Water Research 277 (2025) 123245

Contents lists available at ScienceDirect

Water Research

journal homepage: www.elsevier.com/locate/watres

Global energy consumption of water treatment technologies

Michele Magni [a,*], Edward R. Jones [a], Marc F.P. Bierkens [a,b], Michelle T.H. van Vliet [a]

[a] Department of Physical Geography, Faculty of Geosciences, Utrecht University, Utrecht, the Netherlands
[b] Unit Subsurface and Groundwater Systems, Deltares, Utrecht, the Netherlands

ARTICLE INFO

Keywords:
Conventional drinking water treatment
Desalination
Wastewater treatment
Sanitation
Global hydrology
Water-energy nexus

ABSTRACT

Access to safe drinking water and sanitation is crucial for protecting human health and achieving many Sustainable Development Goals. However, the provision of these services requires significant amounts of energy, which are poorly quantified at the global scale. In this study, we develop a spatially explicit model framework (5 arcmin resolution) for quantifying the energy consumption of water treatment technologies globally, focusing on desalination, wastewater treatment and conventional drinking water treatment (i.e. from ground and suface water sources). We estimate that these processes required 379–1,159 TWh (1.36–4.17 EJ) globally in 2015, corresponding to 1.8–5.4% of total global electricity consumption. Individually, 189–331 TWh (0.68–1.19 EJ) were consumed for desalination, 85–279 TWh (0.31–1.00 EJ) for wastewater treatment and 105–549 TWh (0.38–1.98 EJ) for conventional drinking water treatment. The largest energetic tolls of the three technologies are found in the Middle East and North Africa (desalination), Western Europe (wastewater treatment) and South Asia (conventional drinking water treatment), where they contribute up to 18.6 %, 2.4 % and 4.7 % of the electricity consumption in these regions, respectively. Considering the identified uncertainties, the model framework can be used to represent spatially explicit patterns of energy consumption for water treatment in Integrated Assessment Models and Energy System Models. These developments enable projections of the future energy demands of water treatment technologies and a better understanding of the water-energy nexus, under global change and at multiple spatial scales.

1. Introduction

It is estimated that 2 billion people across the globe lack access to a safe source of drinking water and that 3.6 billion people are not connected to safely managed sanitation, corresponding to 26 % and 46 % of the world population, respectively (United Nations, 2023a). The expansion of technologies for drinking water and wastewater treatment is considered a key strategy to tackle global challenges in water supply and sanitation (Moe and Rheingans, 2006) and to support multiple Sustainable Development Goals (Abu-Zeid, 1998; Sorenson et al., 2011; Irannezhad et al., 2022; United Nations, 2023b). The rapid increase in urban population simultaneously represents an opportunity to upscale inclusive and sustainable development of water infrastructure in cities (Larsen and Gujer, 1997; Marlow et al., 2013; Hoekstra et al., 2018). However, technologies and processes across the water supply are energy intensive (Gleick, 1994; King et al., 2008; Rothausen and Conway, 2011; Plappally et al., 2012; Sanders and Webber, 2012; Wakeel et al., 2016) and could therefore conflict with climate change mitigation if their development is not supported by renewable energy sources (Hussey and Pittock, 2012; Hejazi et al., 2015; Lee et al., 2017; Parkinson et al., 2019).

Modelling the current energy use of water treatment technologies is therefore essential to forecast their future energetic demands and to improve our understanding of the water-energy nexus, i.e. the interdependencies between the water and energy sectors (Olsson, 2015; Hamiche et al., 2016; Dai et al., 2018), under global change. Yet, existing research has predominantly focused on local (e.g. Bodik and Kubaska (2013); Panepinto et al. (2016)) to regional (e.g. Sanders and

Abbreviations: COD, Chemical Oxygen Demand; CDWT, Conventional drinking water treatment; EAP, East Asia and Pacific; ED, Electrodialysis; EECA, Eastern Europe and Central Asia; GDP, Gross Domestic Product; GW, Groundwater; GWT, Groundwater treatment; LAC, Latin America and Caribbean; MED, Multi-effect distillation; MENA, Middle East and North Africa; MSF, Multi-stage flash distillation; MVC, Mechanical vapor compression; NAM, North America; PCR-GLOBWB, PCRaster - GLOBal Water Balance; RO, Reverse osmosis; SAS, Southern Asia; SSA, Sub-Saharan Africa; SW, Surface water; SWT, Surface water treatment; TVC, Thermal vapor compression; USD, United States Dollar; WE, Western Europe; WWT, Wastewater treatment; WWTP, Wastewater treatment plant.

* Corresponding author.
E-mail address: m.magni@uu.nl (M. Magni).

https://doi.org/10.1016/j.watres.2025.123245
Received 25 October 2024; Received in revised form 22 December 2024; Accepted 3 February 2025
Available online 13 February 2025

Webber (2012); Chini and Stillwell (2018); Molinos-Senante et al. (2018)) scales, with global inter-comparisons limited to a few cities (Lam et al., 2017) or countries (Longo et al., 2016; Wang et al., 2016; Wakeel et al., 2016). Previous studies have also typically lacked spatial or temporal distribution, limiting their application in continental and global assessments. The most comprehensive global-scale estimates of energy-for-water, i.e. the energy consumption of the water sector excluding end-uses (Kyle et al., 2016), were brought forward by Liu et al. (2016), who coupled values of energy use intensities for processes across the water supply with country-level statistics of water use. Despite their study setting a groundbreaking benchmark in global energy-for-water research, it is characterized by coarse country-scale resolutions, hindering the characterization of local patterns of energy consumption for clean water provision.

The main goal of this research is therefore to develop a spatially explicit model framework of the energy consumed globally by water treatment technologies. To this end, we gathered comprehensive spatial data and characteristics of desalination and wastewater treatment plants, in addition to mapping safe access to drinking water worldwide. We then collected energy intensity ranges of these water treatment technologies with a thorough literature study, to render the uncertainties in their global energy consumption. The framework can produce gridded outputs of energy consumption for desalination, wastewater treatment, and drinking water treatment from ground and surface water sources (hereinafter "conventional drinking water treatment" (Hofman-Caris and Hofman, 2019)) at 5 arcmin resolution (approximately 10 km at the equator). These datasets enable the representation of the energy demands for water treatment in Integrated Assessment Models (Van Asselt and Rotmans, 2002; van Beek et al., 2020; Kyle et al., 2021) and Energy System Models (Schrattenholzer, 1981; Jebaraj and Iniyan, 2006). This should allow for better evaluations of the future energy demands to alleviate global clean water scarcity (Grafton et al., 2015; Straatsma et al., 2020) and the energetic implications of different water infrastructure development schemes across evolving rural and urban settings (Wilderer and Schreff, 2000; Gikas and Tchobanoglous, 2009; Rabaey et al., 2020).

2. Materials and methods

Limited data on water infrastructure and energy consumption of water technologies exist (Chini and Stillwell, 2017, 2018), requiring various assumptions in model structure and producing relatively large uncertainties in model output. For instance, while detailed information on desalination plants, such as capacity, technology and feedwater type, is available between 1945 and 2019 (Global Water Intelligence, 2019), data on global wastewater treatment plants contains uncertainties in population served, treated volumes, current status and technology (Ehalt Macedo et al., 2022). A dataset of conventional drinking water treatment plants at the global scale is currently entirely lacking. Furthermore, plant-specific energy consumption varies widely across countries (Wakeel et al., 2016) and technologies, and is often inconsistently reported (Chini et al., 2021). The data used for each considered water treatment technology (desalination, wastewater treatment, conventional drinking water treatment) are summarized in Table S1.

Considering these limitations, we built a simple plant-scale model of energy consumption for water treatment as follows:

$$E_p = Q_p E_i \tag{1}$$

where Q_p is the capacity or the volume of water treated by a plant (m^3 y^{-1}), and E_i is an energy intensity range collected from various literature sources (kWh m^{-3} or J m^{-3}), enabling us to account for uncertainties, resulting in a low, mean and high value of yearly energy consumption E_p (kWh y^{-1} or J y^{-1}) for each plant. Since literature studies usually report energy consumption intensities for water treatment technologies in kWh m^{-3}, calculations are initially made in kWh and then converted to J using a multiplication factor of $3.6 \cdot 10^6$. The units of kWh and J are then used interchangeably and do not carry any meaning regarding the specific energy sources employed (i.e. primary energy sources or electricity).

The focal point of this study is to quantify the total energy consumption of water treatment processes. Due to a lack of global data about in-situ energy production, the analysis of net energy consumption is outside of the scope of this work. To make the results easily integrable with other gridded models, point estimates are then assigned to the closest centroid on a 5 arcmin grid. On the temporal scale, the framework is currently set up to produce annual estimates. Sub-yearly, i.e. seasonal, fluctuations in energy consumption for these processes are not covered at this stage. In the following, materials and methods for the three technologies are briefly presented in order of data availability and quality, beginning with desalination, followed by wastewater treatment and conventional drinking water treatment. Detailed descriptions of the model framework are given in Section A.1 of the Appendix.

The location, technology, feedwater type, capacity and initial year of operations of desalination plants worldwide are obtained from DesalData (Global Water Intelligence, 2019) (Fig. S1). We estimate the energy consumption of 19,112 plants worldwide that use one of the four main desalination technologies, categorized into distillation, i.e. Multi-stage flash (MSF) and Multi-effect distillation (MED), and membrane processes, i.e. Reverse Osmosis (RO) and Electrodialysis (ED). The energy consumption of membrane technologies is dependent upon feedwater salinity, while energy consumed for distillation is constant across feedwaters (Elimelech and Phillip, 2011; Al-Karaghouli and Kazmerski, 2013; Lin, 2019; Nassrullah et al., 2020) (Table S2 and Table S3). For RO, we model the increasing energy efficiency over time with an exponential decay curve, fitted to values reported by Elimelech and Phillip (2011) and linearly scaled with salinity (Fig. S2). Further information on the approach used for desalination is detailed in Section A.1.1 of the Appendix.

To quantify the energy consumption of wastewater treatment, we consider the characteristics of 58,426 wastewater treatment plants, obtained by combining the global database HydroWASTE (Ehalt Macedo et al., 2022) with a detailed national database for China (Chen et al., 2019) (Fig. S3). Energy consumption in wastewater treatment is dependent on the volumes and quality of the incoming water (Longo et al., 2016; Niu et al., 2019), and the level of treatment (primary, secondary, advanced). To this end, we built a model routing wastewater production to wastewater treatment plants (Fig. S4), using 5 arcmin treated wastewater volumes (Jones et al., 2021) and population (Klein Goldewijk and van Drecht, 2006) maps for 2015 (Fig. S5). By assuming that treatment happens in the same country (World Bank, 2020) (Table S4) and in the same catchment (Linke et al., 2019), information on treated volumes and population attached to a specific plant was generated. For secondary treatment, a two-parameter exponential model (volume and Population Equivalent Chemical Oxygen Demand) (adapted from Niu et al. (2019)) was fit to energy consumption data, following Longo et al. (2016) (Fig. S6 and Table S5). Energy intensity ranges were used to quantify the energy consumption of primary and advanced treatment. Detailed information on this approach is provided in Section A.1.2 of the Appendix.

As no global dataset of conventional drinking water treatment plants exists, additional steps were required to model the energy consumption of surface and groundwater treatment for drinking water provision (Fig. S7). First, we mapped access to safely managed water at 5 arcmin resolution, based on country-level water access data (Food and Agriculture Organization, 2019; World Bank, 2019a) (Fig. S8), in combination with high resolution (5 arcmin) datasets of population (Klein Goldewijk and van Drecht, 2006) and Gross Domestic Product (GDP) (Chen et al., 2022) (Fig. S9). Essentially, a population cap of safe water access in rural and urban settings was calculated at the country level. Gridcells with the highest GDP per capita were then sequentially assigned safe drinking water, until exhaustion of such cap. All the remaining population gridcells were classified as having access to either basic or untreated drinking water. Volumes of drinking water treatment were then estimated using the municipal water demands of 2015 from the global hydrological model PCR-GLOBWB 2 (Wada et al., 2014; Sutanudjaja et al., 2018) (Fig. S10A), which neglects water leakages in distribution networks. Where present, safe access gridcells were first assigned to desalinated drinking water, using information from DesalData (Global Water Intelligence, 2019) (Fig. S10B), until reaching plant capacities. Finally, all other population gridcells with safe water access were assigned to either surface water or groundwater, depending on the closest source in the water withdrawals of PCR-GLOBWB 2 (Sutanudjaja et al., 2018) (Fig. S10C-E). These are the volumes that we assumed to be passing through conventional drinking water treatment plants. To calculate the energy consumption, we collected energy intensity ranges for various drinking water treatment technologies (Plappally et al., 2012; Grzegorzek et al., 2023) (Table S6) and matched them to eight different plant configurations (TU Delft OpenCourseWare, 2024) (Fig. S11). These setups characterize the increasing complexity and energy consumption for treatment of groundwater and surface water sources (Santana et al., 2014). The uncertainty in energy intensity for conventional drinking water treatment is then the total range across these combinations of plants configurations and technologies. An in-depth description of these developments and assumptions is given in Section A.1.3 of the Appendix.

3. Results

3.1. Desalination

A complete overview of global trends in desalination (1945–2019) is given in Fig. 1. Global desalination capacity of the four major technologies (MSF, MED, RO, ED) grew at an average pace of 0.44 $km^3\,y^{-1}$ from 1945 to 2019, reaching 33 km^3 in 2019. RO is by far the most employed technology (69.6 % of total installed capacity), followed by MSF (20.1 %), MED (7.6 %) and ED (2.7 %). Almost 50 % of global desalination capacity is currently located in the Middle East and North Africa (MENA), followed by East Asia Pacific (EAP, 18.7 %), North America (NAM, 12.8 %) and Western Europe (WE, 9.8 %), while the other regions

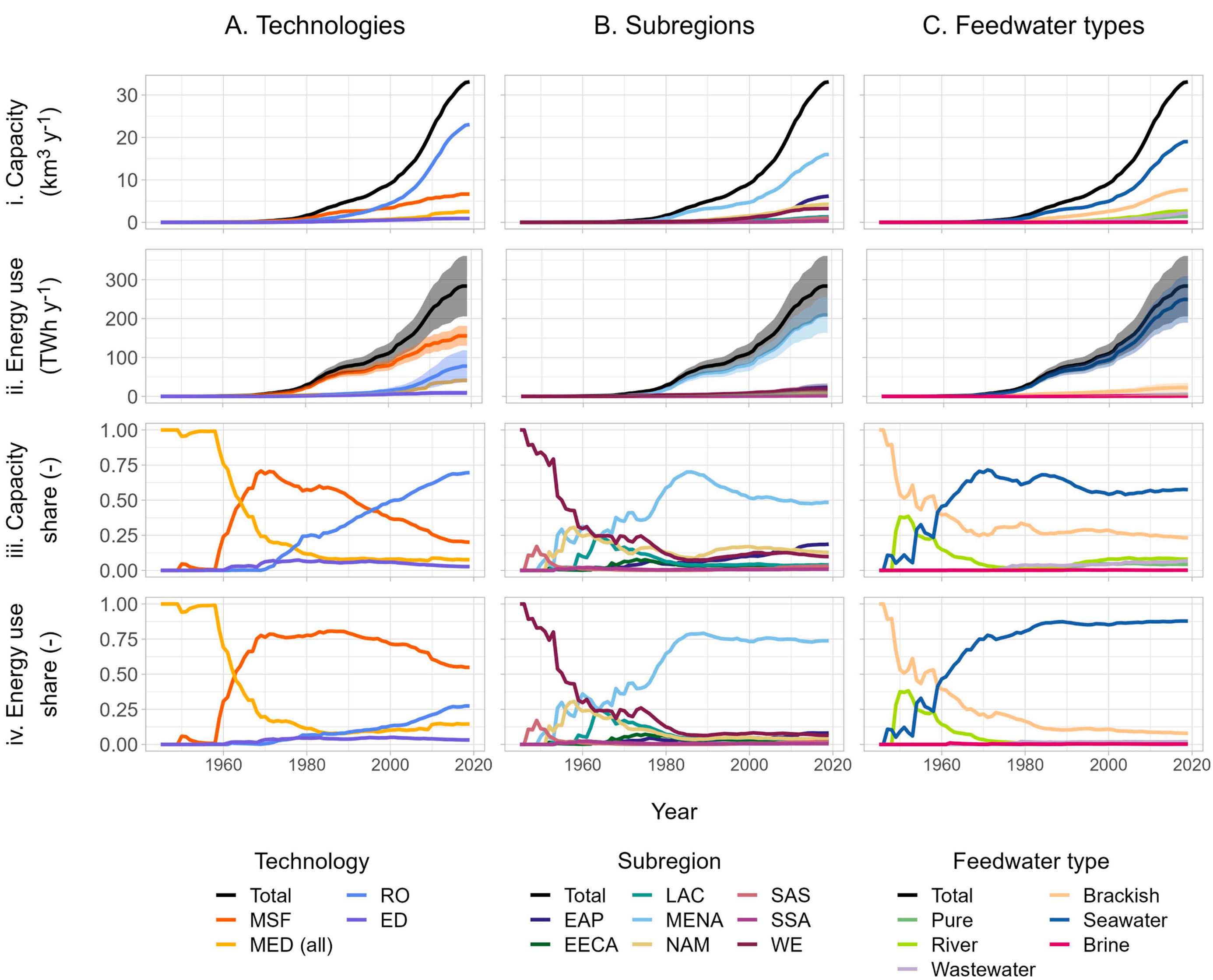

Fig. 1. Global desalination trends (1945–2019) in: i) cumulative capacity; ii) cumulative energy consumption; iii) capacity share; and iv) energy consumption share per A) technology; B) subregion; and C) feedwater type. Energy use shares are calculated for average modelled energy use. Technologies: MSF = Multi-Stage Flash; MED = Multi-Effect Distillation; RO = Reverse Osmosis; ED = Electrodialysis. Subregions: EAP = East Asia and Pacific; EECA = Eastern Europe and Central Asia; LAC = Latin America and Caribbean; MENA = Middle East and North Africa; NAM = North America; SAS = Southern Asia; SSA = Sub-Saharan Africa; WE = Western Europe.

together make up for just over 10 %. Regarding feedwater types, most desalination focuses on seawater (57.5 %) and brackish water (23.3 %), followed by river water (8.1 %), wastewater (6.7 %) and pure water (4.2 %).

In terms of energy consumption, we model that desalination technologies required 205–361 TWh (0.74–1.30 EJ) globally in 2019, with an average growth of 2.74–4.81 TWh y^{-1} (0.01–0.017 EJ y^{-1}) from 1945. Energy shares during early development are highly correlated to the expansion of MSF and MED, with these two technologies each contributing about half of global energy consumption for desalination at the beginning of the 1960s. The increasing adoption of RO and improvements in membrane efficiency have produced a decoupling between the capacity and energy share of the different technologies. For example, the share of global installed desalination capacity was roughly equal for RO (43.6 %) and MSF (42.2 %) in 1996, yet we estimate that at this time their contribution to energy consumption was 10.8 % (4.9–14.8 TWh) and 75.1 % (58.6–81.5 TWh), respectively. This trend has continued to the present day, as production of 23 km^3 y^{-1} of

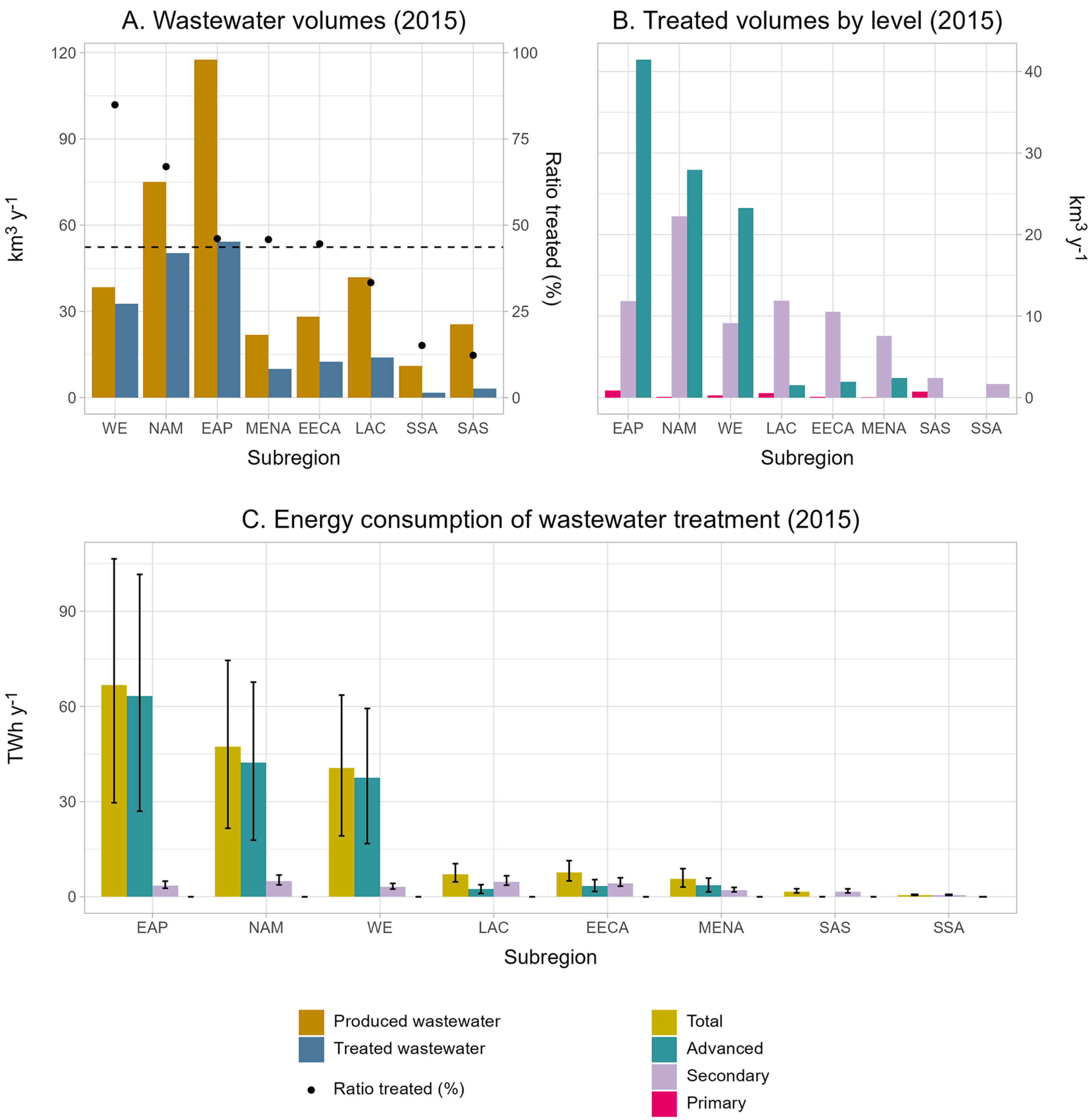

Fig. 2. Modelled state of wastewater treatment in 2015: A) estimated produced and treated wastewater volumes, and their regional ratios; B) treated wastewater volumes divided by treatment level; and C) calculated energy consumption (total and by treatment level). Subregions: EAP = East Asia and Pacific; EECA = Eastern Europe and Central Asia; LAC = Latin America and Caribbean; MENA = Middle East and North Africa; NAM = North America; SAS = Southern Asia; SSA = Sub-Saharan Africa; WE = Western Europe.

freshwater by RO consumes 35.9–118.6 TWh y^{-1}, compared to the 130–181 TWh y^{-1} required by MSF to produce 6.7 km^3 y^{-1} in 2019. For the same year, MED and ED are respectively modelled to consume 36.2–46.2 TWh and 3.1–15.0 TWh, each producing 2.5 km^3 y^{-1} and 0.9 km^3 y^{-1} of freshwater.

Regional trends in energy consumption for desalination are even more pronounced. Until the early 1960s, patterns in energy consumption shares follow the evolution in capacity across subregions, led by Western Europe (WE), South Asia (SAS), Middle East and North Africa (MENA), and North America (NAM). From the early 1960s until the mid-1980s, the rise of thermal technologies produced a rapid spike in the overall energy consumed for desalinated water production in the MENA region. The decoupling between capacity and energy share began around this time, when other regions increase the development of mostly RO plants. While the capacity share of the MENA region has declined through to the present day, we model its energy shares to remain approximately the same. We estimate that today 163–255 TWh y^{-1} (or 74 % of the global burden) are consumed in the MENA, despite contributing to only 48 % of freshwater produced through desalination globally.

Concerning energy consumption by feedwater type, trends in capacity and energy share are highly correlated during earlier development, dominated by brackish, river and seawater desalination. From the late 1950s onwards, seawater overtakes the overall energetic burden, driven by three main factors: 1) seawater is the main feedwater type used in the MENA, the biggest developer of desalination after the 1960s; 2) most plants developed at the end of the 20th century in the MENA employ distillation technologies, with a long lifetime cycle and much lower energetic efficiency than RO, impacting the energy consumption of the region to this day; and 3) the slightly higher growth in RO of seawater compared to brackish water RO. Our estimates show that, in 2019, seawater consumed 87.8 % of total global energy for desalination (189–309 TWh y^{-1}), despite contributing to 57.5 % of globally produced freshwater (19 km^3 y^{-1}). Brackish water desalination is the second main energy consumer, using up to 10–34 TWh y^{-1} (7.9 %), while all other feedwater types combined only make up 4.3 % of global energy consumption for desalination.

3.2. Wastewater treatment

Modelled wastewater production (Jones et al., 2021) and treated volumes in 2015 are shown in Fig. 2A. Our wastewater flow model shows that, of the 359 km^3 produced, about 176 km^3 were treated within 50 km of a wastewater treatment plant (WWTP) (Fig. S12), serving 2.71 billion people. We therefore found global treatment rates to be lower by roughly 3 % compared to Jones et al. (2021). Modelled treated volumes and population attached to WWTPs were evaluated against reported or estimated values in the original datasets, showing overall good agreement across regions (Fig. S13). Out of the 58,426 WWTPs analysed, model estimates show that 43,809 (75.0 %) are currently operational (Fig. S14). The highest treatment rates are found in Western Europe (WE, 84.9 %) and North America (NAM, 67.0 %), while the lowest are modelled for Sub-Saharan Africa (SSA, 15.1 %) and South Asia (SAS, 12.5 %). The largest absolute volumetric gap in wastewater treatment is found in the East Asia Pacific (EAP) region, corresponding to approximately 63.3 km^3, therefore contributing 35 % of untreated wastewater worldwide.

The level of treatment is further detailed in Fig. 2B. We find that 2.6 km^3 of wastewater were treated to primary levels, 77.2 km^3 with secondary treatment technologies, and 98.5 km^3 went through advanced WWTPs. 137 km^3 of wastewater (77 % of the total treated wastewater volumes worldwide) were processed in the East Asia Pacific (EAP), North America (NAM) and Western Europe (WE). These three regions also show overall higher rates of advanced wastewater treatment (WWT) compared to secondary WWT. A total of 92.6 km^3 of wastewater were treated with advanced technologies in these three regions, corresponding to 94 % of global advanced WWT. The opposite trend is observed in all other regions, where secondary technologies are more widespread. In South Asia (SAS), we find negligible advanced WWT, which is otherwise entirely lacking in Sub-Saharan Africa (SSA).

Globally, WWT is estimated to have consumed 85–279 TWh (0.31–1.00 EJ) in 2015. Our model shows that primary treatment consumed 0.00019–0.034 TWh, while secondary and advanced treatment required 19–35 TWh and 66–244 TWh, respectively. Primary treatment therefore contributes to a minor portion of the total global energy consumed in 2015 for WWT (0.01 %). Secondary and advanced treatment have the most significant impact (13.9 % and 86.1 %, respectively). Regionally, wastewater production and treatment rates, and the adoption of different WWT technologies are reflected in the energy consumption of this process (Fig. 2C). The highest modelled absolute energy consumptions for WWT are found in East Asia Pacific (31–102 TWh), followed by North America (26–74 TWh) and Western Europe (20–60 TWh). Together, these three regions contribute on average to 87.2 % of the total global energy consumed for WWT. Furthermore, with the exception of the Middle East and North Africa (MENA), we find that secondary WWT consumed more energy than advanced WWT in all other regions. Overall, it is evident that the largest uncertainties in our model of energy consumption for WWT stem from insufficient parametrization of advanced WWT processes.

3.3. Conventional drinking water treatment

The modelled global status of drinking water access, contribution of different water resources and the modelled energy consumption for conventional drinking water treatment (CDWT) in the year 2015 are shown in Fig. 3. Our model represents 7.00 billion people across 163 countries (against a global population of 7.35 billion in 2015), of which 5.21 billion people are estimated to have been connected to a drinking water treatment plant in 2015. Globally, 1.79 billion people lacked access to safely managed drinking water, including 667 million without access to even basic water services. Spatially explicit maps of modelled drinking water access are presented in Fig. S15, showing comparable large-scale patterns for rural and urban population gridcells.

Similar to wastewater treatment, the highest rates of access to safely managed drinking water (including desalination) are found in Western Europe (WE, 97.5 %) and North America (NAM, 97.4 %), while the lowest access is found in Sub-Saharan Africa (SSA, 34.5 %), with a wide gap from the second lowest, Latin America – Caribbeans (LAC, 65.0 %) (Fig. 3A). Results show that at least 118 million people are dependent on desalination for their drinking water, with the highest rates in the Middle East and North Africa (MENA, approximately 20 % of served population). High exposure rates to untreated drinking water are found in Sub-Saharan Africa (SSA, 32.6 %) and MENA (11.3 %), while less than 10 % of people were found to be exposed to untreated water sources in all other regions. We thus estimate that 73.8 % of the global population was connected to a drinking water treatment plant (76.9 % when accounting for desalination), and that 9.5 % of the analysed population used untreated drinking water sources in 2015.

The sources of drinking water (Fig. 3B) contain strong uncertainties, due to difficulties in precisely locating them in global hydrological models (Hanasaki et al., 2018). Nonetheless, we find that, out of the 507 km^3 of municipal water demands in 2015 represented in our model, 422 km^3 (83.23 %) were deemed to be safe (252 km^3 from treated surface water, 162 km^3 from treated groundwater and 9 km^3 from desalination). Globally, 59 km^3 (11.6 %) allow access to basic water services (34 km^3 from surface water and 25 km^3 from groundwater). We also estimate that only 26 km^3 (5.1 % of total considered demands for 2015) were used untreated for drinking purposes, 11 km^3 of which came from groundwater and 15 km^3 from surface water sources.

Concerning energy consumption, model results show that 106–551 TWh (0.38–1.98 EJ) were used for CDWT in 2015 (Fig. 3C). Surface water treatment consumed 103–433 TWh (0.38–1.56 EJ), while

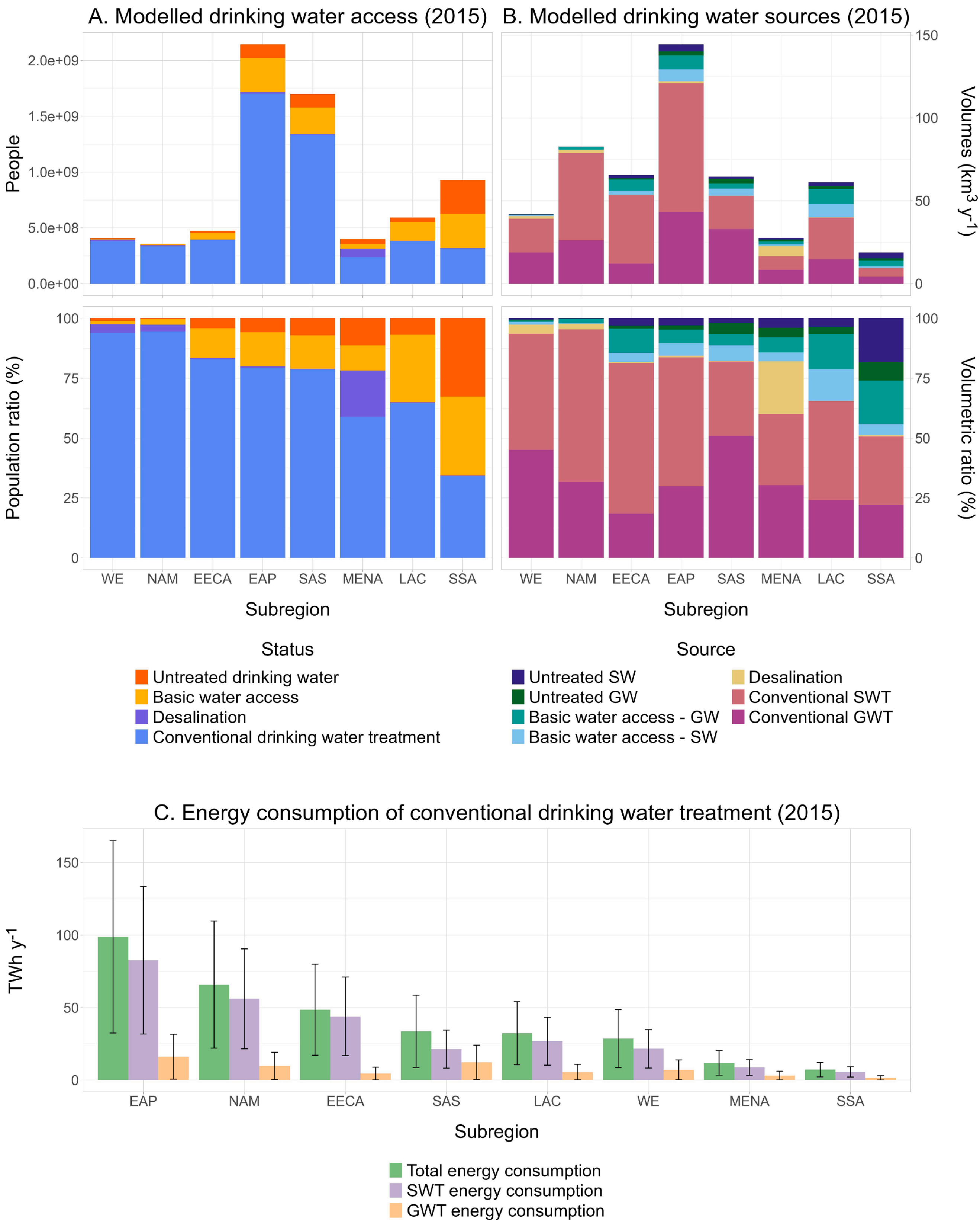

Fig. 3. Modelled state of drinking water status treatment in 2015: A) drinking water access by population; B) drinking water sources by volumes; and C) calculated energy consumption of conventional drinking water treatment. Bars in (A) and (B) are ordered by decreasing safe water access. SW = surface water; GW = groundwater, SWT = surface water treatment; GWT = groundwater treatment. Subregions: EAP = East Asia and Pacific; EECA = Eastern Europe and Central Asia; LAC = Latin America and Caribbean; MENA = Middle East and North Africa; NAM = North America; SAS = Southern Asia; SSA = Sub-Saharan Africa; WE = Western Europe.

groundwater treatment contributed to 2.42–118 TWh (0.009–0.43 EJ). The minimum value of energy consumption for the latter considers that all groundwater is treated exclusively with softening, which is a very low energy intensity process. The highest contributor to energy consumption for CDWT worldwide is the East Asia Pacific (EAP) region, likely due to high population and good water access (for instance in China, Japan, and Australia). The second and third largest consumers are North America (NAM), and Eastern Europe – Central Asia (EECA), where much lower population is characterized by very high per capita water demands and large shares of surface water. Overall, we find that high water access rates, rich economies and high proportions of surface water treatment can all compound to exacerbate energy consumption in CDWT.

4. Discussion

4.1. Implications of energy consumption for water treatment

Our results show that water treatment contributes to a considerable proportion of global energy consumption. Irrespectively of the specific

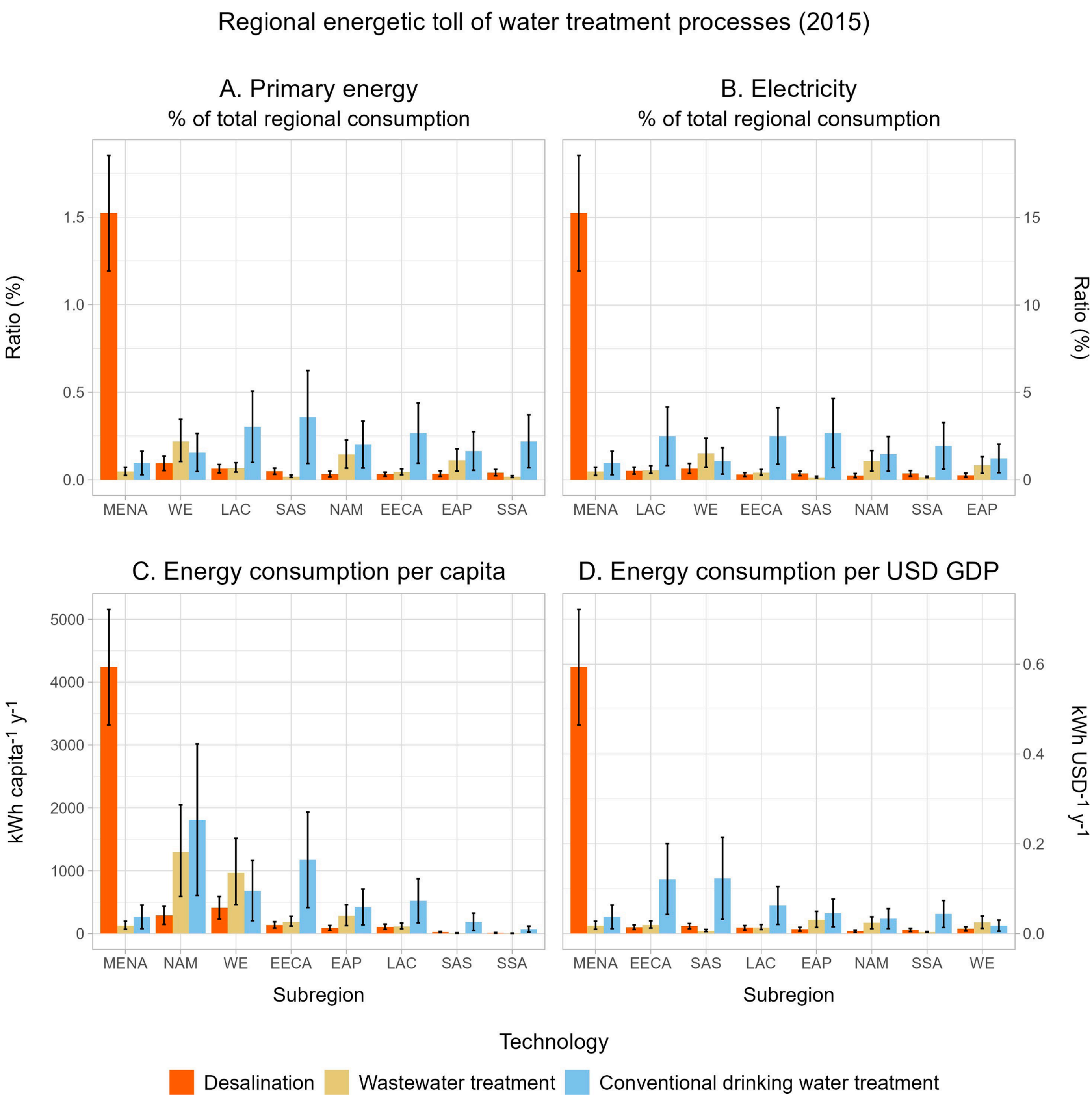

Fig. 4. Regional ratios of the energetic toll of desalination, wastewater treatment and conventional drinking water treatment in 2015, shown as percentage of: A) total regional primary energy consumption; and B) total regional electricity consumption. Panels (C) and (D) show the regional energy consumption per capita and per United States Dollar (USD) of Gross Domestic Product (GDP), respectively. Subregions: EAP = East Asia and Pacific; EECA = Eastern Europe and Central Asia; LAC = Latin America and Caribbean; MENA = Middle East and North Africa; NAM = North America; SAS = Southern Asia; SSA = Sub-Saharan Africa; WE = Western Europe.

energy source employed, we estimate that, in 2015, water treatment technologies consumed a total of 379–1159 TWh (1.36–4.17 EJ). This is divided into 189–331 TWh (0.68–1.19 EJ) for desalination, 85–279 TWh (0.31–1.00 EJ) for wastewater treatment and 105–549 TWh (0.38–1.98 EJ) for conventional drinking water treatment. Using data from the Energy Information Administration (EIA, 2022a, b), we calculate that these processes accounted for 0.2–0.7 % of total global primary energy consumption, or 1.8–5.4 % of total net electricity consumption in 2015. While these are global averages, energy consumption varies strongly across world regions (Fig. 4A and Fig. 4B): the largest energetic tolls of the three technologies are found in the Middle East and North Africa (desalination), Western Europe (wastewater treatment) and South Asia (conventional drinking water treatment), where they contribute up to 18.6 %, 2.4 % and 4.7 % of electricity consumption in these regions, respectively. The Middle East and North Africa show the largest energy consumption of water treatment processes per capita (United Nations, 2024) (Fig. 4C) and per dollar of Gross Domestic Product (World Bank, 2019b) (Fig. 4D). Significant energy consumption per capita is also found in North America, Western Europe, and in the Eastern Europe and Central Asia regions.

In this context, conflicts between alleviation of global water scarcity and mitigation of anthropogenic climate change may arise (Hussey and Pittock, 2012; Hejazi et al., 2015; Lee et al., 2017; Parkinson et al., 2019). For instance, improvements in safe water access (UNICEF and WHO, 2023), stricter environmental legislation (Hart et al., 1999; World Health Organization, 2022) and emerging contaminants (Jiang et al., 2013; Tran et al., 2018; Mukhopadhyay et al., 2022) are expected to increase burden on the water treatment industry (Sonune and Ghate, 2004; Stackelberg et al., 2004; Morin-Crini et al., 2022). Pressure on water resources is also steadily rising due to the general unsustainability of current water use and management practices (Wada and Bierkens, 2014; Cosgrove and Loucks, 2015), the combined impacts of population growth and economic development (Falkenmark, 1997; Distefano and Kelly, 2017; Fukuda et al., 2019; Dolan et al., 2021), and their complex interplay with climate change (Vorosmarty et al., 2000; Haddeland et al., 2014) and water quality issues (Whitehead et al., 2009; Schwarzenbach et al., 2010; van Vliet et al., 2017, 2021). These factors are contributing to the increasing adoption of energy-intensive unconventional water resources, such as desalination (Schiffler, 2004; Jones et al., 2019; Gude, 2016; Shahzad et al., 2017) and treated wastewater reuse (Salgot et al., 2006; Salgot and Folch, 2018; Christou et al., 2024), to alleviate cross-sectoral water scarcity (Gude, 2017; Jaramillo and Restrepo, 2017; Ungureanu et al., 2020; van Vliet et al., 2021). Higher volumes of water treated to drinking standards, increased rates of advanced wastewater treatment and desalination, and rising surface and groundwater pollution all have the potential to exacerbate the energy requirements of water treatment technologies (Smith et al., 2019; Cardenes et al., 2020; Pesqueira et al., 2020).

The following examples of best practices should therefore be considered to reduce water and energy waste, and limit the adverse environmental impacts of the water supply: 1) completing the transition from distillation to membrane technologies for desalination, using renewable energy sources to power plants (Sood and Smakhtin, 2014; Gude, 2016; Ghazi et al., 2022) and exploring the potential of brine as a resource rather than waste product (Desai et al., 2018; Zhang et al., 2021; Park et al., 2022); 2) moving towards zero-discharge approaches in wastewater treatment (Tong and Elimelech, 2016), exploiting wastewaters treated to high purity standards for non-potable purposes (Christou et al., 2024) and resources extraction (Mo and Zhang, 2013; Li et al., 2015; Guven et al., 2023); 3) considering wastewater sludge as a form of energy, to reduce greenhouse gas emissions and the demand for other energy sources upstream (McCarty et al., 2011; Gude, 2015; Zib III et al., 2021); 4) significantly upscaling the monitoring and maintenance of water distribution networks to limit unnecessary leakages in critical water supplies (Farley and Trow, 2003; Liemberger and Wyatt, 2019), reducing the amount of water that needs to be treated to drinking standards and therefore energy expenditures (Aubuchon and Roberson, 2014; Coelho and Andrade-Campos, 2014); and 5) evaluating the capabilities of decentralized planning to optimize operational costs and enhance the resilience of water supply systems (Wilderer and Schreff, 2000; Eggimann et al., 2015; Rabaey et al., 2020; Helmrich et al., 2021; Schwetschenau et al., 2022)

4.2. Model validation

In comparison with Liu et al. (2016), to our knowledge the only global study quantifying the energy consumption of the water sector, we present slightly higher estimates for desalination (0.68–1.19 EJ vs. 0.8 EJ), while evidently lower ones are obtained for wastewater (0.31–1.00 EJ vs. 1.8 EJ) and conventional drinking water treatment (0.38–1.98 EJ vs. 2.8 EJ) (Fig. S16). This is due to two main differences: 1) benchmark calculations were conducted for different years (2015 here vs. 2010 in their study); and 2) Liu et al. (2016) considered desalination as part of municipal water treatment. In the latter case, comparable values are however obtained when desalination and conventional drinking water treatment are merged in our estimates (1.06–3.17 EJ vs. 2.8 EJ). Further divergences exist in input data, model assumptions and parameters. For example, in the case of conventional drinking water treatment, Liu et al. (2016) exclusively acquired data on municipal water access from AQUASTAT, which actually refers to basic water access, and may consequently represent water that is not directly provided by a treatment plant. The same holds for wastewater treatment, where we used modelled gridded data on wastewater generation (Jones et al., 2021), differing from the country-level data of AQUASTAT.

Overall, the greatest strength of our study lies in the spatially explicit nature of the employed model, allowing it to breach across scales when estimating the energy consumption of different water treatment technologies, from local plants to countries to global levels (Fig. 5). At present, however, it is not possible to fully validate our results, as public data on energy consumption for water treatment are limited to only a few countries (Chini et al., 2021), or available at too small scales (i.e. plant or city scale). To this end, we therefore browsed through data sources in the literature (e.g. all papers reviewed by Chini et al. (2021)) to collect values of energy consumption for different processes in the water sector (see Data Availability Statement). Within uncertainty, we see that the estimates of our model are comparable to previous country-level studies and reports, especially in the low to mean values in model outcomes. For example, 10–30 % of energy consumption in the Middle East and North Africa has been reported to go towards desalination (Weinthal and Sowers, 2020), reaching 20–25 % of Saudi Arabia's (Rambo et al., 2017; United Nations, 2023a) and 29 % of Kuwait's total oil and gas production (Darwish et al., 2009), while our estimates set these ratios at 12–19 %, 14–21 % and 29–42 % in 2015, respectively. Wastewater treatment, on the other hand, has been previously estimated to require 24.7 TWh y^{-1} in the EU-28 (Ganora et al., 2019), 30 TWh y^{-1} in the USA (Reekie and et al. Reekie, 2013) and 16.7–25.2 TWh y^{-1} in China (Zhang and Ma, 2020; Zhu et al., 2024); for these three key actors, our model also shows promising results: 20.7–66.8 TWh in the EU-28, 19.4–68.0 TWh in the USA, and 17.4–60.6 TWh in China in 2015.

Concerning drinking water treatment, challenges are posed by modelling the exact sources of drinking water and their country-level proportions using global hydrological models (Hanasaki et al., 2016, 2018). For instance, good results were found for the USA, where we matched the surface water to groundwater ratio at roughly 65/35 (Environmental Protection Agency, 2024). However, we overestimate surface water treatment across various countries in Europe (e.g. Hungary, Finland, Slovakia) compared to reported data (EurEau, 2021), and thus potentially the overall energy consumption of drinking water treatment in this region. These discrepancies are reflected in the accuracy of the model for this process. In the case of the USA, public water supply is estimated to consume 39.2 TWh (Reekie and et al. Reekie, 2013), whereas we find 19.2–98.0 TWh. However, results are mixed in

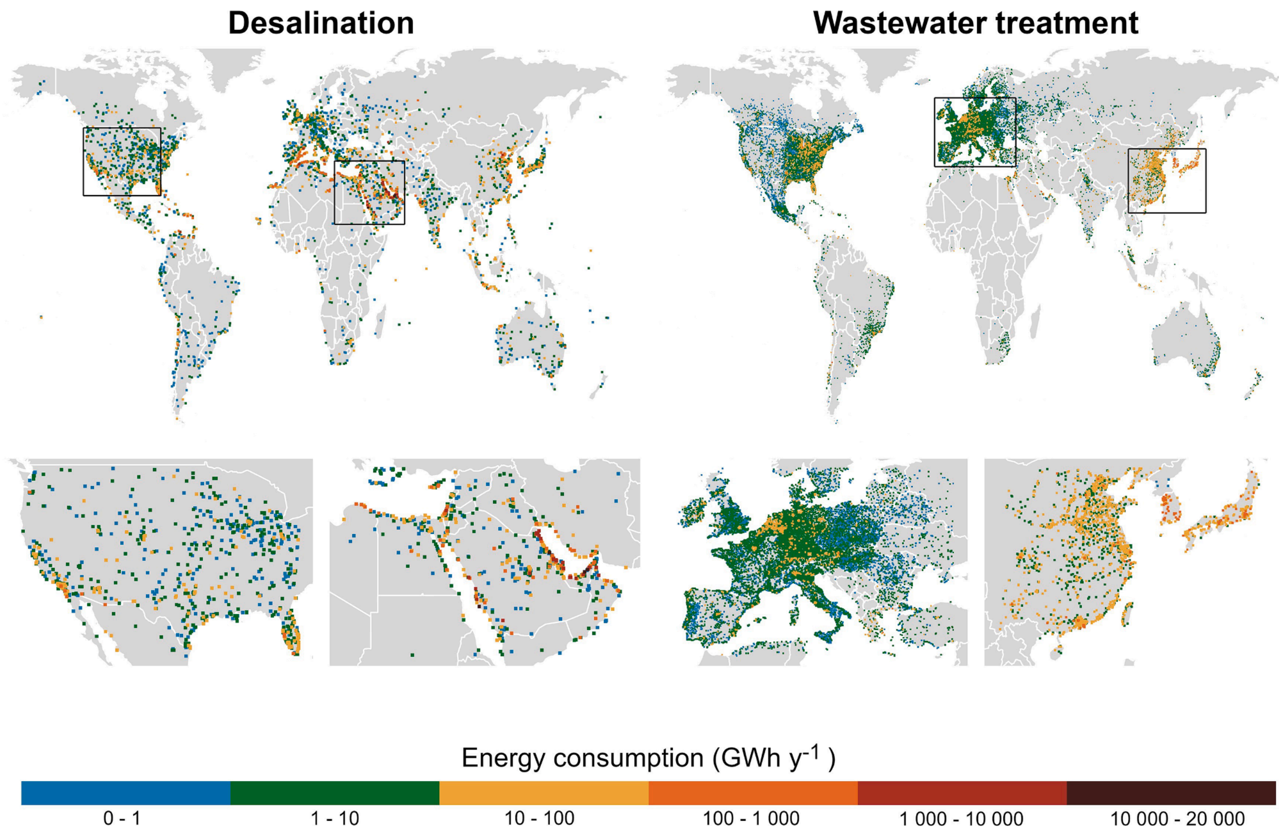

Fig. 5. Spatial patterns (5 arcmin) of average modelled energy consumption for desalination and wastewater treatment in 2015, with selected regional zooms.

other countries. For example, the water supply in China reportedly consumed 12 TWh in 2012 (Smith et al., 2018), while our model grossly overestimates this value at 20.3–104 TWh. Moreover, many studies either report the total energy consumed by the water sector (e.g. Hardy et al. (2012); Vincent et al. (2014); Niu et al. (2019)) or at very small scales (e.g. Slagstad and Brattebø (2014); Chhipi-Shrestha et al. (2017)), making it difficult to validate the results for conventional drinking water treatment in isolation or at the country level.

4.3. Model limitations and applicability

Most limitations in our energy-for-water treatment framework are currently related to the paucity of input data (Liu et al., 2016; Chini and Stillwell, 2017, 2018). For example, while detailed information exists for desalination plants between 1945 and 2019, our analysis of energy consumption for wastewater treatment and conventional drinking water treatment focused on the year 2015, mainly due to a lack of data on the initial year of plant operations. Technological developments were therefore only analyzed for desalination, with a focus on modelling the increasing efficiency of reverse osmosis plants over time (Elimelech and Phillip, 2011). Moreover, seasonal dynamics, i.e. finer than yearly, are currently not characterized in our model, impairing a deeper understanding of the interdependencies between the water and energy sectors during climatic extremes (Hasan and Foliente, 2015; Hamiche et al., 2016; Forzieri et al., 2018). Regarding wastewater treatment, reported data (Longo et al., 2016) allowed us to find that energy consumption in secondary treatment plants is dependent on the scale and climate in a specific region, as smaller facilities and less concentrated wastewaters generally increase energy intensity (Section A.1.2.3 of the Appendix). However, a poor characterization of advanced wastewater treatment in our framework remains a major factor of uncertainty, mainly due to: 1) a lack of representation of economies of scale at this treatment level; 2) an inadequate parametrization of water quality parameters treated in advanced processes (i.e. nitrogen and phosphorus); and 3) scarcity of data relating these parameters to energy consumption in advanced wastewater treatment plants.

From a spatial perspective, the lack of location data of conventional drinking water treatment plants complicates the quantification of drinking water flows, limiting the estimates of energy consumption for this process to the catchment and country levels. It is also unclear how much of the current drinking water demands are satisfied by bottled water, and the associated implications on the total energy consumed for drinking water treatment (Gleick and Cooley, 2009). The overall energy consumption for this process may be further underestimated, since water leakages in distribution networks are neglected in the domestic water demands used as model input (Sutanudjaja et al., 2018). These volumes may therefore not correspond to the total raw water abstracted. This is however necessary when comparing the energy consumed by municipal water supplies across countries (Gerbens-Leenes, 2018). Additionally, recent studies show lower rates of safe drinking water in low- and middle- income countries (Greenwood et al., 2024), where we may then overestimate energy consumption for drinking water treatment.

Applications of the presented model framework should be carefully evaluated after considering all the identified uncertainties. For example, it could prove useful for downscaling large-scale scenarios of water treatment technologies to 5 arcmin resolution (e.g. country-scale projections produced by Integrated Assessment Models). The broad range of possible outcomes in the evolution of treatment facilities and technologies may also influence future projections of energy consumption. Furthermore, insights gained from model development can guide the collection of data and further progress in other fields. For instance, better data should be collected on the global location, initial year of operation and technologies employed in wastewater and conventional drinking water treatment. Measurements of quality parameters for the water flowing through treatment plants and the associated energy consumption for individual processes (e.g. nitrogen and phosphorus removal in advanced wastewater treatment, and novel contaminants in conventional drinking water treatment) are also needed. Such data would significantly reduce the uncertainties in energy consumption that currently characterize these two processes. Finally, refining the allocation of specific water sources (i.e. surface water, groundwater and desalination) and the representation of water leakages in distribution networks holds the potential to improve water balance estimates in global hydrological models.

5. Conclusions

We have presented here the first spatially explicit assessment of global energy consumption for water treatment processes, namely desalination, wastewater treatment and conventional drinking water treatment. Notwithstanding the limitations and uncertainties of the model framework, our study sets a basis to improve the current knowledge of the energetic demands of these technologies and their future evolution, on both sides of the water-energy nexus. Future work may be directed towards: 1) incorporating our methods into Integrated Assessment Models and Energy System Models to project the energy demands for water treatment, under global climate change and evolving socio-economic settings; 2) collection of data from plant to national scales to improve the understanding of the systems analyzed here and their technological development over time; and 3) enhancing the representation of anthropic processes and water treatment technologies in global hydrological models, potentially refining water balance estimates. Understanding the energetic demands of water treatment will be key in evaluating the implications of clean water and energy transition developments, while shedding light on the tradeoffs and synergies across Sustainable Development Goals.

CRediT authorship contribution statement

Michele Magni: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Edward R. Jones:** Writing – review & editing, Supervision, Software, Data curation. **Marc F.P. Bierkens:** Writing – review & editing, Supervision, Conceptualization. **Michelle T.H. van Vliet:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

M.M. thanks all PhD candidates and postdocs in the Department of Physical Geography at Utrecht University for the fruitful discussions throughout the past year of research, especially Gabriel Antonio Cárdenas Belleza for the comments on the wastewater and drinking water models, Sioux Fanny Melo León for the remarks on incorporating economics in the drinking water model, and Oriol Pomarol Moya for the feedbacks on the visualization of maps. We also thank: Stefano Longo for providing the data to model the energy consumption of secondary wastewater treatment; Landon Marston, Ashlynn Stillwell and Christopher Chini for the suggestions and words of encouragement from overseas; Edward Byers, Adriano Vinca and Marina Andrijevic from the International Institute for Applied Systems Analysis (IIASA) for the positive comments on our work; Susan Jenkins for the feedbacks during the writing course, which helped complete the first draft of this manuscript. We also appreciate the anonymous reviewers for taking the time to read our work and helping to improve the overall quality of the manuscript. This study was financially supported by the European Research Council (ERC) under the European Union's Horizon Europe research and innovation programme (grant agreement no. 101039426 B-WEX awarded to M.T.H.v.V.).

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.watres.2025.123245.

Data availability

Model code is stored at https://github.com/SustainableWaterSystems/ ENERWAT-GLOB. Model inputs (including the spreadsheet with compiled validation data) and outputs can be found at https://doi.org/10.5281/zenodo.13961187 and https://doi.org/10.5281/zenodo.13961387, respectively.

References

Abu-Zeid, M.A., 1998. Water and sustainable development: the vision for world water, life and the environment. Water Policy 1 (1), 9–19.
Al-Karaghouli, A., Kazmerski, L.L., 2013. Energy consumption and water production cost of conventional and renewable-energy-powered desalination processes. Renew. Sustain. Energy Rev. 24, 343–356.
Aubuchon, C.P., Roberson, J.A., 2014. Evaluating the embedded energy in real water loss. J. Am. Water Works Assoc. 106 (3), E129–E138.
Bodik, I., Kubaska, M., 2013. Energy and sustainability of operation of a wastewater treatment plant. Environ. Prot. Eng. 39 (2), 15–24.
Cardenes, I., Hall, J.W., Eyre, N., Majid, A., Jarvis, S., 2020. Quantifying the energy consumption and greenhouse gas emissions of changing wastewater quality standards. Water Sci. Technol. 81 (6), 1283–1295.
Chen, J., Gao, M., Cheng, S., Hou, W., Song, M., Liu, X., Liu, Y., 2022. Global 1 km× 1 km gridded revised real gross domestic product and electricity consumption during 1992–2019 based on calibrated nighttime light data. Sci. Data 9 (1), 202.
Chen, X., Strokal, M., Van Vliet, M.T., Stuiver, J., Wang, M., Bai, Z., Ma, L., Kroeze, C., 2019. Multi-scale modeling of nutrient pollution in the rivers of china. Environ. Sci. Technol. 53 (16), 9614–9625.
Chhipi-Shrestha, G., Hewage, K., Sadiq, R., 2017. Water–energy–carbon nexus modeling for urban water systems: system dynamics approach. J. Water Resour. Plann. Manage. 143 (6), 04017016.
Chini, C.M., Excell, L.E., Stillwell, A.S., 2021. A review of energy-for-water data in energy-water nexus publications. Environ. Res. Lett. 15 (12), 123011.
Chini, C.M., Stillwell, A.S., 2017. Where are all the data? the case for a comprehensive water and wastewater utility database. J. Water Resour. Plann. Manage. 143 (3), 01816005.
Chini, C.M., Stillwell, A.S., 2018. The state of us urban water: data and the energy-water nexus. Water Resour. Res. 54 (3), 1796–1811.
Christou, A., Beretsou, V.G., Iakovides, I.C., Karaolia, P., Michael, C., Benmarhnia, T., Chefetz, B., Donner, E., Gawlik, B.M., Lee, Y., et al., 2024. Sustainable wastewater reuse for agriculture. Nat. Rev. Earth Environ. 1–18 pages.
Coelho, B., Andrade-Campos, A., 2014. Efficiency achievement in water supply systems—a review. Renew. Sustain. Energy Rev. 30, 59–84.
Cosgrove, W.J., Loucks, D.P., 2015. Water management: current and future challenges and research directions. Water Resour. Res. 51 (6), 4823–4839.
Dai, J., Wu, S., Han, G., Weinberg, J., Xie, X., Wu, X., Song, X., Jia, B., Xue, W., Yang, Q., 2018. Water-energy nexus: a review of methods and tools for macro-assessment. Appl. Energy 210, 393–408.
Darwish, M., Al-Najem, N., Lior, N., 2009. Towards sustainable seawater desalting in the gulf area. Desalination 235 (1–3), 58–87.
Desai, D., Beh, E.S., Sahu, S., Vedharathinam, V., van Overmeere, Q., de Lannoy, C.F., Jose, A.P., Volkel, A.R., Rivest, J.B., 2018. Electrochemical desalination of seawater and hypersaline brines with coupled electricity storage. ACS Energy Lett. 3 (2), 375–379.
Distefano, T., Kelly, S., 2017. Are we in deep water? water scarcity and its limits to economic growth. Ecol. Econ. 142, 130–147.
Dolan, F., Lamontagne, J., Link, R., Hejazi, M., Reed, P., Edmonds, J., 2021. Evaluating the economic impact of water scarcity in a changing world. Nat. Commun. 12 (1), 1915.
Eggimann, S., Truffer, B., Maurer, M., 2015. To connect or not to connect? modelling the optimal degree of centralisation for wastewater infrastructures. Water Res. 84, 218–231.
Ehalt Macedo, H., Lehner, B., Nicell, J., Grill, G., Li, J., Limtong, A., Shakya, R., 2022. Distribution and characteristics of wastewater treatment plants within the global river network. Earth Syst. Sci. Data 14 (2), 559–577.
EIA, 2022b. U.s. Energy Information administration. Electricity Net consumption (Billion Kwh). https://www.eia.gov/international/data/world/electricity/electricity-consumption.

EIA, 2022a. U.s. Energy Information administration. Primary Energy consumption (Quad Btu). https://www.eia.gov/international/data/world/total-energy/total-energy-consumption.
Elimelech, M., Phillip, W.A., 2011. The future of seawater desalination: energy, technology, and the environment. Science 333 (6043), 712–717.
Environmental Protection Agency, 2024. Safe Drinking Water Information System (sdwis) Federal Reporting Services - water systems. https://ordspub.epa.gov/ords/sfdw_rest/r/sfdw/sdwis_fed_reports_public/103. last access: 29 January 2024.
EurEau, 2021. Europe's Water in Figures – an overview of the European Drinking Water and Waste Water Sectors. https://www.eureau.org/resources/publications/eureau-publications/5824-europe-s-water-in-figures-2021/file.
Falkenmark, M., 1997. Meeting water requirements of an expanding world population. Philos. Trans. R. Soc. Lond. B Biol. Sci. 352 (1356), 929–936.
Farley, M., Trow, S., 2003. Losses in Water Distribution Networks. IWA publishing.
Food and Agriculture Organization, 2019. Access to Improved Drinking Water Source. https://data.apps.fao.org/aquastat/.
Forzieri, G., Bianchi, A., e Silva, F.B., Herrera, M.A.M., Leblois, A., Lavalle, C., Aerts, J.C., Feyen, L., 2018. Escalating impacts of climate extremes on critical infrastructures in europe. Glob. Environ. Chang. 48, 97–107.
Fukuda, S., Noda, K., Oki, T., 2019. How global targets on drinking water were developed and achieved. Nat. Sustain. 2 (5), 429–434.
Ganora, D., Hospido, A., Husemann, J., Krampe, J., Loderer, C., Longo, S., Bouyat, L.M., Obermaier, N., Piraccini, E., Stanev, S., et al., 2019. Opportunities to improve energy use in urban wastewater treatment: a european-scale analysis. Environ. Res. Lett. 14 (4), 044028.
Gerbens-Leenes, P., 2018. Energy for freshwater supply, use and disposal in The netherlands: a case study of dutch households. Energy For Water. Routledge, pp. 60–73 pages.
Ghazi, Z.M., Rizvi, S.W.F., Shahid, W.M., Abdulhameed, A.M., Saleem, H., Zaidi, S.J., 2022. An overview of water desalination systems integrated with renewable energy sources. Desalination 542, 116063.
Gikas, P., Tchobanoglous, G., 2009. The role of satellite and decentralized strategies in water resources management. J. Environ. Manage. 90 (1), 144–152.
Gleick, P.H., 1994. Water and energy. Ann. Rev. Energy Environ. 19 (1), 267–299.
Gleick, P.H., Cooley, H.S., 014009, 2009. Energy implications of bottled water. Environ. Res. Lett. 4 (1).
Global Water Intelligence, 2019. Desaldata. https://www.desaldata.com/.
Grafton, R.Q., Williams, J., Jiang, Q., 2015. Food and water gaps to 2050: preliminary results from the global food and water system (gfws) platform. Food Secur. 7, 209–220.
Greenwood, E.E., Lauber, T., van den Hoogen, J., Donmez, A., Bain, R.E., Johnston, R., Crowther, T.W., Julian, T.R., 2024. Mapping safe drinking water use in low-and middle-income countries. Science 385 (6710), 784–790.
Grzegorzek, M., Wartalska, K., Kaźmierczak, B., 2023. Review of water treatment methods with a focus on energy consumption. Int. Commun. Heat Mass Trans. 143, 106674.
Gude, V.G., 2015. Energy and water autarky of wastewater treatment and power generation systems. Renew. Sustain. Energy Rev. 45, 52–68.
Gude, V.G., 2016. Desalination and sustainability–an appraisal and current perspective. Water Res. 89, 87–106.
Gude, V.G., 2017. Desalination and water reuse to address global water scarcity. Rev. Environ. Sci. Bio/Technol. 16 (4), 591–609.
Guven, H., Ersahin, M., Ozgun, H., Ozturk, I., Koyuncu, I., 2023. Energy and material refineries of future: wastewater treatment plants. J. Environ. Manage. 329, 117130.
Haddeland, I., Heinke, J., Biemans, H., Eisner, S., Flörke, M., Hanasaki, N., Konzmann, M., Ludwig, F., Masaki, Y., Schewe, J., et al., 2014. Global water resources affected by human interventions and climate change. Proc. Natl. Acad. Sci. 111 (9), 3251–3256.
Hamiche, A.M., Stambouli, A.B., Flazi, S., 2016. A review of the water-energy nexus. Renew. Sustain. Energy Rev. 65, 319–331.
Hanasaki, N., Yoshikawa, S., Kakinuma, K., Kanae, S., 2016. A seawater desalination scheme for global hydrological models. Hydrol. Earth Syst. Sci. 20 (10), 4143–4157.
Hanasaki, N., Yoshikawa, S., Pokhrel, Y., Kanae, S., 2018. A global hydrological simulation to specify the sources of water used by humans. Hydrol. Earth Syst. Sci. 22 (1), 789–817.
Hardy, L., Garrido, A., Juana, L., 2012. Evaluation of spain's water-energy nexus. Int. J. Water Resour. Dev. 28 (1), 151–170.
Hart, B.T., Maher, B., Lawrence, I., 1999. New generation water quality guidelines for ecosystem protection. Freshw. Biol. 41 (2), 347–359.
Hasan, S., Foliente, G., 2015. Modeling infrastructure system interdependencies and socioeconomic impacts of failure in extreme events: emerging r&d challenges. Nat. Hazards 78 (3), 2143–2168.
Hejazi, M.I., Voisin, N., Liu, L., Bramer, L.M., Fortin, D.C., Hathaway, J.E., Huang, M., Kyle, P., Leung, L.R., Li, H.-Y., et al., 2015. 21st century united states emissions mitigation could increase water stress more than the climate change it is mitigating. Proc. Natl. Acad. Sci. 112 (34), 10635–10640.
Helmrich, A., Markolf, S., Li, R., Carvalhaes, T., Kim, Y., Bondank, E., Natarajan, M., Ahmad, N., Chester, M., 2021. Centralization and decentralization for resilient infrastructure and complexity. Environ. Res. Infrastruct. Sustain. 1 (2), 021001.
Hoekstra, A.Y., Buurman, J., Van Ginkel, K.C., 2018. Urban water security: a review. Environ. Res. Lett. 13 (5), 053002.
Hofman-Caris, R., Hofman, J., 2019. Limitations of conventional drinking water technologies in pollutant removal. Applications of Advanced Oxidation Processes (AOPs) in Drinking Water Treatment, pp. 21–51 pages.
Hussey, K., Pittock, J., 2012. The energy–water nexus: managing the links between energy and water for a sustainable future. Ecol. Soc. 17 (1).
Irannezhad, M., Ahmadi, B., Liu, J., Chen, D., Matthews, J.H., 2022. Global water security: a shining star in the dark sky of achieving the sustainable development goals. Sustain. Horizons 1, 100005.
Jaramillo, M.F., Restrepo, I., 2017. Wastewater reuse in agriculture: a review about its limitations and benefits. Sustainability 9 (10), 1734.
Jebaraj, S., Iniyan, S., 2006. A review of energy models. Renew. Sustain. Energy Rev. 10 (4), 281–311.
Jiang, J.-Q., Zhou, Z., Sharma, V., 2013. Occurrence, transportation, monitoring and treatment of emerging micro-pollutants in waste water—a review from global views. Microchem. J. 110, 292–300.
Jones, E., Qadir, M., van Vliet, M.T., Smakhtin, V., Kang, S.-m., 2019. The state of desalination and brine production: a global outlook. Sci. Total Environ. 657, 1343–1356.
Jones, E.R., Van Vliet, M.T., Qadir, M., Bierkens, M.F., 2021. Country-level and gridded estimates of wastewater production, collection, treatment and reuse. Earth Syst. Sci. Data 13 (2), 237–254.
King, C.W., Holman, A.S., Webber, M.E., 2008. Thirst for energy. Nat. Geosci. 1 (5), 283–286.
Klein Goldewijk, K., van Drecht, G., 2006. Integrated Modelling of Global Environmental change: An overview of Image 2.4, chap. Hyde 3: Current and historical population and Land Cover. MNP – Netherlands Environmental Assessment Agency, Bilthoven, The Netherlands, pp. 93–112 pages.
Kyle, P., Hejazi, M., Kim, S., Patel, P., Graham, N., Liu, Y., 2021. Assessing the future of global energy-for-water. Environ. Res. Lett. 16 (2), 024031.
Kyle, P., Johnson, N., Davies, E., Bijl, D.L., Mouratiadou, I., Bevione, M., Drouet, L., Fujimori, S., Liu, Y., Hejazi, M., 2016. Setting the System Boundaries of "energy for water" For Integrated Modeling.
Lam, K.L., Kenway, S.J., Lant, P.A., 2017. Energy use for water provision in cities. J. Clean. Prod. 143, 699–709.
Larsen, T.A., Gujer, W., 1997. The concept of sustainable urban water management. Water Sci. Technol. 35 (9), 3–10.
Lee, M., Keller, A.A., Chiang, P.-C., Den, W., Wang, H., Hou, C.-H., Wu, J., Wang, X., Yan, J., 2017. Water-energy nexus for urban water systems: a comparative review on energy intensity and environmental impacts in relation to global water risks. Appl. Energy 205, 589–601.
Li, W.-W., Yu, H.-Q., Rittmann, B.E., 2015. Chemistry: reuse water pollutants. Nature 528 (7580), 29–31.
Liemberger, R., Wyatt, A., 2019. Quantifying the global non-revenue water problem. Water Suppl. 19 (3), 831–837.
Lin, S., 2019. Energy efficiency of desalination: fundamental insights from intuitive interpretation. Environ. Sci. Technol. 54 (1), 76–84.
Linke, S., Lehner, B., Ouellet Dallaire, C., Ariwi, J., Grill, G., Anand, M., Beames, P., Burchard-Levine, V., Maxwell, S., Moidu, H., et al., 2019. Global hydro-environmental sub-basin and river reach characteristics at high spatial resolution. Sci. Data 6 (1), 283.
Liu, Y., Hejazi, M., Kyle, P., Kim, S.H., Davies, E., Miralles, D.G., Teuling, A.J., He, Y., Niyogi, D., 2016. Global and regional evaluation of energy for water. Environ. Sci. Technol. 50 (17), 9736–9745.
Longo, S., d'Antoni, B.M., Bongards, M., Chaparro, A., Cronrath, A., Fatone, F., Lema, J. M., Mauricio-Iglesias, M., Soares, A., Hospido, A., 2016. Monitoring and diagnosis of energy consumption in wastewater treatment plants. a state of the art and proposals for improvement. Appl. Energy 179, 1251–1268.
Marlow, D.R., Moglia, M., Cook, S., Beale, D.J., 2013. Towards sustainable urban water management: a critical reassessment. Water Res. 47 (20), 7150–7161.
McCarty, P.L., Bae, J., Kim, J., 2011. Domestic Wastewater Treatment As a Net Energy Producer–Can This Be Achieved?.
Mo, W., Zhang, Q., 2013. Energy–nutrients–water nexus: integrated resource recovery in municipal wastewater treatment plants. J. Environ. Manage. 127, 255–267.
Moe, C.L., Rheingans, R.D., 2006. Global challenges in water, sanitation and health. J. Water Health 4 (S1), 41–57.
Molinos-Senante, M., Sala-Garrido, R., Iftimi, A., 2018. Energy intensity modeling for wastewater treatment technologies. Sci. Total Environ. 630, 1565–1572.
Morin-Crini, N., Lichtfouse, E., Fourmentin, M., Ribeiro, A.R.L., Noutsopoulos, C., Mapelli, F., Fenyvesi, E., Vieira, M.G.A., Picos-Corrales, L.A., Moreno-Piraján, J.C., et al., 2022. Removal of emerging contaminants from wastewater using advanced treatments. a review. Environ. Chem. Lett. 20 (2), 1333–1375.
Mukhopadhyay, A., Duttagupta, S., Mukherjee, A., 2022. Emerging organic contaminants in global community drinking water sources and supply: a review of occurrence, processes and remediation. J. Environ. Chem. Eng. 10 (3), 107560.
Nassrullah, H., Anis, S.F., Hashaikeh, R., Hilal, N., 2020. Energy for desalination: a state-of-the-art review. Desalination 491, 114569.
Niu, K., Wu, J., Qi, L., Niu, Q., 2019. Energy intensity of wastewater treatment plants and influencing factors in china. Sci. Total. Environ. 670, 961–970.
Olsson, G., 2015. Water and energy: Threats and Opportunities. IWA publishing.
Panepinto, D., Fiore, S., Zappone, M., Genon, G., Meucci, L., 2016. Evaluation of the energy efficiency of a large wastewater treatment plant in italy. Appl. Energy 161, 404–411.
Park, S., Kim, N., Kim, Y., Son, M., Cho, K.H., 2022. Seawater battery desalination with a reverse osmosis membrane for simultaneous brine treatment and energy storage. J. Clean. Prod. 333, 130188.
Parkinson, S., Krey, V., Huppmann, D., Kahil, T., McCollum, D., Fricko, O., Byers, E., Gidden, M.J., Mayor, B., Khan, Z., et al., 2019. Balancing clean water-climate change mitigation trade-offs. Environ. Res. Lett. 14 (1), 014009.
Pesqueira, J.F., Pereira, M.F.R., Silva, A.M., 2020. Environmental impact assessment of advanced urban wastewater treatment technologies for the removal of priority

substances and contaminants of emerging concern: a review. J. Clean. Prod. 261, 121078.
Plappally, A., et al., 2012. Energy requirements for water production, treatment, end use, reclamation, and disposal. Renew. Sustain. Energy Rev. 16 (7), 4818–4848.
Rabaey, K., Vandekerckhove, T., Van de Walle, A., Sedlak, D.L., 2020. The third route: using extreme decentralization to create resilient urban water systems. Water Res. 185, 116276.
Rambo, K.A., Warsinger, D.M., Shanbhogue, S.J., Ghoniem, A.F., et al., 2017. Water-energy nexus in saudi arabia. Energy Procedia 105, 3837–3843.
Reekie, L., et al., 2013. Electricity Use and Management in the Municipal Water Supply and Wastewater Industries. Water Research Foundation.
Rothausen, S.G., Conway, D., 2011. Greenhouse-gas emissions from energy use in the water sector. Nat. Clim. Chang. 1 (4), 210–219.
Salgot, M., Folch, M., 2018. Wastewater treatment and water reuse. Curr. Opin. Environ. Sci. Health 2, 64–74.
Salgot, M., Huertas, E., Weber, S., Dott, W., Hollender, J., 2006. Wastewater reuse and risk: definition of key objectives. Desalination 187 (1–3), 29–40.
Sanders, K.T., Webber, M.E., 2012. Evaluating the energy consumed for water use in the united states. Environ. Res. Lett. 7 (3), 034034.
Santana, M.V., Zhang, Q., Mihelcic, J.R., 2014. Influence of water quality on the embodied energy of drinking water treatment. Environ. Sci. Technol. 48 (5), 3084–3091.
Schiffler, M., 2004. Perspectives and challenges for desalination in the 21st century. Desalination 165, 1–9.
Schrattenholzer, L., 1981. The Energy Supply Model MESSAGE. *IIASA Research Report. IIASA, Laxenburg, Austria*.
Schwarzenbach, R.P., Egli, T., Hofstetter, T.B., Von Gunten, U., Wehrli, B., 2010. Global water pollution and human health. Annu. Rev. Environ. Resour. 35, 109–136.
Schwetschenau, S.E., Kovankaya, Y., Elliott, M.A., Allaire, M., White, K.D., Lall, U., 2022. Optimizing scale for decentralized wastewater treatment: a tool to address failing wastewater infrastructure in the united states. ACS ES&T Eng. 3 (1), 1–14.
Shahzad, M.W., Burhan, M., Ang, L., Ng, K.C., 2017. Energy-water-environment nexus underpinning future desalination sustainability. Desalination 413, 52–64.
Slagstad, H., Brattebø, H., 2014. Life cycle assessment of the water and wastewater system in trondheim, norway–a case study: case study. Urban Water J. 11 (4), 323–334.
Smith, K., Guo, S., Zhu, Q., Dong, X., Liu, S., 2019. An evaluation of the environmental benefit and energy footprint of china's stricter wastewater standards: can benefit be increased? J. Clean. Prod. 219, 723–733.
Smith, K., Liu, S., Liu, Y., Guo, S., 2018. Can china reduce energy for water? a review of energy for urban water supply and wastewater treatment and suggestions for change. Renew. Sustain. Energy Rev. 91, 41–58.
Sonune, A., Ghate, R., 2004. Developments in wastewater treatment methods. Desalination 167, 55–63.
Sood, A., Smakhtin, V., 2014. Can desalination and clean energy combined help to alleviate global water scarcity? JAWRA J. Am. Water Resour. Assoc. 50 (5), 1111–1123.
Sorenson, S.B., Morssink, C., Campos, P.A., 2011. Safe access to safe water in low income countries: water fetching in current times. Soc. Sci. Med. 72 (9), 1522–1526.
Stackelberg, P.E., Furlong, E.T., Meyer, M.T., Zaugg, S.D., Henderson, A.K., Reissman, D. B., 2004. Persistence of pharmaceutical compounds and other organic wastewater contaminants in a conventional drinking-water-treatment plant. Sci. Total Environ. 329 (1–3), 99–113.
Straatsma, M., Droogers, P., Hunink, J., Berendrecht, W., Buitink, J., Buytaert, W., Karssenberg, D., Schmitz, O., Sutanudjaja, E.H., Van Beek, L., et al., 2020. Global to regional scale evaluation of adaptation measures to reduce the future water gap. Environ. Modell. Softw. 124, 104578.
Sutanudjaja, E.H., Van Beek, R., Wanders, N., Wada, Y., Bosmans, J.H., Drost, N., Van Der Ent, R.J., De Graaf, I.E., Hoch, J.M., De Jong, K., et al., 2018. Pcr-globwb 2: a 5 arcmin global hydrological and water resources model. Geosci. Model Dev. 11 (6), 2429–2453.
Tong, T., Elimelech, M., 2016. The global rise of zero liquid discharge for wastewater management: drivers, technologies, and future directions. Environ. Sci. Technol. 50 (13), 6846–6855.
Tran, N.H., Reinhard, M., Gin, K.Y.-H, 2018. Occurrence and fate of emerging contaminants in municipal wastewater treatment plants from different geographical regions-a review. Water Res. 133, 182–207.
TU Delft OpenCourseWare, 2024. Water Treatment Schemes. https://ocw.tudelft.nl/wp-content/uploads/Water-treatment-schemes-1.pdf.
Ungureanu, N., Vlădut, V., Voicu, G., 2020. Water scarcity and wastewater reuse in crop irrigation. Sustainability 12 (21), 9055.
UNICEF and WHO, 2023. Progress On Household Drinking water, Sanitation and Hygiene 2000–2022: Special Focus On Gender. https://data.unicef.org/resources/jmp-report-2023/.
United Nations, 2023b. Independent Group of Scientists Appointed By the secretary-general, global Sustainable Development Report 2023: Times of crisis, Times of change: Science for Accelerating Transformations to Sustainable Development. https://sdgs.un.org/gsdr/gsdr2023.
United Nations, 2023a. The United Nations World Water Development Report 2023: Partnerships and Cooperation for Water. UNESCO, Paris. https://www.unesco.org/reports/wwdr/2023/en.
United Nations, 2024. World Population Prospects 2024. https://population.un.org/wpp/downloads.
Van Asselt, M.B., Rotmans, J., 2002. Uncertainty in integrated assessment modelling. Clim. Change 54 (1–2), 75–105.
van Beek, L., Hajer, M., Pelzer, P., van Vuuren, D., Cassen, C., 2020. Anticipating futures through models: the rise of integrated assessment modelling in the climate science-policy interface since 1970. Glob. Environ. Chang. 65, 102191.
van Vliet, M.T., Flörke, M., Wada, Y., 2017. Quality matters for water scarcity. Nat. Geosci. 10 (11), 800–802.
van Vliet, M.T., Jones, E.R., Flörke, M., Franssen, W.H., Hanasaki, N., Wada, Y., Yearsley, J.R., 2021. Global water scarcity including surface water quality and expansions of clean water technologies. Environ. Res. Lett. 16 (2), 024020.
Vincent, L., Michel, L., Catherine, C., Pauline, R., 2014. The energy cost of water independence: the case of singapore. Water Sci. Technol. 70 (5), 787–794.
Vorosmarty, C.J., Green, P., Salisbury, J., Lammers, R.B., 2000. Global water resources: vulnerability from climate change and population growth. Science 289 (5477), 284–288.
Wada, Y., Bierkens, M.F., 2014. Sustainability of global water use: past reconstruction and future projections. Environ. Res. Lett. 9 (10), 104003.
Wada, Y., Wisser, D., Bierkens, M.F., 2014. Global modeling of withdrawal, allocation and consumptive use of surface water and groundwater resources. Earth Syst. Dyn. 5 (1), 15–40.
Wakeel, M., Chen, B., Hayat, T., Alsaedi, A., Ahmad, B., 2016. Energy consumption for water use cycles in different countries: a review. Appl. Energy 178, 868–885.
Wang, H., Yang, Y., Keller, A.A., Li, X., Feng, S., Dong, Y.-n., Li, F, 2016. Comparative analysis of energy intensity and carbon emissions in wastewater treatment in usa, germany, china and south africa. Appl. Energy 184, 873–881.
Weinthal, E., Sowers, J., 2020. The water-energy nexus in the middle east: infrastructure, development, and conflict. Wiley Interdiscip. Rev. Water 7 (4), e1437.
Whitehead, P.G., Wilby, R.L., Battarbee, R.W., Kernan, M., Wade, A.J., 2009. A review of the potential impacts of climate change on surface water quality. Hydrol. Sci. J. 54 (1), 101–123.
Wilderer, P.A., Schreff, D., 2000. Decentralized and centralized wastewater management: a challenge for technology developers. Water Sci. Technol. 41 (1), 1–8.
World Bank, 2019a. People Using Safely Managed Drinking Water Services. https://data.worldbank.org/indicator/SH.H2O.SMDW.ZS.
World Bank, 2019b. World Development Indicators - gdp (Current us$). https://databank.worldbank.org/reports.aspx?source=2&series=NY.GDP.MKTP.CD&country#.
World Bank, 2020. World Bank Official Boundaries. https://datacatalog.worldbank.org/search/dataset/0038272/World-Bank-Official-Boundaries.
World Health Organization, 2022. Guidelines For Drinking-Water quality: Fourth Edition Incorporating the First and Second Addenda. https://www.who.int/publications/i/item/9789240045064.
Zhang, M., Ma, Y., 2020. Energy Use and Challenges in Current Wastewater Treatment Plants.
Zhang, X., Zhao, W., Zhang, Y., Jegatheesan, V., 2021. A review of resource recovery from seawater desalination brine. Rev. Environ. Sci. Bio/Technol. 20, 333–361.
Zhu, W., Duan, C., Chen, B., 2024. Energy efficiency assessment of wastewater treatment plants in china based on multiregional input–output analysis and data envelopment analysis. Appl. Energy 356, 122462.
Zib III, L., Byrne, D.M., Marston, L.T., Chini, C.M, 2021. Operational carbon footprint of the us water and wastewater sector's energy consumption. J. Clean. Prod. 321, 128815.