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Water Footprint Index (WFTP) for Poznań as a Tool for Assessing Water Management in Urban Areas

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Abstract: The paper assesses the volume and type of water consumption in Poznań using a water footprint indicator (WFTP) consisting of such components as green, blue and grey water consumption. Average rainfall over many years, water retention within the city, pollution indicators found in sewage and the amount of sewage treated from the city area were assessed. The water footprint obtained for Poznań was compared with the values of indicators for Wrocław. The presented analysis of the results of WFTP calculations should constitute the basis for assessing direct and indirect water consumption by consumers and producers of Poznań and serve better water management and maintenance in the urban area.

Keywords: water footprint, water resources, water management in urban areas

1. Introduction

Growth in urbanisation leads to the concentration of water intake for water supply purposes, seals the surface, and increases surface runoff from the area of urban-industrial agglomerations. It affects surface water and groundwater resources and quality on a regional scale. Water consumption is estimated to increase by 50% in developed countries and 18% in developing countries by 2025 (GEO-4 2007). In recent years, in the EU, special attention has been paid to ensuring access to freshwater resources for residents, as there has been a decrease in the value of the infiltration rate in urban areas. The goal is achievable by using the WFTP indicator to support a decision-making process for better water management in urban areas.

Europeans seldom realise water's importance, albeit a scarce natural resource. Recent EU research confirms that there is a potential to reduce water consumption by 40% in urban areas. The concept of Water Footprint (WF) has been developing since the 1990s. For the first time, the idea of "virtual" water, i.e., water used to produce and deliver goods, was defined by Allan (1998). Later, in 2002, Arjen Hoekstra proposed the concept of water footprint as the total consumption of freshwater resources in terms of volume (expressed, i.e., in $m^3 \cdot unit^{-1}$ of product or $m^3 \cdot year^{-1}$) analysed for a region, product or service, considering both the amount of consumed water and its quality regarding pollutants introduced into the environment (Hoekstra et al. 2011, Hoekstra 2002). In 2014, the water footprint indicator was standardised in the international standard ISO 14046:2014, which provides the principles, requirements and guidelines related to the water footprint assessment of products, processes and organisations based on Life Cycle Assessment (LCA). The standard only includes calculations of emissions to air and soil that affect water quality. However, it does not include all water footprint components. For these reasons, most studies are based on the water footprint methodology developed by Hoekstra (2012). Here, three components can be distinguished in this water footprint concept: blue, green and grey footprint. The blue water footprint determines the volume of groundwater and surface water (Hoekstra 2002). Consumption of this type of water is closely related to the reduction in water resources in the catchment area. The blue water footprint includes water collected from rivers, lakes, ponds and underground reservoirs. The green water footprint is that part of rainfall water that plants use up, and excess water is evaporated into the atmosphere through evapotranspiration. It is water stored in the soil and taken up by plants. The grey water footprint is expressed as the hypothetical volume of water necessary to dilute pollutant loads introduced into the water to such an extent that the water quality does not exceed established norms and standards (Hoekstra et al. 2011).

In order to achieve this goal, an attempt was made to use the Water Footprint Indicator (WFTP) as a decision-making support tool for better water management and maintenance in urban areas. The Urban Water Footprint project aims to provide tools to compare water consumption with good and bad water management practices benchmarks. Water Footprint was first defined in 2002 as an indicator of freshwater consumption, expressed in cubic meters per year and per person ($m^3 \cdot a^{-1}$ $person^{-1}$), including both direct and indirect consumption of water by consumers or producers (Hoekstra et al. 2011, Hoekstra 2002).

The purpose of the study was to determine the Water Footprint Indicator (WFTP) for the city of Poznań, which will help define strategic solutions modifying water distribution and treatment systems as well as sewage disposal and treatment from the city. Two methods are used to calculate the values of WFTP indicators in the literature (Bulsink et al. 2010). The Water Footprint Network (WFTPPN) developed the first approach – volumetric – and the LCA Community, the second – Life Cycle Analysis. Many detailed WFTP analyses have been performed for both European (Aldaya et al. 2008, Allan 1998, Burszta-Adamiak & Fiałkiewicz 2018, Fiałkiewicz et al. 2013, Hoekstra 2002, Hoff et al. 2013) and non-European countries (Huang et al. 2013, Liu & Savenije 2008, Oel et al. 2009, Sonnenberg et al. 2009, Vanham 2013, Vanham et al. 2013). The global average value of the WFTP indicator is 1385 $m^3 \cdot a^{-1} \cdot person^{-1}$. The Polish WFTP indicator is 1405 $m^3 \cdot a^{-1} \cdot person^{-1}$, of which 24.7% is external WFTP (imported products and services) (Hoekstra & Mekonnen 2012). In the United States, the WFTP value is high due to large consumption, while in Nigeria or Thailand, for instance, the high WFTP value results from the ineffective use of water for production (Verma et al. 2009).

2. Material and Methods

The transport of water, its treatment, and the operation of sewage systems contribute to an increase in energy consumption, the production of which also requires significant amounts of water. For these reasons, an attempt was made to determine the value of WFTP in the urbanised area of the city of Poznań. For an urban area, WFTP can be designated using the same procedure as for countries or regions (GEO-4 2007). Concerning the city, WFTP is the total amount of freshwater consumed within the city's geographical limits per year and capita. The original WFTP model for cities considers the annual and real water balance. The real water stream supplying cities consists of atmospheric precipitation, water collected for consumption, water for the needs of industry and agriculture, and water import. The water that leaves urban areas comes from evaporation, surface runoff, infiltration into groundwater, losses in the transportation of drinking water, industrial and agricultural activities, and water exported beyond designated city boundaries.

Calculations of the total real water balance in the city were made using the equation:

$$Qn - Qw = Qr \tag{1}$$

where:
Qn – water flowing into the city, $m^3 \cdot a^{-1}$,
Qw – water flowing out of the city, $m^3 \cdot a^{-1}$,
Qr – water retention in the city, $m^3 \cdot a^{-1}$.

The difference between the water flowing in and out of the city was determined as the amount of water that did not leave the city at any given time and could be used up in the dry season or runoff in the wet season. Water Footprint (WFT_{Pr}) in the city area, including real water, was calculated from the equation: $WFT_{Pr} = WFT_{Pz} + WFT_{Pn} + WFT_{Ps}$ [$m^3 \cdot a^{-1}$], where: WFT_{Pn} – blue WFTP, which is the part of rainwater that does not run off the surface and does not feed into groundwater but it is retained in the soil or remains temporarily on the surface of soil or plants, WFT_{Pz} – green WFTP, indicating the volume of water available at a given time that is consumed (which means it is not immediately returned to the same catchment area), WFT_{Ps} – grey WFTP, showing the volume of water required to such a dilution of pollutants contained in wastewater so that water quality standards are not exceeded.

Calculations of individual components of the WFTP indicator were determined based on the following equations: WFTP of green water was calculated according to Formula: $WFT_{Pz} = PREC \cdot Kp \cdot Ap$ [$m^3 \cdot a^{-1}$], where: PREC – annual rainfall [$mm \cdot a^{-1}$], Kp – evaporation rate in permeable areas [%], Ap – [m^2], permeable area (Statistical Yearbook of Poznań 2021). Calculations for WFTP of blue water were made according to Formula: $WFT_{Pn} = PREC \cdot (Ki \cdot Ai + Kw \cdot Aw) + Qx + Qr$ [$m^3 \cdot a^{-1}$], where: Ki – evaporation rate in impermeable areas [%], Ai – impermeable areas [m^2], Kw – evaporation rate from the surface of the water [%], Aw – total area covered by water in the city [m^2], Qx – the annual volume of water exported [$m^3 \cdot a^{-1}$] equal to 0, Qr – water retained in the city [$m^3 \cdot a^{-1}$]. Calculations used the volume of water from the following reservoirs: Malta (2 003200 m^3) and Rusałka (697 300 m^3). According to the Report on the condition of Poznań (2014), the area of Poznań is 261.90 km^2. 49% of this area (128.33 km^2) consists of terrains that infiltrate water (arable land, forests, trees and wastelands). Developed and urbanised lands and other water-impermeable areas constitute 48%, occupying 125.71 km^2 of the city area (Statistical Yearbook of Poznań 2021). The remaining 3% are water areas (7.86 km^2). Calculations for WFTP of grey water were made according to Formula: $WFT_{Ps} = c(i) \cdot Qs \cdot [c_{max}(i) - c_0(i)]^{-1}$ [$m^3 \cdot a^{-1}$], where: c(i) – the value of the i-th pollution index in treated sewage [$g \cdot m^{-3}$], (Table 2), Qs – annual volume of treated sewage [$m^3 \cdot a^{-1}$], $c_{max}(i)$ – permissible value of the i-th sewage pollution index in the treated sewage [$g \cdot m^{-3}$], $c_0(i)$ – the value of the i-th pollution index in the abstracted water [$g \cdot m^{-3}$].

3. Results

The total WFTP value in an urban area consists of WFT_{Pr} – including real water and WFT_{Pv} – including virtual water. Virtual water is water used to manufacture and deliver goods, energy, and services necessary to produce a unit of volume of real water delivered to consumers. The virtual water balance covers the entire cycle of production processes. As a result of exporting and importing products between countries and regions, it is also possible to export and import virtual water. WFT_{Pv} also includes blue, green and grey WFTP (Fiałkiewicz et al. 2013, Vanham 2013). The methodology presented above for determining the WFTP indicator was applied to the example of Poznań. According to data from the Statistical Office in Poznań (Statistical Yearbook of Poznań 2021), the number of inhabitants is approximately 671000. Poznań is situated in the catchment area of the Warta River and its tributaries: Bogdanka, Cybina, Główna, Głuszynka, Kopla, Junikowski Stream and Różany Potok, and within the Greater Poland Lake District. As a result, in the city, next to the extensive network of rivers, there are large, naturally shaped lakes and numerous small post-glacial ponds. There are approximately 150 artificial water reservoirs, including the two largest – Malta and Rusałka. In the city, 97.9% of residents use the water supply system, while 94.7% use the sewage system administered by Aquanet. Annual water consumption per capita is 40 m^3. The density of the technical infrastructure distribution network, which has been converted into 100 km^2 for the city area, is 373 km of the sewage network and 453 km of the water supply network. There are also 3.7 thousand non-discharge liquid waste tanks and 260 household sewage treatment plants (Statistical Yearbook of Poznań 2021). The average air temperature in Poznań is 8.7°C. Based on meteorological data from the Meteorological Modelling Centre, IMGW Poznań – Ławica station, the average total rainfall for 1951-2020 was 522 mm (Statistical Yearbook of Poznań 2021).

Table 1. Types of surface areas in the city of Poznań (Statistical Yearbook of Poznań 2021)

Type of area	km^2
Total surface	261.90
Permeable areas	128.33
Impermeable areas	125.71
Water surfaces	7.86

Below are presented the results of individual components of the WFTP indicator. WFT_{Pz} (WFTP of green water) = $0{,}522 \cdot 0.38 \cdot 12.833 \cdot 10^7 = 2.55 \cdot 10^7 = 25.5$ m $m^3 \cdot a^{-1}$. To calculate the WFTP indicator of blue water, the retained water in the city Qr was assumed as the water volume in the reservoirs: Rusalka (volume 697,300 m^3) and Malta (volume 2,003,200 m^3).

$WFT_{Pn} = 697300 + 2003200 = 2700500\ m^3 = 27.005 \cdot 10^5\ m^3$, (Qr),

$125.71\ km^2 = 12.571 \cdot 10^7\ m^2$, $7.86\ km^2 = 0.786 \cdot 10^7\ m^2$, $WFT_{Pn} =$

$= 0.522 \cdot (0.22 \cdot 12.571 \cdot 10^7 + 0.10 \cdot 0.786 \cdot 10^7) + 0 + 27.005 \cdot 10^5 =$

$= 1.75 \cdot 10^7 = 17.5$ m $m^3 \cdot a^{-1}$.

When calculating the WFTP indicator of grey water, the annual volume of treated sewage for Poznań was assumed to be approximately 38,502,999 m^3.

$WFT_{Ps}(_{ChZT}) = 49.1 \cdot 385029999 \cdot (125\text{-}9) = 1.63 \cdot 10^7 = 16.3$ m $m^3 \cdot a^{-1}$,

$WFT_{Ps}(_{BZT5}) = 4.21 \cdot 385029999 \cdot (15\text{-}3) = 1{,}35 \cdot 10^7 = 13.5$ m $m^3 \cdot a^{-1}$,

$WFT_{Ps}(_{z.o}) = 7.33 \cdot 385029999 \cdot (35\text{-}01) = 8.09 \cdot 10^6$ m $m^3 \cdot a^{-1}$.

$WFT_{Ps}(_{Nc}) = 7.74 \cdot 385029999 \cdot (10\text{-}4) = 4.97 \cdot 10^7 = 49.7$ m $m^3 \cdot a^{-1}$,

$WFT_{Ps}(_{Pc}) = 0.47 \cdot 385029999 \cdot (1\text{-}0{,}4) = 3.02 \cdot 10^7 = 30.2$ m $m^3 \cdot a^{-1}$ (Table 2).

The highest WFTP value of grey water is found in total nitrogen pollution, which is 49.7 $m^3 \cdot a^{-1}$. The value of total phosphorus pollution is $3.02 \cdot 10^7$ $m^3 \cdot a^{-1}$, BOD5 is $1.35 \cdot 10^7$ $m^3 \cdot a^{-1}$, and COD is $1.63 \cdot 10^7$ $m^3 \cdot a^{-1}$ (Fig. 1). The lowest pollutant content comes from organic compounds, amounting to $8.09 \cdot 10^6$ $m^3 \cdot a^{-1}$.

Table 2. List of pollution indicators in water and sewage in Poznań in 2018 (based on data from Aquanet and WIOŚ)

	ChZT	BZT_5	general suspension	N_c	P_c
	mg · dm^{-3}				
c(i)	49.1	4.21	7.33	7.74	0.47
$c_{max}(i)$	125	15	35	10	1
$c_0(i)$	9	3	0.1	4	0.4

Where: c(i) – value of the i-th pollution index in treated sewage [$g \cdot m^{-3}$] $c_{max}(i)$ – permissible value of the i-th sewage pollution index in the treated sewage [$g \cdot m^{-3}$], $c_0(i)$ – value of the i-th pollution index in the abstracted water [$g \cdot m^{-3}$]

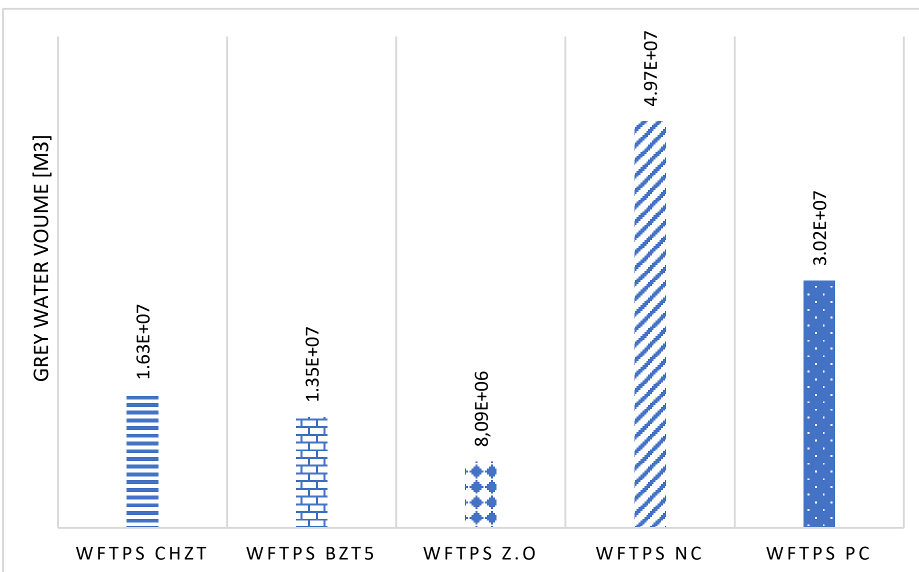

Fig. 1. Grey water values for individual pollution indicators

The WFTPs value was determined based on the total nitrogen content in treated sewage (10 g $N \cdot m^{-3}$) and amounted to 49.7 m $m^3 \cdot a^{-1}$. Thus, the value of the WFTP of real water for the city of Poznań was: $WFT_{Pr} = WFT_{Pz} + WFT_{Pn} + WFT_{Ps} = 2.55 \cdot 10^7 + 1.75 \cdot 10^7 + 4.97 \cdot 10^7 = 9.25 \cdot 10^7 = 92.5$ m $m^3 \cdot a^{-1}$ (Fig. 2). The largest share in the WFT_{Pr} indicator ($9.25 \cdot 10^7$ $m^3 \cdot a^{-1}$) has WFT_{Ps} (grey water), amounting to $4.97 \cdot 10^7$ $m^3 \cdot a^{-1}$. On the other hand, the WFTP of blue water has the lowest share in the WFT_{Pr} indicator of real water, which is $1.78 \cdot 10^7$ $m^3 \cdot a^{-1}$. The WFTP indicator of green water from calculations is $2.49 \cdot 10^7$ $m^3 \cdot a^{-1}$ (Fig. 2). In Poznań, green water accounts for 27.47% of the total WFTP value of real water, blue water for 18.93% and grey water for 53.6% (Fig. 3).

The values of individual indicators of Water Footprint per inhabitant for Poznań amounted to:

$WFT_{Pz} = 2.49 \cdot 10^7 \cdot 6.71 \cdot 10^5 = 37.94$ $m^3 \cdot a^{-1} \cdot person^{-1}$,

$WFT_{Pn} = 1.78 \cdot 10^7 \cdot 6.71 \cdot 10^5 = 26.15$ $m^3 \cdot a^{-1} \cdot person^{-1}$,

$WFT_{Ps} = 4.97 \cdot 10^7 \cdot 6.71 \cdot 10^5 = 74.02$ $m^3 \cdot a^{-1} \cdot person^{-1}$.

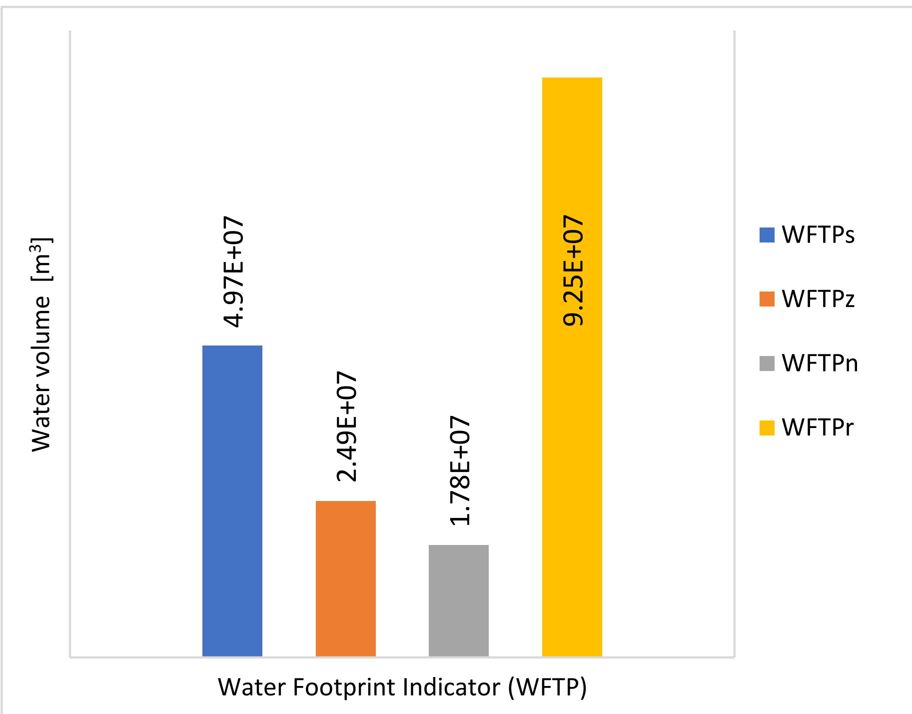

Fig. 2. Values of individual components of the WFTP indicator of real water for Poznań

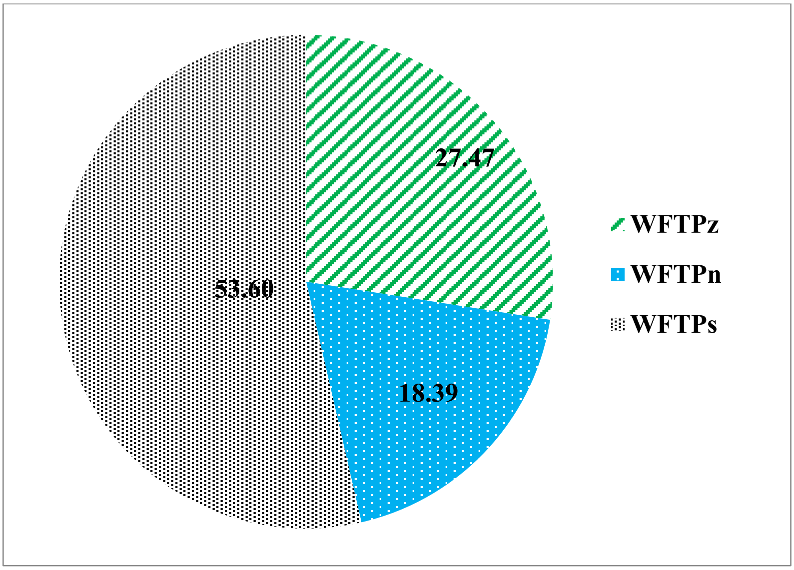

Fig. 3. Percentage share of individual elements of the actual Water Footprint index in the structure of the city of Poznań

After Hoekstra and Mekonnen (2012), the WFTP of virtual water was estimated at $WFT_{Pv} = 1385\ m^3 \cdot a^{-1} \cdot people^{-1}$. Comparison of the calculated results of the WFTP indicator for Poznań and Wrocław based on the work by Fiałkiewicz et al. (2013). The values of elements of the Water Footprint indicator for Wrocław are greater than the calculated values of the WFTP indicators for Poznań by over 50%. It is because Wrocław has more water resources from retention reservoirs with a total volume of approx. 6.6 million m^3, which were needed to calculate the WFTP of blue water (Fig. 4). The average annual rainfall for Wrocław is greater than for Poznań and amounts to 573 mm, necessary to calculate the WFTP of green water. Wrocław is characterised by a greater amount of treated wastewater with a volume of 45 million m^3, where this data was necessary to calculate the WFTP indicator of grey water (Table 3).

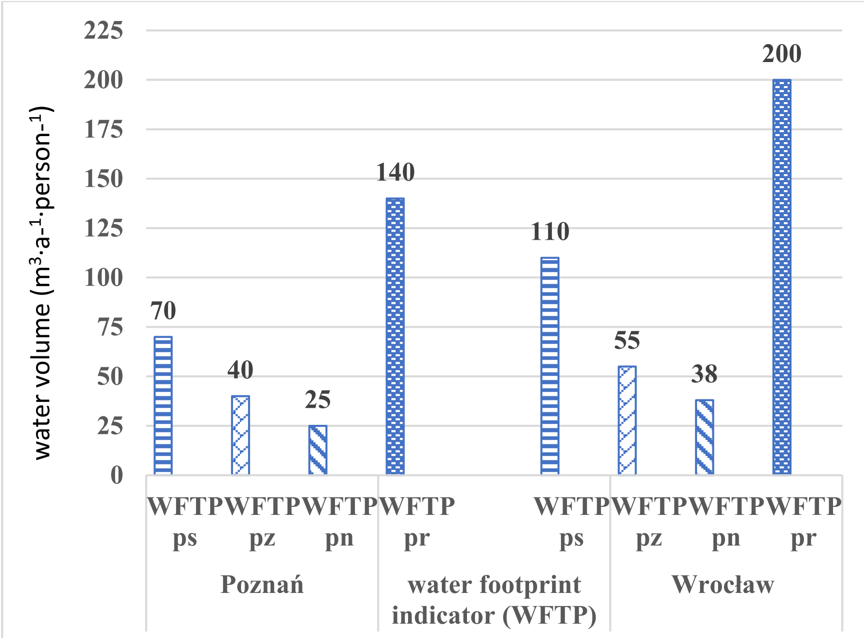

Fig. 4. Comparison of the values of the Water Footprint elements for Poznań and Wrocław

Table 3. Summary of individual data for Poznań obtained from Aquanet and WIOŚ, and Wrocław based on the study

	Poznań	*Wrocław*	Unit
Water retention	$27 \cdot 10^5$	$66 \cdot 10^5$	m^3
Average rainfall over many years	522	573	mm
Treated sewage	$38.5 \cdot 10^6$	$45 \cdot 10^6$	m^3

4. Conclusions

Recognition of the values of Water Footprint indicators (WFTP) for the city of Poznań and the compilation and comparison of data will enable the development of optimal long-term strategies for modifying the water treatment and distribution system as well as wastewater treatment and disposal. It will increase the efficiency of operation of water supply and sewage systems and support decision-making processes for better management and maintenance of water resources in urban areas.

It can contribute to developing and implementing new technologies and alternatives to the natural water cycle. The integrated way of managing the system would differ from the conventional one in combining the entire water and sewage infrastructure. Simultaneously, it would optimise energy consumption based on the virtual water quantity indicators. The determined values of the WFTP indicators for Poznań will make it possible to compare the water balance of other cities in Poland. It should also contribute to the development of a strategy for the sustainable protection of water resources.

1. In the structure of the actual Water Footprint for Poznań, a strategy should be set that will enable an increase in the percentage of the green WFTP indicator and a reduction in the blue and grey WFTP indicators.
2. For instance, green roofs should be installed to increase the indicator level for the green water footprint. They will increase the biologically active surface, while reducing the sealed surface. Also, permeable surfaces, i.e., openwork slabs, will increase rainwater retention and reduce the annual runoff to 60%.
3. Reducing the blue footprint is associated with residents' awareness of saving water. Water-saving measures should include the collection of rainwater within households and then using it, for instance, for watering plants or grasslands, flushing the toilet or washing cars. A critical factor in reducing the blue footprint of water consumption should be an effective modernisation of the water supply network.
4. On the other hand, an increase in the quality standards for industrial wastewater discharged into the municipal sewage system, and the modernisation of wastewater treatment will contribute to lowering the amount of grey indicator water consumption.

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