ) is described as the Assimilation Capacity of

the flow [17]. A list of monitored parameters with their natural and maximum concentration values is given in Table 1.

## 3 Results and Discussion

### 3.1 Pollution produced

Over the course of 15 years, the number of WWTPs in the Czech part of the Odra River Basin increased by 38% (from 164 to 227) and the GWF of inflowing pollution to WWTPs increased in total by 33%. An overview of the development of pollution produced in tonnes is given in Figure 2.

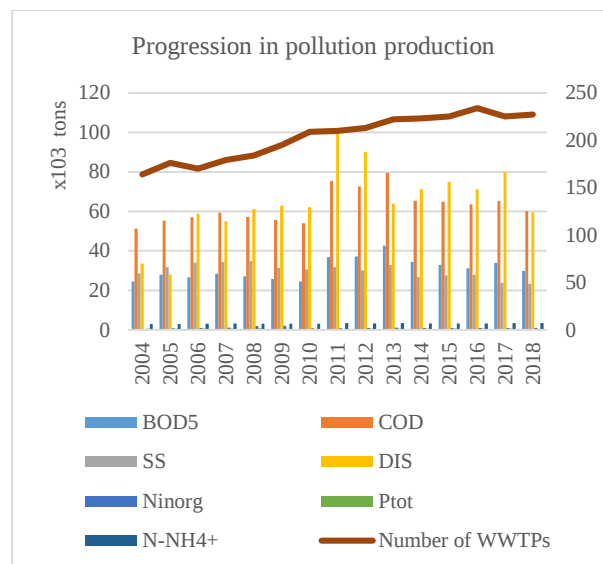


Figure 2: Progression in the amount of pollution supplied and treated at WWTPs (the secondary y-axis shows an increasing number of WWTPs in the Odra river basin, CZ)

Table 1: Monitored parameters with their natural and maximum concentration values

| Parameter                   |                                |      | $C_{nat}$ | $C_{max}$ | Assimilation capacity<br>( $C_{max} - C_{nat}$ ) |
|-----------------------------|--------------------------------|------|-----------|-----------|--------------------------------------------------|
| Biochemical oxygen demand   | BOD <sub>5</sub>               | mg/L | 2         | 4         | 2                                                |
| Chemical oxygen demand      | COD                            | mg/L | 15        | 25        | 10                                               |
| Suspended solids            | SS                             | mg/L | 15        | 25        | 10                                               |
| Dissolved inorganic solids* | DIS                            | mg/L | 300       | 450       | 150                                              |
| Inorganic nitrogen          | N <sub>inorg</sub>             | mg/L | 2.75      | 5.55      | 2.8                                              |
| Total phosphorus            | P <sub>tot</sub>               | mg/L | 0.05      | 0.15      | 0.1                                              |
| Ammonium nitrogen           | N-NH <sub>4</sub> <sup>+</sup> | mg/L | 0.2       | 0.4       | 0.2                                              |

\* There are no values in the regulations set for the DIS assimilation capacity. It was derived based on the assumption that DIS are a subset of Total Dissolved Solids (TDS). The DIS assimilation capacity was determined on the level of ¼ assimilation capacity of TDS according to ČSN 75 7221 [12]

If we relate the development of the produced pollution of individual pollutants to the beginning of the monitoring, we find that suspended solids show a permanent slight decrease in the order of percent units. The decline in suspended solids

could be related to the drought of recent years. The phosphorus pollution produced remains more or less at the same level (phosphate detergents have been replaced by others, which could cause phosphorus stagnation). The initial increase and subsequent decrease of organic pollution (expressed in BOD<sub>5</sub> and COD) at inflows to WWTPs may be caused by the originally growing popularity of kitchen waste disposers, which have fallen into disfavor in recent years and are clearly not recommended. The amount of DIS pollution shows doubled values (compared to 2004) and the amount of produced inorganic nitrogen pollution tripled.

### 3.2 Pollution discharged and the GWF reduction

More efficient methods of wastewater treatment are making a reduction in GWF more significant. While the average reduction of GWF at WWTPs in 2004 was 86%, after fifteen years it was 93% (in 2018). The value of the GWF reduction has more or less stabilized over the last 8 years, especially in the size categories over 20,000 m<sup>3</sup>/year (Figure 3). While the total GWF at the WWTPs inflows was  $3.06 \times 10^{11}$  m<sup>3</sup>; the total GWF at the WWTPs effluents was  $2.6 \times 10^{10}$  m<sup>3</sup>, detailed in Table 2. Also, the increasing efficiency of the GWF reduction at WWTPs is significant (Figure 3).

### 3.3 Parametres causing the GWF

While the GWF of incoming pollution is caused predominantly by ammonium nitrogen ( $\frac{3}{4}$  of cases), after passing through the WWTP, the GWF of the discharged pollution is caused, in addition to ammonium nitrogen, mainly by the discharged phosphorus. Comparison between inflows and outflows from a point of view of which parameter causes pollution the most is given in Figure 4. This has not been investigated in former studies which calculate GWF reduction at WWTPs. In the studied area, the GWFs at inflows were often

determined by different parameters than the GWFs at outflows (Table 3).

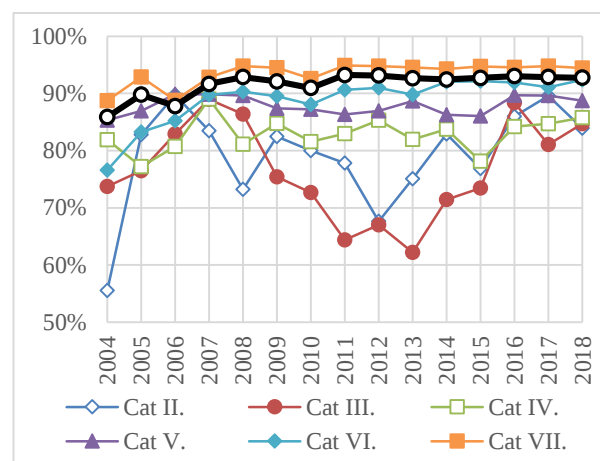


Figure 3: The percentage of the GWF reduction at monitored WWTPs

### 3.4 Effect of a WWTP size category on the GWF

The two largest size categories contribute the most to the total value of the GWF of discharged pollution, in a total of 82%. The share of medium-sized WWTPs (2001-10,000 PE) is 11% and the share of GWF pollution discharged from all WWTPs smaller than 2,000 PE is 8% (Table 4). In the case of the smallest and small WWTPs, the GWF of the discharged pollution is almost always caused by ammonium nitrogen (Table 3, 5). When considering the size categories, the overview is provided in Table 3.

Table 2: Comparison of the GWF at inflows and outflows from WWTPs

|                   | GWF at the WWTP                 |                              | GWF reduction by passing through the WWTP |           |           |           |           |           |           |
|-------------------|---------------------------------|------------------------------|-------------------------------------------|-----------|-----------|-----------|-----------|-----------|-----------|
|                   | inflows                         | outflows                     | All                                       | Cat. II   | Cat. III  | Cat. IV   | Cat. V    | Cat. VI   | Cat. VII  |
|                   | $\times 10^6$<br>m <sup>3</sup> | $\times 10^6$ m <sup>3</sup> | %                                         | %         | %         | %         | %         | %         | %         |
| 2004              | 16,089                          | 2,301                        | 86                                        | 56        | 74        | 82        | 85        | 77        | 89        |
| 2005              | 18,177                          | 1,866                        | 90                                        | 83        | 76        | 77        | 87        | 83        | 93        |
| 2006              | 17,670                          | 2,173                        | 88                                        | 90        | 83        | 81        | 90        | 85        | 89        |
| 2007              | 18,684                          | 1,581                        | 92                                        | 84        | 89        | 89        | 90        | 90        | 93        |
| 2008              | 19,052                          | 1,384                        | 93                                        | 73        | 86        | 81        | 90        | 90        | 95        |
| 2009              | 17,439                          | 1,406                        | 92                                        | 82        | 75        | 85        | 87        | 90        | 94        |
| 2010              | 17,219                          | 1,585                        | 91                                        | 80        | 73        | 82        | 87        | 88        | 93        |
| 2011              | 24,104                          | 1,650                        | 93                                        | 78        | 64        | 83        | 86        | 91        | 95        |
| 2012              | 23,981                          | 1,663                        | 93                                        | 68        | 67        | 85        | 87        | 91        | 95        |
| 2013              | 27,236                          | 2,072                        | 92                                        | 75        | 62        | 82        | 89        | 90        | 95        |
| 2014              | 18,251                          | 1,439                        | 92                                        | 83        | 71        | 84        | 86        | 92        | 94        |
| 2015              | 21,641                          | 1,637                        | 92                                        | 77        | 73        | 78        | 86        | 92        | 95        |
| 2016              | 21,608                          | 1,586                        | 93                                        | 86        | 88        | 84        | 90        | 92        | 95        |
| 2017              | 23,429                          | 1,758                        | 92                                        | 90        | 81        | 85        | 90        | 91        | 95        |
| 2018              | 21,337                          | 1,555                        | 93                                        | 84        | 85        | 86        | 89        | 92        | 94        |
| <b>Total Avg.</b> | <b>305,918</b>                  | <b>25,655</b>                | <b>91.4</b>                               | <b>79</b> | <b>78</b> | <b>83</b> | <b>88</b> | <b>90</b> | <b>94</b> |

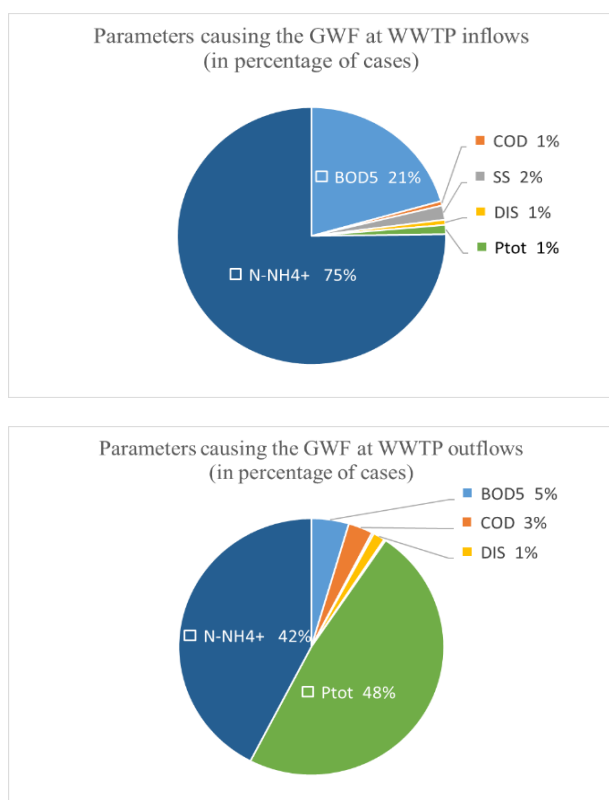


Figure 4: Proportional overview of pollutants that causes the GWF (comparison between WWTPs inflows vs. outflows)

Small WWTPs generally must deal with less stable nitrification (some older small WWTPs are not equipped for the process of nitrification at all) - this results in higher GWF caused by ammonium nitrogen at their effluents. In addition,

small WWTPs are often not operated very professionally and emission standards for ammonium nitrogen are set up for WWTPs from a capacity of 2,000 PE, so the operators do not have to focus on the ammonium nitrogen removal. As the size of the WWTP enlarges, the share of the effluent GWF caused by total phosphorus increases. For the WWTPs size category IV (i.e. of projected capacity for 501–2,000 PE), the GWF of discharged pollution is almost equally caused either by ammonium nitrogen (47%) or by total phosphorus (46%). For WWTPs for 2,000 PE and larger, the effluent GWF is most often determined by total phosphorus (Table 3, 5). The effect of the WWTP size category on total GWF reduction is given in Table 5. The average value of GWF reduction for all categories was 91.4%. The GWF of the WWTPs inflows is most often caused by ammonium nitrogen. This is due to the composition of municipal wastewater and the prevailing reduction conditions in the sewer. In terms of effluents from WWTPs, the greatest burden for watercourses under the WWTPs is pollution caused by ammonium nitrogen and total phosphorus (among basic chemical parameters). The level of discharged nitrogen is important for two reasons - eutrophication and the ammonium nitrogen toxicity to fish (the dissociated form of  $\text{NH}_4^+$ , which predominates at lower pH, is relatively harmless to fish; however the undissociated  $\text{NH}_3$  causes acute poisoning of fish at very low concentrations,  $\leq 0.1 \text{ mg/L}$ ). On the other hand, ammonium nitrogen is not stable in surface water, and after discharge, it undergoes nitrification relatively quickly - so the negative effect on water quality is rather local. Both essential nutrients - nitrogen and phosphorus - contribute significantly to water eutrophication. In conditions of the Czech Republic, the nitrogen supply from point sources of pollution is prevailed by nitrogen load from agriculture and other diffuse pollution sources although action plan to reduce nitrogen load from agriculture exists [18,19].

Table 3: Parameters causing the GWF at inflows and outflows (in the percentage of cases), overviewed according to WWTP size categories

| WWTP size category | BOD <sub>5</sub> |         | COD    |         | SS     |         | DIS    |         | N <sub>inorg</sub> |         | P <sub>tot</sub> |         | N-NH <sub>4</sub> <sup>+</sup> |         |
|--------------------|------------------|---------|--------|---------|--------|---------|--------|---------|--------------------|---------|------------------|---------|--------------------------------|---------|
|                    |                  |         |        |         |        |         |        |         |                    |         |                  |         |                                |         |
|                    | inflow           | outflow | inflow | outflow | inflow | outflow | inflow | outflow | inflow             | outflow | inflow           | outflow | inflow                         | outflow |
|                    | % of cases       |         |        |         |        |         |        |         |                    |         |                  |         |                                |         |
| Cat. I             | 0                | 0       | 0      | 0       | 0      | 0       | 0      | 0       | 0                  | 0       | 0                | 0       | 100                            | 100     |
| Cat. II            | 43               | 23      | 2      | 8       | 0      | 1       | 2      | 2       | 0                  | 0       | 1                | 23      | 54                             | 43      |
| Cat. III           | 17               | 5       | 1      | 3       | 0      | 0       | 0      | 0       | 0                  | 0       | 2                | 33      | 81                             | 59      |
| Cat. IV            | 18               | 4       | 1      | 3       | 1      | 0       | 0      | 0       | 0                  | 0       | 2                | 46      | 79                             | 47      |
| Cat. V             | 18               | 2       | 0      | 3       | 1      | 0       | 0      | 1       | 0                  | 0       | 1                | 65      | 80                             | 30      |
| Cat. VI            | 19               | 2       | 0      | 3       | 3      | 1       | 3      | 3       | 0                  | 0       | 1                | 49      | 74                             | 42      |
| Cat. VII           | 30               | 0       | 0      | 1       | 13     | 0       | 1      | 11      | 0                  | 0       | 1                | 57      | 55                             | 31      |

Table 4: Contribution of particular WWTP size categories on the total GWF of discharged pollution

| WWTP size category | No. of records in the Water Balance |  | Contribution to GWF of total discharged pollution |  |
|--------------------|-------------------------------------|--|---------------------------------------------------|--|
|                    |                                     |  |                                                   |  |
|                    |                                     |  | %                                                 |  |
| Cat. I             | (< 50 PE)                           |  | 3                                                 |  |
| Cat. II            | (51–200 PE)                         |  | 127                                               |  |
| Cat. III           | (201–500 PE)                        |  | 312                                               |  |
| Cat. IV            | (501–2,000 PE)                      |  | 674                                               |  |
| Cat. V             | (2,001–10,000 PE)                   |  | 575                                               |  |
| Cat. VI            | (10,001–100,000 PE)                 |  | 343                                               |  |
| Cat. VII           | (> 100,000 PE)                      |  | 114                                               |  |

Table 5: General overview – total values of the GWF at inflows and outflows during the reported period; parameters that predominantly determine the GWF at inflows and outflows; and the percentage of GWF reduction at particular WWTPs size categories

| WWTP size category | GWF at the WWTPs inflows       | Parameter predominantly causing the GWF at inflows | GWF at the WWTPs outflows      | Parameter predominantly causing the GWF at outflows | GWF reduction by WWTPs | Change of indicator causing the GWF at inflows vs. outflows* |
|--------------------|--------------------------------|----------------------------------------------------|--------------------------------|-----------------------------------------------------|------------------------|--------------------------------------------------------------|
|                    | 10 <sup>6</sup> m <sup>3</sup> |                                                    | 10 <sup>6</sup> m <sup>3</sup> |                                                     |                        | % of cases                                                   |
| Cat. I             | 1.3                            | N-NH <sub>4</sub> <sup>+</sup>                     | 0.3                            | N-NH <sub>4</sub> <sup>+</sup>                      | 74%                    | 0                                                            |
| Cat. II            | 198                            | N-NH <sub>4</sub> <sup>+</sup>                     | 41                             | N-NH <sub>4</sub> <sup>+</sup>                      | 79%                    | 39                                                           |
| Cat. III           | 1,361                          | N-NH <sub>4</sub> <sup>+</sup>                     | 306                            | N-NH <sub>4</sub> <sup>+</sup>                      | 78%                    | 41                                                           |
| Cat. IV            | 8,269                          | N-NH <sub>4</sub> <sup>+</sup>                     | 1,389                          | N-NH <sub>4</sub> <sup>+</sup> / P <sub>tot</sub>   | 83%                    | 57                                                           |
| Cat. V             | 22,132                         | N-NH <sub>4</sub> <sup>+</sup>                     | 2,637                          | P <sub>tot</sub>                                    | 88%                    | 73                                                           |
| Cat. VI            | 79,311                         | N-NH <sub>4</sub> <sup>+</sup>                     | 8,272                          | P <sub>tot</sub>                                    | 90%                    | 61                                                           |
| Cat. VII           | 194,021                        | N-NH <sub>4</sub> <sup>+</sup>                     | 12,389                         | P <sub>tot</sub>                                    | 94%                    | 87                                                           |

\* The percentage of cases when the GWF of inflow is caused by a different parameter than the GWF of outflow.

Conversely, phosphorus load discharged from the point sources of pollution prevails the diffuse pollution sources. High calculated GWF values of ammonium nitrogen and total phosphorus are inter alia caused due to these parameters having the lowest determined water assimilation capacity; the difference between the maximum concentration in the receiving water body and the determined natural (background) concentration is only 0.1 mg/L for P<sub>tot</sub>, and 0.2 mg/L for N-NH<sub>4</sub><sup>+</sup>.

## 4 Conclusions

The implementation of European Directive 91/271/EEC has significantly reduced discharges from point sources of pollution. In this work, we focused on the evaluation of a 15-year period of intensive construction of new and intensification and modernization of existing wastewater treatment plants, in terms of reducing pollution of basic chemical parameters. The Greywater footprint methodology was used for the evaluation. The GWF expresses the hypothetical amount of water needed to dilute the pollution to the level of immission limits. In the period from 2004 to 2018, the number of WWTPs in the Czech part of the Odra river basin increased by 38% (from 164 to 227 facilities). The GWF of centrally treated wastewater increased by 33%. Despite this fact, the total GWF of discharged pollution decreased by 32% - thanks to the modernizations and intensifications. By treating wastewater at the WWTPs, the GWF of pollution is reduced by 91.4%. The efficiency of the smallest WWTP size categories in GWF reduction is 74%. As the wastewater treatment plant's capacity increases increases also the percentage of GWF reduction. At the largest WWTPs is the GWF reduction of 94%. The GWF of pollution at inflows to the WWTPs is in 75% caused by ammonium nitrogen and in 21% by BOD<sub>5</sub>. The GWF of pollution at the effluents from the WWTPs is most often caused by total phosphorus (48% of cases; it occurs mainly at effluents from larger and large WWTPs) and ammonium nitrogen (42% of cases; it occurs mainly at effluents from small WWTPs). In 5% of cases, the GWF of discharged pollution is caused by BOD<sub>5</sub>. When evaluating the GWF, special attention must be paid to the concentration limits, as these strongly affect the final GWF value. The pollution evaluation via the GWF methodology can offer a suitable complement to the traditional quantification of absolute values of the amount of pollution.

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## Conflict of interest statement

Ethical issues - including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy, etc have been completely observed by the authors.

## Author Contributions

Stejskalová L. (M.Sc) conducted conceptualization, methodology, investigation, and wrote an original draft. Ansorge L. (Ph.D.) conducted methodology, investigation, and reviewed & edited the writing. Kučera J. (Eng.) conducted validation and reviewed & edited the writing.

## Nomenclature

|                                |                                   |
|--------------------------------|-----------------------------------|
| BOD <sub>5</sub>               | Biochemical oxygen demand         |
| Cat.                           | Category                          |
| C <sub>max</sub>               | Maximum permissible concentration |
| C <sub>nat</sub>               | Natural concentration             |
| COD                            | Chemical oxygen demand            |
| CZ                             | Czech Republic                    |
| DIS                            | Dissolved inorganic solids        |
| GWF                            | Grey water footprint              |
| N <sub>inorg</sub>             | Inorganic nitrogen                |
| N-NH <sub>4</sub> <sup>+</sup> | Ammonium nitrogen                 |
| PE                             | Personal equivalent               |
| P <sub>tot</sub>               | Total phosphorus                  |
| SS                             | Suspended solids                  |
| TDS                            | Total Dissolved Solids            |
| WFA                            | Water Footprint Assessment        |
| WWTP(s)                        | Wastewater treatment plant(s)     |

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