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New approach to domestic grey water footprinting: country-scale accounting using statistical methods in Türkiye

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ABSTRACT

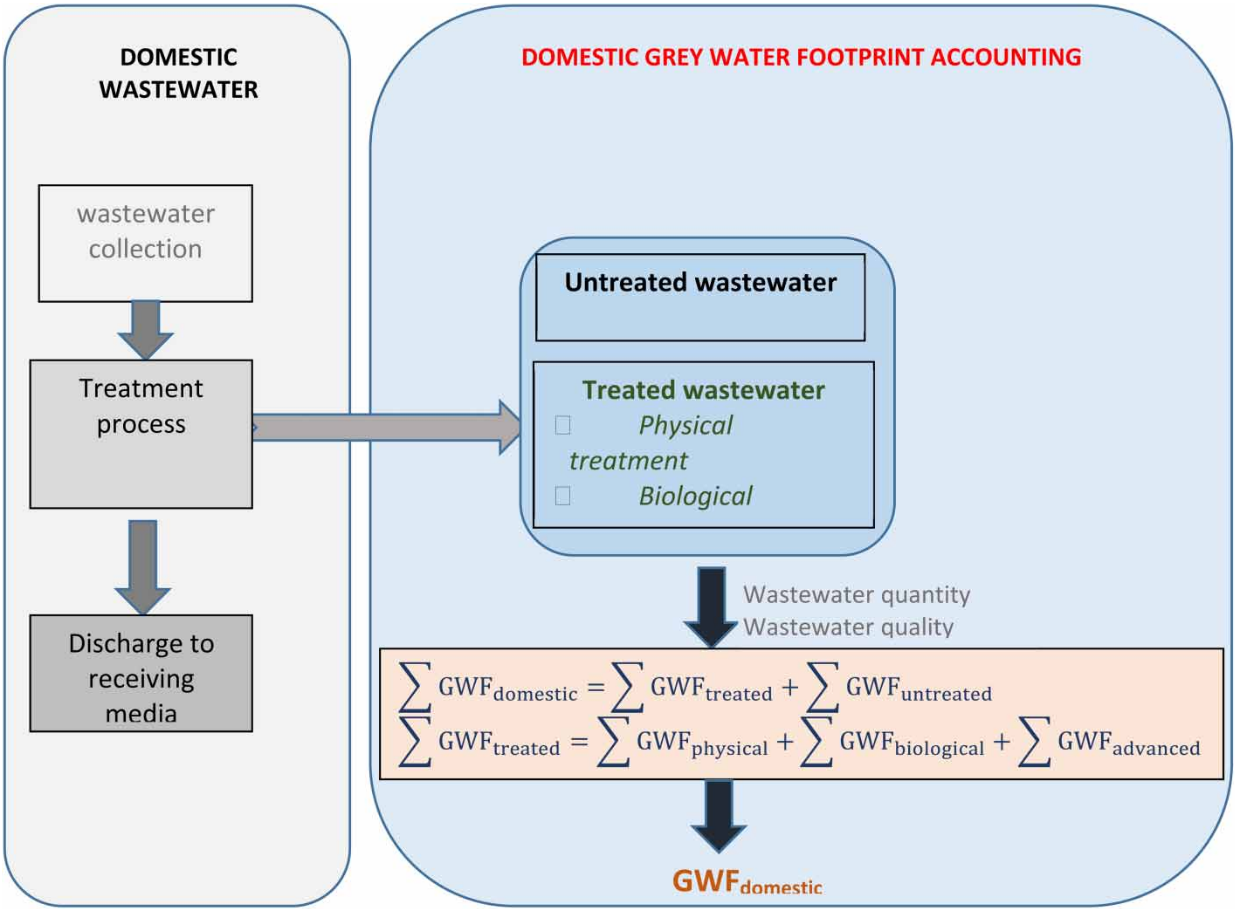
This study aimed to develop an approach for country-scale domestic grey water footprint ($GWF_{domestic}$) accounting and examine spatio-temporal differences using statistical methods. In this scope, the $GWF_{domestic}$ was calculated as the amount of water required to reduce the total nitrogen concentrations of domestic wastewater released into receiving media from 81 cities in Türkiye. $GWF_{domestic}$ values were estimated based on the data on wastewater amount and applied wastewater treatment process. $GWF_{domestic}$ was calculated by dividing the pollutant load of discharged water by the critical concentration in the surface water. The empirical results showed that (a) the produced wastewater amount increased up to 125 m^3/year in some cities. (b) $GWF_{domestic}$ values showed a difference between 330 and 1,900 depending on the level of treatment, and the average value was about 750 m^3/ca.year. (c) A total of 81 cities were grouped under four categories, and applied water treatment technology was the main characteristic of this classification. (f) $GWF_{domestic}$ has not statistically significantly changed over time in a large part of the country. It can be concluded that country-scale $GWF_{domestic}$ accounting can assist water managers in developing prevention measures by analyzing spatio-temporal differences in the water footprint of domestic discharges.

Key words: domestic grey water footprint-$GWF_{domestic}$, factor analysis, Mann–Kendall test, maximum allowable concentration, natural background concentration

HIGHLIGHTS

- An approach to account for the country-scale domestic grey water footprint-$GWF_{domestic}$ was proposed.
- $GWF_{domestic}$ was calculated as the amount of water required to reduce total nitrogen concentrations.
- Spatio-temporal differences in $GWF_{domestic}$ were examined using factor analysis and Mann–Kendall tests.
- $GWF_{domestic}$ values showed a difference between 330 and 1,900 across the country, and the average value was about 750 m^3/ca. year.

GRAPHICAL ABSTRACT



INTRODUCTION

Freshwater scarcity has become a global environmental problem. Along with population growth and climate change, the consumption of water resources is expected to increase significantly in the future. Global water demand for all uses is expected to increase between 20 and 30% by 2050 with significant differences across global regions (Baggio *et al.* 2021). To minimize future pressures on water resources, it is essential to analyze the current state of water resources from a sustainability perspective (Dong *et al.* 2022).

In 2002, Professor Arjen Y. Hoekstra from the University of Twente, Netherlands, created the water footprinting (WF) approach, and since then, several initiatives have emerged incorporating the WF concept (Hoekstra 2017). The WF includes not only direct freshwater use but also indirect water (needed to produce, grow, or manufacture the items) along the supply. It is also a multidimensional indicator that investigates quantities of water consumption by source and volumes of water-diluting pollutants. The term 'blue WF' describes how blue water resources (surface and groundwater) are used for unit production. The use of green water resources is referred to as 'green WF'. Grey WF is the volume of freshwater required to assimilate the discharged pollutant loads into the surface waters (Hoekstra *et al.* 2011). In other words, it is the amount of fresh water needed to dilute pollutants (treated or untreated) in order to meet specified ambient water quality standards. The GWF can reflect the degree of water pollution and has been used in recent years to determine the effectiveness of management strategies (Dong *et al.* 2022).

There are a few studies in the literature that deal with grey water footprinting of anthropogenic activities on a national and global scale. The preceding studies generally focused on a specific sector such as industry, agriculture, etc. (Ayni *et al.* 2011; Shrestha *et al.* 2013; Sun *et al.* 2013; Cao *et al.* 2014; Denis *et al.* 2016; Li *et al.* 2021, 2022; Banerjee *et al.* 2023). The studies evaluating domestic uses did not investigate country-scale grey water footprints by assessing temporal and spatial differences using high-resolution (spatially and temporally) site-specific data (e.g., applied treatment technology, wastewater production rate, etc.).

In these researches, nitrogen emissions were estimated per year and per country and were generally based on dietary per capita protein consumption, which was abstracted from statistical institutions (Herrebrugh 2018), as well as typical wastewater production rates and water pollutant loads (per capita) taken from the literature. Mekonnen & Hoekstra (2015) studied nitrogen-related water pollution in river basins with a specification of the pollution by economic sector and by crop for the agricultural sector. Zhang *et al.* (2019) evaluated the GWF characteristics of 31 Chinese provinces. They mostly investigated GWF as a total amount on the basin or country scale instead of giving value on a smaller spatial scale per capita. Mekonnen & Hoekstra (2011) published a report on 'National Water Footprint Accounts: The Green, Blue, and Grey Water Footprint of Production and Consumption.' In this study, $GWF_{domestic}$ showed variation between 150 and 500 m^3/ca.year in European countries. Boyacioglu (2018) developed an approach to investigate the GWF of municipalities in the Aegean Region in Türkiye. In that study, $GWF_{domestic}$ was changeable from one city to another and had a range of 450–1,500 m^3/ca.year.

In this study, 81 city municipalities in Türkiye were assessed to account for $GWF_{domestic}$. The wastewater production and treatment profiles of the cities were examined, and then the $GWF_{domestic}$ was calculated. Furthermore, spatial and temporal variations were assessed using statistical methods. This will be one of the first studies assessing municipal grey water footprints and examining differences at a country-scale with high spatial and temporal resolution.

STUDY AREA

Türkiye has a total area of 780,043 km^2 and is surrounded by the Aegean Sea in the west, the Black Sea in the north, and the Mediterranean Sea in the south (see Figure 1). The country is located in a semi-arid climate zone and is one of the Mediterranean countries most affected by climate change. The average annual rainfall is 574 mm. Water abstraction from the municipal water supply network that serves 100% of the total country population (83.6 million inhabitants) in 81 cities was 6,500 million m^3 as of the year 2020. Water abstraction per capita in the municipalities was 228 liters per day

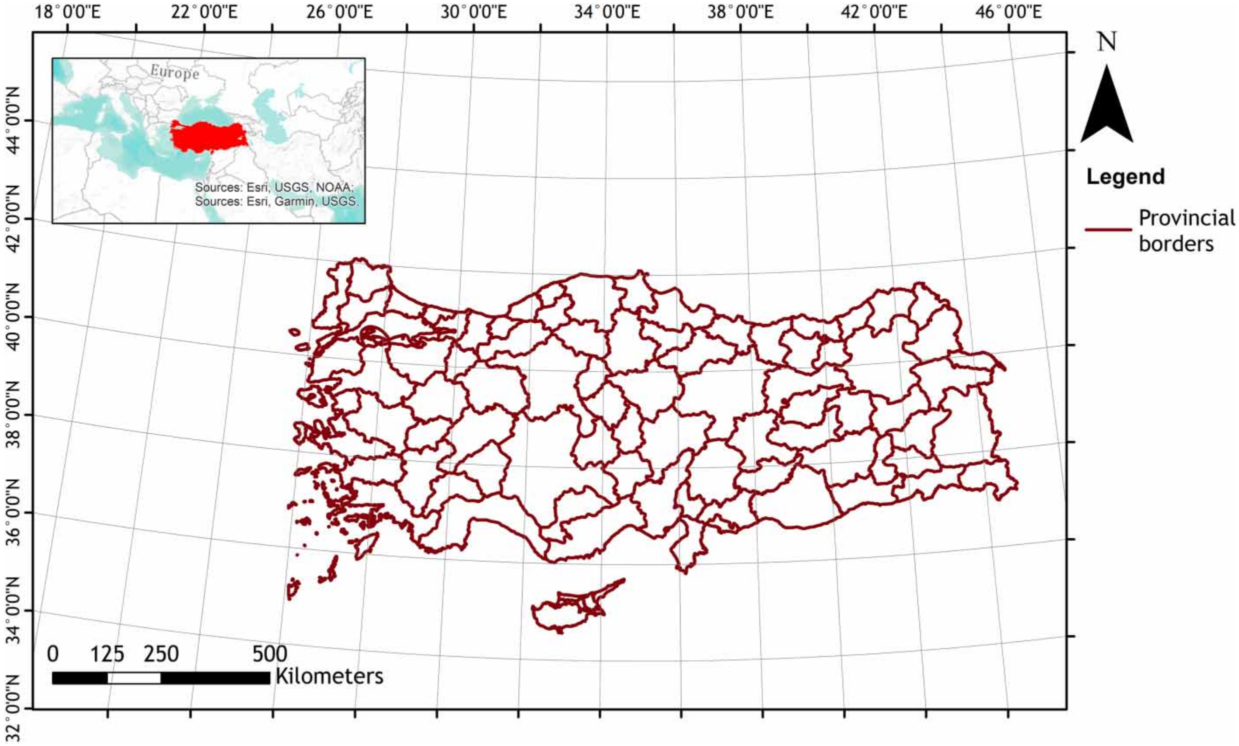


Figure 1 | Türkiye cities map.

(L/ca.day). The distribution of the water according to the source is as follows: 41% from reservoirs, 29% from wells, 16% from springs, and the rest from rivers and lakes (TUIK 2023).

STUDY METHOD

The GWF is calculated by dividing the pollutant load discharged to the water body by the critical concentration, which is the difference between the maximum allowable concentration and the natural concentration in the receiving water body.

$$\mathrm{GWF} = \frac{\mathrm{Load}}{(C_{\max} - C_{\mathrm{nat}})} \tag{1}$$

where GWF is the grey water footprint (volume/time); load denotes the pollutant load (from treated or untreated discharged wastewater) (mass/time); $C_{\max}$ is the maximum acceptable concentration in the receiving water body (mass/volume). C_{nat} is the natural concentration of N in the receiving water body (mass/volume).

The natural concentration (C_{nat}) of a water quality variable in a waterbody is the concentration representing pristine condition (before human influences in the catchment). Maximum allowable concentration ($C_{\max}$) is the criteria for safe levels of exposure to chemicals that can be used to assess the acceptability of receiving media for intended uses (Franke *et al.* 2013).

In the study, the $\mathrm{GWF}_{\mathrm{domestic}}$ was calculated as the amount of water necessary to reduce the total nitrogen concentrations of domestic wastewaters (treated or untreated) released into receiving media (river, sea, etc.) from 81 cities where the total population served by sewage systems was about 72 million inhabitants as of the year 2020 (TUIK 2021). The reason to choose this variable was that discharging large amounts of domestic wastewater drastically increases the reactive nitrogen content in discharged media, which causes severe ecological stress and biodiversity loss.

Data were provided from the series of official waste water surveys at the municipal level published annually or bi-annually by the National Institute of Statistics (TUIK) since 2001.

The analysis framework of the $\mathrm{GWF}_{\mathrm{domestic}}$ model and domains of intervention is depicted in Figure 2.

Pollutant loads were calculated based on the following components for each city individually:

- amount of untreated wastewater
- amount of treated wastewater that was classified according to the applied treatment process as:
    - ○ physical treatment
    - ○ biological treatment (secondary)
    - advanced treatment (nutrient removal)

In the calculations, discharged wastewater total N concentration (C) values were referenced from the literature. The total N levels of various types of wastewater are given in Table 1. Load-L was calculated by multiplying the wastewater amount (Q) by these concentration values. The GWF was then estimated by dividing the pollutant load by the difference between $C_{\max}$ and C_{nat}.

Since the receiving media were rivers for the municipal discharges across the country, in the GWF calculations, threshold values set for rivers were considered. In this scope, C_{nat} was accepted as 0.38 mg N/L. This was the average value in rivers that was reported by Meybeck (1982). As was proposed by the Canadian Council of Ministers of the Environment-CCME based on the guidelines for the protection of aquatic life, $C_{\max}$ was considered to be 2.96 mg N/L (CCME 2013).

In the following section of the study, maps depicting the amount of waste water discharges (m^3/ca.year), untreated and treated wastewater percentages (%) according to applied technology (biological, physical, and advanced), and $\mathrm{GWF}_{\mathrm{domestic}}$ were created using Arc Map 10.3.1.

Moreover, factor analysis was used to group cities by explaining the correlations between the data sets in terms of the underlying factors that cannot be observed directly. In the scope of this analysis: (a) for all the variables, a correlation matrix was generated; (b) factors were extracted from the correlation matrix based on the correlation coefficients of the variables; (c) to maximize the relationship between some of the factors and variables, the factors were rotated (Boyacioglu 2006). The analysis was performed using SPSS-20.0 (2011) for Windows.

Classification of the cities using factor analysis was based on the following data. Amount of:

- wastewater production
- untreated wastewater
- treated wastewater – physically

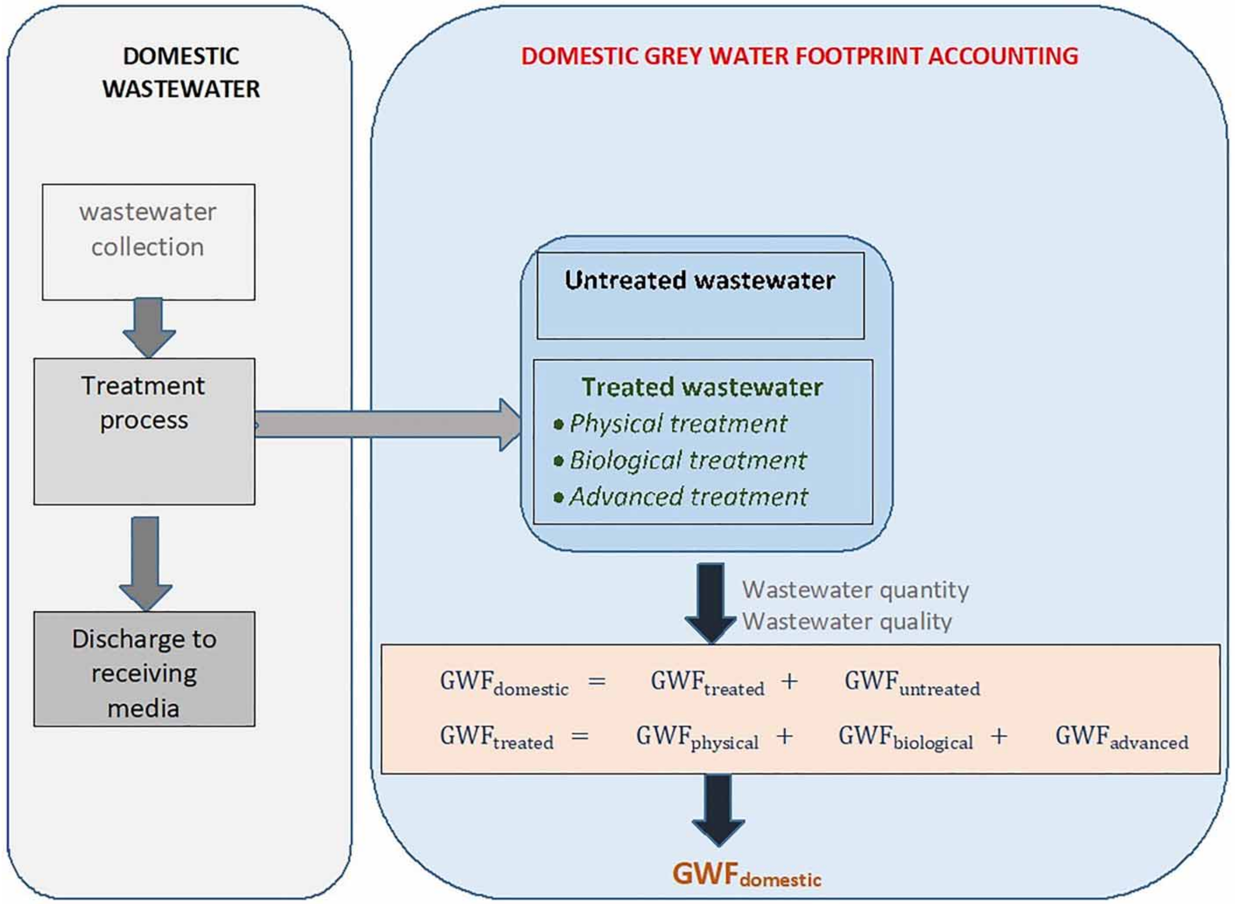


Figure 2 | Analysis framework of $GWF_{domestic}$ model and domains of intervention.

Table 1 | Total N levels of various types of wastewaters (Eddy 1991; after Official Gazette 2010)

Type of treatment process	Total N –(milligram nitrogen per liter –mg N/L)
Untreated wastewater	60
Treated wastewater (biological)	30
Treated-wastewater (physical)	40
Treated-wastewater (advanced)	15

- treated wastewater – biologically
- treated wastewater – using advanced technology

In addition to spatial differences, temporal variations in $GWF_{domestic}$ values were analyzed using the non-parametric trend analysis technique. The objective was to determine the significance of a trend using the Mann–Kendall test. It is a non-parametric signed rank test and has been widely used in environmental studies. It examines the sign of the difference between later and earlier data. Each later set of data is compared to all earlier ones, yielding a total of $n(n-1)/2$ data pairings, where n is the total number of data. The data set does not have to fit a particular distribution (Hipel *et al.* 1988; Helsel & Hirsch 2002; Burn *et al.* 2012).

RESULTS

$GWF_{domestic}$ profile

Descriptive statistics of data covering the amount of total untreated and treated (according to the applied treatment process) wastewater representing 81 cities as of the year 2020 in L/ca.day are presented in Table 2. It was the latest survey result published by the Turkish Statistics Institute (TUIK 2023).

Wastewater production was about 165 L/ca.day on average. On the other hand, it increased to 339 L/ca.day. The mean value for the amount of untreated wastewater across the country was 42.2 L/ca.day. Domestic wastewater was mainly treated using an advanced or biological treatment process.

Figure 3, depicting the spatial distribution of the annual total wastewater amount, shows that the value increased up to 125 m^3/ca. year in some cities. On the other hand, the distribution pattern was not homogeneous across the country. Wastewater treatment rates were remarkably higher in the western part, and above 70% of the wastewater was discharged to receiving media after being treated (see Figure 4). Only a few cities that were not used for almost any treatment process were concentrated in the most eastern part. Applied treatment technology in each city was also evaluated, and results revealed that biological and advanced treatment processes were the most commonly used technologies across the country (see Figure 5).

The calculated $GWF_{domestic}$ for each city is depicted in Figure 6. The values showed a difference between 330 and 1,900, and the average value was about 750 m^3/ca. year. The lower footprint profile observed in the west and mid-part of the country can be explained by high treatment ratios and also by applied treatment technologies removing pollutants (advanced and biological).

Investigation of spatial differences in $GWF_{domestic}$

In the study using factor analysis, cities were grouped based on their similarities regarding waste water production and treatment characteristics, representing the year 2020. In this context, 81 cities were grouped into four categories, and 100% of the variance in the data set was explained by these four factors. The spatial distribution of cities grouped under each factor is depicted in Figure 7. Descriptive statistics of the data belonging to cities classified under each factor are presented in Table 3.

Based on the characteristics of cities grouped under each factor, it can be concluded that:

- Factor 1 represents cities that treat wastewater by dominantly using advanced treatment technologies.
- Factor 2 reflects cities that primarily treat wastewater by utilizing biological treatment technologies.
- Factor 3 represents cities that do not use treatment processes for a high percentage of wastewater.
- Factor 4 represents cities that treat wastewater predominantly using physical treatment technologies.

A total of 60 cities out of 81 were comprised of the first two factors. The common features of the cities were that they used either advanced or biological treatment processes. Only a few cities treated their wastewater after physical treatment. On the

Table 2 | Descriptive statistics of wastewater production and treated wastewater-ww amount (units are in L/ca.day)

		Total ww	Untreated ww	Treated ww-biological	Treated ww-physical	Treated ww-advanced
Mean		164.9	42.2	55.9	10.2	56.6
Std. error of mean		5.3	4.6	6.9	4.1	7.2
Median		154.0	27.1	29.0	0.0	22.0
Std. deviation		48.1	41.5	62.5	36.6	64.8
Skewness		1.32	1.31	0.94	4.69	0.98
Kurtosis		2.67	1.04	−0.15	24.48	0.31
Minimum		73.0	.0	.0	.0	.0
Maximum		339.0	169.0	247.5	245.6	276.6
Percentiles	25	134.0	13.6	2.1	.0	.0
	50	154.0	27.1	29.0	.0	22.0
	75	191.0	60.1	98.4	.0	108.8

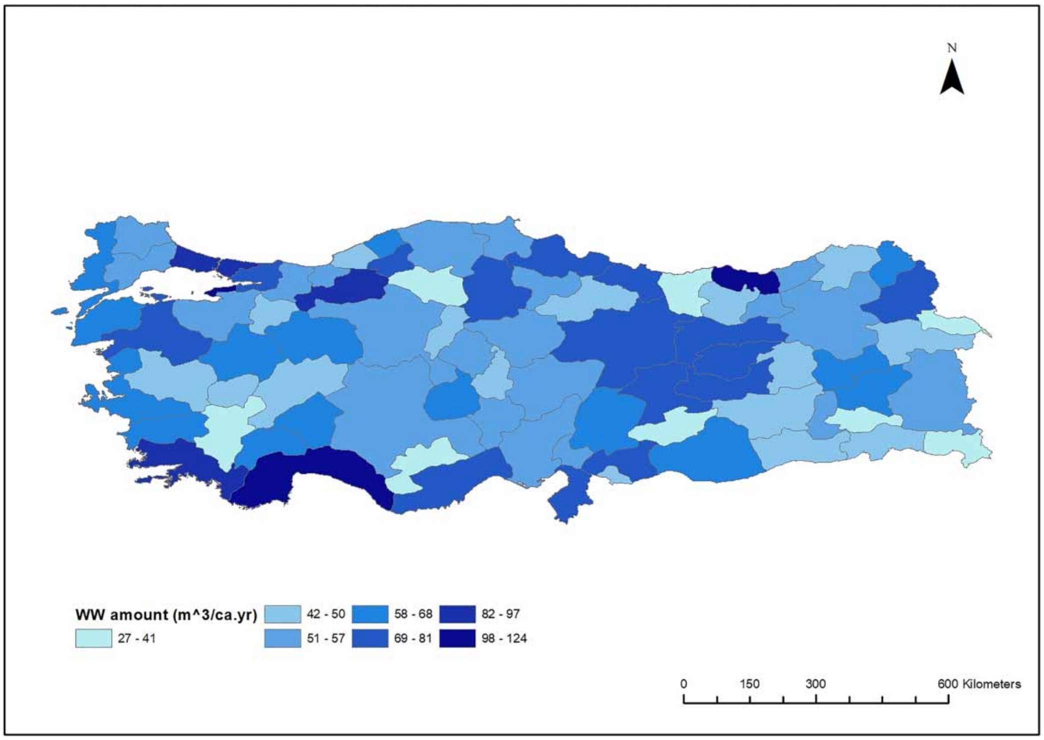


Figure 3 | Spatial distribution of domestic wastewater amount (m^3/ca. year) as of 2020.

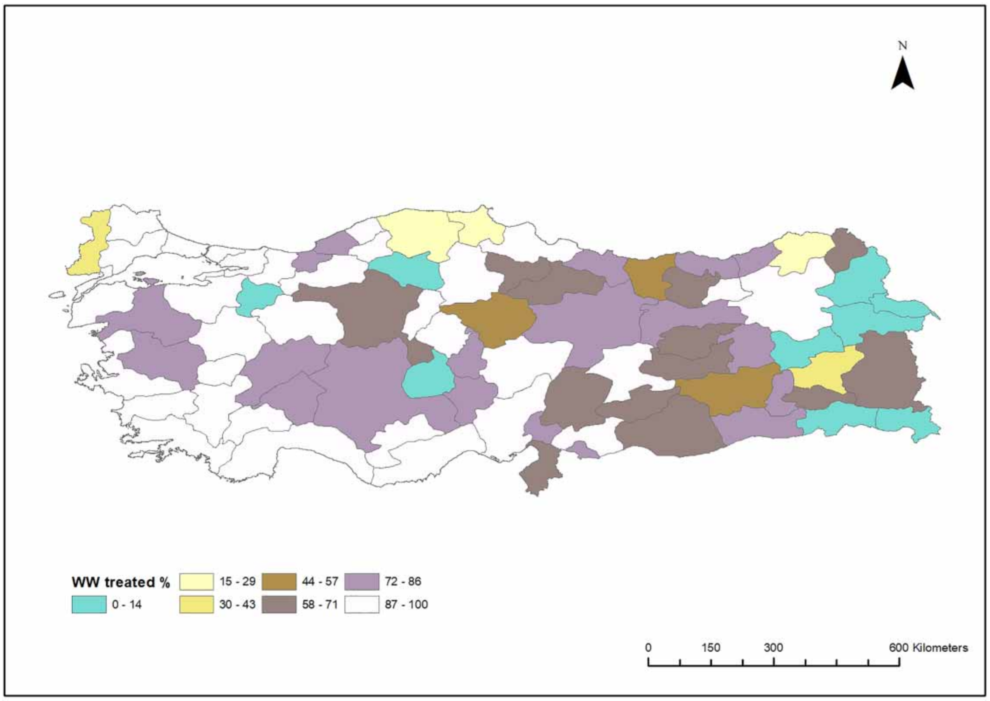


Figure 4 | Spatial distribution of treated domestic wastewater percentage (%) as of 2020.

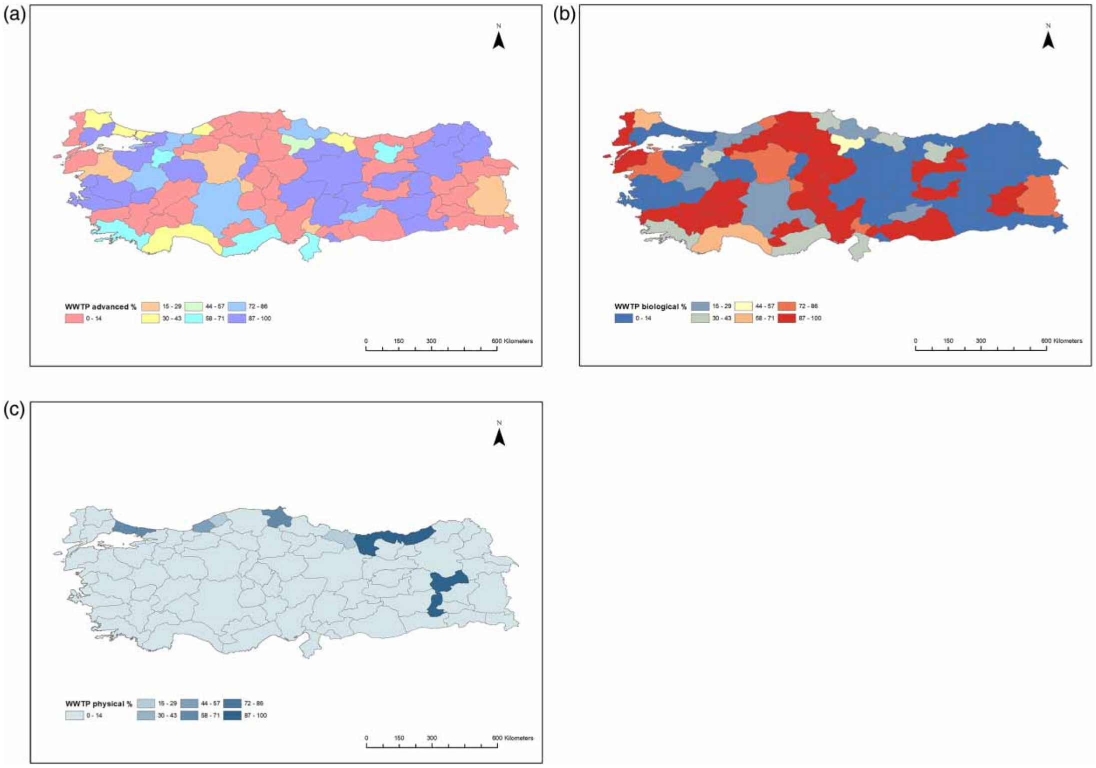


Figure 5 | Spatial distribution of the percentage of treated domestic wastewater amount using (a) advanced, (b) biological, and (c) physical treatment technology (%).

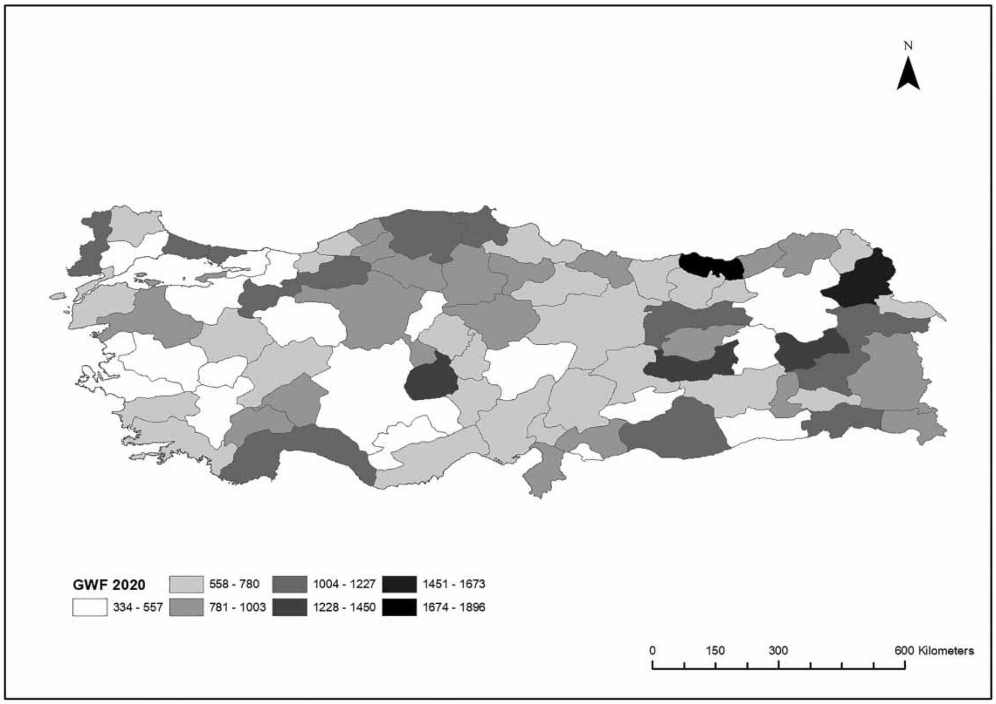


Figure 6 | Spatial distribution of $\text{GWF}_{\text{domestic}}$ (m^3/ca. year) as of 2020.

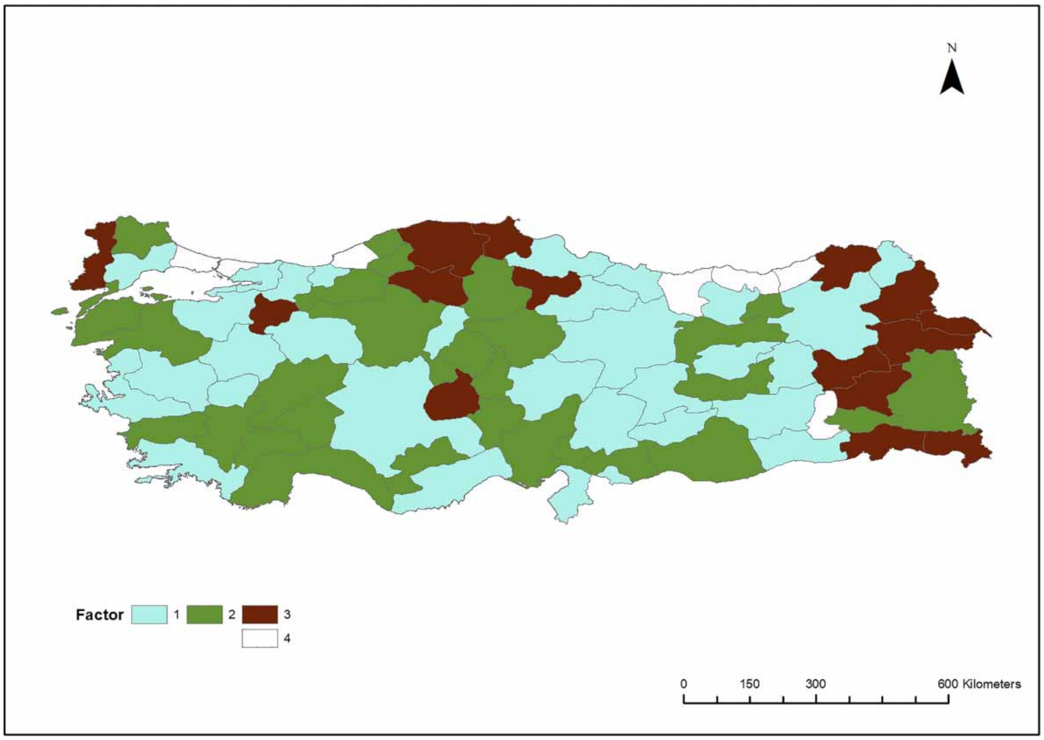


Figure 7 | Classification of cities based upon factor analysis.

Table 3 | Descriptive statistics for the data belonging to each factor group (units are in L/ca.day)

		# of cities grouped under the factor	Median	Mean	Std. deviation
Factor 1	Wastewater amount	32	156.0	168.1	47.5
	Untreated wastewater amount		14.6	15.7	13.3
	Treated wastewater amount (biological)		5.3	9.8	10.5
	Treated wastewater amount (physical)		0.0	0.7	3.4
	Treated wastewater amount (advanced)		73.9	73.8	16.3
	$GWF_{domestic}$		1,519.5	1,517.3	483.0
Factor 2	Wastewater amount	28	162.5	171.0	46.8
	Untreated wastewater amount		13.3	15.9	12.6
	Treated wastewater amount (biological)		80.5	76.6	13.4
	Treated wastewater amount (physical)		0.0	0.7	3.4
	Treated wastewater amount (advanced)		0.0	6.8	10.3
	$GWF_{domestic}$		2,156.4	2,215.9	555.3
Factor 3	Wastewater amount	15	139.0	140.9	31.7
	Untreated wastewater amount		90.1	83.9	17.5
	Treated wastewater amount (biological)		3.7	10.5	14.0
	Treated wastewater amount (physical)		0.0	1.1	3.6
	Treated wastewater amount (advanced)		0.0	4.4	8.1
	$GWF_{domestic}$		3,016.7	2,951.5	658.6
Factor 4	Wastewater amount	6	143.5	179.0	78.6
	Untreated wastewater amount		20.4	21.3	14.3
	Treated wastewater amount (biological)		0.9	3.3	6.4
	Treated wastewater amount (physical)		66.6	63.5	18.6
	Treated wastewater amount (advanced)		3.1	12.0	16.8
	$GWF_{domestic}$		2,453.6	2,793.8	1,378.6

other hand, in the 15 cities that were grouped by Factor 3, a high percent of wastewater was discharged untreated. Only six cities were classified under Factor 4.

Investigation of temporal differences in $GWF_{domestic}$

In the study, the Mann–Kendall test was applied to evaluate whether a significant increase or decrease in $GWF_{domestic}$ values for each city occurred. In this scope, the examined data set covered the survey results for the 2001–2020 period. Trend analysis was performed using Minitab 15 (Minitab 15 2007). Test statistics (z-scores) were calculated, and the critical z-value at the 5% significance level (1.645) was taken from the standard normal distribution table. Results showed that 23 out of 81 cities had negative trends, 9 cities had positive trends, and 49 cities had no trends. In other words, $GWF_{domestic}$ per capita did not statistically significantly change over time in most parts of the country (49 cities). On the other hand, while 23 cities showed a decreasing trend, only 9 of these $GWF_{domestic}$ values increased over time. The spatial distribution of the results is depicted in Figure 8. Although northern cities had no trend, GWF values in southern cities generally showed a decreasing trend. This could be explained by either high wastewater treatment rates or the usage of advanced treatment technology in the region (see Figures 4 and 5).

DISCUSSION

The empirical results of the study showed that:

(a) the produced wastewater amount increased up to 125 m^3/ca.year in some cities;

(b) wastewater treatment rates were remarkably higher in the western part, and above 70% of the wastewater was discharged to receiving media after the treatment process;

(c) biological and advanced treatment processes were the mostly used technology over the country;

(d) $GWF_{domestic}$ values fluctuated between 330 and 1,900 m^3/ca.year, and the average value was about 750. Hoekstra and Mekonnen conducted research in 2012 and estimated the national average GWF value as about 500 m^3/ca.year for Türkiye (Hoekstra & Mekonnen, 2012). Hence, the estimated average value of 750 m^3/ca.year in this study was

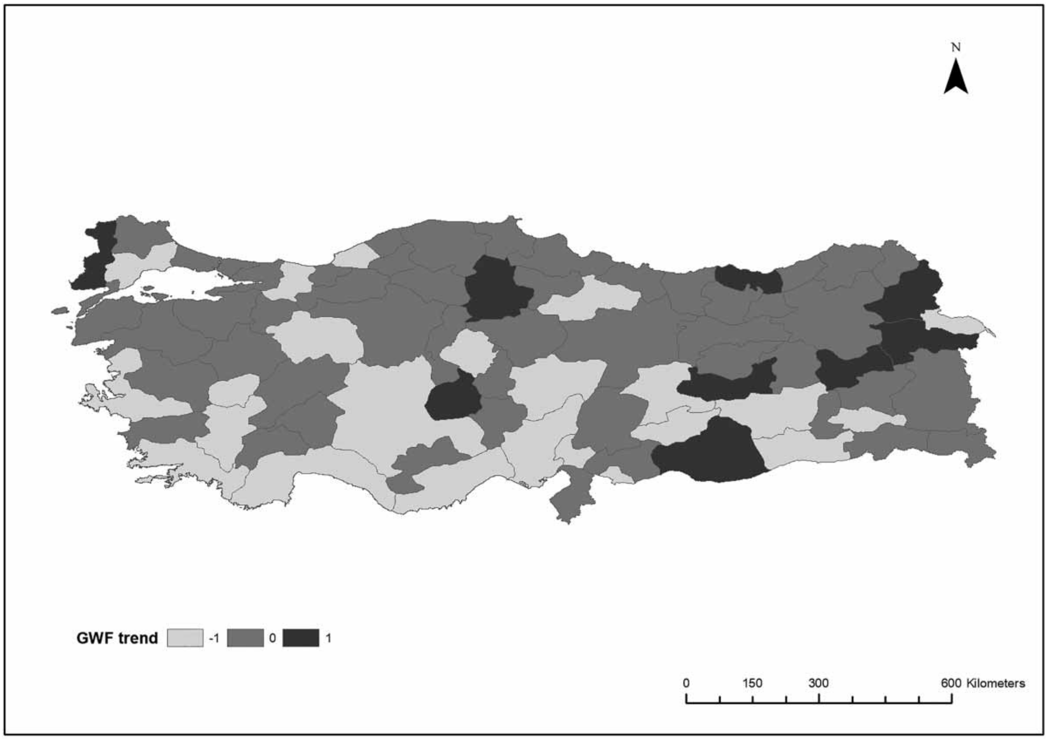


Figure 8 | Spatial distribution trends in $GWF_{domestic}$ (−1: downward trend, 0: no trend, +1: upward trend).

comparatively high. The reason could be that previous research has made estimations using limited data at country scales around the world.

(e) A total of 81 cities were classified into four groups, and dominantly used water treatment technology was the characteristic for this classification. A total of 60 cities out of 81 were comprised by the first two factors, and they used either advanced or biological treatment processes.

(f) while 23 cities showed a decreasing trend in $GWF_{domestic}$, only in 9 cities values increased over time.

CONCLUSIONS

There are a few studies in the literature that deal with grey water footprinting of anthropogenic activities on a national and global scale. The preceding studies generally focused on a specific sector and none of which investigated country-scale grey water footprints by assessing temporal and spatial differences. This will be one of the first studies assessing municipal grey water footprints at a country-scale with high spatial and temporal resolution. In the scope of the study, a new approach to domestic $GWF_{domestic}$ was proposed for country-scale accounting using statistical methods. The application of the methodology was demonstrated in Türkiye using data from municipalities in 81 cities, where 72 million inhabitants were served by sewage as of 2020. Data were handled within the series of waste water official surveys at a municipal level published annually or bi-annually by the National Institute of Statistics (TUIK). The wastewater production and treatment profiles of the cities were examined. Then the $GWF_{domestic}$ was calculated as the amount of water required to reduce the total nitrogen concentrations of domestic wastewater released into receiving media. Furthermore, factor analysis and Mann–Kendal trend analysis tests were performed to classify cities based on $GWF_{domestic}$ components and also determine the significance of a trend in $GWF_{domestic}$. The results of the study investigated spatial and temporal differences across the country. The proposed approach is believed to assist decision-makers in developing pollution prevention measures by analyzing site-specific high-resolution data.

AUTHOR CONTRIBUTIONS

Both authors contributed to the study's conception and design. H. B. mainly contributed to data collection and statistical analysis, and H. B. contributed to data collection and water footprint calculations. Both authors read and approved the final manuscript.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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