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ROLE OF WASTEWATER TREATMENT PLANTS IN POLLUTION REDUCTION – EVALUATED BY GREY WATER FOOTPRINT INDICATOR

Key words: grey water footprint, Odra river basin, pollution, wastewater treatment plant, water footprint assessment

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 where evaluated whether the existing rules have reached their objectives and whether they still serve their purpose (Pistocchi et al., 2019). 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 grey water footprint (GWF) methodology was used. The water footprint assessment (WFA) was introduced in 2002 (Hoekstra & Hung, 2003) and methodology was standardized by the Water Footprint Network (WFN) (Hoekstra, Chapagain, Aldaya & Mekonnen, 2012). The grey water footprint is defined as the volume of freshwater required to assimilate the load

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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 and Chen (2013), Gu et al. (2016), Morera, Corominas, Poch, Aldaya and Comas (2016), Gómez-Llanos, Duran-Barroso and Matías-Sánchez (2018), Ansorge, Stejskalová, Dlabal and Kučera (2019), Johnson and Mehrvar (2019), Yapicioğlu (2019), Ansorge, Stejskalová, Dlabal and Čejka (2020), Gómez-Llanos, Matías-Sánchez and Durán-Barroso (2020), Stejskalová, Ansorge, Kučera and Vološinová (2021).

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 in municipalities and discharged from WWTPs over the period of 15 years (2004–2018) has been analyzed, from a point of view of basic chemical pollution parameters reduction.

This work is an extension of the publication (Ansorge et al., 2020) monitoring the impact of municipal wastewater treatment plants on the reduction of pollutants in the Czech part of the international Odra basin.

Methods

Grey water footprint (GWF)

Grey water footprint is a part of the water footprint introduced in 2002 (Hoekstra & Hung, 2003) and points to the level of pollution. It is defined as the volume of freshwater 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" (Hoekstra et al., 2012). 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* (Eq. 2). The *GWF* of a system under assessment is the sum of the GWFs of all pollutant emission points into the aquatic environment (Eq. 3).

$$GWF_{j,i} = \frac{L_{j,i}}{C_{\max,j,i} - \mathrm{C}_{\mathrm{nat},j,i}} \tag{1}$$

$$GWF_j = \max\{GWF_{j,1}, GWF_{j,2} \ldots, GWF_{j,i}\} \tag{2}$$

$$GWF = \sum_{j=1}^{n} GWF_j \tag{3}$$

where:

$GWF_{j,i}$ – GWF of the pollutant *i* released into water at the point *j* [volume unit per time unit],

GWF_j – GWF of pollutant at the point *j* [volume unit per time unit],

GWF – GWF of the subject [volume unit per time unit],

$L_{j,i}$ – quantity of the pollutant *i* being emitted into water at the point *j* [weight unit per time unit],

$C_{\max,j,i}$ – maximum permissible concentration of the substance *i* in receiving water at the point *j* [weight unit per volume unit],

$C_{\mathrm{nat},j,i}$ – natural concentration of the substance *i* in receiving water at the point *j* [weight unit per volume unit],

n – number of discharge points.

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 (Fig. 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 the area of 7,217 km^2.

Data sources

For the purpose of this study, data on all WWTPs listed in the Water balance database (ces. *vodní balance*) were analyzed. The principles of operation and data collection of the Water balance are regulated by the Decree of the Ministry of Agriculture 431/2001 (Vyhláška Ministerstva zemědělství 431/2001 Sb.). It is a national register of withdrawals and discharges. It orders all subjects discharging wastewater into surface or groundwater in quantities exceeding annually 6,000 m^3 or monthly 500 m^3 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 seven size categories, which reflect the most common size division of wastewater treatment plants according to EU and Czech regulations and standards (the annual amount of treated wastewater is given in brackets):

– Category I for less than 50 PE (< 2,000 m^3),
- Category II for 51–200 PE (2,001––8,000 m^3),
- Category III for 201–500 PE (8,001––20,000 m^3),
- Category IV for 501–2,000 PE (20,001––80,000 m^3),
- Category V for 2,001–10,000 PE (80,001–400,000),

FIGURE 1. Odra river basin district in the middle-north Europe (the area of interest is highlighted by hatch pattern; coordinates 49°95′ N, 18°33′ E)

- Category VI for 10,001–100,000 PE (400,001–4,000,000 m^3),
- Category VII for more than 100,000 PE (> 4,000,000 m^3).

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 (Liu, Antonelli, Liu & Yang, 2017; Miglietta et al., 2017). Maximum acceptable concentrations (C_{max}) of a pollutant in a receiving watercourse are set by the Czech Technical Standard ČSN 75 7221 determining classification of surface water quality (Class II – Moderate polluted water) (Mičaník, Hanslík, Němejcová & Baudišová, 2017). Surface water quality according to Class II is described as being affected by human activities, but water quality indicators still reach values that allow for the existence of a rich, balanced and sustainable ecosystem. Natural concentration values (C_{nat}) are given by the same standard (Class I – Unpolluted water). 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 (Jamshidi, 2019). A list of monitored parameters with their natural and maximum concentration values is given in Table 1.

TABLE 1. Monitored parameters with their natural and maximum concentration values

Parameter	Symbol	Unit	C_{nat}	C_{max}	Assimilation capacity ($C_{max} - C_{nat}$)
Biochemical oxygen demand	BOD_5	$mg \cdot l^{-1}$	2	4	2
Chemical oxygen demand	COD	$mg \cdot l^{-1}$	15	25	10
Suspended solids	SS	$mg \cdot l^{-1}$	15	25	10
Dissolved inorganic solids*	DIS	$mg \cdot l^{-1}$	300	450	150
Inorganic nitrogen	N_{inorg}	$mg \cdot l^{-1}$	2.75	5.55	2.8
Total phosphorus	P_{tot}	$mg \cdot l^{-1}$	0.05	0.15	0.1
Ammonium nitrogen	$N\text{-}NH_4^+$	$mg \cdot l^{-1}$	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 l' assimilation capacity of TDS (Ansorge et al., 2019) according to the ČSN 75 7221 (Česká agentura pro standardizaci [ČAS], 1998).

Results and discussion

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 facilities) and the GWF of inflowing pollution to WWTPs increased in total by 33%. Progression in the amount of pollution supplied and treated at WWTPs as well as the increasing number of WWTPs in a given period are shown in Figure 2.

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

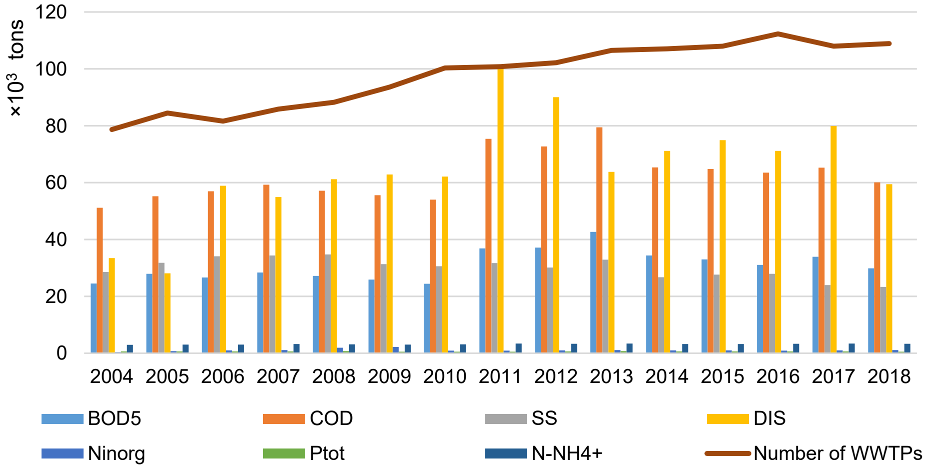

FIGURE 2. Development of the amount of pollution treated at the WWTPs in individual monitored parameters (Y-axis) and the increasing number of WWTPs (secondary Y-axis) in the monitored area (source: the Water balance database)

phosphorus stagnation). The initial increase and subsequent decrease of organic pollution (expressed in BOD_5 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.

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 15 years it was 93% (in 2018). The value of the GWF reduction has more or less stabilized over the last eight years especially in the size categories over 20,000 m^3 per year (Fig. 3).

While the total GWF at the WWTPs inflows was $3.06 \cdot 10^{11}$ m^3; the total GWF at the WWTPs effluents was $2.6 \cdot 10^{10}$ m^3, detailed in Table 2. Also the increasing efficiency of the GWF reduction at WWTPs is significant (Fig. 3).

While the GWF of incoming pollution is caused predominantly by ammonium nitrogen ($^3/_4$ 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.

Parameters causing the GWF

Comparison between inflows and outflows from a point of view which parameter causes pollution the most in 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 parameter than the GWFs at outflows

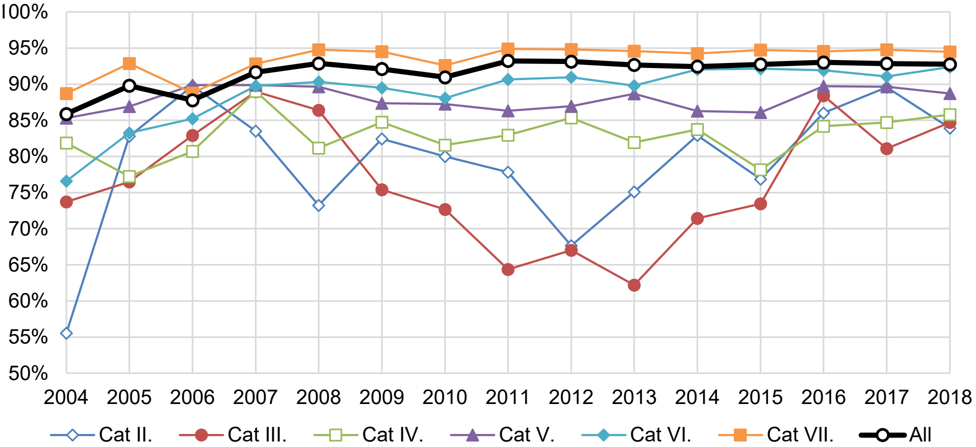

FIGURE 3. The GWF reduction at monitored WWTPs

TABLE 2. Comparison of the GWF at inflows and outflows from WWTPs

Year	GWF at the WWTP		GWF reduction by passing through the WWTP size category						
	inflows	outflows	all	Cat. II	Cat. III	Cat. IV	Cat. V	Cat. VI	Cat. VII
	$\times10^6$ m^3		%						
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
	total		AVG						
	305 918	25 655	91.4	79	78	83	88	90	94

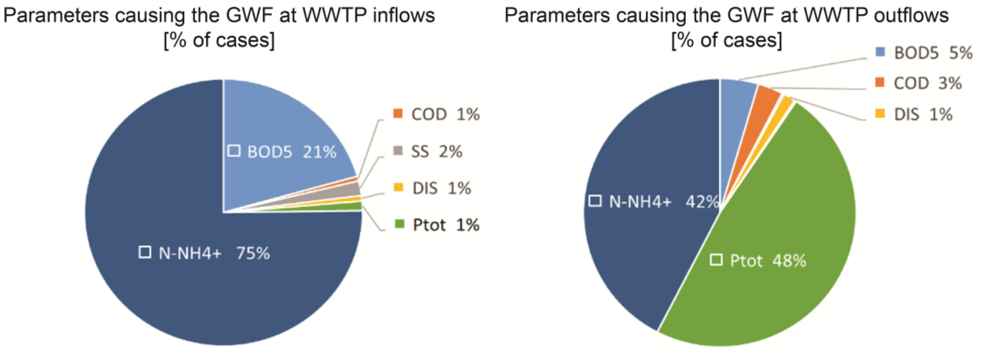

FIGURE 4. Proportional overview of pollutants which causes the GWF (comparison between inflows and outflows of WWTPs)

TABLE 3. Parameters causing the GWF at inflows and outflows, overviewed according to WWTP size categories

WWTP size category	BOD_5		COD		SS		DIS		N_{inorg}		P_{tot}		$N\text{-}NH_4^+$	
	inflow	outflow	inflow	outflow	inflow	outflow	inflow	outflow	inflow	outflow	inflow	outflow	inflow	outflow
	% of cases													
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 3). When considering the size categories, the overview is provided in Table 3.

Effect of a WWTP size category on the GWF

Wastewater treatment plants, which belong to the two largest size categories (> 10,000 PE and > 100,000 PE), account for 82% of the total GWF value of discharged pollution. The share of medium-sized WWTPs (2,001–10,000 PE) is 10% and the share of GWF pollution discharged from all WWTPs smaller than 2,000 PE is only 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 (Tables 3 and 5). 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.

TABLE 4. Contribution of particular WWTP size categories on the total GWF of discharged pollution

WWTP size category	Annual amount of treated wastewater	Number of records in the Water balance	Contribution to GWF of total discharged pollution [%]
Cat. I	< 50 PE	3	0
Cat. II	51–200 PE	127	0
Cat. III	201–500 PE	312	2
Cat. IV	501–2 000 PE	674	6
Cat. V	2 001–10 000 PE	575	10
Cat. VI	10 001–100 000 PE	343	38
Cat. VII	> 100 000 PE	114	44

In addition, small WWTPs are often not operated very professionally and emission standards for ammonium nitrogen are set up for WWTPs from the 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 of 2,000 PE and larger, the effluent GWF is most often determined by total phosphorus (Tables 3 and 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 NH_4^+, which predominates at lower pH, is relatively harmless to fish; however the undissociated NH_3 causes acute poisoning of fish at very low concentrations, $\leq 0.1 \text{ mg·l}^{-1}$). On the other hand, ammonium nitrogen is not stable in surface water and after discharge, it undergoes the 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 (Hrabánková, 2016, 2018). 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 have the

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 [$\times 10^6$ m^3]	Parameter predominantly causing the GWF at inflows	GWF at the WWTPs outflows [$\times 10^6$ m^3]	Parameter predominantly causing the GWF at outflows	GWF reduction by WWTPs [%]	Change of indicator causing the GWF at inflows vs. outflows* [% of cases]
Cat. I	1.3	$N\text{-}NH_4^+$	0.3	$N\text{-}NH_4^+$	74	0
Cat. II	198	$N\text{-}NH_4^+$	41	$N\text{-}NH_4^+$	79	39
Cat. III	1 361	$N\text{-}NH_4^+$	306	$N\text{-}NH_4^+$	78	41
Cat. IV	8 269	$N\text{-}NH_4^+$	1 389	$N\text{-}NH_4^+/P_{tot}$	83	57
Cat. V	22 132	$N\text{-}NH_4^+$	2 637	P_{tot}	88	73
Cat. VI	79 311	$N\text{-}NH_4^+$	8 272	P_{tot}	90	61
Cat. VII	194 021	$N\text{-}NH_4^+$	12 389	P_{tot}	94	87

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

lowest determined water assimilation capacity; the difference between the maximum concentration in the receiving water body and the determined natural (background) concentration are only 0.1 mg·l^{-1} for P_{tot}, and 0.2 mg·l^{-1} for $N\text{-}NH_4^+$.

Conclusions

The substantial contribution of this study is the long-term data interpretation using a tool of grey water footprint. The grey water footprint is defined as the volume of freshwater required to assimilate the load of pollutants.

The study deals with the grey water footprint of municipal pollution in the Odra river basin on the Czech Republic territory. Over the course of 15 years, the number of WWTPs increased in the analyzed area by 38%, i.e. from 164 to 227 facilities. The grey water footprint of pollution drained from municipalities by sewers to WWTPs increased by 33%, mainly due to the construction of new WWTPs.

The reconstructions and introduction of more efficient techniques and advanced technologies into the process of wastewater treatment have made the GWF reduction very significant. While in 2004 the average GWF reduction by passage through the WWTP was 86% (total GWF at WWTPs inflows and outflows were $16 \cdot 10^9$ and $2.3 \cdot 10^9$ m^3 respectively); in 2018, the average GWF reduction at municipal WWTPs was 93% (total GWF at WWTPs inflows and outflows were $21 \cdot 10^9$ and $1.55 \cdot 10^9$ m^3 respectively).

The efficiency of the smallest WWTP size categories in GWF reduction is less and during the analyzed period risen up from 56 to 84%. As the wastewater treatment plant's capacity increases, the percentage of GWF reduction rises up. The GWF reduction at largest WWTPs was 89% in 2004 and in average 94% in 2018.

The GWF of pollution at inflows to the WWTPs is predominantly caused by ammonium nitrogen and secondarily also by BOD_5. The GWF of pollution at the WWTPs discharges is most often caused by total phosphorus (it occurs mainly at effluents from larger and large WWTPs) and ammonium nitrogen (mainly at effluents from small WWTPs). In 5% of cases, the GWF of discharged pollution is caused by BOD_5.

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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Summary

Role of wastewater treatment plants in pollution reduction – evaluated by grey water footprint indicator. The study 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 (GWF) of discharged pollution was determined both in terms of individual size categories of WWTPs and in terms of the parameter that most affects the level of pollution. The share of the small WWTPs size categories (up to 2,000 PE) on the total GWF value of discharged pollution is only 8%, although these are the most numerous. The share of the WWTPs of the size category > 10,000 PE on the total GWF value of discharged pollution is 82%. Total phosphorus (at large WWTPs) and ammonium nitrogen (at small WWTPs) were identified as the key pollutants that most determine the value of the grey water footprint of discharged pollution.