

## Article

# Identifying Water–Energy–Carbon Links in Urban Water Sectors: A Case Study of Incheon Metropolitan City, Republic of Korea

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**Abstract:** Water and energy are essential resources for human life, and carbon emissions (CEs) occur in tandem with their use. Thus, water, energy, and carbon are closely inter-related. Approximately 4% of the global energy is used in urban water sectors (UWSs), which encompass various processes such as water intake, treatment, and distribution and wastewater collection and treatment, all of which consume significant energy and emit CO<sub>2</sub>. Several countries are actively working toward achieving carbon neutrality by 2050–2060. Therefore, increasing energy efficiency and reducing CEs through comprehensive evaluations of UWSs is essential. This study aimed to quantify energy consumption and CEs in UWSs and proposed a methodology for analyzing water–energy–carbon (WEC) links at the city level. By applying it to Incheon Metropolitan City (IMC), we first identified the UWSs and established a WEC database. Based on this database, the WEC consumption and emissions were analyzed by process or administrative district, and visualizations using Sankey diagrams and Geographic Information System Mapping were created to enhance their understandability. In 2021, the UWSs in IMC consumed 308,496,107 kWh of energy, representing 32.7% of the public electricity consumption of IMC, with an average energy intensity of 0.46 and 0.38 kWh/m<sup>3</sup> for water supply systems (WSSs) and sewerage systems (SSs), respectively. Their carbon emissions totaled 315,765,358 kg CO<sub>2</sub>, accounting for 2.7% of IMC’s total carbon emissions, with an average carbon intensity of 0.21 and 0.58 kg CO<sub>2</sub>/m<sup>3</sup> for WSSs and SSs, respectively. The proposed methodology was used to comprehensively evaluate WEC consumption and emissions in IMC. It is expected to enable relevant stakeholders to develop measures, such as water reuse and increasing renewable energy usage in water treatment and wastewater treatment plants, to build sustainable UWSs.

**Keywords:** water–energy–carbon (WEC) links; urban water sectors; Sankey diagram



**Citation:** Min, K.; Lee, G.; Kim, H.; Hwang, T.; Kim, E.; Lee, J.; Kang, D. Identifying Water–Energy–Carbon Links in Urban Water Sectors: A Case Study of Incheon Metropolitan City, Republic of Korea. *Water* **2024**, *16*, 2473. <https://doi.org/10.3390/w16172473>

Academic Editors: Christiana M. Papapostolou and Georgios Tzanes

Received: 18 July 2024

Revised: 23 August 2024

Accepted: 29 August 2024

Published: 30 August 2024



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## 1. Introduction

Carbon reduction is a critical solution to climate change, and reducing greenhouse gas (GHG) emissions is key to mitigating global warming and ensuring a sustainable future. According to the “Special Report on Global Warming of 1.5 °C”, released by the Intergovernmental Panel on Climate Change (IPCC) in 2018 to support the goals of the Paris Agreement [1], carbon emissions (CEs) must reach zero by 2050 to maintain the global average temperature rise below 1.5 °C. Failure to limit the temperature increase to 1.5 °C would not only lead to rising sea water levels but also have adverse effects on biodiversity and ecosystems and threaten global economic growth. “Net Zero 2050” refers to achieving zero carbon dioxide emissions globally by 2050. Net Zero is a process aimed at achieving this goal by minimizing GHG emissions and reducing the remaining emissions

to zero. According to the “Climate Action Tracker”, approximately 140 countries have announced or are considering Net Zero targets, and the “Net Zero Tracker” in the UK estimates that 139 countries have passed laws, created policies, or initiated discussions to achieve these targets. The European Union has adopted CE regulatory systems to reduce emissions from the industrial and transportation sectors. Similarly, China and India are actively encouraging renewable energy development and pursuing policies to reduce GHG emissions. Additionally, Sweden and New Zealand enacted legislations aimed at achieving carbon neutrality by 2045 and 2050, respectively, and implemented various policies to increase renewable energy use and reduce CEs. In December 2021, South Korea submitted its aim of reducing GHG emissions by 40% by 2030 compared with 2018 to the UN. Many countries and companies have adopted Net Zero, with the aims of actively using renewable energy, achieving decarbonization in energy use, and employing carbon capture technologies instead of fossil fuels. These efforts have promoted global responses to issues related to global warming, and the successful realization of Net Zero is crucial for a sustainable future.

Approximately two-thirds of global GHG emissions are attributed to energy production and consumption, and rapid industrial development has led to a sharp increase in energy consumption across sectors. According to the fuel share of CO<sub>2</sub> emissions from fuel combustion, 2019 [2], the total global CEs amounted to 3.284 billion tons in 2017. China ranked first, with 926 billion tons (28.2%), followed by the United States (476 billion tons; 14.5%) and India (216 billion tons; 6.6%). South Korea ranked seventh globally, accounting for 60 billion tons (1.8%) of global emissions. In terms of global energy consumption, China ranked first at 3801 Mtoe, followed by the United States at 2182 Mtoe and India at 1005 Mtoe. South Korea ranked eighth globally, with 294 Mtoe.

Various forms of energy, such as electricity, coal, and gas, are used across urban water sectors (UWSs), including supplying water to end-users and treating the water used at those points. In UWSs, electrical energy is predominantly consumed [3]. It is estimated that approximately 1000 TWh of electrical energy was used in UWSs worldwide in 2020, accounting for about 4% of global electricity demand in 2021 [4]. According to the Energy Census [5], electric energy consumption (EEC) accounts for 99.4 and 92.7% of the annual energy consumption in water supply systems (WSSs) and sewerage systems (SSs), respectively. Racoviceanu et al. [6] conducted a life cycle assessment to evaluate the energy consumption in Toronto’s urban water supply, revealing a significant finding: 94% of the energy used for water supply comes from electricity, which is responsible for 90% of the total CEs.

Research on the identification of water–energy–carbon (WEC) linkages in UWSs is ongoing because it is important to improve resource efficiency, reduce environmental impacts, lower economic costs, support sustainable development, formulate aid policies, manage risks, and enhance resilience. WEC are interconnected, and each system can influence the other. Identifying these linkages can help reduce resource wastage and minimize energy consumption and CEs. Additionally, efficient resource management can lower operating costs and achieve development goals by allowing policymakers to establish more efficient policies and strengthen the system resilience and urban stability.

The following studies have attempted to identify WEC links in UWSs: Sowby and Capener [7] estimated the CEs associated with water supply in 10 major U.S. cities by combining existing observations on the energy intensity of water supply and the CEs of energy systems, reporting a range of 21 to 560 gCO<sub>2</sub>eq per cubic meter of water delivered. Their study highlights the potential environmental benefits of water conservation by integrating data on water, energy, and carbon emissions, particularly in cities with high energy intensities for water supply. A projected 10% reduction in water use could lead to significant CE reductions, ranging from 1200 to 65,000 tCO<sub>2</sub>eq per year, offering critical insights for sustainability planning and decision-making. Duan and Chen [8] examined the WEC nexus within urban environments by focusing on the interconnectedness of energy production, water use, and CEs. Their study offered actionable guidelines for

enhancing urban energy efficiency and reducing CEs. Meng et al. [9] reviewed the WEC interdependencies in urban settings and highlighted their collective impact on sustainability. They detailed the interactions between these elements and proposed methods for their effective management, which are crucial for shaping urban climate policies. Tian et al. [10] investigated the WEC nexus in the context of regional trade in China and analyzed how trade affects resource consumption and environmental policies across different regions. This study offered insights into optimizing resource usage and improving environmental strategies through regional interactions. Li et al. [11] conducted a specific case study at the North China University of Water Resources and Electric Power to explore the WEC nexus at the campus level. They assessed the implications of resource usage and CEs and proposed strategies to increase efficiency and promote sustainability within educational institutions. Venkatesh et al. [12] compared four types of urban water utilities to understand the WEC nexus, identify key factors, and propose management strategies. Their findings offered valuable insights into enhancing infrastructure and informing policy decisions for UWSs. Each of these studies contributed to the understanding of the WEC nexus and provided a foundation for future research and practical applications of UWSs.

Some representative studies related to UWSs and energy consumption are as follows: Sharif et al. [13] reviewed the water–energy nexus within WSSs by focusing on energy efficiency and optimization. They discussed the integration challenges and environmental impacts associated with these systems, highlighting the need for better management practices to enhance sustainability and identifying areas for future research. Filion [14] examined how structural changes in WSSs and variations in population density affect energy consumption. This study identified radial and monocentric network configurations as particularly energy-efficient and proposed that modifications in the urban form and water infrastructure could mitigate environmental impacts. Collectively, these studies enhance our understanding of the intricate connections between water and energy management in urban settings, emphasizing the potential for strategic improvements to support the sustainability of water systems.

Moreover, some recent studies have focused on the UWSs and CEs. Liu et al. [15] presented a novel energy–water nexus interconnected with renewable energy generation sources. By developing a new simulation tool, they identified an integrated energy generation mix involving energy storage in water reservoirs, heat recovery from sewage, and wind and solar power generation. Finally, they proposed an ideal integrated system capable of reducing CEs by 60% compared to all heat demand satisfied by natural gas and showed that such a system can help reduce CEs in the UK by 18%. Rani et al. [16] explored the pathways to achieve a net-zero-carbon water sector by employing energy-extracting wastewater technologies. They investigated various approaches and technologies for extracting energy from wastewater to mitigate CEs in the water sector, with the aim of providing insights and strategies for transitioning toward sustainable and carbon-neutral water infrastructures. Friedrich et al. [17] used a life cycle assessment and carbon footprint analysis to evaluate the environmental performance of urban water supply and sanitation systems. The results identified major environmental contributors, such as water losses in distribution and the energy-intensive processes in wastewater treatment plants. Targeting these contributors can significantly reduce CEs, particularly in developing countries where resources are limited. The study also highlights that while ozonation is effective for disinfection, its high energy requirements lead to increased CEs.

The Sankey diagram, developed by the German engineer Matthias Hermann Joseph Wilhelm Sankey, is a flowchart that illustrates thermodynamic diagrams. It visually represents the quantity of flow through arrow widths and is typically employed to visualize the movement of energy, fuel, or other masses. Hu et al. [18] analyzed the energy–water nexus in Beijing using a Sankey diagram to visualize the flow of energy and water within the city, providing insights into their interdependence and efficiency. This study contributed to our understanding of resource management and sustainability in urban areas, particularly in terms of water and energy consumption. Curmi et al. [19] created a stochastic

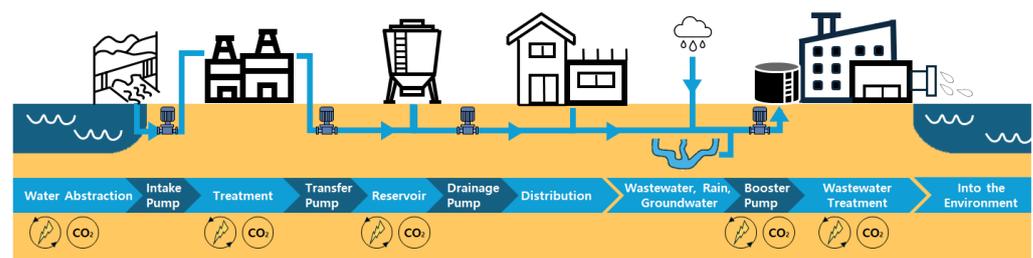
model of California's water resources using Sankey diagrams to depict the complex flow of water resources within the Californian water system, accounting for the uncertainties and variabilities inherent in the system. Lehrman [20] visualized water infrastructures using Sankey maps and conducted a case study to map the Los Angeles Aqueduct in California. Sankey maps were used to illustrate the flow of water through the aqueduct system, providing a clear and comprehensive representation of the water allocation. This case study demonstrated the effectiveness of Sankey maps in understanding and communicating with complex water infrastructure systems.

This study focuses on understanding and visualizing the primary processes within UWSs that contribute to WEC consumption and emissions, which have been lacking in previous studies. We aimed to (1) clarify the WEC linkage in the detailed processes within UWSs, (2) analyze WEC consumption and emissions by administrative district in the target city's UWSs, and (3) use Sankey diagrams and Geographic Information System (GIS) Mapping to visualize the results. Our findings suggest that specific interventions for UWSs, such as optimizing water treatment processes and enhancing energy recovery facilities, can significantly reduce WEC consumption and emissions and promote more sustainable urban water management systems.

## 2. Materials and Methods

### 2.1. Urban Water Sectors (UWSs)

As shown in Figure 1, UWSs primarily comprise water supply systems (WSSs) and sewerage systems (SSs). WSSs are designed to provide drinking water and primarily involve the following processes: Water is sourced from rivers or lakes, usually at the beginning of a WSS. The sourced water is then sent to water treatment plants (WTPs), where it undergoes purification, which mainly involves sedimentation, coagulation, filtration, and disinfection. The treated water is transported to reservoirs and distributed to residential, commercial, and industrial consumers. Wastewater treatment plants (WWTPs) collect and treat wastewater before discharging it into the environment. Wastewater is usually collected from discharge points, mainly from households, factories, and commercial facilities through sewer pipes. The collected wastewater flows into the WWTPs, where it undergoes purification to remove pollutants through biological and chemical treatments, including sedimentation, filtration, disinfection, and precipitation. The treated effluent is then discharged into rivers or seas. Thus, WSSs and SSs involve various processes related to the production, supply, use, treatment, and discharge of water.



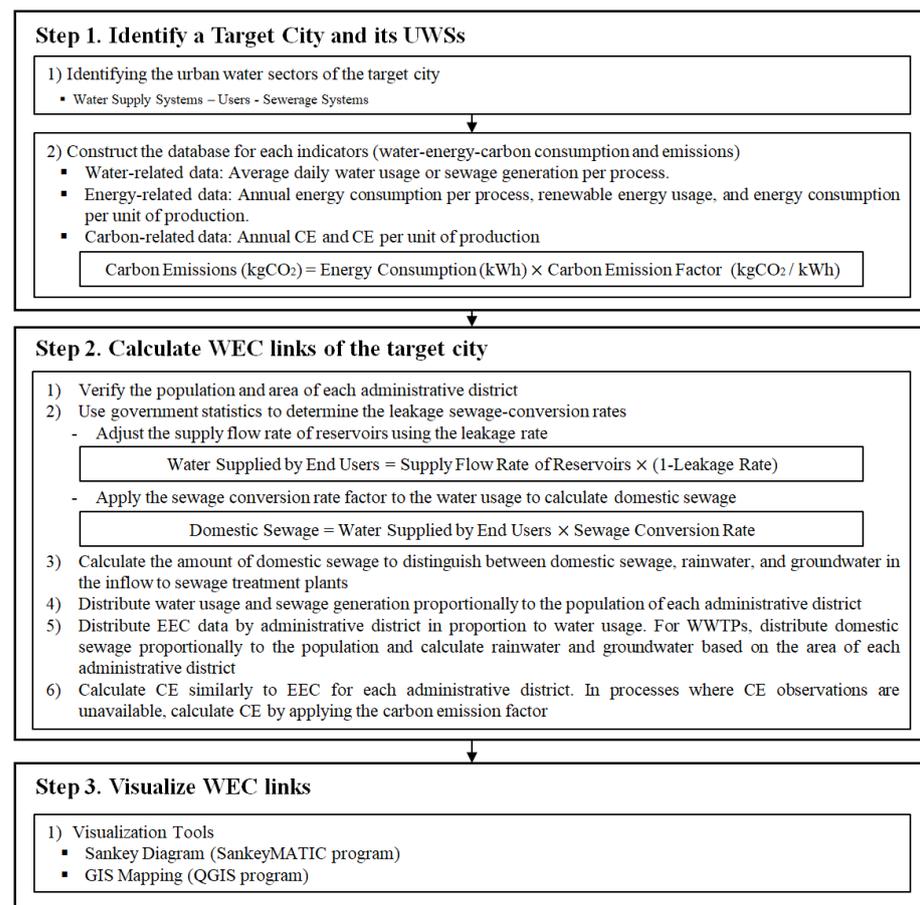
**Figure 1.** Water flows in urban water sectors (UWSs).

The energy consumption and CEs associated with WSSs and SSs primarily stem from the operation of various infrastructural components. In WSSs, energy is consumed throughout the entire process, from water intake to delivery to WTPs, water treatment at WTPs, and sending the treated water to reservoirs and from there to consumers. Similarly, in SSs, energy is required to transport wastewater through sewer pipes, treat it at WWTPs, and discharge the treated effluent. The operation of pumps, aerators, blowers, and other equipment in these facilities contribute to the energy consumption and CEs. Additionally, energy is required for the maintenance and repair of infrastructure components in both WSSs and SSs. In addition to energy consumption, CEs are a byproduct of energy generation, particularly when fossil fuels are used. Therefore, reducing the energy consumption of UWSs can

indirectly lower CEs. Efforts to improve energy efficiency, optimize treatment processes, and adopt renewable energy sources can help mitigate the environmental impacts of energy use and CEs associated with UWSs.

## 2.2. Study Procedure and Methodology

The procedure of this study is outlined in Figure 2 and includes three main stages: step 1—identification of a target city and its UWSs; step 2—calculation of the WEC links in the target city at the administrative level; and step 3—visualization of WEC links.



**Figure 2.** Study procedure.

### 2.2.1. Step 1: Identify the Target City and Its UWSs

This step focused on selecting a target city, identifying its UWSs (WSSs and SSs), and gathering relevant information. Subsequently, the managing department for each process was identified, and WEC consumption and emission data from these departments and public organizations were collected, as listed in Table 1. Water-related data included the average daily water usage or sewage generation per process; energy-related data included annual energy consumption per process, renewable energy usage, and energy consumption per unit of production; and carbon-related data included the annual CEs and CEs per unit of production. Additionally, CEs of the electricity production in the region could be calculated by multiplying the EEC by the CE factor ( $=0.46625 \text{ kgCO}_2\text{/kWh}$ ). The CE factor was obtained from relevant authorities or government statistics.

**Table 1.** Water–energy–carbon data.

Data Classification		Water Supply Systems			Sewerage Systems	
		Intake Facilities	WTPs	Reservoirs	WWTPs	
①	Water	Usage (m <sup>3</sup> /day)	Intake volume	Treated volume	Discharge volume	Inflow and outflow volume
②	Energy	Annual energy consumption (kWh)	Annual electric energy consumption (EEC)	Annual EEC	Annual EEC	Annual EEC
				Renewable energy usage		Renewable energy usage
③		Energy consumption per unit production (kWh/m <sup>3</sup> )	EEC per unit production			
④	Carbon	Annual carbon emissions (CEs) (kgCO <sub>2</sub> )	Annual CEs			
⑤		CEs per unit production (kgCO <sub>2</sub> /m <sup>3</sup> )	CEs per unit production			

### 2.2.2. Step 2: Calculate WEC Links of the Target City

In this step, the WEC consumption and emissions of UWSs were analyzed. First, the population and area of each administrative district were verified. Although process-specific data could be collected, data for administrative districts were lacking; therefore, the following calculations were performed. When analyzing water-related data by administrative district, the flow rate supplied from reservoirs was adjusted using the leakage rate, and the sewage conversion rate factor was applied to the water usage to calculate the domestic sewage. Government statistics were used to determine the leakage and sewage conversion rates. By calculating the amount of domestic sewage, it was possible to distinguish between domestic sewage, rainwater, and groundwater inflows to WWTPs. Water usage and sewage production were proportionally distributed based on the population of each administrative district. When analyzing the EEC data by administrative district, it was found to be distributed in proportion to water usage. However, in WWTPs, domestic sewage was distributed proportionally to the population and the proportions of rainwater and groundwater were calculated based on the area of each administrative district. Additionally, CEs were similarly calculated for each administrative district. The CEs for processes for which CE observations were unavailable were calculated by applying the CE factor.

### 2.2.3. Step 3: Visualize WEC Links

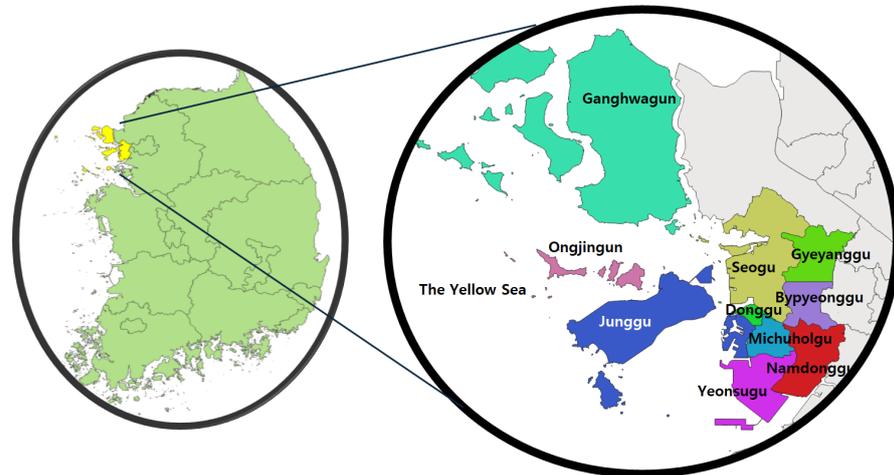
This step aimed to employ Sankey diagrams and GIS Mapping techniques to visualize the analysis results. The Sankey diagram illustrated the relationship between WEC consumption and emissions across different processes, while GIS Mapping visualized the spatial distribution of these elements across the administrative districts. The analysis was conducted using SankeyMATIC [21], a user-friendly web-based tool for creating customizable Sankey diagrams, and QGIS 3.36.1 [22], open-source Geographic Information System software for mapping and spatial analysis. These visualization tools can provide managing departments or public organizations with valuable insights into WEC consumption and emissions, helping guide subsequent actions.

## 2.3. Case Study

### 2.3.1. UWSs in IMC

This study employed Incheon Metropolitan City (IMC), located in northwestern South Korea, as shown in Figure 3, as the target city for the case study. IMC is bordered by the West Sea to the west and by the capital city of Seoul to the east. Centered around the Incheon Port and Incheon International Airport, it is a city where manufacturing, logistics, and industries have flourished. The administrative area of IMC is 1067 km<sup>2</sup>, and it is the

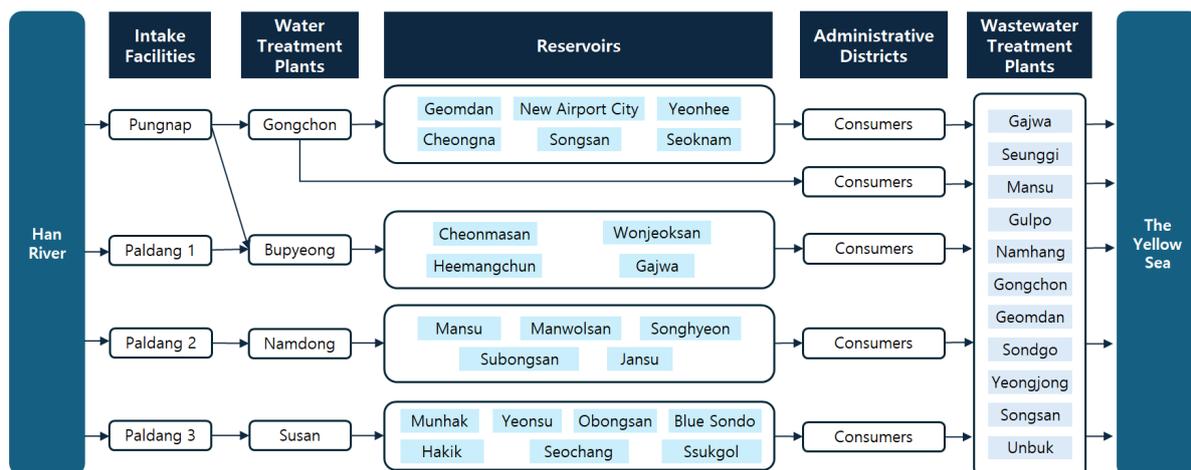
third most populous city in South Korea, with 2,967,314 residents and 1,322,632 households as of December 2022. The administrative divisions comprise eight districts (Seogu, Junggu, Gyeongyang, Michuholgu, Donggu, Bupyeonggu, Namdonggu, and Yeonsugu) and two counties (Ganghwagun and Ongjingun). The analysis in this study was only conducted for the eight districts, and the two counties were excluded owing to their significantly low water usage.



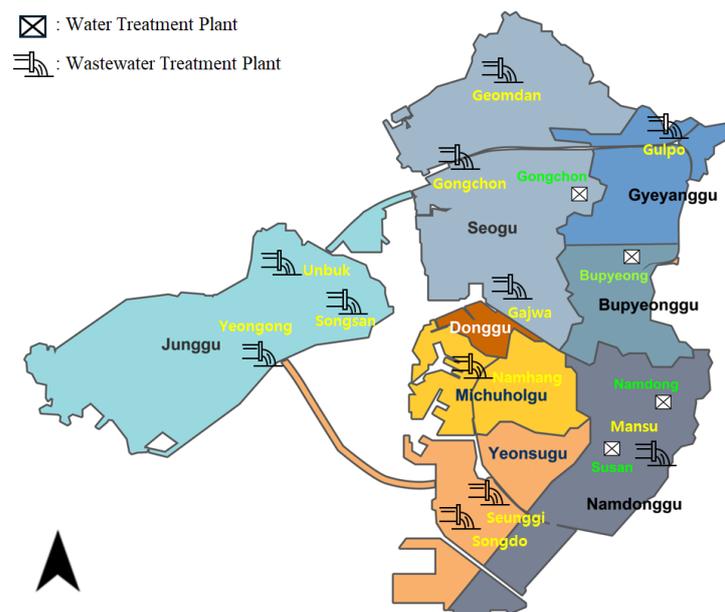
**Figure 3.** Location of Incheon Metropolitan City (IMC) in South Korea.

2.3.2. Location of Facilities

As shown in Figure 4, the UWSs of IMC comprise four facilities (Pungnap, Paldang 1, Paldang 2, and Paldang 3) that intake water from the Han River, four WTPs (Gongchon, Bupyeong, Namdong, and Susan), and 25 reservoirs that supply water to consumers. Wastewater is collected in 11 WWTPs (Gajwa, Seunggi, Mansu, Gulpo, Namhang, Gongchon, Geomdan, Songdo, Yeongjong, Songsan, and Unbuk) and discharged into the Yellow Sea after treatment. The locations of the WTPs and WWTPs are shown in Figure 5, where the WTPs are labeled in green and the WWTPs are indicated in yellow.



**Figure 4.** UWSs in IMC.



**Figure 5.** Locations of water treatment plants (WTPs) and wastewater treatment plants (WWTPs) in IMC.

### 2.3.3. Data Acquisition

All statistical data regarding the UWSs in IMC were obtained from the Ministry of Environment. WSSs data were collected from the Ministry of Environment website [23] and the IMC Waterworks Headquarters website [24]. Data on SSs were collected from the Ministry of Environment website [25] and the Environmental Corporation of Incheon website [26]. Note that the latest statistical data for the IMC are available for 2021, and the simulations were conducted using these data.

## 3. Results

### 3.1. Water

Water usage and sewage volumes for 2021 are shown in Figure 6 using a Sankey diagram, which illustrates the flow of water throughout the UWSs, including the water intake from the source (Han River), WTPs, distribution, end-users, WWTPs, and discharge into the Yellow Sea. Based on the statistical data obtained from the Ministry of Environment, a leakage rate of 9.7% along the distribution pipelines was applied [23], and a wastewater conversion rate of 0.9 was used to calculate the amount of domestic wastewater produced by end-users. The amount of water supplied to each administrative district area is included under the administrative district section. As the statistical values for the water supply for each administrative district were unavailable, we identified the administrative districts supplied by the reservoirs and proportionally distributed the water based on their populations to calculate the total amount of water supplied to each administrative district. The domestic wastewater volume was calculated by applying a sewage conversion rate of 0.9 according to the Ministry of Environment statistics and is indicated under the WWTP column. Additionally, the inflow sewage volume for each WWTP was measured. The amount of rainwater and groundwater infiltrating the sewer lines was determined by subtracting the domestic wastewater volume from the total WWTP influent volume. Thus, the WWTP influent volume is recorded in the “\_in” column, and the amounts treated and discharged are included in the “\_out” column. This Sankey diagram allowed us to understand the entire process of the UWSs and confirmed the total amount of discharge into the West Sea.

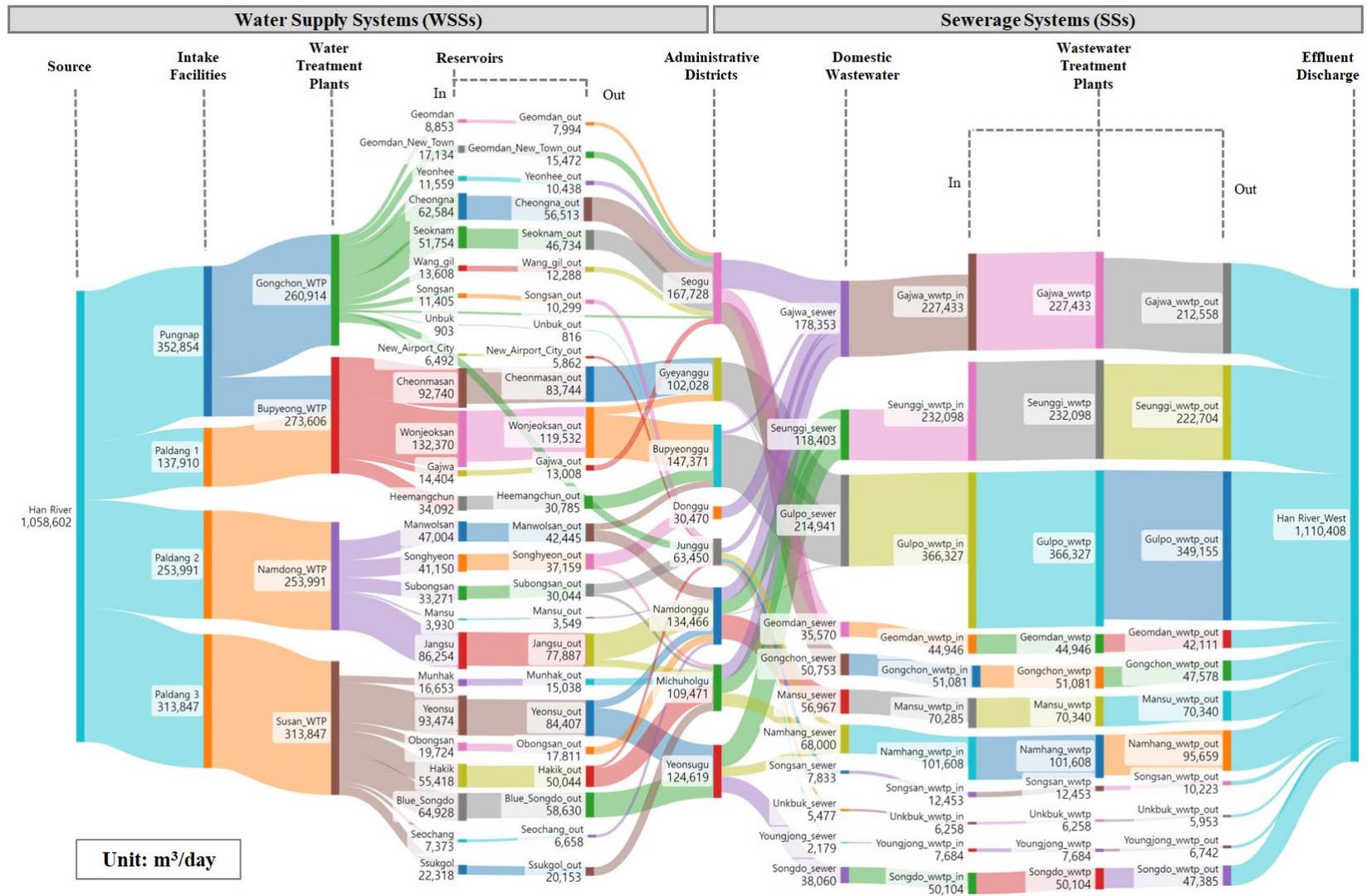


Figure 6. Sankey diagram of daily water flow in IMC (unit: m<sup>3</sup>/day).

The water usage and sewage volumes of each administrative district in IMC are shown in Figure 7. Water usage was calculated by distributing the water in proportion to the population of each administrative district. The sewage volume was calculated by distributing WWTPs' influent volumes in proportion to the district population and area. Seogu exhibited the highest water usage, whereas Donggu exhibited the lowest. Additionally, Bupyeonggu showed the highest volume of sewage production, whereas Donggu showed the lowest.

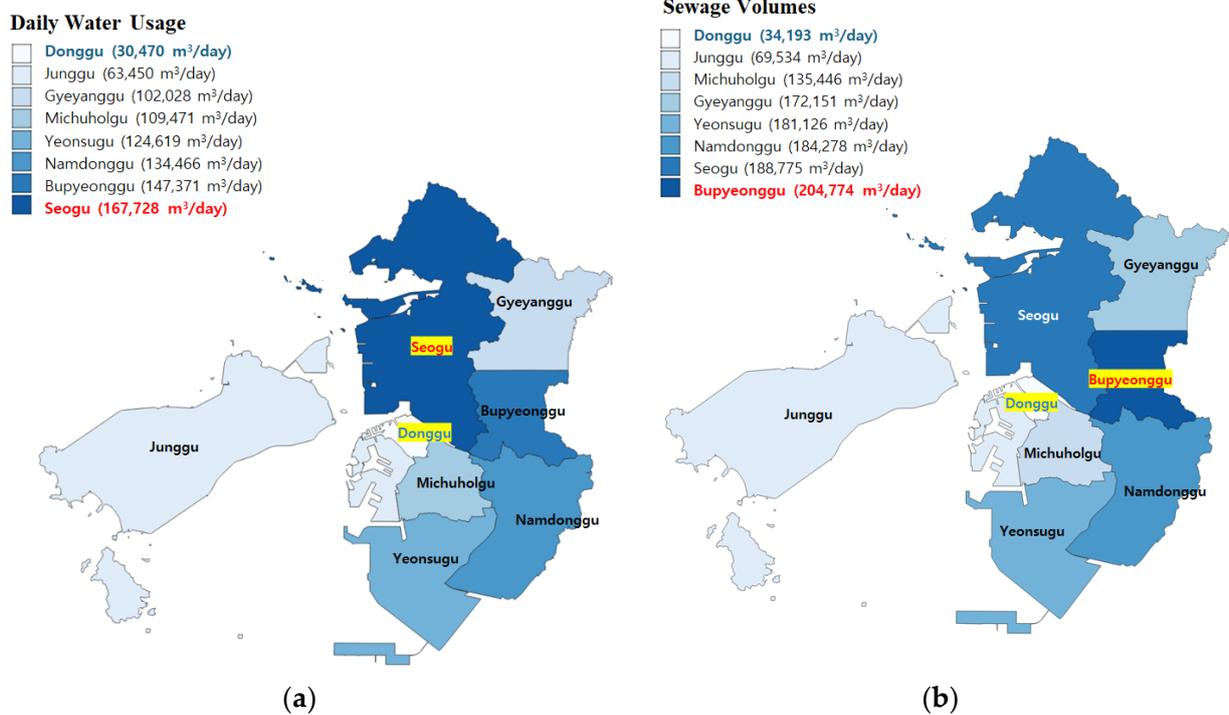
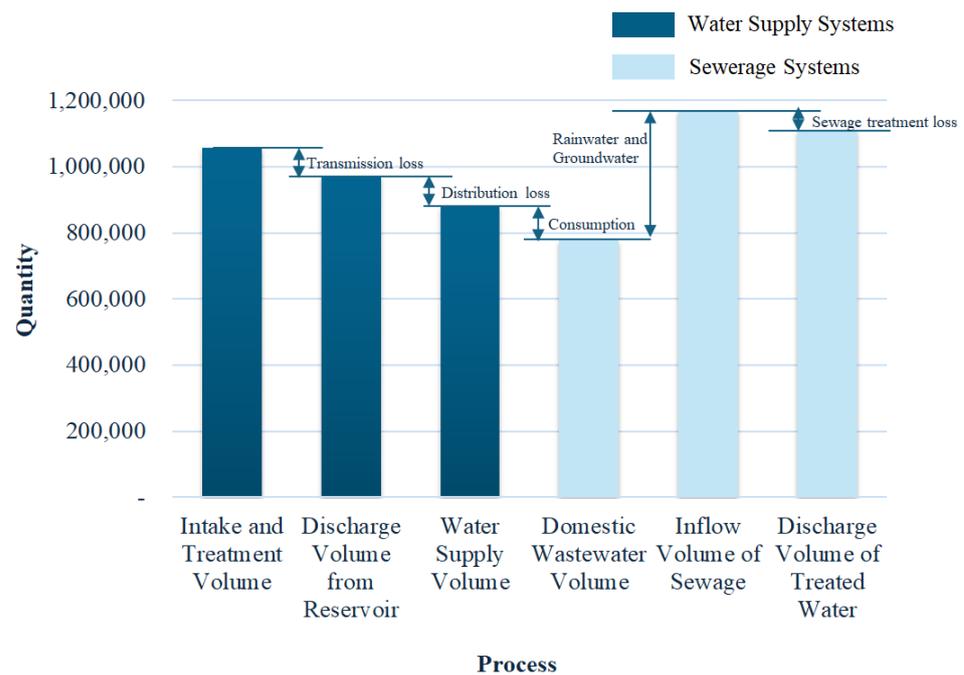


Figure 7. (a) Daily water usage and (b) sewage volumes in the administrative districts of IMC.

The daily water volumes of the individual processes in IMC are shown in Figure 8. Compared with the intake and treated volumes, the reservoir discharge volume decreased owing to water losses in the pipelines during transmission. Compared to the reservoir discharge, the supplied water volume decreased because of leakages in the distribution process. The difference between the water supply and wastewater generation was due to water consumption by end-users (i.e., a wastewater conversion rate of 0.9 was applied). The inflow volume of WWTPs increased because of the external inflow of rainwater and groundwater in addition to wastewater generation. The inflow of rainwater and groundwater through the sewer lines accounted for 34% of the total WWTPs' influent volume. Owing to the losses occurring during wastewater treatment, the amount of treated effluent was lower than the inflow.



**Figure 8.** Changes in water volumes along the UWSs processes in IMC (unit: m<sup>3</sup>/day).

### 3.2. Energy

Figure 9 shows the cumulative annual EEC along the UWS processes in IMC. Thus, the EEC listed in the administrative district column reflects the cumulative EEC of each district along the WSSs. The EEC shown in the last column indicates the total EEC of each district combining WSSs and SSs, that is, total energy consumption from water intake to the final sewage treatment and discharge. Therefore, by adding the values in the last column, we can estimate the total EEC in UWSs of IMC.

The proportions of the annual EEC for the processes were compared using a pie chart, as shown in Figure 10. Evidently, most of the energy in the WSSs was consumed at the intake and transfer pumps, while the energy consumption of the water treatment process was only 14%. However, in SSs, most of the energy (96%) was consumed for wastewater treatment. The total EEC of the UWSs in IMC was 308,496,107 kWh, accounting for approximately 32.7% of the public electricity consumption in IMC in 2021.

The annual EEC was divided into total, WSSs, and SSs and visualized by administrative district, as shown in Figure 11. In the WSSs, Namdonggu exhibited the highest annual EEC and Donggu exhibited the lowest. In the SSs, Seogu showed the highest EEC, whereas Donggu showed the lowest. Additionally, the total EEC was highest in Seogu and lowest in Donggu.

Using information on water production, supply, and treatment amounts (Figure 7) and the corresponding energy consumption information (Figure 11), the energy intensity (i.e., energy consumption per unit production of water; kWh/m<sup>3</sup>) for each administrative area was estimated and compared, as illustrated in Figure 12. Evidently, Donggu had the highest energy consumption per unit water supply, whereas Seogu had the lowest. For the SSs, Junggu had the highest energy consumption per unit of sewage collection and treatment, whereas Bupyeonggu had the lowest.

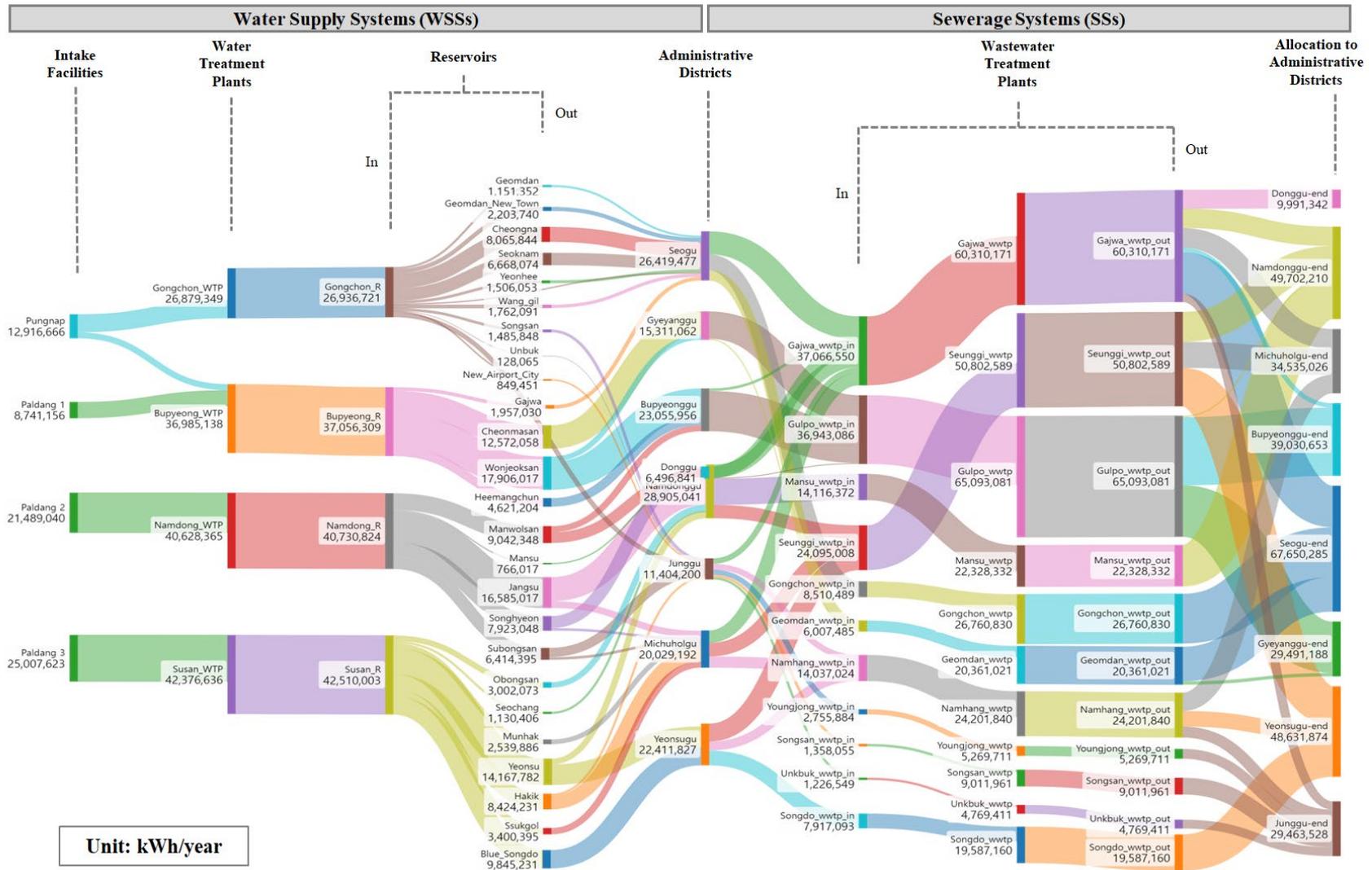


Figure 9. Cumulative annual electric energy consumptions (EECs) of the UWs in IMC (unit: kWh/year).

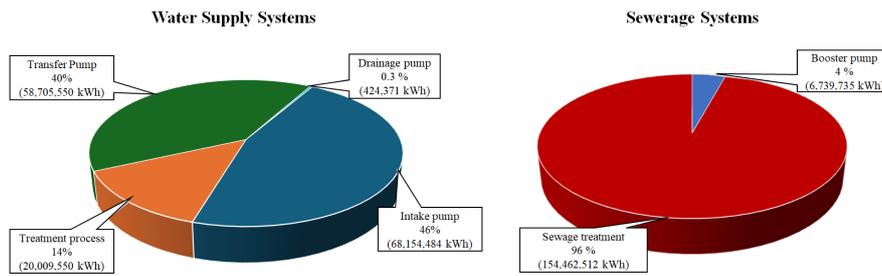


Figure 10. Proportions of annual EEC of each UWS process in IMC.

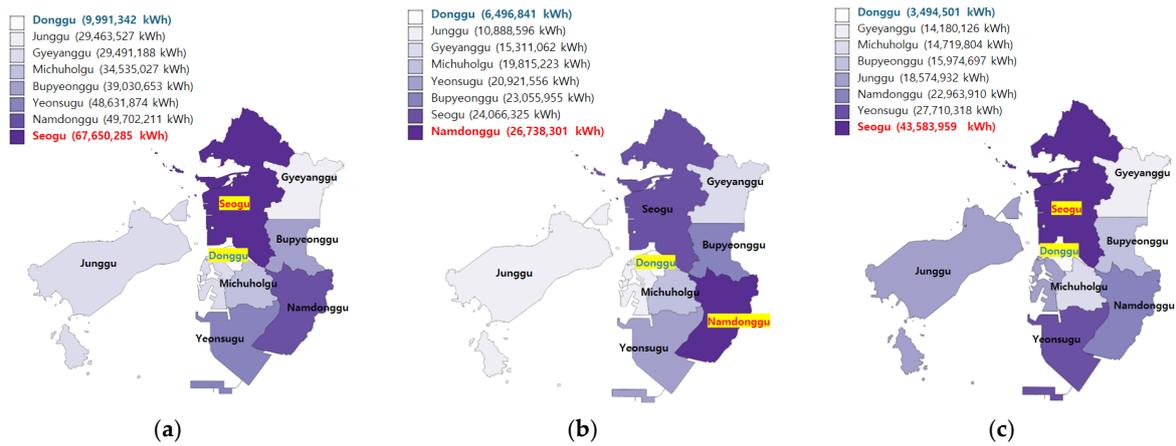


Figure 11. Annual EECs of the UWSs in IMC: (a) Total; (b) WSSs; (c) SSs.

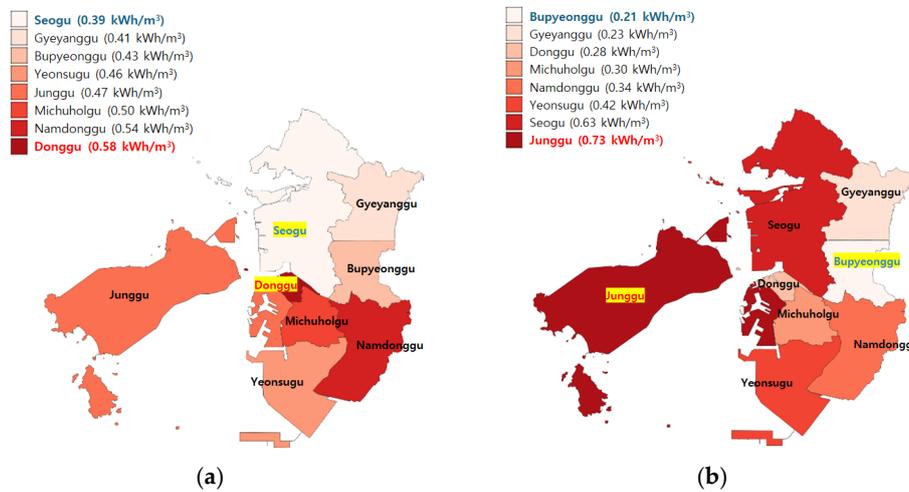


Figure 12. Energy intensities of each administrative district: (a) WSSs; (b) SSs.

The average energy intensity of the WSSs was 0.46 kWh/m<sup>3</sup>, while the SSs had an average energy intensity of 0.38 kWh/m<sup>3</sup>. Chini and Stillwell [27] analyzed the energy intensity across the United States, and we found that the average energy intensity of the UWSs in IMC were similar to the U.S. national average. However, compared to the results from various cities in the world provided by Lam et al. [28], the average energy intensity of the UWSs in IMC ranked at a relatively high position.

### 3.3. Carbon

The cumulative annual CEs along the UWSs in IMC were visualized using a Sankey diagram, as shown in Figure 13.

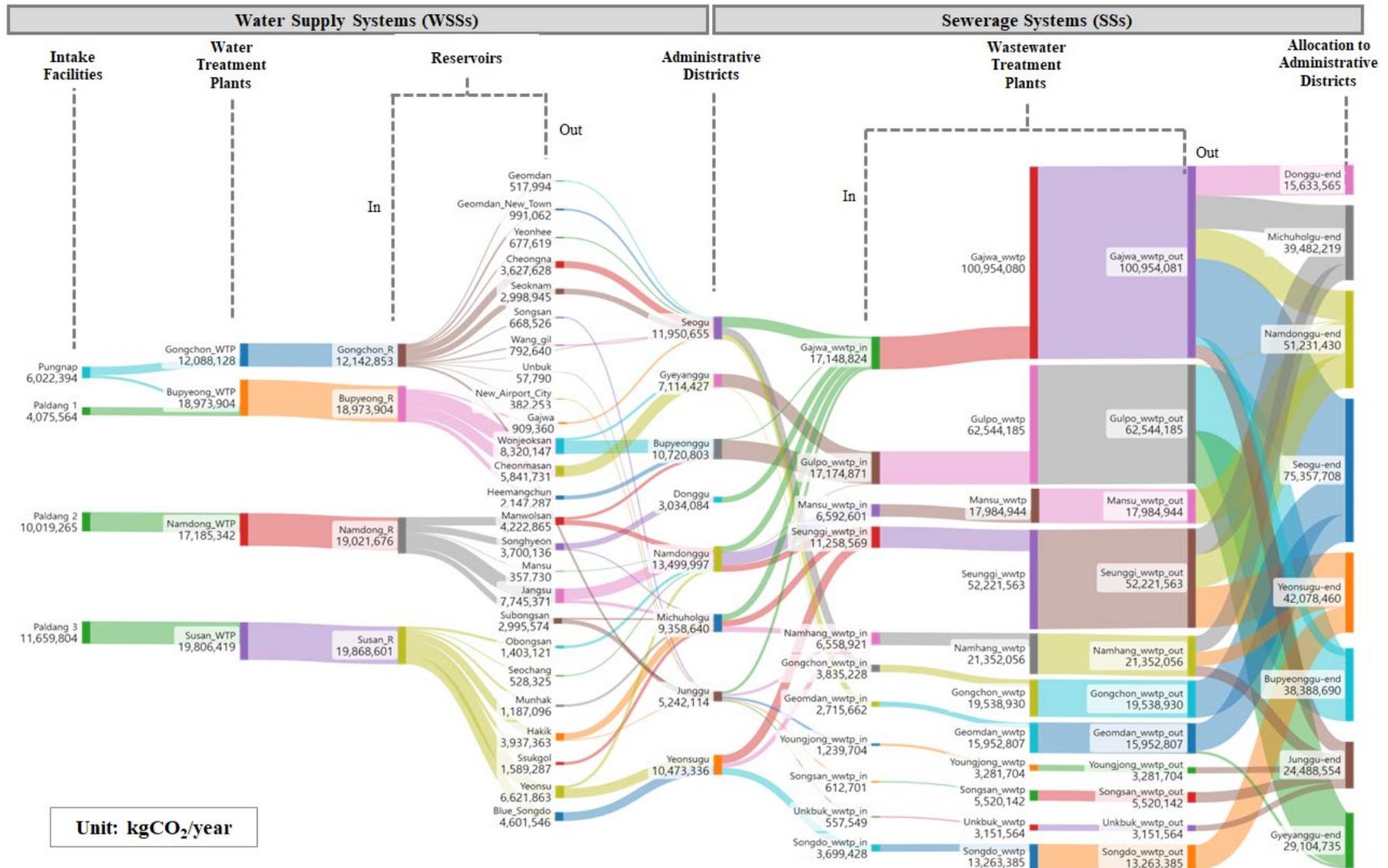


Figure 13. Cumulative annual carbon emissions (CEs) of the UWSs in IMC (unit: kgCO<sub>2</sub>/year).

Carbon emissions can be categorized as either direct or indirect. Direct emissions result from activities occurring within the facility, such as fuel combustion, whereas indirect emissions arise from the generation of electricity or heat provided by external sources. In WSSs, most emissions are indirect, primarily driven by the electricity used to power the system. In contrast, SSs produce direct emissions from biological decomposition processes, while indirect emissions are linked to the electricity needed to run treatment facilities. These differences contribute to some variation in trends between EEC and CE, as illustrated in Figure 13.

The proportions of the annual CE for each process in the UWSs were compared using a pie chart. Similar to energy consumption patterns, most CEs in WSSs were caused by the intake and transfer pumping. However, in SSs, most CEs occurred during wastewater treatment, accounting for 99% of the total CEs as shown in Figure 14. The total annual CEs of UWSs in IMC were 315,765,358 kgCO<sub>2</sub>, which is equivalent to 2.7% of the total CEs of IMC converted from the electricity consumption in 2021. The annual CEs were also divided into total, WSSs, and SSs. In the WSSs, this showed the same pattern as EEC. In the SSs, Seogu showed the highest CEs, whereas Donggu showed the lowest. Additionally, the total CEs were the highest in Seogu and lowest in Donggu, as shown in Figure 14. Using the water production, supply, and treatment information (Figure 7) and the corresponding CEs, the carbon intensity (i.e., the amount of CEs per unit production of water, kgCO<sub>2</sub>/m<sup>3</sup>) for each administrative area could be estimated and compared. In the WSSs, this showed the same pattern as EEC. In the SSs, Donggu showed the highest intensity, whereas Gyeongyang showed the lowest.

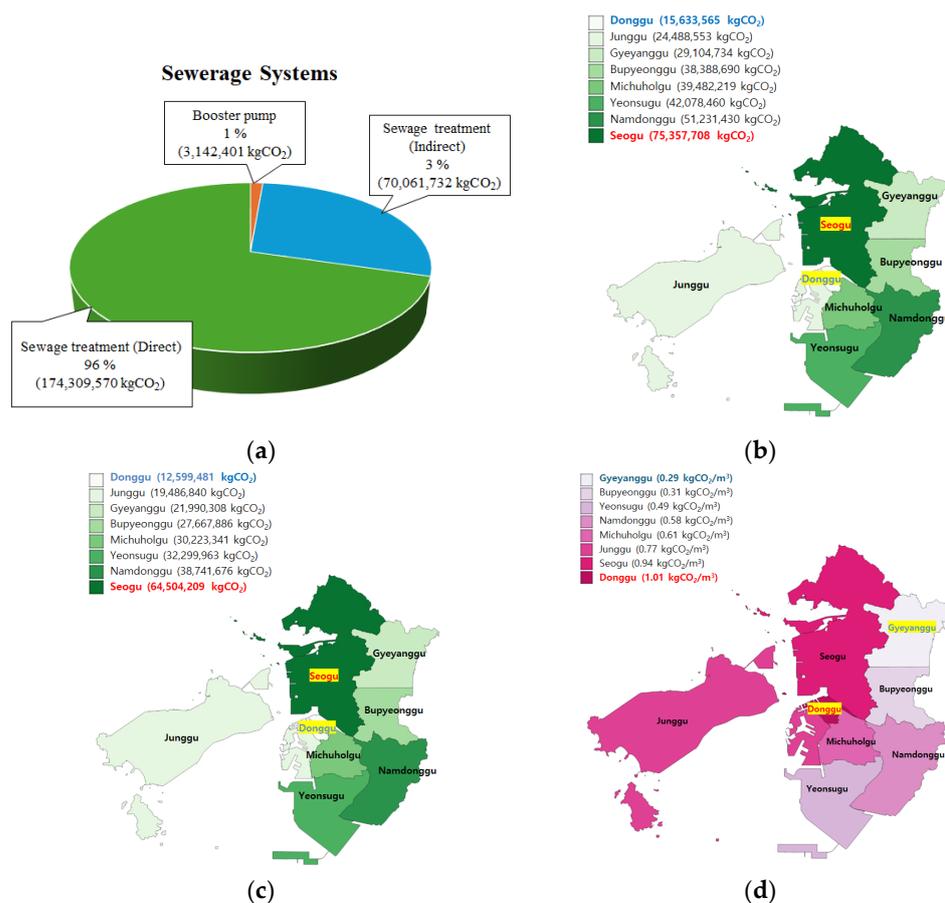


Figure 14. Annual CEs and carbon intensities of UWS and SS in IMC: (a) proportions of annual CEs by UWS process; (b) total annual CEs of UWS; (c) annual CEs of SS; (d) carbon intensities of SS.

#### 4. Discussion

The geographical characteristics of the Incheon metropolitan area are flat, with approximately 79.1% of the total area being less than 50 m above sea level and 77.7% having gentle terrain with slopes of <10%. The population of IMC in 2021 was 2,918,314, with Donggu having the lowest population and Seogu the highest. Additionally, the population density was the highest in Michuholgu and lowest in Junggu. According to the data presented in Table 2, general households, businesses, and manufacturing plants are predominantly located in Namdonggu, Bupyeonggu, Seogu, and Michuholgu. Additionally, Seogu has the highest residential, industrial, and commercial land-plot ratios, whereas the building density is high in Michuholgu, Seogu, Namdonggu, and Bupyeonggu. All these factors affect the WEC consumptions and emissions in the UWSs of the city. Using the approach proposed in this study, city planners can create citywide plans for individual administrative districts to ensure sustainable management of the water sector in the city.

**Table 2.** Characteristics of administrative districts in IMC.

Indicators	Junggu	Donggu	Muchuholgu	Yeonsugu	Namdonggu	Bupyeonggu	Gyeyanggu	Seogu
Population	147,535	61,486	416,551	408,946	529,200	489,118	298,802	566,676
Population density (population/km <sup>2</sup> )	1052	8540	16,796	7449	9268	15,285	6553	4848
Household	62,254	25,984	175,389	146,830	210,772	197,396	116,818	210,245
Businesses	13,589	7875	28,017	19,802	41,071	32,420	18,712	36,650
Manufacturing businesses	58	77	300	159	1772	518	238	1400
Hotels	93	-	1	3	13	1	6	11
Medical institutions	115	92	475	393	729	745	367	533
Public sports facilities	116	45	161	65	139	116	78	153
Residential land-plot ratio (number of plots/area)	8715 (5)	2679 (16)	19,139 (19)	17,094 (10)	20,817 (20)	22,611 (26)	12,848 (12)	23,493 (8)
Commercial land-plot ratio (number of plots/area)	5808 (15)	231 (19)	5549 (27)	7897 (49)	4224 (35)	5490 (48)	411 (10)	5016 (9)
Industrial land-plot ratio (number of plots/area)	96 (0)	255 (3)	570 (4)	3 (0)	1286 (2)	2479 (12)	570 (15)	3739 (3)
Buildings	17,819	9960	34,875	8264	26,941	23,306	12,738	32,216
Average floor area per building	819	413	884	4351	1241	1356	895	1178
Average number of floors per building	2.3	2.3	3.0	5.7	3.4	3.2	2.9	3.2
Units per building	60,347	23,789	171,483	162,402	202,671	200,038	119,343	215,871

##### 4.1. Water

Water usage was the highest in Seogu and lowest in Donggu. It is estimated that Seogu has the highest water usage owing to the high numbers of businesses, manufacturing plants, and hotels, as well as the highest numbers of land parcels in residential, commercial, and industrial areas. Therefore, water conservation efforts must be employed in Seogu by implementing water-saving facilities, water-reuse policies, and rainwater utilization facilities. Moreover, Bupyeonggu is presumed to have the highest sewage volume owing to the inflow of wastewater and rainwater through the combined sewer system. Therefore, reducing the inflow of wastewater through the installation of a separate sewerage system is necessary as part of a long-term plan in Bupyeonggu.

##### 4.2. Energy

The annual energy consumption of the WSSs was highest in Namdonggu and lowest in Donggu. Although Namdonggu does not have the highest water usage, it is inferred

that the process of supplying water to this area (i.e., extraction, treatment, and pump distribution) consumes the most energy. Encouraging the use of renewable energy in the Namdonggu and Susan WTPs, as well as improving pump efficiency in the extraction and distribution processes, is necessary to reduce the annual energy consumption. The annual energy consumption of the WWTPs was highest in Seogu and lowest in Donggu. It is inferred that significant energy is consumed by the treatment plants in Gajwa, Gongchon, and Geomdan, which handle wastewater from Seogu. Therefore, encouraging the use of renewable energy in these treatment plants can reduce the annual energy consumption.

#### 4.3. Carbon

The CEs from the WSSs were the highest in Namdonggu and lowest in Donggu, reflecting a pattern similar to that of energy consumption, and similarly, encouraging the use of renewable energy in Namdonggu and Susan WTPs could help reduce CEs. Additionally, CEs from WWTPs were highest in Seogu and lowest in Donggu, which was primarily attributed to the treatment plants in Gajwa, Gongchon, and Geomdan, as mentioned previously. Encouraging the use of renewable energy in these treatment plants could help reduce CEs in these areas.

### 5. Conclusions

WEC are closely inter-related, and UWSs are estimated to consume approximately 7% of global energy production. UWSs encompass various processes such as water intake, treatment, and distribution and wastewater treatment, all of which consume significant amounts of energy and emit carbon dioxide. Owing to the challenges posed by global warming and climate change and the aims of several countries to achieve carbon neutrality by 2060, it is essential to enhance energy efficiency and reduce CEs through comprehensive evaluations of UWSs.

This study proposed a methodology for analyzing the WEC consumption and emissions of UWSs in IMC, South Korea. First, the UWSs in IMC were identified and a WEC database was established. Based on this database, WEC consumption and emissions were analyzed for each process and administrative district, and visual analyses using Sankey diagrams and GIS Mapping were conducted for intuitive interpretation and understanding.

Through the proposed methodology, the entire UWS process, from water intake to effluent discharge, was analyzed in detail using a subprocess, and a visualization tool was developed to quantify the data down to the administrative district level. The methodology and results of this study can allow stakeholders to achieve a more comprehensive understanding and evaluate the WEC consumption and emissions of a UWS in a specific city. The proposed visualization tool can help process-specific operators develop plans to improve operations and mitigate CEs. Consequently, it can allow the formulation of plans and policies to reduce water and energy consumption and CEs, such as water reuse and the establishment of additional renewable energy facilities for specific processes, thereby creating sustainable urban water systems.

Future research could employ various scenarios to reduce water and energy usage, as well as CEs. For instance, by increasing the self-sufficiency rate of renewable energy by a certain extent in a specific process, the EEC and CEs can be compared and analyzed before and after their application. Additionally, applying the proposed approach to the UWSs of a particular city can provide city-specific WEC linkage visualization tools.

**Author Contributions:** Conceptualization, all authors; methodology, all authors; software, K.M. and G.L.; validation, D.K. and T.H.; formal analysis, D.K. and T.H.; investigation, H.K., E.K. and J.L.; resources, K.M.; data curation, K.M. and G.L.; writing—original draft preparation, K.M.; writing—review and editing, all authors; visualization, K.M.; supervision, D.K. and T.H.; project administration, H.K., E.K., J.L., G.L. and H.K.; funding acquisition, D.K. and T.H. All authors have read and agreed to the published version of the manuscript.

**Funding:** This work was supported by (1) Korea Environmental Industry & Technology Institute (KEITI) through a technology development project to optimize the planning, operation, and maintenance of urban flood control facilities funded by the Korea Ministry of Environment (MOE), grant number RS-2024-00398012, and (2) Korea Environment Industry & Technology Institute (KEITI) through an environmental R&D project for developing an innovative drinking water and wastewater technology program funded by the Korea Ministry of Environment (MOE), grant number 2020002700004.

**Data Availability Statement:** The data supporting the reported results can be obtained by contacting the first author via email.

**Conflicts of Interest:** The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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