Journal of
Water & Climate Change

Journal of Water and Climate Change Vol 14 No 1, 223 doi: 10.2166/wcc.2022.267

Assessment of energy performance and GHG emissions for the urban water cycle toward sustainability

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ABSTRACT

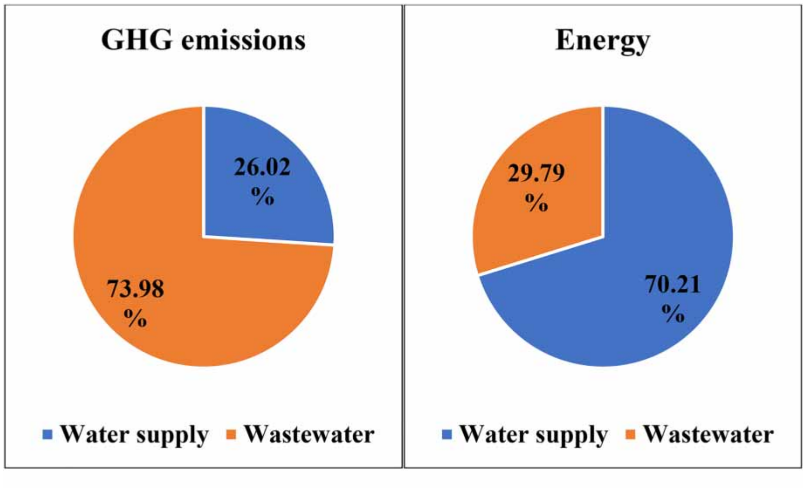
This study presents a holistic approach to evaluate energy performance and greenhouse gas (GHG) emissions from urban water supply and sanitation stages, which are important for sustainable water management and climate change mitigation. The study was conducted for Antalya city of Turkey to compare baseline and improved scenario conditions using the Energy Performance and Carbon Emissions Assessment and Monitoring (ECAM) tool. The current application of urban water and wastewater services was defined as the baseline scenario. For the improved urban water cycle, the reduction of non-revenue water, onsite sanitation prevention, increase in energy efficiency, biogas production and reuse of treated wastewater were investigated. Water supply and sanitation stages contributed to approximately 26 and 74% of total GHG emissions and 70 and 30% of energy consumption for the baseline scenario, respectively. GHG emissions were determined approximately as 52,423 tCO_2eq/year for CO_2 (40%), 47,029 tCO_2eq/year for CH_4 (35%) and 33,006 tCO_2eq/year for N_2O (25%) for the baseline scenario. The total GHG emissions of 132,457 tCO_2eq/year and energy consumption of 136,328 MWh/year were reduced by 27.65% for GHG emissions and 16.48% for energy consumption for the improved urban water cycle. The outcomes of this research are expected to achieve sustainable cities and combat climate change.

Key words: Antalya city, climate change, energy efficiency, greenhouse gas emissions, sanitation, water supply

HIGHLIGHTS

- Energy performance and carbon emission assessment and monitoring study for the urban water cycle is conducted.
- The baseline condition and improved water supply and sanitation stages are assessed.
- Impacts of non-revenue water, onsite sanitation reduction and treated wastewater reuse on GHG emissions are investigated.
- Energy and carbon footprint analyses are performed.
- GHG emissions, energy performance and service level indicators for wastewater collection and treatment are examined.

GRAPHICAL ABSTRACT



Baseline scenario for urban water cycle

LIST OF ACRONYMS

ASAT	Antalya Water and Wastewater Authority
BOD_5	5-day biochemical oxygen demand
CF	carbon footprint
ECAM	Energy Performance and Carbon Emissions Assessment and Monitoring
EF	energy footprint
ETS	Emissions Trading System
EU	European Union
GHG	greenhouse gas
GWP	global warming potential
IPCC	Intergovernmental Panel on Climate Change
IWA	International Water Association
LCA	life cycle assessment
MMA	Metropolitan Municipality of Antalya
NDCs	Nationally Determined Contributions
NRW	non-revenue water
SIV	system input volume
TN	total nitrogen
TP	total phosphorus
WDN	water distribution network
WWTP	wastewater treatment plant

INTRODUCTION

Climate change is a very crucial global issue that threatens all nations by raising the Earth's surface temperature, causing sea-level rise, changes in precipitation patterns and intensities, evapotranspiration rates, and more intense and frequent occurrences of floods and droughts (Valipour 2017; Hamdi *et al.* 2020). These consequences lead to adverse impacts on the quality and quantity of water resources, human life, houses and infrastructure, agricultural production and the ecosystem. The threats of water scarcity and desertification impose challenges to ecosystems, social and economic activities that require effective water stress mitigation measures (Tsanov *et al.* 2020) and the evaluation of public services delivery performance mainly in developing countries (Siddiqui *et al.* 2021). The urban water cycle, which is composed of water supply, wastewater collection, treatment and disposal, is one of the critical sectors threatened by climate change. Increasing demand for adequate and hygienic water supply and more stringent quality standards for wastewater treatment plant (WWTP) effluents cause increases in energy consumption and consequently greenhouse gas (GHG) emissions. The urban water cycle was reported to account for 1–3% of total electric energy consumption (Longo *et al.* 2016), as much as 40% of municipal energy use, and 3–10% of the global warming potential (GWP) by direct and indirect GHG emissions, in many European countries (Samuelsson *et al.* 2018). Increasing energy demand and global commitments to reduce GHG emissions led many countries to renewable energy production, and therefore, small-scale hydropower plants showed a massive expansion (Kuriqi *et al.* 2019). However, the balance between hydropower production and ecosystem conservation needs to be studied in detail by coupling hydrologic and ecohydraulic approaches (Kuriqi *et al.* 2020), analyzing ecological impacts (Kuriqi *et al.* 2021) and assessing energy storage benefits (Malka *et al.* 2022). Sustainable management of the urban water cycle, which leads to low-carbon emissions, is highly dependent on water-use efficiency, energy efficiency, energy recovery, reuse of treated wastewater and nutrient recycling.

In the last two decades, the estimation of water and carbon footprint (CF) studies gained high interest. Several models and tools have been presented in the literature to estimate CF from different components of the urban water cycle (WWTPs, water and wastewater services and biological treatment units). In addition, different emission categories have been addressed, namely, direct and dissolved GHG, sludge disposal, energy, chemicals and transport. CFCT (Gustavsson & Tumlin 2013), CF-TOOL CTRL (Baeza *et al.* 2017), CHEApet (2011), BSM2G (Flores-Alsina *et al.* 2012) and BSM2-e (Sweetapple *et al.* 2013) models are applicable to WWTPs, whereas DEEM and ASMN (Guo *et al.* 2012) are used to estimate CF from biological wastewater treatment units. WESTWeb (2022), Energy Performance and Carbon Emissions Assessment and Monitoring (ECAM; WaCCliM 2022) and WWEECarb (Marinelli *et al.* 2021) tools address urban water and wastewater services for the assessment of carbon emissions. There are several studies for the application of the life cycle assessment (LCA) approach to estimate CF of water and wastewater services, such as for Pamplona, Columbia (Ortiz-Rodriguez *et al.* 2020), Ukraine (Levkovska *et al.* 2020), Denmark and Sweden (Delre *et al.* 2019), Gold Coast region of Australia (Lane *et al.* 2015), municipality of Aveiro in Portugal (Lemos *et al.* 2013) and USA (Zib *et al.* 2021).

The recent research studies related to the sanitation stage of the urban water cycle addressed the analysis of wastewater infrastructure for total energy and GHG emissions considering the water–energy–carbon nexus (Singh & Kansal 2018), carbon neutrality of wastewater treatment systems for energy, nutrient and water recovery (Mo & Zhang 2012), comparison of different wastewater and sludge treatment technologies and disposal alternatives for the lowest CF (Chai *et al.* 2015), analysis of energy consumption in WWTPs to evaluate water, CF and energy footprints (EF), and gray water footprint reduction (Gu *et al.* 2016), application of a new methodological approach to determine direct and indirect emissions from WWTPs according to the guidelines of ISO 14064-1 (Marinelli *et al.* 2021) and CF estimation of municipal water and wastewater services by embodied energy associated with topographic characteristics, efficiency of water and wastewater treatment systems and pumps (Bakhshi & Demonsabert 2012). In the case of the water supply stage, the relevant research studies focused on the evaluation of alternatives for the water supply infrastructure system by integrated CF and cost–benefit analysis (Qi & Chang 2012), analysis of the water cycle by LCA considering the impacts of water treatment and desalination plants, water losses in the water works, electrical consumptions and network maintenance (Del Borghi *et al.* 2013), implementation of performance indicators to compare impacts of energy-saving, energy production and water losses reduction on water supply (Puleo *et al.* 2015), evaluation of water cycle for hot spots of carbon emissions and pumping efficiency (Lin & Kang 2019) and comparison of current and future alternative water reclamation and resource recovery scenarios (Lahmouri *et al.* 2019).

In the literature, there is no holistic study for the assessment of CF, energy performance and GHG emissions for both water supply and sanitation stages of the urban water cycle, which considers critical management scenarios such as the reduction of non-revenue water (NRW), an increase of wastewater reuse and improvements in wastewater treatment processes. Therefore, the main objective of this study is to present a holistic approach for evaluating CF, energy performance and GHG emissions of the urban water supply (abstraction, treatment and distribution) and sanitation stages (wastewater collection, treatment, discharge, sludge management and onsite sanitation) with the consideration of critical management scenarios for NRW reduction, improvements in wastewater treatment processes and wastewater reuse. The application site is Antalya city, which faces the common problems of high NRW and very limited recovery of treated water and nutrients. Consequently, there is an urgent need to improve the sustainable management of urban water by increasing water and energy efficiency and reducing GHG emissions. For this purpose, ECAM methodology was implemented. In the ECAM tool, GHG emissions are assessed in consistency with the methodology of the Intergovernmental Panel on Climate Change (IPCC), and the performance indicators of the International Water Association (IWA) are used for water supply and sanitation service levels and energy performance (ECAM 2018). The novelty of this research is to assess the impacts of several management scenarios related to the urban water supply (reduction of physical water losses and energy recovery from the excess water pressure in water distribution networks (WDN)) and sanitation stages (preventing onsite sanitation, increasing energy efficiency, biogas production and reuse of treated wastewater) on CF, energy performance and GHG emissions. The outcomes of this research are expected to provide a valuable contribution to the reduction of indirect and direct emissions of the urban water cycle to combat climate change. The presented study for Antalya city covers the urban water cycle in a holistic approach with several management scenarios, being different from the previous studies in the literature. The paper is organized as follows: the section 'Material and Methods' presents information about the study area and methodology, the section 'Results and Discussion' includes the results of applied scenarios and their discussion, and finally, the last section presents the conclusions.

MATERIAL AND METHODS

Urban water supply and sanitation in the study area

Antalya city is in the south of Turkey and along the Mediterranean Sea coast. The population of Antalya city was reported at 1,420,166 for the year 2020. The city is a worldwide famous domestic and international tourist destination. Despite the COVID-19 pandemic which was widespread and risky in the years 2020 and 2021, the whole of Antalya province received more than 9 million international tourists in 2021. The Antalya Water and Wastewater Authority (ASAT) is responsible for the municipal water and wastewater services in Antalya province, which covers a surface area of 20,723 km^2. The water supply and distribution system in Antalya city is shown in Figure 1 where all the urban water is supplied from groundwater sources. There are seven main pressure zones (P1–P7) in the water supply and distribution system in Antalya city, as depicted in Figure 1 with different colors. These pressure zones were designed based on the topography and the desired water pressure levels in the WDN. The pressure zones P3 and P7 cover considerably high surface areas with respect to the other pressure

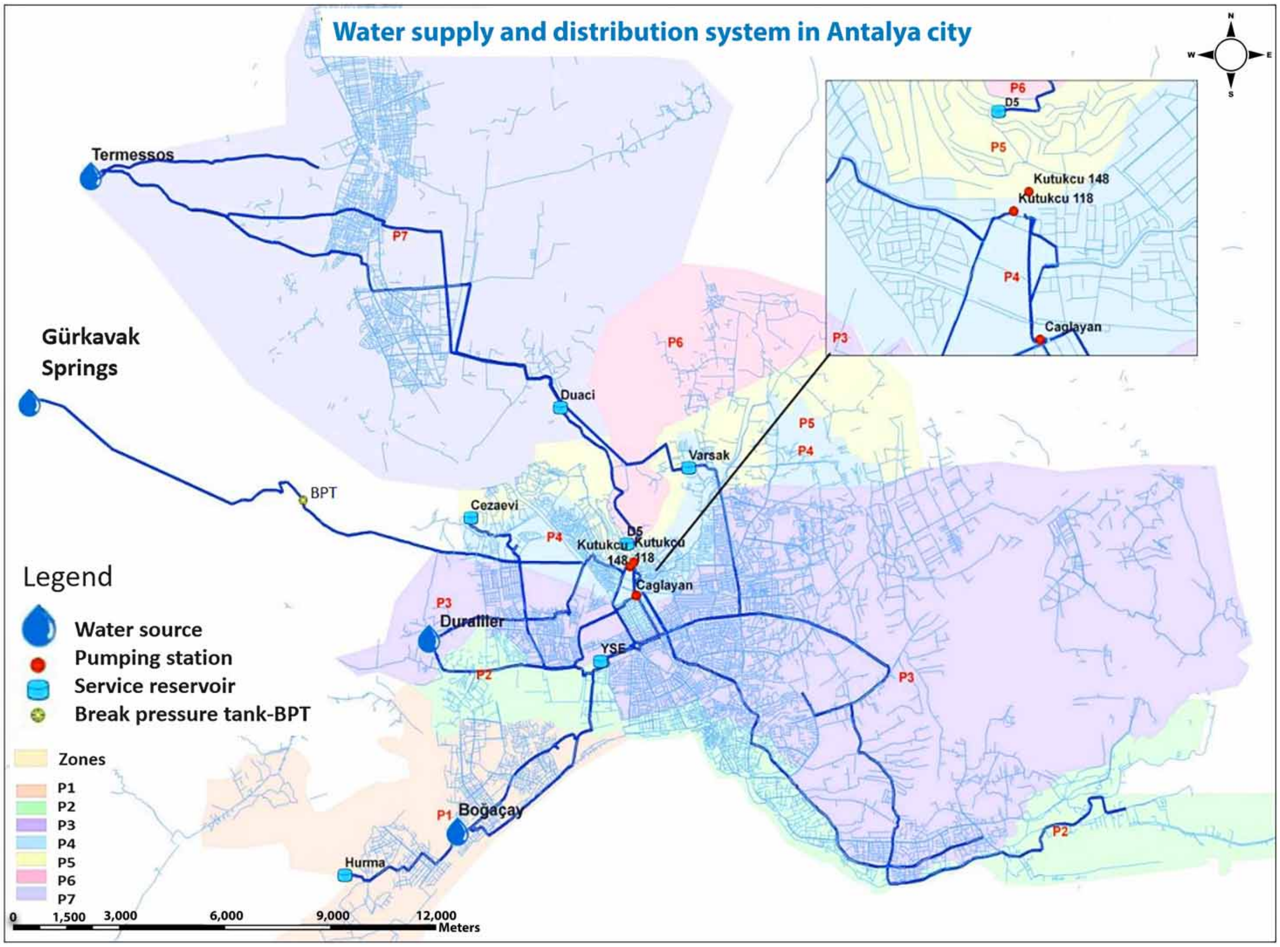


Figure 1 | Water supply system of Antalya city with the pressure zones.

zones where P7 is located at the highest elevation. Additionally, pressure zones P1 and P2, which lie along the Mediterranean Sea coast, have the lowest elevation levels.

The sources of water supply, served population, abstracted volumes of water and the energy consumed for water abstraction are given in Table 1. Arsenic treatment by pressurized filters and disinfection is applied at *Termessos* Wells, whereas only disinfection by chlorine is applied at the rest of the water supply sources. The annual energy consumed for arsenic treatment was estimated at 2,756,179 kWh in 2020. There is an increasing demand for urban water supply in Antalya province as the per capita water consumption increased from 293 to 329 L/person/day between the years 2010 and 2018 (TSI 2021). The level of NRW in Antalya city WDN was reported as 44.1%, which corresponds to more than 63 million m^3 of water for the year 2020 and the physical water losses level was 35.37%. The water balance for Antalya city in 2020 is depicted in Supplementary Table S1.

Approximately 87% of the population of Antalya city is connected to sewers, and the entire collected wastewater receives an advanced level of treatment. There are two WWTPs, namely *Hurma* and *Lara*, in Antalya city, and the plant effluents are discharged to the Mediterranean Sea by deep sea outfall systems following disinfection. Treatment capacities, influent pollution loads and treatment efficiencies of these WWTPs are presented in Table 1. About 1.3% of *Hurma* WWTP effluents (1.14 million m^3/year) are reused for in-plant green area irrigation and as cooling water in the thermal sludge drying unit. Mechanical thickening, anaerobic digestion, dewatering and thermal drying processes are applied for sludge treatment at the *Hurma* WWTP, and the biosolids with more than 90% dry solids are transported to a cement factory for incineration. In the case of *Lara* WWTP, the excess sludge is mechanically dewatered up to 25% dry solids and then transferred to the *Hurma* WWTP for thermal drying. The volume of biogas produced at the *Hurma* WWTP is more than 5.5 million m^3/year, and 50% of the biogas is valorized at the cogeneration unit to obtain heat and electricity simultaneously, which is used to heat the anaerobic digester and the thermal drying units. As depicted in Supplementary Figure S1, the biological units of the *Lara* WWTP are fully covered by a football field and the sedimentation tanks are covered by a special design of caps. This unique design of the treatment plant was selected to improve the landscape view, as this plant is located within an intense tourism area.

The total electricity consumption of ASAT in Antalya province was reported approximately 349.5 million kWh/year, which corresponds to 4.5% of electricity consumption in Antalya province (ASAT 2021). Furthermore, the consumed electricity for water and wastewater services in Antalya city was nearly 95.7 and 40.6 million kWh/year in 2020, respectively. There is a need for a holistic study to assess the energy performance and GHG emissions from the urban water cycle and to propose alternative solutions to improve water and energy efficiency in Antalya city.

Table 1 | Water supply and WWTPs in Antalya city

Water supply

Source	**Served population (people)**	**Volume of abstracted water (m^3/year)**	**Energy consumed from the grid for abstraction (kWh)**
Bogacay Pumping Station	137,206	13,821,306	7,018,757
Duraliler Pumping Station	589,384	59,370,947	47,922,051
Gurkavak Springs	20,928	2,108,124	0
Termessos Wells	520,481	52,430,001	24,805,611
Other wells	152,167	15,328,400	13,217,068
Total	1,420,166	143,058,778	92,963,487
Sanitation			
WWTP name and capacity	**Population equivalent**	**Influent loads[a] (kg/year)**	**Treatment efficiency[a] (%)**
Hurma 210,000 m^3/day	1,400,000	$BOD_5 = 25,417,542$ $TN = 3,358,276$ $TP = 408,261$	$BOD_5 = 96$ $TN = 88$ $TP = 83$
Lara 62,500 m^3/day	500,000	$BOD_5 = 6,908,802$ $TN = 887,589$ $TP = 160,726$	

BOD_5, 5-day biochemical oxygen demand; TN, total nitrogen; TP, total phosphorus.

ECAM assessment tool

ECAM is a web-based, free, and open-source decision support tool developed by the Water and Wastewater Companies for Climate Mitigation (WaCClim) Project to guide water utilities toward energy and carbon neutrality (ECAM 2018). ECAM is a practical tool to quantify GHG emissions and to assess energy performance for the urban water cycle in a holistic approach, as depicted in Figure 2.

In the ECAM tool, direct and indirect emissions from the urban water cycle are defined in three different scopes according to the IPCC Guidelines for National Greenhouse Gas Inventories and Biosolids Emissions Assessment Model (BEAM). Scope 1 includes direct CO_2, CH_4 and N_2O emissions from onsite fossil fuel combustion, CH_4, CO_2 and N_2O emissions from biological wastewater treatment, and CH_4 and N_2O emissions from fecal sludge management. In Scope 2, indirect GHG emissions from grid energy are computed considering an energy balance between energy inputs (electrical energy purchased from the grid and self-produced renewable energy) and energy outputs (surplus renewable electricity and energy consumption for the operation of equipment). Finally, Scope 3 involves CO_2 and N_2O emissions from untreated wastewater discharged directly to water bodies, N_2O emissions from the effluent discharge to receiving waters, CO_2, CH_4 and N_2O emissions from the transport of sludge or water off-site from the WWTP, and CH_4 and N_2O emissions from sludge and fecal sludge management. Sludge management covers storage, disposal (landfilling, land application, incineration, composting and stockpiling) and transport to a disposal site. The ECAM tool also computes the GHG emission offset from water reuse, nutrient recovery and carbon sequestration from sludge management. In this application, GHG emissions avoided due to wastewater treatment were investigated for biogas valorization, nutrient (total nitrogen (TN) and total phosphorus (TP)) reuse by displacing synthetic fertilizers and wastewater reuse by eliminating discharge to receiving waters. In the ECAM tool, the electrical energy produced (kWh) from biogas valorization (defined as wwt_nrg_biog) is considered to estimate GHG emissions avoided due to biogas valorization using Equation (1):

$$\mathrm{CO_2\ equiv.avoided(kgCO_2e)} = \mathrm{wwt\_nrg\_biog} * \mathrm{emission\ factor(kgCO_2e/kWh)} \tag{1}$$

In this equation, the emission factor was defined as 0.36 $\mathrm{kgCO_2e/kWh}$ for Turkey (EIB 2020).

Additionally, the GHG emissions avoided due to TN and TP reused are calculated as follows:

$$\mathrm{CO_2\ equiv.avoided(kgCO_2e)} = \mathrm{TNreused(kg/m^3)} * \mathrm{default\ conversion\ factor(kgCO_2/kgN)} \tag{2}$$

$$\mathrm{CO_2\ equiv.avoided(kgCO_2e)} = \mathrm{TPreused(kg/m^3)} * \mathrm{default\ conversion\ factor(kgCO_2/kgP)} \tag{3}$$

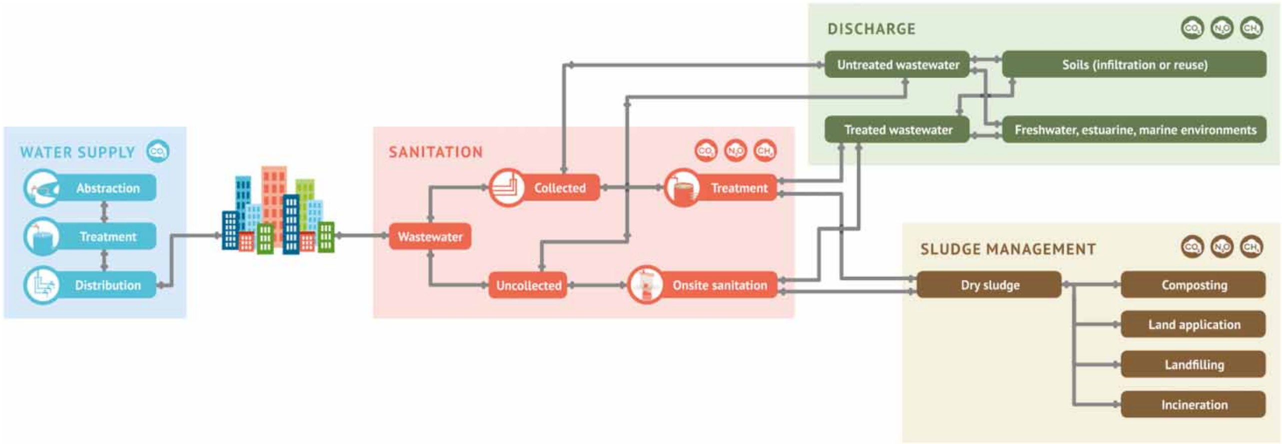


Figure 2 | Stages of the urban water cycle in the ECAM tool (ECAM 2018).

Furthermore, GHG emissions avoided due to wastewater reuse were quantified by the amount of GHG (N_2O) avoided by not discharging the treated effluent to a receiving body. The simplified equation for this quantification is given below:

$$CO_2\,\text{equiv.avoided}(\text{kgCO}_2\text{e}) = \text{TN}_{\text{eff}}(\text{mg/L})/1000 * \text{V}_{\text{eff}}(\text{m}^3) * \text{default conversion factors} \tag{4}$$

where TN_{eff} is the TN concentration in the effluent and V_{eff} is the volume of reused effluent.

CH_4 and N_2O emissions from sewers, CO_2, CH_4 and N_2O emissions from truck transport of water, emissions from the manufacture and transport of chemicals and emissions from the construction materials used are not included in the ECAM tool. The scope of application, methodology, conceptual background and all the mathematical formulations are presented elsewhere (ECAM 2018). In the ECAM tool, the emissions are counted in terms of CO_2 equivalents. In this study, the 100-year GWP for CH_4 and N_2O were taken as 34 and 298 times of CO_2 according to the IPCC 5th Assessment Report (IPCC 2013). The emission factor for grid electricity in Turkey was taken as 0.36 kg CO_2eq/kWh (EIB 2020). The main inputs for the sanitation stage are given in Supplementary Table S2. Emission factors for CH_4 and N_2O were 0.018 kg CH_4/kg $\text{BOD}_{\text{removed}}$ and 0.016 kg N_2O-N/kg N for wastewater treatment and 0.068 kg CH_4/kg $\text{BOD}_{\text{removed}}$ and 0.005 kg N_2O-N/kg $\text{N}_{\text{removed}}$ for treated wastewater discharge.

Management scenarios

The ECAM tool was applied to evaluate different management scenarios for urban water supply and sanitation stages as described below:

- *Baseline scenario*: The current conditions of water and wastewater services in Antalya city were investigated as the baseline scenario. Physical water losses level is given as 35.37% in the year 2020 (ASAT 2021).
- *Improved water supply scenario*: The related Turkish legislation states that total water losses should not be higher than 25% of the system input volume (SIV) (MFWA 2014). Physical water losses usually make up 60% of the total water losses in Turkey (Muhammetoglu & Muhammetoglu 2017). Thus, physical water losses should not be higher than 15% of SIV according to Turkish legislation. This means that the existing physical water losses in Antalya city should be reduced from 35.37 to 15%. The improved water supply scenario includes two components.
  - reduction of NRW (reducing total water losses to 25% which implies reducing physical water losses to 15% of SIV) and
  - energy production from excess pressure in water transmission lines.
- *Improved sanitation-stage scenario:* This scenario includes four components as given below:
  - increasing the population connected to sewers to 100%,
  - increasing energy efficiency in WWTPs by 10%,
  - increasing biogas production in the Hurma WWTP by 5%, and
  - increasing reuse of treated wastewater to 5%.

The above-mentioned scenario components were reported as performance improvement targets by ASAT in their yearly progress reports (ASAT 2022). These components are to be realized by operational improvements in the WWTP processes, the use of more energy-efficient equipment and increased reuse of treated wastewater. Likewise, operational optimization and technology improvements in WWTPs were reported to achieve 5–30% energy-savings (Longo *et al.* 2016). In fact, the improved water supply and sanitation-stage scenarios are realistic for Antalya city and all the other metropolitan municipalities in Turkey because the water utilities are enforced to reduce total water losses in urban WDNs below 25% of system input volume till 2028, and also there are national projects to increase reuse of treated wastewater in Turkey. Furthermore, many water utilities in the metropolitan cities of Turkey have similar operational targets and projects to improve urban water supply and sanitation services.

RESULTS AND DISCUSSION

Baseline scenario

GHG emissions and energy consumption values for the baseline scenario are presented in Table 2, as given by the ECAM tool. The total GHG emissions for both water supply and sanitation stages were about 132,457 tCO_2eq/year for Antalya city for the year 2020. The distributions of GHG emissions for the water supply and sanitation stages were about 34,459 tCO_2eq/year (26.02%) and 97,998 tCO_2eq/year (73.98%), respectively. In the case of the urban water cycle, abstraction

Table 2 | GHG emissions and energy consumption for the baseline scenario

Stage	GHG emissions (kg CO_2eq/ year)	GHG emissions (%)	GHG emissions (kg CO_2eq/ year/ capita)	Energy consumption (kWh/year)	Energy consumption (%)
Abstraction	33,466,855	25.27	23.57	92,963,487	68.19
Treatment	992,224	0.75	0.70	2,756,179	2.02
Distribution	0	0	0	0	0
Total water supply stage	**34,459,080**	**26.02**	**24.27**	**95,719,666**	**70.21**
Collection	712,269	0.54	0.58	1,978,524	1.45
Treatment	61,184,121	46.19	49.72	38,630,103	28.34
Onsite sanitation	36,101,368	27.25	190.49	0	0
Total sanitation stage	**97,997,758**	**73.98**	**79.63**	**40,608,627**	**29.79**
Total	**132,456,837**	**100**		**136,328,293**	**100**

caused the highest CO_2 emissions (64%), whereas distribution did not cause any GHG emissions. Considering water supply and sanitation stages, GHG emissions were determined approximately as 52,423 tCO_2eq/year for CO_2 (40%), 47,029 tCO_2eq/year for CH_4 (35%) and 33,006 tCO_2eq/year for N_2O (25%), as shown in Figure 3. There were no CH_4 and N_2O emissions from the water supply stage. Within the sanitation stage, onsite sanitation was the main contributor to CH_4 emissions (77%), whereas wastewater treatment was the only contributor to N_2O emissions. For the sanitation stage, the collection of wastewater caused the lowest GHG emissions (0.54%), while treatment processes caused the highest (46.19%) and the contribution of onsite sanitation to GHG emissions was also high (27.25%). In the case of energy consumption, the total energy consumption for the urban water cycle of Antalya city was about 136,328 MWh/year for the year 2020. Water supply and sanitation stages consumed about 95,720 MWh/year (70.21%) and 40,609 MWh/year (29.79%), respectively. Abstraction was the main contributor (68.19%) to energy consumption of the urban water cycle, whereas water and wastewater treatment consumed 30.36% of all energy consumption. For the baseline scenario, NRW in Antalya city was high (44.1%) and also physical water losses were as high as 35.37% (Supplementary Table S1). This means that 35.37% of the consumed energy and the GHG emissions of the water supply stage are due to physical losses.

Improved water supply scenario

The first component of the improved water supply scenario involved the reduction of NRW and physical water losses levels to 25 and 15%, respectively. Table 3 summarizes GHG emissions and energy consumption for the improved water supply

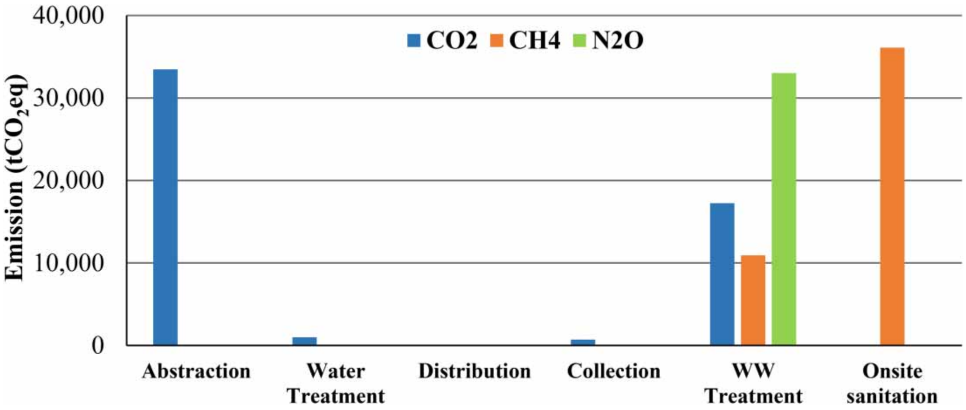


Figure 3 | CO_2, CH_4 and N_2O emissions of the urban water cycle for the baseline scenario.

Table 3 | GHG emissions and energy consumption for improved water supply and sanitation-stage scenarios

Stage	GHG emissions (kg CO_2eq/year)	GHG emissions (%)	GHG emissions (kg CO_2eq/ year/ capita)	Energy consumption (kWh/ year)	Energy consumption (%)
Abstraction	25,060,387	26.15	17.65	69,612,187	61.14
Treatment	742,990	0.78	0.52	2,063,860	1.81
Distribution	0	0	0	0	0
Total water supply stage	**25,803,377**	**26.93**	**18.17**	**71,676,047**	**62.96**
Collection	739,762	0.77	0.52	2,054,895	1.80
Treatment	69,285,113	72.30	48.79	40,121,110	35.24
Onsite sanitation	0	0	0	0	0
Total sanitation stage	**70,024,875**	**73.07**	**49.31**	**42,176,005**	**37.04**
Total	**95,828,252**	**100**		**113,852,052**	**100**

scenario. The GHG emission of the improved water supply scenario was estimated at 25,803 tCO_2eq/year, which corresponded to 26.93% of all GHG emissions for the urban water cycle. In the case of energy consumption, the improved water supply stage consumed about 71,676 MWh/year, which makes 62.96% of all urban water energy use. With the reduction of physical water losses, 25% reduction in GHG emissions and energy consumption was achieved with respect to the baseline scenario. The abstraction substage was the main source of CO_2 emissions (around 97%) from the water supply stage where there were no emissions of CH_4 and N_2O as shown in Figure 4.

GHG emissions and specific energy of the different water sources demonstrated wide variations as shown in Table 4 for the abstraction substage for the baseline and improved urban water supply scenarios. As the energy consumed for abstraction, treatment and distribution was null for *Gurkavak* Springs, there were no GHG emissions for this source. For the baseline scenario, the GHG emissions of different water supply sources varied between 17.16 and 31.27 $kgCO_2$eq/year/capita. However, GHG emissions for the abstraction substage of the improved water supply scenario were reduced, and the values were between 12.85 and 23.41 $kgCO_2$eq/year/capita for the same water supply sources.

The second component of the improved water supply scenario involved energy production from excess pressure in water transmission lines. *Termessos* Wells is an important water supply source for Antalya city which is 375 m above mean sea level (asl), and it supplies water by gravity to residential areas close to the sea level with a 1,000 mm diameter steel pipe. Additionally, the surface level of *Gurkavak* Springs is 260 m asl which supplies water by gravity to much lower elevations by a 350 mm cast iron pipe. Currently, break pressure tanks are used to break the excess pressure; however, ASAT prepared feasibility

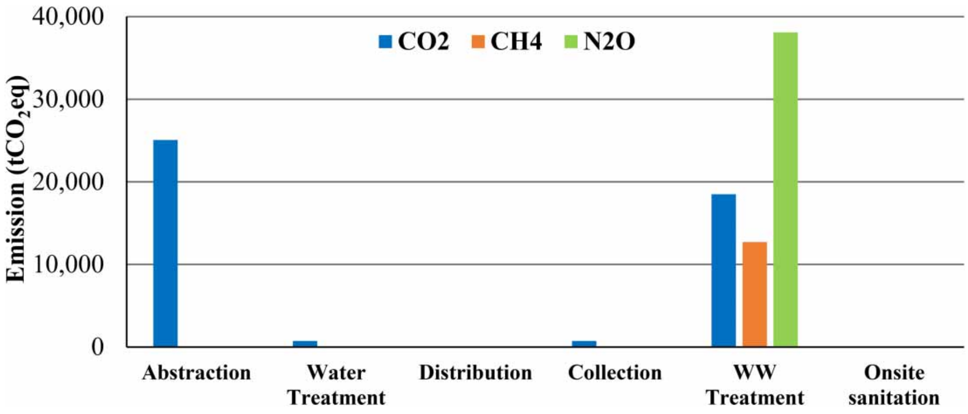


Figure 4 | CO_2, CH_4 and N_2O emissions of the urban water cycle for the improved water supply and sanitation-stage scenarios.

Table 4 | GHG emissions and energy consumptions for abstraction substages of different water sources for baseline and improved water supply scenarios

Water supply source	GHG emission (kg CO_2eq/year)	GHG emission (kg CO_2eq/year/capita)	Energy consumption (kWh/year)	Energy consumption per unit abstracted water (kWh/m^3)
Baseline scenario				
Bogacay Pumping Station	2,526,753	18.42	7,018,757	0.51
Duraliler Pumping Station	17,251,938	29.27	47,922,051	0.81
Gurkavak Springs	0	0	0	0
Termessos Wells	8,930,020	17.16	24,805,611	0.47
Other wells	4,758,144	31.27	13,217,068	0.86
Improved water supply scenario				
Bogacay Pumping Station	1,892,063	13.79	5,255,730	0.51
Duraliler Pumping Station	12,918,461	21.92	35,884,613	0.81
Gurkavak Springs	0	0	0	0
Termessos Wells	6,686,907	12.85	18,574,743	0.47
Other wells	3,562,956	23.41	9,897,101	0.86

projects to produce energy from this excess pressure. Energy production from the excess water pressure in these two water transmission lines was designed as follows:

- *Termessos-2* Pressure Reduction Power Station with a capacity of 0.98 Mwe, yearly electricity production of 7,816,000 kWh and a pay-back period of 5 years
- *Kutukcu* Pressure Reduction Power Station with a capacity of 1.5 Mwe, yearly electricity production of 8,898,120 kWh and a pay-back period of 4 years for *Gurkavak* Springs

Thus, the total energy production is estimated at 16,714,120 kWh/year, which corresponds to 12.26% of all urban water energy consumption for the baseline scenario. Consequently, the energy recovered from excess water pressure corresponds to a saving of 6,017,083 kg CO_2eq/year of GHG emissions.

Improved sanitation-stage scenario

For the implementation of the improved sanitation-stage scenario, all the scenario components (extension of wastewater collection and treatment services to the whole resident population of Antalya city, increasing wastewater reuse to 5%, increasing biogas production by 5% and increasing energy efficiency in WWTPs by 10%) were applied simultaneously. GHG emissions and energy consumption levels for the improved sanitation stage are presented in Table 3 and Figure 4. GHG emissions and total energy consumption of the improved sanitation stage were estimated at 70,025 tCO_2eq/year and 42,176 MWh/year, respectively. Wastewater collection and treatment substages constituted 0.77 and 72.30% of total GHG emissions, respectively. In the case of energy consumption, collection and treatment substages consumed 1.80 and 35.24% of all urban water energy use, respectively. GHG emissions of the improved sanitation stage contributed to 73.07% of the total GHG emissions and 37.04% of the total urban water energy use. Since there is no onsite sanitation for the case of the improved sanitation stage, which implies full coverage of wastewater collection and treatment, GHG emissions and energy consumption were null for onsite sanitation (Figure 4). With the implementation of the improved sanitation stage scenario, 29% reduction in GHG emissions was achieved with respect to the baseline scenario. The energy consumed for the sanitation stage increased by 3.85% with respect to the baseline scenario due to the extension of wastewater collection and treatment services to the whole resident population of Antalya city. A detailed assessment of GHG emissions, energy performance and service level indicators for improved sanitation-stage scenario are given in Table 5.

The improved sanitation-stage scenario was effective to reduce energy consumption for wastewater collection (from 0.022 to 0.02 kWh/m^3) and wastewater treatment (from 0.43 to 0.39 kWh/m^3). With the prevention of onsite sanitation, the organic material removed at the WWTPs increased to more than 35,812 tBOD_5/year and energy consumed for the removal of organic

Table 5 | Detailed assessment of GHG emissions, energy performance and service level indicators for wastewater collection and treatment

Stages	**Baseline scenario**		**Improved sanitation-stage scenario**	
Collection				
Energy consumption per wastewater conveyed to treatment	0.022 kWh/m^3		0.02 kWh/m^3	
Treatment				
Energy consumption per treated wastewater	0.43 kWh/m^3		0.39 kWh/m^3	
BOD_5 mass removed	31,033,290 kg/year		35,812,417 kg/year	
Energy consumption per BOD_5 mass removed	1.24 kWh/kg BOD *(good)*		1.12 kWh/kg BOD *(good)*	
Energy production from biogas valorization per volume of treated wastewater	0.086 kWh/m^3 *(good)*		0.09 kWh/m^3 *(good)*	
Unit biogas produced per BOD_5 mass removed in wastewater treatment	43% *(good)*		43% *(good)*	
Sludge production	0.24 kg/m^3 *(good)*		0.24 kg/m^3 *(good)*	
Treatment	**kg CO_2eq/ year**	**kg CO_2eq/year/served population**	**kg CO_2eq/ year**	**kg CO_2eq/year/served population**
Electric (indirect emission)	13,906,837	11.3	14,443,600	10.17
Treatment process	38,148,693	31.0	44,023,494	31.0
Biogas (anaerobic sludge digestion)	4,916,267	3.99	5,957,041	4.19
Sludge management	29,815	0.024	34,364	0.024
Discharged water	4,182,508	3.4	4,826,614	3.4

material decreased to 1.12 kWh/kg BOD. Energy production from biogas valorization, unit biogas produced per BOD_5 mass removed in wastewater treatment and sludge production rate were all improved and classified as good operation. Moreover, service level indicators were improved for indirect GHG emissions of electric use and direct GHG emissions due to biogas production.

The ECAM tool was applied to analyze GHG emissions avoided due to wastewater treatment, biogas valorization, nutrient and wastewater reuse for the baseline and the improved sanitation scenarios, as well (Figure 5). The investigated scenario components of onsite sanitation prevention, a 10% increase in energy efficiency, a 5% increase in biogas production and an increasing reuse of treated wastewater to 5% were effective to avoid high amounts of GHG emissions with respect to the baseline scenario.

The GHG emissions avoided due to wastewater treatment, including biogas valorization, nutrient (TN and TP) and wastewater reuse components, mainly depend on the following factors: population with onsite sanitation, served population of

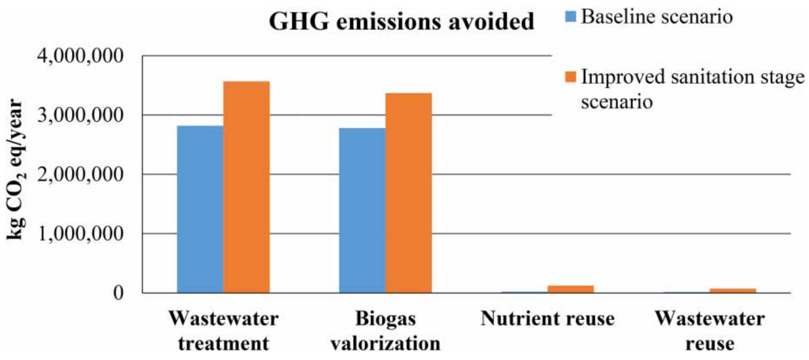


Figure 5 | GHG emissions avoided due to wastewater treatment, biogas valorization, nutrient and wastewater reuse for the baseline and improved sanitation-stage scenarios.

wastewater treatment, volume of treated wastewater, volume of reused effluent, valorized biogas and reused TN and TP. For the baseline scenario, served population of wastewater treatment, volume of treated wastewater, volume of reused effluent, valorized biogas and reused TN and TP values were all lower than the improved sanitation scenario condition. Consequently, the GHG emissions avoided in total for wastewater treatment were higher for the improved sanitation scenario than the baseline scenario. One of the main reasons for this difference was onsite sanitation, which was valid only for the baseline scenario for a population of 189,516 persons. Furthermore, biogas valorization was the major process for the avoidance of GHG emissions (>94% for both scenarios) where the cumulative contribution of nutrient and wastewater reuse to the total GHG emissions avoided due to wastewater treatment was very low (5.6% for the improved sanitation stage and 1.3% for the baseline scenarios) as depicted in Figure 6.

DISCUSSION

The ECAM tool was very effective in analyzing CF, energy performance and GHG emissions for the urban water cycle of Antalya city and comparing water supply and sanitation stages. The results showed that the contribution of the sanitation stage to GHG emissions (CF) was significantly higher than the water supply stage in Antalya city where wastewater treatment and onsite sanitation were the most contributing substages. Conversely, the energy consumption of the water supply stage (EF) was significantly higher than the sanitation stage mainly due to the high energy consumption of groundwater abstraction to supply urban water to Antalya city. There were no emissions of CH_4 and N_2O from the water supply stage, whereas wastewater treatment caused emissions of CO_2, CH_4 and N_2O and onsite sanitation caused only CH_4 emissions.

The ECAM tool was previously applied in several countries such as Mexico, Peru, Burkina Faso, Egypt, Jordan, Zambia, India and Thailand to analyze energy efficiency and GHG emissions (WaCCliM 2022). In the study of Arsene *et al.* (2019), only the sanitation stage of the urban water cycle was evaluated by the ECAM tool for four Italian and Romanian WWTPs. In that study, two scenario conditions related to served population and energy efficiency were also investigated, being similar to the current study. Biogas recovery was reported to improve energy performance, while the largest contributions to GHG emissions were caused by energy consumption and methane production in wastewater treatment. Additionally, the national conversion factor, which is linked to each country's local energy mix, was mentioned as a key parameter. In another study, the baseline carbon emission assessment was conducted by the ECAM tool for water utilities in Madaba, Jordan considering the whole urban water cycle (Saidan *et al.* 2019). In that study, abstraction and distribution substages of water supply were estimated to consume approximately 90% of the total energy used in the urban water cycle and also water supply stage was the major contributor to the GHG emissions. In a recent study, CF and EF for the urban water cycle in Amman, Jordan were also investigated using the ECAM tool (Al-Omari *et al.* 2022). The results of the study showed that energy and CFs of the water supply stage were significantly higher than the sanitation stage mainly due to high energy consumption for the abstraction substage. CF of the sanitation stage was attributed to emissions of CH_4 and N_2O in WWTPs in addition to fossil fuel combustion for electricity production. Additionally, CF and EF for NRW in Amman were reported to be high, like Antalya city of Turkey.

There are global and regional actions to reduce GHG emissions and one of these attempts was the 2020 climate and energy package, set by the leaders of the European Union (EU) in 2007 and enacted in 2009. The package set three targets for the EU member state for 2020: (i) a 20% reduction in GHG emissions from the levels of 1990, (ii) a 20% increase in renewable energy

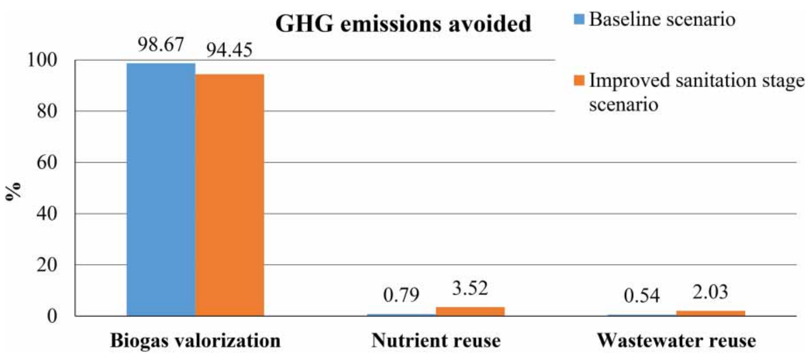


Figure 6 | Percentage values of GHG emissions avoided due to wastewater treatment for the baseline and improved sanitation-stage scenarios.

share of the total energy mix and (iii) 20% improvement in energy efficiency (EC 2022). The EU has achieved these 2020 targets by reducing GHG emissions by 31% from the 1990 levels, mainly due to the reduction of GHG emissions from the power plants, industry and aviation sectors included within the EU Emissions Trading System (ETS). Additionally, the share of renewable energy sources was 21.3% in 2020. However, 60% of total EU GHG emissions originate from the sectors not covered by the EU ETS such as housing, waste, non-ETS industry, agriculture and transport fields (EC 2022). Furthermore, all EU member states have their national targets for reducing GHG emissions from these sectors. According to the EU Green Deal Action Plan Declaration in 2019, the new EU targets were adopted to achieve 55% net emission reductions by 2030 and climate neutrality by 2050 (EC 2019).

On the global scale, the Paris Agreement was the first legally binding universal agreement for climate change, which was adopted by 196 parties at the Paris Climate Conference (COP21), in December 2015, and enacted in 2016. According to this agreement, governments agreed to take necessary actions that will keep the global average temperature increase to well below 2 °C, with the aim of 1.5 °C, above the pre-industrial levels. The Paris Agreement further aims to reduce global carbon emissions by 50% by 2030 and to achieve net-zero emissions by 2050. To achieve these global targets, countries submit their own national climate action plans, known as their Nationally Determined Contributions (NDCs). Turkey signed the Paris Agreement in 2016 and ratified it on October 6, 2021. Turkey's carbon emissions were reported to increase over the last decade with an average economic growth rate of 6.41% between the years 2010 and 2018. Turkey produced 369.5 million metric tons of CO_2 emissions in 2020 and is ranked 16th among the countries with the highest GHG emissions in the world, with a share of around 1% (Statista 2022). Recently, Turkey has committed to reducing CO_2 emissions by 21% by 2030 and to adopt net-zero emissions by 2053. The actions to achieve these goals were defined within the Green Deal Action Plan of Turkey, in addition to the major actions related to the water sector such as the sustainable management of water resources, the sustainable use of water in production and consumption, increasing the reuse of wastewater, controlling water losses in WDNs, increasing water efficiency and water saving, and reducing water consumption. In Turkey, water losses in urban water supply and distribution networks are challenging issues for all water utilities. The average value of NRW in Turkey was officially reported at 35% in 2018, but the actual NRW level is estimated to be much higher (Muhammetoglu & Muhammetoglu 2017). Additionally, the reuse of treated urban wastewater is very limited in Turkey being less than 2% (Nas *et al.* 2020). Consequently, there is an urgent need to reduce NRW (Firat *et al.* 2021), to increase the reuse of treated wastewater and nutrient recovery in Turkey, like many countries in the world.

Cities are among the large emitters of GHG emissions, and there is a need to estimate GHG emissions from urban areas (Kanakoudis & Papadopoulou 2014). According to the Sustainable Energy Action Plan of Metropolitan Municipality of Antalya (MMA), GHG emissions of Antalya city were investigated and the distribution of GHG emissions was estimated as follows: 40.9% from houses, 30.2% from transportation, 8.5% from energy production, 8.2% from the urban water cycle, 6.1% from industry and 6% from agriculture and husbandry (MMA 2021). Based on this Action Plan, CO_2 emissions per capita were reported as 4.25 ton CO_2eq (including industry) for the year 2019. MMA is a partner in the Covenant of Mayors for Climate & Energy, and it aims to reduce 40% of CO_2 emissions by 2030 and achieve net-zero emissions by 2050. MMA received the 'Climate Friendly Organization Certificate' from the Turkish Standards Institute in 2021 as the first organization in Turkey. In this current study, the reduction of GHG emissions and energy consumption were estimated by the ECAM tool for the improved water supply and sanitation stages of Antalya city as 36,628,585 kg CO_2eq/year (equivalent to carbon sink of around 3.6 million trees) and 22,476,241 kWh/year (equivalent to the annual electricity demand of around 8,500 houses), respectively. The implementation of an improved urban water cycle will contribute to the climate change mitigations of Antalya city. Furthermore, these actions are very crucial to manage urban water resources, increase water and energy efficiency in the urban water cycle, comply with the national Green Deal Action Plan for reducing GHG emissions and achieve sustainable cities. The research outcomes showed the importance of increasing energy and water efficiency in the urban water cycle that contributes to GHG emissions, but there is an urgent need for a broader study to further reduce GHG emissions from the houses and transportation in Antalya city.

CONCLUSIONS

This study presents a holistic approach to assess CF, energy performance and GHG emissions from the urban water cycle by considering critical management scenarios for water supply and sanitation stages. The study was conducted for Antalya city in Turkey, which faces common problems of high NRW in WDNs, the existence of onsite sanitation and very low levels of treated wastewater reuse. GHG emissions and energy consumption were compared for the baseline and improved water supply and sanitation stages for the year 2020 using the ECAM tool. Regarding the current applications of urban water and wastewater services as the baseline scenario, considerably high GHG emissions (132,457 tCO_2eq/year) and energy consumption (136,328 MWh/year) were estimated where water supply contributed to approximately 26% of all urban water GHG emissions and 70% of all urban water energy consumption. One important conclusion for the study is that the EF of the water supply stage was much higher than the sanitation stage, but the CF of the sanitation stage was much higher than the water supply. In the case of improved water supply and sanitation stages, total GHG emissions and energy consumption were estimated at 95,828 tCO2eq/year and 113,852 MWh/year, respectively, which imply 27.65% reduction in GHG emissions and 16.48% reduction in energy consumption with respect to the baseline scenario. The management scenarios are effective to accomplish considerable reductions in GHG emissions and energy consumption to combat the adverse impacts of climate change. Reduction of NRW and energy recovery from excess water pressure are effective to produce renewable energy and to reduce CF and EF in the water supply stage. Likewise, the prevention of onsite sanitation, reuse of treated wastewater, biogas valorization, improving energy efficiency in WWTPs by operational optimization and technology improvements are effective to reduce GHG emissions and to increase energy performance. There is a need for a more decisive and effective mechanism to force water utilities to improve their water and wastewater services at the urban scale. The presented study provides a good example to practitioners and researchers for the low-carbon operation of the urban water cycle and to increase water and energy efficiency, energy recovery and reuse of water and nutrients.

ACKNOWLEDGEMENTS

This publication is the outcome of the cooperation between the Environmental Engineering Department at Akdeniz University, Antalya, Turkey and the Water, Energy and Environment Center of the University of Jordan, Amman within the framework of the SWINDON/EXCEED project funded by the German Academic Exchange (DAAD). The authors wish to express their gratitude to the DAAD for funding this cooperation.

FUNDING

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

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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First received 15 July 2022; accepted in revised form 7 December 2022. Available online 20 December 2022