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Comparative assessment of green supply chain management (GSCM) in drinking water service industry in Lao PDR, Thailand, and South Korea

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ABSTRACT

The industrial manufacturing of a commodity as well as service sectors, such as drinking water supply systems, is responsible for environmental impacts across its supply chain. Lowering these impacts at each stage of the supply chain is often termed green supply chain management (GSCM). This study assesses energy use, waste generation, chemical use, consumptive water use, and GHG emissions in typical drinking water treatment plant (WTP) operations in Lao PDR, Thailand, and South Korea and consolidates these supply chain impacts broadly into water footprint (WF) and carbon footprint (CF). The respective CFs were found to be 9.4, 375.4, and 359.5 g CO_2-eq, while the respective WFs were 335.4, 501.4, and 300.4 L/m^3. Among the three countries of the study, only South Korea has implemented various greening activities, such as energy management systems, sludge reuse, GHG target management, and renewable energy development, for meeting its strict government policy and regulations. WTPs in Lao PDR and Thailand, however, have yet to implement GSCM strategies and policies. This study instigates best practices for "greening" the drinking water supply chain in the region.

Keywords: Carbon footprint; Drinking water service industry; Greenhouse gas emissions; Green supply chain management; Water footprint

1. Introduction

Drinking water is one of the most basic human needs. However, increasing population and the concentration of the population in urban centers are putting immense pressure on the local authorities to meet the ever-increasing water demand. According to the World Health Organization's statistics, a staggering 1.1 billion people have no access to any type of improved drinking water source. Water is a common thread that links all aspects of human development, securing political, health, economic, personal, food, energy, and environmental sustainability. The drinking water service industry thus has a direct role in aiding these global sustainable development goals. At the same time, drinking water supply chains are responsible for significant environmental impacts, such as the depletion of natural resources in the abstraction of water and the indirect release of

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pollutants (chemicals and sludge) into the water, land, and air, and greenhouse gas (GHG) emissions through energy use in water treatment and the distribution chain [1]. According to GHG emissions by EU economic activities in 2013 [2], manufacturing industry sector had the largest proportion, accounting for 28.8%, while mining industry sector had the lowest rate, 1.8%. Public water supply and construction sector accounted for 10.9%. In water consumption in the United States in 2010 [3], thermoelectric power sector had the highest percentage (45.4%) and livestock sector had the lowest percentage (0.56%) of national water use. Public water supply sector accounted for relatively high percentage, 11.8%. In the context of water scarcity, reducing water use remains one of the most needed solutions for alleviating serious water shortage. Establishing and managing "green" practices across the drinking water supply chain—water extraction, production, and distribution—are equally important for cutting water loss (both at the raw water extraction and production stages, as well as for reducing leakage in the distribution phase), reducing damage to natural surface water sources. Additionally, water extraction, reducing GHG emissions associated with energy use in water treatment plants (WTPs), and the proper treatment and management of chemicals and sludge are important in order to avoid environmental pollution.

With such environmental implications surfacing in the water supply chain, starting over a decade ago, well-known methods, such as life cycle assessment (LCA), carbon footprint (CF), and water footprint (WF), have been applied for the evaluation of environmental impacts in water supply systems. Usually, LCA evaluates the environmental aspects of a product or service through all the life cycle phases [4]. CF is used to characterize the global climate change impact as a holistic estimate of total GHG emissions [5], while WF refers to the total volume of freshwater consumed directly and indirectly for a product or service over the full supply chain. However, green supply chain management (GSCM) is the integration of environmental thinking into the supply chain of a product or service in many respects [6] and is an extension of the life cycle analysis, CF, and WF concepts. Typically, GSCM focuses on reducing energy use, cutting down water volume, scrubbing or sequestering GHGs, and minimizing the impact of waste disposal. Most supply chain management innovations in the twentieth century aim to reduce waste for economic rather than environmental reasons, and it was not until the turn of the twenty-first century that the term "green" gained widespread use and recognition in reference to protecting the environment [7,8]. An important issue in supply chain management (SCM) is related to the environment. GSCM has thus emerged as an important organizational philosophy for reducing environmental risks and improving both economic and environmental performance in the supply chain [9].

To date, most such GSCM studies and strategies are limited to mainly manufacturing industries, such as automobiles, food processing, electronics, mining, power generation, petroleum, and rubber, rather than service industries, such as drinking water supply systems. In the case of the water sector, a few supply chain studies have been conducted for the privately owned bottled water industry, but not for the state-owned piped public water supply service system. This study therefore selected nine drinking WTPs in three Asian countries (Lao PDR, Thailand, and South Korea) and compared energy use, water consumption, chemical use, GHG emissions, and solid waste at each stage of the water supply chain, along with the identification of "greening potential areas" and barriers and enablers to implement GSCM in the public drinking water supply chain.

2. Materials and methods

2.1. Study area

The study selected three Asian countries with three different economic conditions. These countries were classified by the country's income (GNI per capita) into three categories: the high-income economic group (South Korea), the upper middle-income economic group (Thailand), and the lower middle-income economic group (Lao PDR). These countries and economic zones are a representation of the diversity of Asia. Thus, the findings from this study are expected to be suitable for extrapolation in other countries with similar socioeconomic conditions, while the identified GSCM recommendations could also be replicated.

To assess the status and potential for GSCM in the drinking water systems in these countries, the study selected three state-owned water supply companies: Korea Water Resources Corporation (K-water) in South Korea, Provincial Waterworks Authority (PWA) in Thailand, and Nam Papa Nakhone Luang (NPNL) in Lao PDR. The selection of three water companies for the study was based on many factors; these are the largest operators of water treatment facilities in the countries and account for a considerable proportion of the national drinking water supply. Additionally, it was relatively easier to access these WTPs and more convenient to obtain data than for WTPs managed either entirely by local governments or as sole private enterprises.

As a representative sample size, a total of nine WTPs (three from each country) from NPNL, PWA, and K-water were chosen. Detailed characteristics of these WTPs are presented in Table 1. K-water operates a multi-regional water supply system, a facility designed to provide drinking water to more than two local governments, with 37 drinking WTPs in eight provinces. PWA has been supplying drinking water to 74 out of 76 provinces in Thailand with 233 WTPs. NPNL has been supplying drinking water in Vientiane City with four WTPs.

2.2. System boundary

The drinking water supply and sewerage management system comprises several stages starting from raw water extraction to production (water treatment), the distribution of treated water, and the final discharge of wastewater into the environment. Fig. 1, below, shows the drinking water supply chain with a demarcated system boundary for this study.

As presented in Fig. 1, raw water is extracted from surface water (river or reservoir) and is conveyed to the WTP, where it is treated to meet the water quality standard. The treated water is then transmitted to a storage tank with a pump and distributed to households. After its use, the water is again collected and transported to the wastewater treatment plant, where it is purified to an appropriate quality to be released back into nature. This study, however, focuses only on three major stages of the water supply chain (i.e., raw water extraction, water production, and distribution) as the system boundary, excluding the end-use and post-consumer wastewater treatment stages.

2.3. Data collection

Primary data were collected by conducting field surveys in PWA-operated WTPs (Nakhon Sawan, Phichit, Phitsanulok, and Sukhothai) and NPNL (Vientiane City), and K-water-operated WTPs between 2014 and 2015, followed by face-to-face interviews with key persons responsible for the operation and management of the WTPs. The companies' annual reports, research documents, project reports, and published materials were the sources of secondary data. In the case of K-water, the main data were obtained from the waterworks database (intranet information system), annual statistics of waterworks, and case study reports.

2.4. Factors for assessing GSCM

The environmental impacts of the drinking waste supply chain were studied under the following broad categories: energy use and GHG emissions, chemical use and waste generation, and consumptive water use (CWU). The findings from these categories are finally presented with quantified WF and CF values.

2.4.1. Energy use and GHG emissions

Energy generation and its use contribute to climate change, which is one of the most complex environmental issues on the international policy agenda. Energy use and its associated GHG emissions are a matter of concern for drinking water systems too, because the drinking water service industry uses significant energy for raw water pumping, conveyance, water production (mechanical devices), and

Table 1
Description of drinking water treatment plants selected

Water supplier (Country)	WTP	Design capacity (thousand m^3/d)	Water source	Water production[a] (thousand m^3/d)	Construction year
NPNL (Lao PDR)	Kaolieo	60	Mekong River	66.1	1964
	Chinaimo	80	Mekong River	88.6	1980
	Dongmakkhai	20	Nam Neung River	22.6	2006
PWA (Thailand)	Sukhothai	14	Yom River	11.8	1995
	Phichit	14	Nan River	12.3	2001
	Hua Roa	19	Nan River	13.3	2001
K-water (Korea)	Bansong	120	Nakdong River	71.2	1977
	Hwangji	70	Kwangdong reservoir	44.9	1987
	Chungju	250	Namhan River	174.5	2000

[a] Water production: total volume of treated water in 2013.

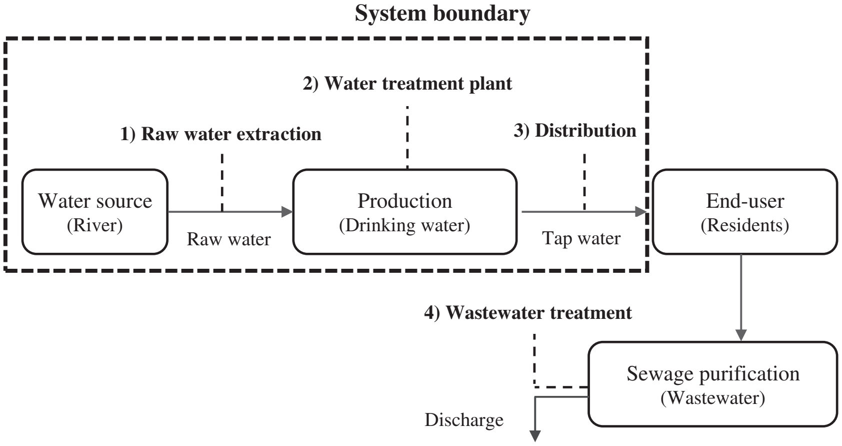


Fig. 1. Drinking water supply chain and system boundary.

the distribution of treated water (pumping station). In addition, the energy costs usually account for between 5 and 30% of total operating costs among the drinking water service industries worldwide [10]. Therefore, improving energy efficiency is at the core of measures to reduce operational costs and GHG emissions.

2.4.2. Chemical use and solid waste generation

Chemicals are mainly used for coagulation, flocculation aid, adsorption, disinfection, and dewatering aid in the water treatment process. Coagulant (alum) and chlorine are always fed into water for coagulation and disinfection, while polymer and powdered activated carbon are intermittently used. Solid waste is generated from sedimentation and filtration processes, and it is usually dewatered by a mechanical dewatering system or sludge-drying bed. The chemicals used in the water treatment stage can remain in the sludge and may enter the natural environment when the sludge is disposed of in the natural environment without proper treatment.

2.4.3. Consumptive water use

Another important issue in the drinking water supply chain is the considerable CWU for raw material (tap water), the water treatment process (operation), and water loss (distribution system). CWU is the sum of indirect water use (electricity, chemicals, and diesel fuel) and direct water use (sludge discharge, backwash, and water loss) in the water supply chain. Water loss is one of the most urgent issues that cause both financial and environmental consequences because it is required to pump and treat more water than is actually needed. Unaccounted for water is not necessarily due to leaks alone, but is also attributed to accounting errors, unauthorized connections, malfunctioning meters and distribution systems, storage tank leakages, reservoir overflow, and authorized unmetered water use. This study considers non-revenue water (NRW) to calculate direct water loss because water service providers lack data between apparent losses (accounting errors, unauthorized connections, and malfunctioning meters) and real losses (leakage and storage overflow).

2.5. Conversion factor for GHG emissions and CWU

The functional unit of GHG and CWU analysis for this study is 1 m^3 of tap water. For estimating GHG emissions (CF) and CWU (WF) from several inputs, the study uses conversion factors suggested from several references, as presented in Table 2.

The conversion factor of GHG emissions from electricity depends on the generation mix of energy sources, such as fossil fuels, nuclear, hydro, geothermal, solar, and biofuels. Therefore, it greatly differs from country to country; in South Korea, it is 0.460 kg CO_2-eq/kWh, in Thailand, it is 0.609 kg CO_2-eq/kWh, and in Lao PDR, it is 0.005 kg CO_2-eq/kWh. In particular, Lao PDR has very a low GHG emission coefficient compared with Korea and Thailand because 100% of its electricity is generated from hydroelectric power plants. WTPs mainly use four kinds of chemicals: alum, chlorine, polymer, and powdered activated carbon. GHG emissions associated with chemical use in drinking water treatment systems can be linked to the production stage of the chemical manufacturing supply chain. This study used conversion factors suggested by ASTE [14] and Novinda [15] for the GHG emissions of chemicals. The diesel fuel consumed by cargo trucks

Table 2
The conversion factor for calculating GHGs emission and CWU

Inputs	Unit	Conversion factors	Refs.
GHG emission			
Electricity (Lao PDR)	kg CO_2-eq/kWh	0.005	[11]
Electricity (Thailand)	kg CO_2-eq/kWh	0.609	[12]
Electricity (South Korea)	kg CO_2-eq/kWh	0.460	[13]
Alum	kg CO_2-eq/kg production	0.248	[14]
Chlorine	kg CO_2-eq/kg production	0.885	[14]
Polymer	kg CO_2-eq/kg production	1.182	[14]
Activated carbon	kg CO_2-eq/kg production	8.500	[15]
Diesel fuel	kg CO_2-eq/L production	3.241	[16]
Consumptive water use			
Electricity (Lao PDR)	L/kWh	80.3	[17,18]
Electricity (Thailand)	L/kWh	8.69	[18,19]
Electricity (South Korea)	L/kWh	2.35	[18,20]
Alum	L/kg production	0.25	Ecoinvent 3.1
Chlorine	L/kg production	0.51	[21]
Polymer	L/kg production	0.25	Ecoinvent 3.1
Activated carbon	L/kg production	50	Ecoinvent 3.1
Diesel fuel	L/L production	37.5	Ecoinvent 3.1

for transporting water treatment chemicals and dewatered sludge was converted into GHG generated using the Defra/DECC conversion factor [16].

The conversion factors of indirect CWU for electricity generation are 80.3, 2.35, and 8.69 L/kWh for NPNL, PWA, and K-water, respectively. NPNL has a very high conversion factor (80.3 L/kWh) because hydroelectric power generation requires significant water volume to generate electricity due to evaporation and seepage from reservoirs or rivers [22]. The water volume embodied in chemicals (alum, chlorine, polymer, and activated carbon) was calculated by the conversion factors of the Ecoinvent database (3.1) and IFC reference [21].

3. Results and discussion

3.1. Drinking water supply chain environmental impact

Environmental impacts (in terms of energy use and GHG emissions, chemicals and waste, and water loss) were observed at the raw water extraction, water production (treatment), and distribution phases of the drinking water supply chain. The findings are presented below.

3.1.1. Raw water extraction

The energy intensity for raw water pumping and conveyance is closely related to the distance of water conveyance and difference in elevation between the water intake station and WTP. As presented in Table 3, K-water has a much longer distance (33.7 km) for water conveyance than NPNL (3.9 km) and PWA (1.3 km) because most WTPs are located far from water sources. In addition, the elevation of geographic location greatly affects energy intensity. For example, the Hwangji WTP in K-water has an elevation difference of around 156 m between the water intake station (elevation 662 m) and WTP (elevation 818 m). This is because K-water's WTPs are situated at a higher elevation in the city, and the tap water to end users is provided through gravity flow. Therefore, K-water has a much higher energy intensity (0.497 kWh/m^3) than NPNL (0.129 kWh/m^3) and PWA (0.136 kWh/m^3). To improve energy intensity, K-water (at the Hwangji and Chungju WTPs) installed additional small-sized pumps in the existing main pumps at the main intake pump station for optimal flow control by combined pump operation.

To extract and convey 1 m^3 of raw water, K-water emitted more than 2.8 times the amount (229 g CO_2-eq) of GHG than PWA (83 g CO_2-eq) because its emission is directly proportional to energy intensity. However, NPNL generated a very small amount of GHG (0.6 g CO_2-eq/m^3) compared with PWA and K-water due to the hydroelectric power plant (GHG coefficient: 0.005 kg CO_2-eq/kWh). NPNL, in contrast, consumed much more water volume (10.3 L/m^3) embodied in electricity production than PWA (1.2 L/m^3) and

Table 3
Environmental impacts at raw water extraction stage

Items	Unit	NPNL (Lao PDR)		PWA (Thailand)		K-water (Korea)	
		Average	Range	Average	Range	Average	Range
Water volume extracted	10^6 m^3/y	23.5	8.7–36.3	4.0	3.3–4.6	32.1	17.5–53.4
Conveyance distance	km	3.9	0.3–11.0	1.3	0.3–3.0	33.7	1.7–78.8
Electricity use	MWh/y	2,407	1,844–3,106	518	20–770	14,416	9,070–18,022
Energy intensity	kWh/m^3	0.129	0.086–0.213	0.136	0.005–0.236	0.497	0.338–0.636
Consumptive water use	10^3 m^3/y	193	148–249	5	0.2–7	34	21–42
Water footprint	L/m^3	10.3	6.9–16.9	1.2	0.04–2.1	1.2	0.8–1.5
GHG emission	t CO_2-eq/y	12	9–15	316	12–469	6,631	4,172–8,290
Carbon footprint	g CO_2-eq/m^3	0.6	0.4–1.0	83	3–144	229	155–292

Note: These data are based for the year 2013.

K-water (1.2 L/m^3) because it depends on the generation mix of energy sources (CWU coefficient: 80.3 L/kWh).

3.1.2. Drinking water production

Electricity use depends on the water treatment process type, such as hydraulic or mechanical systems. K-water is composed of mechanical process types: rapid mixing (mechanical flash mixing, pump diffusers), flocculation (paddle or hydrofoil mixing), sludge collectors, and dewatering machines (belt or filter presses) for meeting strict regulations regarding water quality and environmental protection. On the other hand, NPNL and PWA mainly consist of hydraulic process types, such as static mixing, baffled channels, manual sludge removal, and lagoons (water ponds). However, the energy intensity of water treatment facilities is not high (0.05 kWh/m^3) in comparison with that of a pumping station for raw water extraction and distribution. Recently, the drinking water service industry has introduced renewable energy facilities at water treatment sites as positive activities to cope with future rises in electricity prices and potential supply interruption as well as to achieve sustainable development. K-water has already installed solar photovoltaic facilities at the Hwangji and Bansong WTPs. The investment in renewable energy is expected not only to result in the supply of long-term "clean" energy (62 MWh/y) for water utility operations, but also in the reduction of GHG emissions (−28 t CO_2-eq/y) through carbon offset.

As presented in Table 4, direct CWU (backwashing and sludge drain) accounted for a greater amount (around 99%) of total water consumption in the water production stage. It is noteworthy that PWA consumed a much larger amount of water (219 L/m^3) than K-water (35 L/m^3) and NPNL (54 L/m^3). This is closely related to the frequency of filter backwashing according to media configurations. PWA uses conventional fine sand, rapidly increasing the rate of head loss buildup in the bed, while NPNL and K-water use coarse media (dual media, coarse single media). To produce 1 m^3 of treated water, therefore, PWA consumed a much larger amount of water than NPNL and K-water due to frequent backwashing. In NPNL and PWA, most sedimentation basins are regularly cleaned manually (once every two or three months) with low labor rates. However, the manual cleaning method requires larger amounts of water for removing settled solids than the mechanical sludge removal method.

Chemical use is causative of GHG emissions in its manufacturing stages from 29 to 417 t CO_2-eq/y. K-water has reused 100% of the sludge cake generated from WTPs since 2006 by abiding with the enforced environmental laws and regulations that prohibit the ocean dumping of sludge. Although environmental pollution was decreased by the reuse of sludge cake, sludge disposal costs increased by around 10% compared with those of past disposal methods (landfill or ocean dumping) due to the long transport distance (129 km one way). This cost increase was because the cement manufacturing industry, which reused the sludge, is located far from the WTP. K-water generated about 61 g of waste to produce 1 m^3 of tap water in 2013. On the other hand, NPNL and PWA do not have appropriate sludge disposal alternatives, although some WTPs have small water ponds (lagoons) for the temporary storage of drained sludge. However, accumulated sludge in these water ponds is not removed regularly for appropriate final disposal (landfill or reuse) due to the lax environmental regulations and lack of finance.

Another type of energy use is diesel fuel for transporting chemicals and dewatered sludge cakes to and

Table 4
Environmental impacts at water production stage

		NPNL (Lao PDR)		PWA (Thailand)		K-water (Korea)	
Items	Unit	Average	Range	Average	Range	Average	Range
Chemicals							
Coagulant usage	g/m^3	17.1	13.8–22.4	24.4	20.9–26.9	18.3	9.2–33.6
Chlorine usage	g/m^3	1.7	1.6–1.7	2.4	1.8–3.3	2.5	2.1–3.3
Polymer usage	g/m^3	0.01	0–0.01	–	–	0.07	0–0.16
Powdered activated carbon usage	g/m^3	–	–	–	–	1.0	0–3.1
Total transport distance	10^3 km/y	23.6	7.2–32.2	3.6	3.4–3.7	9.3	5.0–12.2
Waste (sludge disposal)							
Sludge cake generated	ton/y	–	–	–	–	1,768	361–3,081
Total transport distance	10^3 km/y	–	–	–	–	31.2	2.3–78.3
Sludge generation per 1 m^3 water	g/m^3	–	–	–	–	61.1	21.6–126.7
Energy							
Electricity use	MWh/y	19	14–28	146	28–366	1,319	1,047–1,655
Energy intensity	kWh/m^3	0.001	0.001–0.002	0.051	0.007–0.134	0.051	0.024–0.068
Diesel fuel (chemical transport)	m^3/y	10.6	3.3–14.5	1.6	1.6–1.7	4.2	2.2–5.5
Diesel fuel (sludge transport)	m^3/y	–	–	–	–	14.0	1.0–35.2
Diesel fuel use per 1 m^3 water	10^{-3} L/m^3	0.5	0.4–0.6	0.5	0.4–0.6	0.7	0.2–1.7
Renewable energy generated	MWh/y	–	–	–	–	(−)61.7	0–(−)130
Consumptive water use (CWS)							
Chemical use	m^3/y	123	38–166	26	22–30	1,418	95–3,962
Electricity use	m^3/y	1,532	1,142–2,261	1,270	240–3,182	3,099	2,459–3,889
Diesel fuel use for transport	m^3/y	398	122–543	60	58–62	684	123–1,501
Backwash and sludge drain	10^3 m^3/y	1,200	478–2,206	737	525–906	869	727–1,092
Total water loss	10^3 m^3/y	1,202	479–2,209	739	528–997	874	730–1,102
Water footprint	L/m^3	53	38–65	219	185–278	35	14–47
GHG emission							
Chemicals manufacturing	t CO$_2$-eq/y	136	43–187	29	24–34	417	77–914
Electricity use	t CO$_2$-eq/y	0.1	0.07–0.14	89	17–223	607	481–761
Transport (chemical)	t CO$_2$-eq/y	34.4	10.5–47.0	5.2	5.0–5.4	13.5	7.2–17.9
Transport (sludge)	t CO$_2$-eq/y	–	–	–	–	45.5	3.4–114.2
GHG offset by renewable energy	t CO$_2$–eq/y	–	–	–	–	(−)28.4	0–(−)59.8
Total GHG emission	t CO$_2$-eq/y	171	53–233	123	55–256	1,054	544–1,745
Carbon footprint	g CO$_2$-eq/m^3	8	7–9	42	15–94	40	16–72

Note: These data are based for the year 2013.

from the WTPs. According to NAP [23], big cargo trucks have a typical fossil fuel economy ranging from 1.7 to 3.2 km/L. Cargo truck transportation is considered a round trip—one way involving loading (chemicals, sludge cakes) and returning with empty containers; thus, the fuel consumption is assumed to be 1.7 km/L for a loaded truck and 3.2 km/L for an empty truck. NPNL imports most chemicals from Thailand because there is no local factory for manufacturing water treatment chemicals in Lao PDR. As presented in Table 4, NPNL, therefore, has the longest distance (23,600 km/y) and consumes the largest amount of diesel fuel (10.6 m^3/y) for chemical transport per year compared with PWA (3,600 km/y, 1.6 m^3/y) and K-water (9,300 km/y, 4.2 m^3/y).

In terms of GHG emissions (Table 4), PWA and K-water emitted the largest amount of GHG from electricity use, while NPNL generated the greatest amount from chemical use. To produce 1 m^3 of drinking water, PWA and K-water emitted around 40 g of carbon dioxide equivalents (CO$_2$-eq). However, NPNL generated only 8 g of carbon dioxide equivalents (CO$_2$-eq) due to the use of renewable energy (hydropower) and low energy intensity (hydraulic process).

3.1.3. Distribution system

As presented in Table 5, direct CWU (water loss) accounted for over 90% of the total CWU at the distribution stage. The WFs in the distribution system are 272, 282, and 264 L/m^3 for NPNL, PWA, and K-water, respectively.

Other environmental impacts include electricity use for pumping stations and GHG emissions from their use. The energy intensity varies depending on certain characteristics, such as the distance of the distribution system or the difference in elevation [24]. The energy intensity is 0.269, 0.412, and 0.197 kWh/m^3 for NPNL, PWA, and K-water, respectively. There are several reasons why K-water has lower energy intensity than NPNL and PWA. As mentioned before, at the raw water extraction stage, K-water's WTPs are usually located in highland areas to supply tap water to households through low energy intensity. Therefore, K-water has the lowest energy intensity (0.197 kWh/m^3) despite its much longer distribution system. Most importantly, K-water has managed its energy intensity as a key performance indicator for production cost reduction since 2000 through energy goal management, high-efficiency pumps, and an energy management system (EMS).

Electricity consumption for water distribution contributed to large amounts of GHG emissions ranging from 28 to 2,944 t CO_2-eq/y (Table 5). To supply 1 m^3 of tap water to the end user (household), K-water and PWA emitted around 91–251 g of carbon dioxide equivalent (CO_2-eq), while NPNL emitted only 1.3 g of carbon dioxide equivalent (CO_2-eq).

3.1.4. CF and WF

The main inputs and their contribution to CF and WF are indicated in the flowchart (Fig. 2). Each process step is presented as the cumulative CF and WF values. To produce 1 m^3 of tap water in a drinking water supply chain, the CFs are 9.4, 375.4, and 359.5 g CO_2-eq for NPNL, PWA, and K-water, respectively. Additionally, the WFs are 335.4, 501.4, and 300.4 L/m^3 for NPNL, PWA, and K-water, respectively. The study did not include 1 m^3 of tap water (final products) in the WFs and only considered blue WF (surface and ground water).

The contribution to the total CF and WF of each stage in the drinking water supply chain is presented in Figs. 3 and 4.

This study identified that the CFs were substantially higher in the raw water extraction and distribution stage, mainly because of the use of considerable energy by pumping stations. On the other hand, the WFs were significantly higher in the water production (backwash, sludge drain) and distribution system (water loss). K-water had the smallest WF (300.4 L/m^3) due to the implementation of various projects on water treatment optimization (long filter run time, mechanical sludge removal) and water loss reduction.

3.2. GSCM opportunity areas

The greening potential in the drinking water supply chain lies in three major areas: energy efficiency and the reduction of GHG emissions, chemical and waste management, and cutting down water loss.

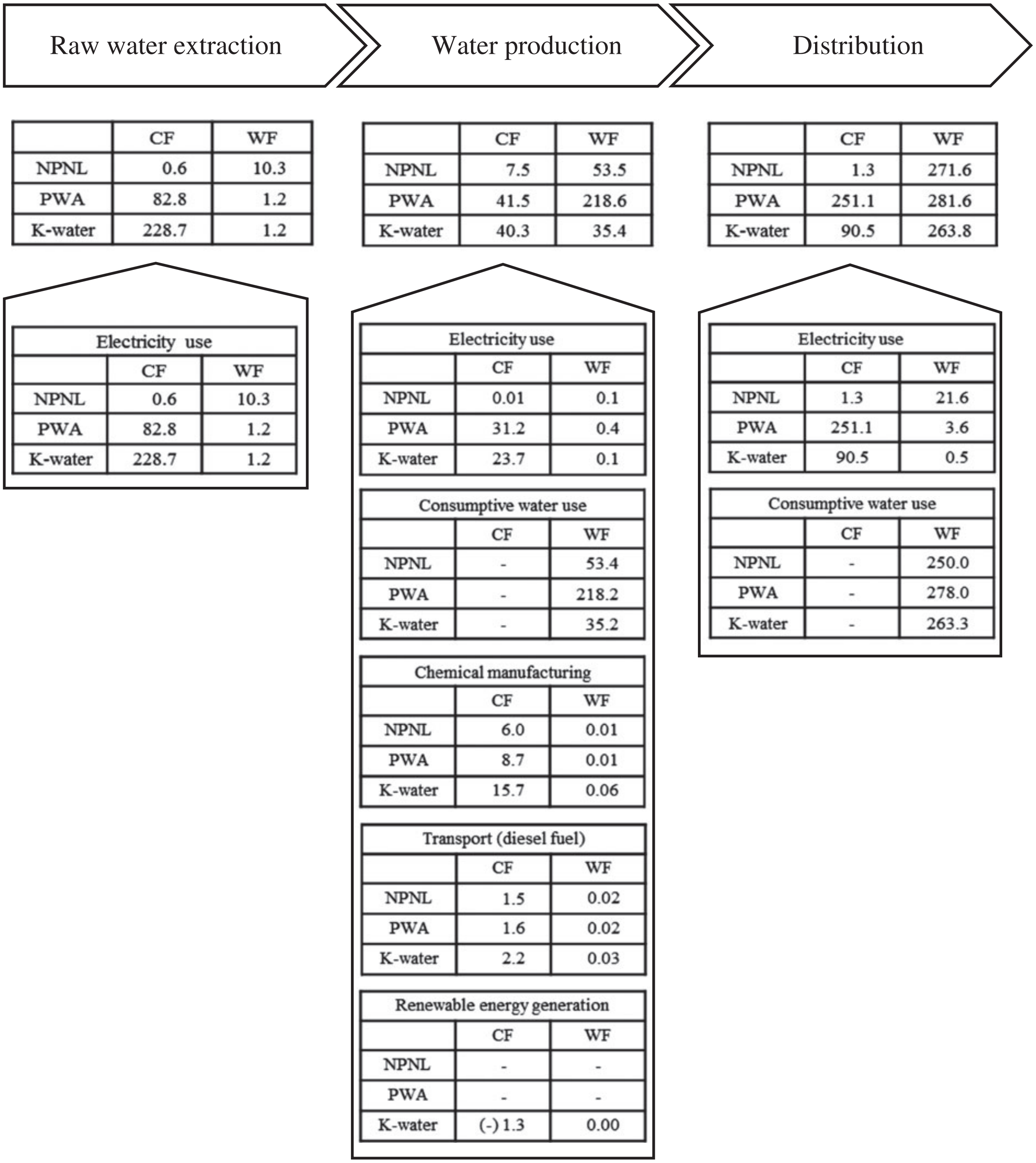
3.2.1. Energy efficiency and GHG emission reduction

Given the limited supply of energy and other natural resources, increasing the efficiency of resources and energy in the water supply chain is a core principle for reducing production costs, resulting in lower tariffs for

Table 5
Environmental impacts at distribution stage

		NPNL (Lao PDR)		PWA (Thailand)		K-water (Korea)	
Items	Unit	Average	Range	Average	Range	Average	Range
Water volume supplied	10^6 m^3/y	22.3	8.3–34.0	2.5	1.8–3.0	31.3	16.8–53.0
Electricity use	MWh/y	5,672	2,574–8,183	846	269–1,539	6,400	306–13,463
Energy intensity	kWh/m^3	0.269	0.240–0.254	0.412	0.091–0.865	0.197	0.013–0.324
Indirect CWS (energy)	10^3 m^3/y	455	207–657	7	2–13	15	0.7–32
Direct CWS (water loss)	10^3 m^3/y	5,564	2,067–8,511	908	775–996	7,142	5,665–8,829
Total CWS	10^3 m^3/y	6,020	2,274–9,168	916	777–1,002	7,157	5,678–8,861
Water footprint	L/m^3	272	269–275	282	208–356	264	167–340
Total GHG emission	t CO_2-eq/y	28	13–40	515	164–937	2,944	141–6,193
Carbon footprint	g CO_2-eq/m^3	1.3	1.2–1.5	251	55–527	91	6–149

Note: These data are based for the year 2013.



Raw water extraction

	CF	WF
NPNL	0.6	10.3
PWA	82.8	1.2
K-water	228.7	1.2

Electricity use

	CF	WF
NPNL	0.6	10.3
PWA	82.8	1.2
K-water	228.7	1.2

Water production

	CF	WF
NPNL	7.5	53.5
PWA	41.5	218.6
K-water	40.3	35.4

Electricity use

	CF	WF
NPNL	0.01	0.1
PWA	31.2	0.4
K-water	23.7	0.1

Consumptive water use

	CF	WF
NPNL	-	53.4
PWA	-	218.2
K-water	-	35.2

Chemical manufacturing

	CF	WF
NPNL	6.0	0.01
PWA	8.7	0.01
K-water	15.7	0.06

Transport (diesel fuel)

	CF	WF
NPNL	1.5	0.02
PWA	1.6	0.02
K-water	2.2	0.03

Renewable energy generation

	CF	WF
NPNL	-	-
PWA	-	-
K-water	(-) 1.3	0.00

Distribution

	CF	WF
NPNL	1.3	271.6
PWA	251.1	281.6
K-water	90.5	263.8

Electricity use

	CF	WF
NPNL	1.3	21.6
PWA	251.1	3.6
K-water	90.5	0.5

Consumptive water use

	CF	WF
NPNL	-	250.0
PWA	-	278.0
K-water	-	263.3

Fig. 2. Flowchart of carbon and WFs in drinking water supply chain.
Notes: CF: Carbon footprint (g CO_2-eq/m^3), WF: Water footprint (L/m^3).

consumers [25], as well as reducing energy-based GHG emissions, greening the water supply chain.

The most effective way to improve energy efficiency is to introduce an efficient pumping system. Easton Consultants [26] stated that pump efficiency may degrade by 10–25% in its lifetime. Replacing a pump with a new, efficient one can reduce energy consumption by 2–10% [27], and higher efficiency motors can also increase the efficiency of the pump system by 2–5% [28]. In addition, an energy audit and diagnosis help to identify major issues in energy use and indicate potential solutions for energy efficiency.

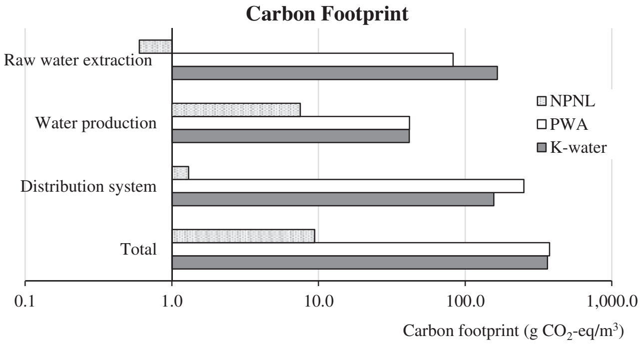


Fig. 3. CF at each stage of drinking water supply chain.

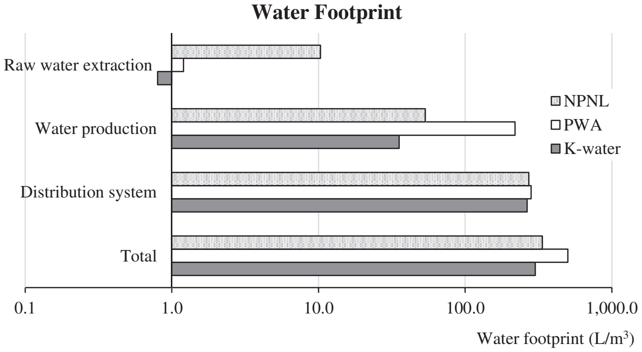


Fig. 4. WF at each stage of drinking water supply chain.

For example, K-water conducted a diagnosis for evaluating the performance of all its pumps (678) in 2011 and identified that 30% (204) of the pumps had deteriorated, leading to lower efficiency (over 7%) than their original performance. To increase energy efficiency, 43 of the 204 degraded pumps were replaced with new pumps between 2012 and 2014. In the cases of NPNL and PWA, a considerable number of pumps in their water pumping stations are more than 15 years old, requiring restoration or a change to high-efficiency new pumps.

EMSs, comprising two main components (a demand forecast and scheduler), have been widely applied in the drinking water supply system for improving energy efficiency. According to Barry [29], the typical electricity-saving range of an EMS is 12–30%, although this varies greatly depending on certain conditions. K-water has introduced EMSs to all pump stations to monitor, control, and optimize the performance of the extraction and distribution system and achieved annual energy savings of 3–5% since 2014. NPNL and PWA need to introduce EMSs to learn where the energy is being used in their facilities and to identify opportunities for energy efficiency improvements.

Opting for renewable energy instead of fossil fuel-based operation can be a good opportunity for greening the drinking water service industry via better energy management. K-water has already installed 23 solar photovoltaic facilities in water intakes, treatment plants, and water sources (on the surface of reservoirs). The annual electricity output generated from them is approximately 4 GWh/y, which provides enough power for 1,180 houses if considering world average electricity consumption (3,392 kWh) per electrified household in 2013 [30]. Solar photovoltaics greatly depend on sunlight intensity and sunshine hours to produce solar energy. Lao PDR and Thailand have more favorable conditions for solar renewable energy than South Korea because these regions are very hot throughout the year.

The largest source of GHG emissions in the drinking water supply chain is the pumping system for raw water intake and distribution to the end user. If the water supply system energy use can be reduced by 10% through energy management, the CF will be reduced by about 9.5%. To reduce GHG emissions, therefore, the drinking water service industry has to focus on energy efficiency. In addition, setting a national policy and strategy can effectively contribute to GHG and energy reduction targets. For example, the Korean government set medium-term targets for national GHG emissions (30% reduction by 2020 compared with business as usual (BAU)) through a framework act on low carbon and green growth in 2010. To achieve this national goal, the government claimed its share of responsibility for reducing GHG emissions in each industry sector. K-water should reduce its GHG emissions by 2.5% by 2020 compared with BAU for meeting the national GHG target and should submit an implementation report of the GHG reduction project to the government every year. This national policy for carbon management can promote the transition to a low-carbon economy in the drinking water service industry.

3.2.2. Water loss management

Water loss reduction, more broadly NRW reduction, has a significant impact on energy consumption as well as water consumption in the drinking water service industry. NRW remains a serious challenge in most developing countries, where it is usually higher than 30% of the produced water volume, compared with less than 10% in global best practices [10]. Leaks are the most frequent causes of NRW. According to statistical data on the waterworks in South Korea [31], water loss from leaks has accounted for 65% of NRW in the last 5 years. Measures to reduce water leaks can provide double benefits to the water service industry by increasing salable water without increasing energy consumption. One of the most critical factors for reducing real losses is rehabilitating or replacing transmission mains and portions of the distribution networks identified in water leakages. This measure can reduce the volume of real losses (leakage), leading to as much energy saving as water saving.

Filter run time (backwash cycle) is also an important performance indicator for reducing direct water consumption. According to K-water's case study in 2013, dual-media filters had about 1.5 times longer filter run time than conventional fine sand filters. Another research result [32] reported that the dual-media filter produced much more filtered water (over 10%) than the fine sand bed due to longer filtration cycles. This is because the dual-media filter can function as a progressive sieve, which can trap larger solids within the coarser (top) anthracite layer, whereas the smaller particles are trapped deeper within the (bottom) sand layer. A dual-media filter can thus be a good alternative for reducing direct CWU by increasing the filtration cycle of the existing filters (conventional fine sand) in PWA. If the Sukhothai WTP of PWA can maintain its filter run time for two days (from one day) through the replacement of the conventional fine sand filter with a dual-media filter, the WF would be reduced by 22%.

3.2.3. Chemicals and waste management

Chemical use impacts on GHG emissions at their manufacturing/production stage and the use of fossil fuels for their transportation to WTPs. To reduce chemical usage, the optimum dosage rate should be determined by a jar test, and an accurate amount should be fed through the chemical feed systems. Most of all, the rapid mixing type greatly affects chemical usage and mixing efficiency. For example, the Sacheon WTP in K-water reduced its coagulant usage by around 27% through the replacement of the rapid mixing type (from an in-line orifice to an advanced static mixer) in 2011. NPNL and PWA use hydraulic jump and in-line static mixing methods that do not require any external energy for rapid mixing. A new mixing method (advanced static mixer) could be an attractive alternative for reducing chemical usage as well as increasing mixing efficiency in PWA and NPNL. Recently, *green chemicals*, the design of chemical products and processes that reduce or eliminate the generation of hazardous substances, have been widely used in water and wastewater treatment plants in developed countries, and their use is steadily increasing in water industries elsewhere too. These green chemicals have a greater potential for GHG emission reduction than the manufacturing of traditional chemicals.

Sludge is a major solid waste concern related to WTPs. K-water has reused 100% of its dewatering sludge cakes, such as cement materials (83.8%), cover materials (12.1%), planting soil (0.9%), and potting soil (0.3%), in 2013 [33]. However, long-distance transport has contributed to an increase in the cost of sludge disposal and the use of fossil fuels. K-water is required to explore diverse reuse sites of sludge disposal that are located in adjacent areas to WTPs to reduce the environmental impacts of sludge management. NPNL and PWA need to introduce a sludge dewatering system to prevent environmental pollution from inappropriate sludge disposal in a natural waterway. However, mechanical sludge stabilization and dewatering technologies are costly and demand significant energy. For example, they accounted for about 30% of WTP energy consumption (not including pumping stations) in K-water (in 2013). Therefore, sludge lagoon drying beds can be the simplest and yet the most cost-effective alternative in Lao PDR and Thailand because these regions are hot throughout the year.

3.3. Drivers and barriers for GSCM

Though there are many practices that can potentially reduce environmental impacts and aid in greening the drinking water supply chain, nevertheless, there are many factors that can either enable or discourage the implementation of GSCM. These drivers and barriers are grouped into "internal" and "external" categories and are presented in Table 6. The internal categories of drivers and barriers are related to the internal decision-making of the companies operating the WTPs, while the external categories are related to environmental compliance regulations and environmental sustainability policies at the national level.

3.3.1. Drivers for GSCM

The desire to reduce the production costs of the company is the most representative "internal" driving force for green supply activities. Water service providers have recently started putting a great deal of effort into improving energy efficiency because electricity costs accounted for 20, 22, and 30% of total operating costs for NPNL, PWA, and K-water, respectively, in 2013. If energy use can be reduced through energy efficiency measures, it directly affects the reduction of

Table 6
Drivers and barriers for implementing GSCM in drinking water services

Drivers	Barriers
Internal	
Reduction of production cost (electricity cost)	Low tariff structure of government
Eco-friendly company image (sustainability report)	Lack of supplier awareness about GSCM
Environmental concerns of decision-makers	Financial constraints in implementing greening practices
External	
Regulatory compliance (stringent criterion)	Lax environmental regulation for preventing pollution
Environmental risk minimization (ISO 14001 & 50001)	Lack of new technology and facilities
Pressure from customers or NGOs for GSCM	Lack of stakeholder awareness

GHG emissions as well as the reduction of production costs. With the growing importance of environmentally sound sustainable development and increasing green consumerism, water service providers are also concerned about the potential reputation risk and public embarrassment that might arise due to companies' poor environmental performance. Therefore, companies are now investing in organizational sustainability efforts and publishing the outcomes in annual sustainability reports. They even use their economic, environmental, social, and governance performance as a marketing strategy. Such concerns were observed in the studied WTPs, too.

Government regulations and legislation have undoubtedly played an important role (strong "external" driver) in the implementation of GSCM. Meeting legislative requirements is the main goal of public service providers, including the drinking water service industry. For example, the government regulation prohibiting the ocean dumping of sludge in South Korea forced K-water to reuse all its dewatering sludge cakes for greening practices. Moreover, external pressure resulting from regulation, such as the ISO 14001 (environmental management systems), ISO 50001 (EMSs), and the restriction of hazardous substances (RoHS) directives have also led water service providers to consider the environmental impact produced by chemicals in the entire supply chain [34]. The deterioration of environmental resources over recent decades has dramatically increased public awareness. Therefore, pressure from the public and other stakeholders (customers, NGOs) is also pushing water service providers to review their environmental supply practices.

3.3.2. Barriers for GSCM

Despite sizeable opportunities for greening the drinking water supply chain, this study also identified a few potential "internal" and "external" barriers that could pose challenges in GSCM implementation. These barriers are summarized above in Table 6.

One of the "internal" barriers could be the cost factor. Usually, companies and even customers associate greening activities with an increased cost of operation and an increased price of the service rendered. As water is a basic necessity of life, the cost concern may pose a serious obstacle to considering environmental factors by investing in greening practices. In Lao PDR, the official tariff policy is to recover operation and maintenance costs as a minimum and to set the tariff to around 3–5% of the household income; thus, any cost increase in implementing greening activities cannot be recovered through water fees.

Most public water sectors have a relative lack awareness of environmental legislation and tend to be ignorant of the environmental impact on the organization's activities and the benefits of adopting a green supply chain compared with other manufacturing industry sectors, which have always been referred to as polluting industries and have therefore been forced to consider lowering their supply chain environmental impacts. Low returns on high investment in GSCM equipment and practices are another financial barrier.

Lax environmental regulations can inhibit the implementation of GSCM, especially in developing countries, where companies and industries are still limited in complying with the required command and control targets. The lack of GSCM policies and regulations may also discourage companies from investing in GSCM activities, because their green supply chain outcomes may not be recognized or certified and therefore cannot be considered legitimate "value addition" for the company's advertisements and reputation.

The lack of information and access to new, cleaner technologies may also act as a barrier in the application of an advanced system and infrastructure within the water supply system for adopting a green supply chain. Similarly, consumers' lack of awareness of a sustainable and ethical supply chain can also lessen companies' attention regarding implementing GSCM in its product or service supply chain. Additionally, the public service sectors, such as the drinking water supply sector, are rarely associated with unsustainable environmental practices compared with manufacturing industries; thus, the implementation GSCM strategies is either dismissed or delayed in such service sectors.

4. Conclusion

The comparative assessment of GSCM in the drinking water service industry in Lao PDR, Thailand, and South Korea showed that energy use and associated GHG emissions (CF) and CWU (WF) are the major environmental impact areas of the supply chain. Similarly, chemical use and sludge disposal are other areas of concern in the drinking water supply chain system.

Among the three countries of the study, only South Korea has implemented various greening activities, such as an EMS, sludge reuse, GHG target management, and renewable energy development, for meeting its strict government policy and regulations. To provide 1 m^3 of tap water to end users, K-water had the smallest WF (300.4 L/m^3), which it achieved through various greening activities involving water treatment optimization and NRW reduction in its supply chain. The WTPs in Lao PDR and Thailand have yet to implement GSCM strategies and policies. NPNL had the lowest CF (9.4 g CO_2-eq/m^3), not necessarily due to its GSCM strategy, but due to the use of cheaply available renewable energy (hydropower).

From the findings of the study, it can be inferred that one of the main drivers of GSCM is "production/operational cost cutting," followed by other drivers, such as strict government regulations, as well as increasing the awareness of the public regarding green consumerism. Technical, financial, regulatory, and awareness constraints, on the other hand, were found to inhibit GSCM practices in the public drinking water service sector. This study concluded that one of the largest potential areas for greening the drinking water supply chain is effective EMSs to reduce GHG emissions, together with reducing water loss and managing chemicals and sludge disposal. Carbon and WF can be reduced by about 10–22% through energy efficiency and water loss management.

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