LETTER

Effect of WWTP size on grey water footprint—Czech Republic case study

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Abstract
The number of wastewater treatment plants (WWTPs) in the Czech Republic is increasing. Wastewater, which was previously disposed of in other ways (e.g. septic tanks, cesspits etc), is now entering the surface water (after treatment at a WWTP). Billions of Czech crowns have been invested in the construction of new WWTPs or reconstruction and intensification of existing ones. This money had been invested to meet discharge standards for individual pollutants. However, the overall level of pollution associated with wastewater discharges has not been assessed. The indicator of grey water footprint was used to assess whether there was an increase in pollution load discharged from WWTPs between 2002 and 2018. Discharged pollution data from 4115 industrial and municipal WWTPs were analysed. The analysis of such a large data set has not been carried out yet and brings new knowledge concerning the effect of WWTP size on the grey water footprint. Overall, the total value of the grey water footprint (and thus of the discharged pollution level) decreased in the monitored period. Grey water footprint caused by the largest WWTPs decreased, while the grey water footprint of small WWTPs increased, due to the increase in their number. The decisive pollutants that determine the value of the grey water footprint are total phosphorus and ammonium nitrogen. Measures targeting these two main pollutants can significantly reduce the overall level of pollution load discharged from WWTPs.

1. Introduction

Water pollution caused by wastewater discharges is one of problems associated with the development of society and with the actual way of life (Bouwer 2000, van den Brandeler et al 2019). Well established water management is essential to ensure sustainable development, including social and economic development, poverty reduction, and sustainable use of natural resources (Ait-Kadi 2016, Ikhlayel and Nguyen 2017).

In 2015, the United Nations presented 17 Sustainable Development Goals (SDGs) with 163 targets covering a broad range of sustainable development issues. These included the end of poverty and hunger, improving health and education, making cities more sustainable, combating climate change, and protecting oceans and forests; all with a timeline till 2030 (Biermann et al 2017).

When implementing individual measures to achieve particular SDG objectives, the broader context and impacts of sub-solutions on all SDGs objectives have to be considered (Zhang et al 2016). Therefore, (Vörösmarty et al 2000) proposed an integrated approach gathering experts in water management, climate change, and socio-economic challenges. The target of SDG 6.3 is focused on water quality improvement by reducing pollution, eliminating dumping, minimizing the release of hazardous chemicals and materials, reducing untreated wastewater discharges, increasing water recycling, and safe wastewater reuse.

Reaching SDG target 6.3 poses an extremely high sanitary and hygiene challenge (Mara and Evans...
Individual countries must choose appropriate and, above all, feasible measures to ensure maximum benefit both in the national context and in the context of bilateral or multilateral agreements on international river basins (Hering 2017).

In order to protect the environment, the Czech Republic invested EUR 10 billion in wastewater management between 1990 and 2018 CzSO (2019). These investments were used for the construction of new wastewater treatment plants (WWTPs), as well as for increasing the efficiency of existing WWTPs, which had a positive effect on the amount of wastewater discharged (Kubová and Hájek 2017).

The number of inhabitants connected to public sewerage systems increased from 7.50 million (72.4% of inhabitants) in 1989 to 9.09 million (85.5% of inhabitants) in 2018, and the number of municipal WWTPs increased from 860 in 1997 to 2677 in 2018 (MoA and MoE 1997–2019). This reflects an increase in the amount of pollution produced by the WWTPs in most indicators (figure 1).

One of the tools suitable for evaluating water use in context with human activity is the water footprint introduced in 2002 Hoekstra (2003). The water footprint is a multidimensional indicator that measures both water consumption and pollution (Hoekstra et al 2017); therefore it is a suitable tool for assessing sustainability in accordance with SDGs (Vanham et al 2018, 2019). This is reflected in the increasing number of water footprint studies globally (Zhang et al 2015), in the Czech Republic (Ansorge et al 2019b) and in the other countries (Zhu et al 2019), including the grey water footprint (GWF) studies of sewage systems and WWTPs (table 1).

According to the methodology (Hoekstra et al 2011), the GWF neglects the possible interactions between different pollutants and includes only one pollutant with the highest contribution. While this study uses the original methodology, there are emerging approaches that extend the standard GWF methodology for the ability to assess the cumulative effects of various pollutants (Yu et al 2020).

In addition to the GWF, other tools are able to assess pollution discharged into water. In principle, a similar tool is the Waste Absorption Footprint (Jiao et al 2013, 2015) which was applied at the level of a river basin in Romania (Gavrilescu et al 2020). The assessment based on a simple expression of the water amount was criticized in that without an interpretation focusing on the impacts associated with water use (Berger and Finkbeiner 2013, Yano et al 2015) it may be misleading in the decision-making process (Gawel and Bernsen 2011, 2013, Wichelns 2015). This complaint is based on the fact that using the same amount of water resources will have different consequences at different places and different times—due to the uneven distribution of freshwater resources (Wichelns 2017).

The water footprint based on Life Cycle Assessment principles (ISO 2014) is also used to assess the impacts associated with wastewater discharges (Jeswani and Azapagic 2011, Larsen 2018).

This study analyzes the discharged pollution from more than 4000 WWTPs in the Czech Republic, based on use the GWF indicator. WWTPs were categorised to the seven size categories. Using the results of this analysis, it defines recommendations for integrated water resources management.

2. Materials and methods

2.1. Grey water footprint

The water footprint consists of three components. The Blue Water Footprint represents the amount of water withdrawn (and consumed) from water sources. The Green Water Footprint represents water consumed (but not taken from water sources); it is water in soil or rainfall, which plants can use for their growth, etc. The Grey Water Footprint is defined as the volume of freshwater required to assimilate the load...
Table 1. List of GWF studies concerning WWTPs.

| Location                  | Focus of study                                                                 | Reference                      |
|---------------------------|-------------------------------------------------------------------------------|--------------------------------|
| 22 WWTPs, Romania         | GWF assessment of WWTPs based on the effluent concentration of important pollution indicators (BOD, COD, ammonia, phenols and detergents) measured monthly at 22 wastewater treatment facilities during 2006–2007 period in the Prut–Bărlad catchment | Ene and Teodosiu (2011)        |
| Beijing, China            | The water footprint and economic direct and indirect water cost of wastewater treatment were combined to the so-called ‘hybrid method’ | Shao and Chen (2013)           |
| La Garriga, Spain         | GWF was calculated for three scenarios of wastewater treatment: (i) without treatment (direct discharge of untreated wastewater into the river); (ii) secondary treatment (removal of organic matter and nitrogen); (iii) tertiary treatment (wastewater treatment with chemical phosphorus removal) | Morera et al (2016)            |
| Segura River Basin, Spain | GWF was used on the river basin scale. Anthropised water cycles were used for the GWF calculation of WWTPs | Pellicer-Martínez and Martínez-Paz (2016) |
| Beijing, China            | Input-Output methodology was used for GWF determination                        | Li et al (2016)                |
| Iasi, Romania             | The study compares Life cycle assessment, environmental impact quantification and water footprint assessment | Teodosiu et al (2016)          |
| 9 WWTPs, China            | The role of WWTPs in reducing the impact of human activity on water resources and derived the ‘grey water footprint reduction’ indicator. | Gu et al (2016)                |
| 2 WWTPs, Spain            | The reduction of the GWF at wastewater treatment plants and derived the ‘Operational grey water footprint’ indicator. | Gómez-Llanos et al (2018)      |
| 12 WWTPs, Spain           | The effect of WWTPs on reducing the GWF of four widespread drugs (carbamazepine, diclofenac, ketoprofen, and naproxen) | Martínez-Alcalá et al (2018)   |
| 4 WWTPs, Canada           | GWF of wastewater from the wine industry treated at a municipal WWTP            | Johnson and Mehrvar (2019)     |
| 31 provinces, China       | GWF of agriculture, industry and households for the period 1998–2012           | Qin et al (2019)               |
| Falmouth, Massachusetts USA | GWF of 5 different wastewater treatment systems                                   | Romeiko (2019)                |
| Hostivice, Czech Republic | The impact of a WWTP on a small river basin, together with a sustainability assessment and the introduction of an uncertainty coefficient | Stejskalová et al (2019)       |
| 14 WWTPs, Czech Republic  | GWF and sustainability assessment in a river basin district                      | Ansorge et al (2019a)         |
| Czech Republic            | Comparison of GWP from domestic, industrial and agricultural WWTPs              | Ansorge et al (2020)          |
of pollutants to the level of existing ambient water quality standards (Hoekstra et al 2011).

The calculation of the GWF of a system 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)).

\[
GWF_{j,i} = \frac{L_{j,i}}{C_{\text{max},j,i} - C_{\text{nat},j,i}}
\]

\[
GWF_j = \max \{ GWF_{j,1}, GWF_{j,2}, \ldots, GWF_{j,j} \}
\]

\[
GWF = \sum_{j=1}^{n} GWF_j
\]

where:
- \( GWF_{j,i} \) = grey water footprint of the pollutant \( i \) released into water at the point \( j \) (volume/time)
- \( GWF \) = grey water footprint of pollutant at the point \( j \) (volume/time)
- \( GWF \) = grey water footprint of the subject (volume/time)
- \( L_{j,i} \) = quantity of the \( i \) being emitted into water at the point \( j \) (weight/time)
- \( C_{\text{max},j,i} \) = maximum permissible concentration of the substance \( i \) in receiving water at the point \( j \) (weight/volume)
- \( C_{\text{nat},j,i} \) = natural concentration of the substance \( i \) in receiving water at the point \( j \) (weight/volume)
- \( n \) = number of discharge points (—)

2.2. Data on discharged pollution

In the Czech Republic, every subject discharging wastewater which exceeds set limits is obliged to provide information on discharged pollution pursuant to Decree No. 431/2001 Coll. The following indicators are reported:

| Indicator                        | Unit          |
|----------------------------------|---------------|
| Biochemical oxygen demand        | (BOD)         |
| Chemical oxygen demand           | (COD)         |
| Suspended solids                 | (SS)          |
| Dissolved inorganic solids       | (DIS)         |
| Ammonium nitrogen                | (N–NH₄⁺)      |
| Total inorganic nitrogen         | (TIN)         |
| Total phosphorus                 | (TP)          |

In addition, the amount of wastewater discharged should be recorded. Thus, it is possible to calculate the amount of discharged pollution \( L_{i,j} \) according to equation (4).

\[
L_{i,j} = RM_j \times c_{\text{out},i,j}
\]

where:
- \( L_{i,j} \) = amount of pollutant \( i \) emitted into water at the point \( j \) (weight/time)
- \( RM_j \) = amount of wastewater discharged at point \( j \) (volume/time)
- \( c_{\text{out},i,j} \) = concentration of the substance \( i \) discharged at point \( j \) (weight/volume)

From the data recorded, records for the period from 2002 to 2018 with data on existence of a WWTP were selected. Due to the fact that this item is not always reliably filled in, an additional condition testing the existence of an abbreviation ‘WWTP’ contained in the name of the discharge point was used for the selection. The result of the selection was 43 942 records concerning 4115 WWTPs. During the reporting period, the number of WWTPs increased from 1524 WWTPs in 2002 to 3213 WWTPs in 2018. Only the smallest (less 2000 m³ year⁻¹) and the largest WWTP size categories (more 400 000 m³ year⁻¹) have not increased in their numbers importantly (figure 2). In the category treating less than 2000 m³ year⁻¹ it is due to this category is not fully included in the dataset used for analysis.

Selected records represent both municipal WWTPs and about 300 industrial WWTPs. Based on the amount of wastewater discharged, the WWTPs were classified into seven size categories table (2). In the Czech Republic, the Population equivalent (PE) = 60 g BOD₅ per day or PE = 150 l per day of wastewater production. We combined these two indicators.

2.3. Concentration limits used for the calculation

The GWF value is strongly influenced by concentration limits (Liu et al 2017, Miglietta et al 2017b); specifically by the difference of \( c_{\text{max}} - c_{\text{nat}} \) which is named as the assimilation capacity (AC) of the flow (Jamshidi 2019). As for the maximum concentration, values set by Czech Technical Standard CSN 75 7221 Water quality—Classification of surface water quality offering the water quality classification, Class II were used. As for the natural concentration, values set by Czech Technical Standard CSN 75 7221 Water quality, Class I were used. There are no values in the literature set for the AC of the flow concerning the parameter of dissolved inorganic solids (DIS). Therefore, the AC value was derived based on the assumption that DIS are a subset of total dissolved solids (TDS). The AC value AC for DIS was determined on the level of ¾ AC of TDS according to CSN 75 7221 (Ansorge et al 2019a). The values used for the GWF calculation are presented in table 3.

3. Results

The GWF of pollution discharged from the Czech WWTPs over the past decade ranged from
Figure 2. The progression in the number of WWTPs in the Czech Republic, shown according to the size categories reflecting the amount of wastewater discharged.

Table 2. WWTPs size categories.

| Cat. | Treated volume          | Aprox. PE |
|------|-------------------------|-----------|
| I    | <2000 m³·year⁻¹         | cca 50    |
| II   | 2000–8000 m³·year⁻¹     | cca 50–200|
| III  | 8000–20 000 m³·year⁻¹   | cca 200–500|
| IV   | 20 000–80 000 m³·year⁻¹ | cca 500–2000|
| V    | 80 000–400 000 m³·year⁻¹| cca 2000–10 00000|
| VI   | 400 000–4000 000 m³·year⁻¹| cca 10 000–100 00000|
| VII  | >4000 000 m³·year⁻¹     | cca > 100 00000|

Table 3. Values used for the calculation (in mg l⁻¹).

|       | BOD | COD | SS | DIS | N–NH₄⁺ | TIN | TP |
|-------|-----|-----|----|-----|--------|-----|----|
| $c_{\text{nat}}$ | 2   | 15  | 15 | 0.2 | 2.75   | 0.05|    |
| $c_{\text{max}}$ | 4   | 25  | 25 | 0.4 | 5.55   | 0.15|    |
| AC    | 2   | 10  | 10 | 150 | 0.2    | 2.8 | 0.1|

16–20 × 10⁹ m³ yr⁻¹, while at the beginning of the reporting period it exceeded 25 × 10⁹ m³ yr⁻¹ (2003 and 2004) and even 35 × 10⁹ m³ yr⁻¹ (in years 2002 and 2005). Stable GWF values during the last 10 years have been achieved despite the gradual increase in the WWTP number. This apparent mismatch is caused by the fact that large sources of pollution (agglomerations under Council Directive 91/271/EEC concerning urban waste-water treatment) were resolved in the Czech Republic during the transition period after joining the EU (ending in 2010) and operation of these WWTPs is now gradually being intensified. Also the volume of discharged wastewater has decreased during this period (figure 5).

The increase in the number of WWTPs is taking place mainly in small municipalities, which contribute very little to the total value of GWF. The small WWTPs with annual discharge up to 80 000 m³ make 50%–70% share of the total number of all WWTPs in the Czech Republic (on average 63% for the whole reporting period); however, their contribution on the total value of the GWF is less than 15% (less than 10% till 2011; 9%–15% in years 2012–2018—see figure 3). Details about the size categories are given in the annex (available online at stacks.iop.org/ERL/15/104020/mmedia). Small WWTPs in the size categories up to 80 000 m³·year⁻¹ (2005 (figure 4) is created by three WWTPs—very probably it is due to errors in data when the values of DIS were recorded as ammonium nitrogen ($N–NH_4^+$). Figure A10 in the annex shows GWF of pollution discharged from WWTPs (sorted by the WWTP size categories) with manually corrected data for these three WWTPs. Figure A11 in the annex shows the dependence of grey water footprint value on the size of WWTPs. As expected, larger WWTPs have higher GWF. Figure 6 shows the GWF values normalised by the outflow from WWTP.
The study has shown that the GWF is mainly determined by parameters of total phosphorus (TP) and ammonium nitrogen (N–NH$_4^+$); see figure 4. These two indicators accounted for 93% of the GWF value for the reporting period; specifically 89%–98% in individual years (figure A12 in the annex). In terms of the number of cases, these indicators determined the GWF at 80% of WWTPs for the reported period; specifically 76%–82% in individual years (figure 6 and table A3 in the annex).

The GWF of discharged ammonium nitrogen (N–NH$_4^+$) is dominant, which prevailed throughout the monitored period. In the first half of the monitored period, it represented 64%–82% of the GWF value, in the second half it decreased to represent 56–64%.

In the first half of the monitored period, both parameters (N–NH$_4^+$ and TP) participated in the GWF in the same number of WWTPs, while in the second part of the monitored period, the parameter of TP prevailed, which corresponds to an increase in the proportion of TP in the total value of GWF. This fact can be mainly explained by the construction of new WWTPs in small municipalities.
Figure 5. Comparison of GWF value with total outflow from WWTPs during 2002–2018.

Figure 6. The parameter determining the GWF (by number of WWTPs). BOD—biochemical oxygen demand; COD—chemical oxygen demand; SS—suspended solids; DIS—dissolved inorganic solids; N–NH₄—ammonium nitrogen; TIN—total inorganic nitrogen; TP—total phosphorus.

Figure 7. GWF values normalized by outflow.
that have not prescribed increased phosphorus removal.

Ammonium nitrogen discharged from a WWTP is not stable in water and is rapidly nitrified—oxidized to nitrites and nitrates (Pitter 1999). Despite the proven local changes in microbial processes and biogeochemistry of rivers (Parker et al 2012), the emission standard is set in the Czech Republic (Government Regulation No. 401/2015) only for small municipal WWTPs (for the size category from 500 to 10 000 Population Equivalent—PE), namely at quite high levels (on average 20, resp. 15 mg l\(^{-1}\)). When calculating the GWF, excluding the parameter of N–NH\(_4^+\), the value decreases by an average of 45%, specifically 34%–65% in each year (figure 8).

4. Discussion

Empirical evidence shows that economic and population growth has had a major impact on the increase in water use over the past 100 years (Duarte et al 2014). The relationship between environmental investments and the state of the environment is a complex matter (John and Pecchenino 1994). Due to extensive investments in the Czech Republic after the Velvet Revolution in 1989 and joining the European Union in 2004, the majority of the population have been connected to sewer systems equipped/terminated by WWTPs. Despite this fact, there has been a decrease in discharged pollution, expressed via the GWF, which corresponds to the course of the empirically derived Environmental Kuznets Curve (EKC) for developed countries. The EKC is a hypothesized relationship between environmental quality and economic development. It assumes that the development of human society is followed by an increase in pollution (developing countries); however, from a certain level of development, human society begins to invest heavily in environmental protection and further economic growth is accompanied by a decrease in pollution (Paudel et al 2005, Duarte et al 2013). The validity of the EKC has also been tested on the GWF indicator (Sebri 2016, Miglietta et al 2017a), especially for total water consumption. To confirm the validity of the EKC in the Czech Republic, it would be necessary to analyze a longer data series concerning the discharged pollution.

The GWF values can be compared with values of total runoff from the Czech Republic (MoA and MoE 1997–2019). The ratio between the GWF value and the total runoff is used for environmental sustainability assessment and is referred to as water pollution level (WPL) (Hoekstra et al 2011). With the exception of the years 2010 and 2013, the GWF value exceeded the value of the total annual runoff from the Czech Republic in all years. When excluding the N–NH\(_4^+\) parameter (ammonium nitrogen rapidly nitrifies in watercourses), the GWF value exceeds the value of the total annual runoff from the Czech Republic only in the years of 2003, 2004, 2014, 2015, and 2018 (figure 7). In these years, there were gaps in precipitation or higher average temperature (or both), and therefore outflow from the territory of the Czech Republic was lower in comparison to the long-term average. Also in years of 2016 and 2017, there were hydrological draught in the Czech Republic. In these two years, the WPL is just below 100%.

It is important to note that this study counts the GWF of pollution discharged from WWTPs and not the GWF of all sources of pollution and human activities in the Czech Republic. Since diffuse pollution, typically from agriculture, is not included, the sustainability assessment is not representative. Foreign studies show that the impact of
diffuse pollution, especially from agriculture, cannot be neglected in the environmental sustainability assessment. For example, a study concerning the GWF of Chinese provinces found that agriculture contributes 3%–23% to the total GWF (Zhang et al 2019). Another Chinese study on organic pollution (expressed in BOD) indicated that agriculture’s share on the GWF is even higher (Qin et al 2019). Similarly, a global study on phosphorus has shown a significant impact of agriculture on the total value of GWF (Mekonnen and Hoekstra 2018).

Another reason why environmental sustainability has not been assessed is the neglect of actual conditions at discharge points as well as neglect of self-cleaning processes in the watercourse. Any assessment aimed at the WPL should compare comparable data. While data on discharged pollution represent values at discharge points, data on runoffs are distributed along the border of the Czech Republic; these are therefore incomparable values. Data on the GWF need to be compared with data from points of discharge (Stejskalová et al 2019, Ansorge et al 2019a). Otherwise it would be necessary to reduce the GWF by self-cleaning values between the point of discharge and the closure profile, for these runoff data are available. In the Czech Republic, self-cleaning ability plays an important role in reducing the pollution level of watercourses (Hubačíková et al 2014); small water reservoirs built mainly on smaller watercourses also have a positive effect (Rozkošný et al 2016).

The pollutant most affecting a GWF value at Czech WWTPs is N–NH$_4^+$+. It is mainly due to the very low AC of the flows (table 3). The analysis of individual WWTPs size categories has shown, this pollutant is a problem at the largest WWTPs in particular, and a solution based on biochemical processes of ammonification would require considerable investment into the intensification of existing WWTP technologies (Novák and Beneč 2017). The ammonium nitrogen emission limits (20 mg l$^{-1}$ for WWTPs up to 2000 PE; 15 mg l$^{-1}$ for WWTPs of capacity for 2001–10 000 PE) are rather high in relation to emission limits, i.e. the concentration required in the watercourse. Higher emission limits might have been set to guarantee regular operation of WWTPs. In the Government Regulation No. 401/2015, Annex 7, the emission concentrations for the Best Available Technologies (BAT) in wastewater treatment are listed. For the parameter of N–NH$_4^+$+ it is 12 mg l$^{-1}$ (WWTPs for 500–2000 PE); resp. 8 mg l$^{-1}$ (WWTPs for 2001–10 000 PE). Even these values are rather high; however, they require the WWTP to be equipped with a sufficiently voluminous nitrification. If the WWTP is equipped with a sufficiently voluminous nitrification, it usually reaches significantly lower values of ammonium nitrogen outflow concentrations.

Many other methods for effective N–NH$_4^+$+ removal from wastewater have been developed worldwide—processes based on biological, physical and chemical treatment, including their combinations (Gupta et al 2015, Huang et al 2018).

The second most important pollutant that affects the GWF value is total phosphorus; also due to the very low AC of the flows (table 2). This pollutant contributes significantly to the GWF value in all WWTP size categories. If the N–NH$_4^+$+ parameter is neglected, total phosphorus becomes a dominant pollutant in the GWF determination (table A11 and figures A8, A9 in the annex). Technically, very low phosphorus concentrations can be achieved in WWTP effluents (Pratt et al 2012). Subsequently, the phosphorus trapped in the sludge can be used in various ways, either by direct application of the sludge as fertilizer or as a raw material for phosphorus recycling. In the case of the most common simultaneous chemical precipitation, phosphorus trapped in the sludge is stored in a form that is difficult for plants to use. Phosphorus recycling is considered to be more environmentally friendly than direct application to fields (Ciešlík and Konieczka 2017).

As described, the AC of ammonium nitrogen and total phosphorus are very low (table 3). The N–NH$_4^+$+ parameter is not used in GWF studies often. (Ene and Teodosiu 2011) used $\epsilon_{\text{max}} = 2$ mg l$^{-1}$ and $\epsilon_{\text{nat}} = 0.4$ mg l$^{-1}$; therefore AC = 1.6 mg l$^{-1}$. It means the 8 times higher value for the AC than we used, and still found the parameter of N–NH$_4^+$+ the most problematic. In later work, Teodosiu et al (2016) use $\epsilon_{\text{max}} = 0.8$ mg l$^{-1}$. Franke et al (2013) described $\epsilon_{\text{nat}} = 0.015$ but did not describe maximum allowable concentration $\epsilon_{\text{max}}$. Previous version of CSN 75 7221 used $\epsilon_{\text{max}} = 0.7$ mg l$^{-1}$ and $\epsilon_{\text{nat}} = 0.3$ mg l$^{-1}$ (Mičanik et al 2017). The parameter TP is used more often. (Liu et al 2017) describe different studies using the AC in interval from 0.07 to 0.43 mg l$^{-1}$, the most studies used value close to AC = 0.1 mg l$^{-1}$. In the sensitivity analysis, there were expected two times higher values of AC. As can be expected, the higher AC has a significant effect on the decrease of GWF values. In the case of N–NH$_4^+$+, the reduction of total GWF is between 26% and 39%. Two times higher AC for N–NH$_4^+$+ represents value before novelisation of CSN 75 7221 in 2017. In the case of TP (when the AC for N–NH$_4^+$+ is not changed), the effect is smaller due to the dominance of N–NH$_4^+$+ on the GWF values. In that case, the reduction varies between 6% and 16%. In case, the AC would be two times higher for both pollutants, the total GWF will be reduced by 42%–49%.

The main advantage of the GWF is transformation of the pollution volume to the water volume. Through the GWF, different pollutants from different sources can be easily compared with available water for dilution, followed by decision on the sustainability of pollution discharged. The GWF seems to be a useful tool for policymakers, water managers and water authorities. However, it is important to know that the GWF covers only chemical status and does not cover
ecological issues directly. Even so, it is appropriate to include GWF among water policy instruments at all policy decision levels about water quality issues.

5. Conclusion

The study confirmed the positive effect of funds invested in the Czech Republic for wastewater treatment. During the 17-year reporting period, the number of WWTPs increased, while the grey water footprint of discharged pollution decreased. Increasing the efficiency of WWTPs is the main cause of the GWF reduction—thereby progressing towards the fulfilment of target 6.3 of SDGs (United Nations).

To continue this positive trend, measures should be considered which target the main pollutants that determine the GWF value the most—phosphorus and ammonium nitrogen. Although these two parameters do not reach the maximum permissible values in wastewater discharge, they achieve the highest GWF values due to the low AC of the watercourse.

Usually the ammonium nitrogen discharge limits are not set in the wastewater discharge permits for large WWTPs. Setting these limits, consequently optimizing treatment processes to encourage the N–NH$_4^+$ removal, would significantly contribute to the reduction of the GWF values. Especially in the case of the largest WWTPs (outflow >400000 m$^3$ yr$^{-1}$; >100 000 PE) such a measure would significantly reduce the GWF value of the point pollution sources.

In the case of the total phosphorus load, attention should be paid to the solution applied for all size WWTP categories. WWTPs for more than 2000 PE already have a statutory obligation for phosphorus removal. Nevertheless, these WWTP size categories account for a major part of the total GWF caused by total phosphorus. To impose an obligation for phosphorus removal on small WWTP size categories would only have a small effect on the total GWF value reduction. The main focus should be on further intensifying phosphorus removal from wastewater. The optimal solution is in the introduction of such technologies that enable the use of the phosphorus as a fertilizer in agriculture and other industries, i.e. implementation of the circular economy principles.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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