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Article

An Analysis of Electricity Consumption Patterns in the Water and Wastewater Sectors in South East England, UK

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Abstract: The water and wastewater sectors are energy-intensive, and so a growing number of utility companies are seeking to identify opportunities to reduce energy use. Though England's water sector is of international interest, in particular due to the early experience with privatisation, for the time being very little published data on energy usage exists. We analyse telemetry data from Thames Water Utilities Ltd. (TWUL), which is the largest water and wastewater company in the UK and serves one of the largest mega-cities in the world, London. In our analysis, we (1) break down sectoral energy use into their components, (2) present a statistical method to analyse the long-term trends in use, as well as the seasonality and irregular effects in the data, (3) derive energy-intensity (kWh m^3) figures for the system, and (4) compare the energy-intensity of the network against other regions in the world. Our results show that electricity use grew during the period 2009 to 2014 due to capacity expansions to deal with growing water demand and storm water flooding. The energy-intensity of the system is within the range of reported figures for systems in other OECD countries. Plans to improve the efficiency of the system could yield benefits in lower the energy-intensity, but the overall energy saving would be temporary as external pressures from population and climate change are driving up water and energy use.

Keywords: water–energy nexus; energy use; energy intensity

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1. Introduction

Water and wastewater systems in England and Wales (E&W) are highly energy-intensive, a topic that has attracted increasing attention over the last decade or so. Modern-day water and wastewater managers face several challenges: (1) meeting rising consumer demands for services induced by population growth, (2) increased frequency of droughts and heavy rainfall that strain water supplies and wastewater systems respectively, (3) increasing stringency in environmental standards driven by legislation from the European Union, and (4) operational losses associated with ageing infrastructure. However, the cost of electricity, as well as the associated greenhouse gas footprint, has also been recognised by utility managers as an important issue. Operational expenditures associated with electricity usage are rising and the UK's recent commitment to 'net zero' carbon emissions means that all utilities need to decarbonise, though for the moment no official emissions reductions targets exist for the water and wastewater industries.

Electricity is needed throughout a complex network of water and wastewater operations, which include: (1) water abstraction, (2) distribution, (3) water treatment, (4) sewage transportation, and (5) wastewater treatment [1]. In the abstraction and distribution of water, electrical inputs are necessary to drive pumps that transport large volumes of water between sources [1,2]. Processes such as filtration, oxidation, and ultraviolet treatment comprise the major component of the energy demand at water treatment facilities [2]. Desalination of brackish water, which is a highly energy-intensive process used for water supply [3], was also introduced to England for the first-time in 2010. In the wastewater supply chain, electricity is needed to transport sewage to local treatment plants, where processes such as aeration and primary treatment to remove grit are the most energy-consumptive unit operations [1,2]. For clarity, we note here that unless explicitly stated, any reference to electricity usage in water and wastewater operations does not include that used by water consumers (*i.e.* households and non-domestic users of municipal water supplies), which is not considered in this study but we recognise that consumers generally use significantly more energy for their water-related services [4].

There are 19 privately-owned water and wastewater or water-only utility companies in E&W. Studies related to energy use in water and wastewater operations in E&W are scarce is the scientific literature, though information does exist within company, regulator, and government reports. It has been reported that the water and wastewater sectors in E&W consume around 2–3% of the overall national energy supply [5]. Further, in the water sector, electricity use increased by over 10% in the 8 years between 2002 and 2010 [6], likely driven by water quality parameters given the amount of water supplied remained largely the same. At the same time, however, there has been a drive to reduce or offset electricity use from the national grid through on-site and renewable power generation schemes. Currently, all water supply companies in E&W are working towards achieving a voluntary target to reduce operational greenhouse gas emissions to net-zero by 2030 [7]. This is expected to be achieved through a combination of: (1) reducing grid electricity use and self-generating renewable energy, (2) increasing process efficiency, (3) active engagement with the electricity markets, (4) working with its goods and service providers, and (5) carbon offsets. It is worth noting that water and wastewater utilities E&W are legally required to provide water and drainage services on demand, and so cannot compromise service to avoid costs or reduce electricity consumption.

It is estimated that around 20% of mains water is currently lost each day due to leakage. The UK National Infrastructure Commission [8] recommended this should be halved by 2050. Coupled with schemes to reduce per capita demands at the consumer level, this would reduce electricity requirements for pumping and treatment [9–11], though the benefits would diminish in time if populations rise as projected. In terms of self-generation of renewable power, several utilities in E&W have already installed solar photovoltaics (PVs) and wind turbines on-site, and the use of anaerobic digestion to generate electricity from bio-gas at wastewater treatment plants is also common. As an example, two of the largest water and wastewater utilities, `Thames Water Utilities Ltd.` and `United Utilities`, both self-generated 22% and 21% of their total electricity consumption respectively [12,13]. The self-generation renewable capacity is expected to grow across E&W as there is scope to expand. For instance, analysis from the water regulator in E&W, Ofwat, suggests that energy-from-sludge schemes can be expanded and optimised to realise £1 billion of benefits for customers [14]. Water and wastewater utilities in E&W are also increasingly engaging with electricity markets through purchasing wholesale electricity from renewable energy providers. In addition, some utilities are also involved in electrical demand-side management schemes, where process operations are adjusted in response to real-time energy market signals. Though the scale of these schemes are not well-reported likely due to commercial reasons, theoretical works have shown the economic benefits of such mechanisms could be significant [15–17].

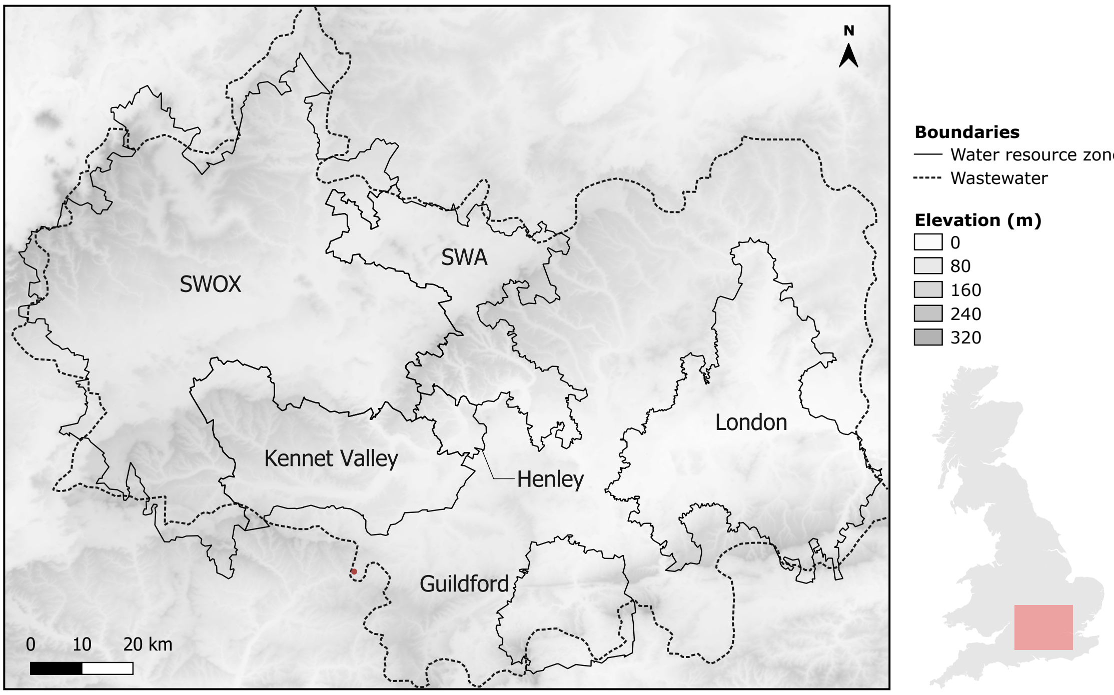

Figure 1. Map of the Thames Water Utilities Ltd. area showing the water supply catchments (black boundaries) and the wastewater resource zone (dotted black line). Elevation is shown in the background.

There is, therefore, a clear momentum to better understand electricity use in the water and wastewater industries of E&W with the aim of driving down grid electricity usage and carbon emissions. However, for the moment the scientific literature is lacking, in that there is very little published data or regional scale case-studies reporting the influence of water-related electricity use in the sectors of E&W. In other parts of the world, this topic is well-developed and it has been argued that localised case-studies on water-related electricity use form a vital pre-requisite in designing policies targeting energy reduction or efficiency in water-related operations in terms of their cost-effectiveness and efficacy [18–20]. For example, in California, research on water-related energy use such as Klein *et al.* [21] from the California Energy Commission, as well as the studies that proceeded, led to policy-driven action to reduce electricity use in the water sector. Reductions of around 1830 GWh in 2-3 years were reported, which was mainly achieved by managing water demands [11]. However, as noted by Kenway *et al.* [22], the policy missed a much larger pool of electricity use associated with electricity use for water provisions at the consumer level, which they argue to be a consequence of miscommunication and unclear reporting frameworks. Meanwhile, in Australia, research such as Kenway *et al.* [23] improved the understanding of the energy footprint associated with urban water and wastewater processes. Research that followed has increasingly focused on electricity use at the consumer-level of the water supply chain, where the greatest proportion of energy is used for water provisions [24–26].

We have not identified any studies in E&W that publish data on energy use in the various sections of the operations supply chain, though we recognise some information is available in company, regulator, and government reports. In the context of the United Kingdom (UK), there have been calls to conduct integrated nexus analyses in the modelling of water-energy systems [27,28], but this can be

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challenging to realise in the absence of accessible region-specific empirical data [29]. Additionally, the water sector in E&W are of international importance in research, particularly due to its relative level of development and experience with privatisation. Therefore, evidence from the UK should form an important contribution to the literature seeking to understand the energy influence of urban water and wastewater operations at a global scale, which for the moment does not report much data from the UK [22,30,31].

With this clear literature gap in mind, we present the first water-related energy use metrics for the UK through a novel case-study of the largest water and wastewater utility in the UK, Thames Water Utilities Ltd. (TWUL), which is also responsible for serving one of the largest mega-cities in the world, London. To do so, we have analysed 5-years of monthly data on electricity consumption across the TWUL system, which was provided to us by the utility company. The purpose of this work is to: (1) produce the first water- and wastewater-related energy metrics in the context of the United Kingdom, (2) present a statistical method to separate the trend, seasonal effect, and random component from the electricity use time series and (3) compare and contrast water and wastewater electricity use in our study against those from other parts of the world.

In this manuscript, we firstly present the TWUL system, details of the company, the data that we received from them, and how this data was processed and analysed (Section 2). We then present the the temporal evolution of electricity consumption across the TWUL system by their functional category and how usage in the region compares with other parts of the world (Section 3). Finally we provide concluding remarks on our findings (Section 4).

2. Materials and Methods

The main purpose of this study is to derive the first energy-intensity metrics for the water and wastewater systems. To do so, we analyse empirical data as follows: (1) time series to understand the trends in energy use and breakdown usage by functions in the supply-chain; (2) each time series is then decomposed using an additive model to understand the long-term trends; and (3) energy-intensity statistics are derived.

2.1. Study Area

This work focuses on the water and wastewater system of TWUL, which is located in the Thames catchment (Figure 1) in the South East of England. The catchment area covers approximately 16,200 km^2 [32]. Within the entire region, TWUL is the largest water utility out of four and the only wastewater utility. The company is also the largest water and wastewater utility company in the United Kingdom and has a customer base of 10 million and 15 million persons in water supply and wastewater respectively [12]. Thames Water Ltd. is privately owned and has an annual turnover of around £2 billion. We note that there are three other water supply companies within the region shown in Figure 1 but these utilities are not studied in this work.

Water resources are sourced from a combination of groundwater and surface water [32]. Drinking water is supplied to customers through around 32,000 km of water mains, 97 water treatment works, 26 raw water service reservoirs, 308 clean water pumping stations, and 235 clean water service reservoirs [33]. Leakages in the water supply network are reported to be around 26% of the total output from water treatment plants [34]. As with most of the UK, a combined system conveys both sewage and urban stormwater runoff through the same sewer network. Post-use wastewater and stormwater drainage is captured and transferred through 109,000 km of sewerage mains and 4,780 wastewater pumping stations, which is eventually treated at one of 351 wastewater treatment works in the area [33]. After employee costs, electricity represents the largest operational expense for TWUL, and so there have been concerted efforts to better understand opportunities for efficiency gains. During the 2017-18 business period, Thames Water Ltd. reportedly self-generated a fifth of their total electricity demand, which is equivalent to 293 GWh and £30 million in operational expenditures [33]. At the demand-side, the water and wastewater utility plans to reduce overall leakages in the distribution system by 15% in the period between 2020 and 2025, as well as install 300,000 smart meters by 2020 (current levels are around 250,000 [33]) in order to incentivise reductions in overall household demand for water and better understand water use and leakage [32].

Figure 1 illustrates the Thames Catchment with the local elevation profile, as well as the major cities within the area. The Thames Water Ltd. water supply area is divided into six water resource zones (WRZs), which represent a standard geographical unit for water resources planning. Descriptive statistics of each WRZ can be found in Table 1. The UK Environment Agency [35] define a WRZ as 'an area within which the abstraction and distribution of supply to meet demand is largely self-contained... so that all customers in the WRZ should experience the same risk of supply failure and the same level of service for demand restrictions'. As it can be observed in Figure 1, the largest WRZ is the area encompassing Swindon and Oxford (SWOX), which is followed by the London WRZ encompassing the Greater London region. Both of these regions are largely reliant on river-based abstractions. The other four zones are Kennet Valley, Henley, SWA (comprising Slough, Wycombe, and Aylesbury), and Guildford. These WRZs are relatively smaller in area and are reliant on both groundwater and river abstractions.

2.2. Electricity data

For this study, we analysed telemetry data that were provided by TWUL between September 2009 and 2016 (60-months). The data are aggregated electricity consumption statistics at monthly time-resolution produced by a proprietary energy auditing system. The primary data (which were not made available for this study) were generated by asset-level electricity meters at half-hourly to daily resolution before being aggregated to the monthly timescales by the energy auditing system. The sample covered 395 sites in total, including: (1) 139 water pumping stations, (2) 112 wastewater pumping stations, (3) 98 wastewater treatment plants, (4) 40 water treatment plants, (5) 1 desalination plant, and (6) 5 other sites including facilities, laboratories, and properties.

2.3. Time series analysis

Electricity consumption data (kWh month^{-1}) for each asset were aggregated by functional categories and converted into time series following a similar approach to previous studies [31,36]. By functional categories, we refer to following specific operations in the supply-chain: (1) wastwater treatment, (2) wastewater networks, (3) water treatment, (4) water networks, (5) desalination, and (6) other auxiliary functions. Time series of electricity use in water systems have previously been observed to exhibit strong seasonality driven by seasonal patterns in demand [36]. The electricity consumption data will also show an overall trend in accordance with, for instance, growth in water demands. Finally, abnormal fluctuations from the mean of the time series might also be observed caused by upsurges in demand during events such as major holidays and sporting events, amongst other factors including weather events. However, these cannot be captured within a long-term seasonal or trend component, and so can be considered as a statistically random component within the time series. Therefore, to understand the influence of such factors on the overall electricity consumption, we use the Seasonal and Trend decomposition method using Loess (STL) [37], which decomposed the time series f into three components such that:

$$f_t = \alpha_t + \beta_t + \gamma_t \tag{1}$$

where α represents the long-term trend in the time series, providing an understanding of the rate of change in the series. The β component captures the seasonal effects in the data, which in the case of water and wastewater flows could be linked to seasonal changes in demand and climate effects. Finally, γ represents a stochastic irregular (random) component that would represent one-off events that can result in unusual fluctuations in the time series. STL is a versatile, robust, and widely-used additive time series decomposition method that was developed by Cleveland *et al.* [38]. A sequence of smoothing operations are applied using locally-weighted polynomial regressions. Whilst STL can handle changes in seasonality in time, we assumed that the seasonal phase in each of our time series was constant given the relatively short timescale of the data. The STL technique can handle multiple types of seasonality, allows the user to define the smoothness of the trend-cycle, and it is robust to outliers in its estimation of the trend and seasonal cycles [37]. A more detailed description of this method, as well as other variants of this technique, can be found it Hyndman and Athanasopoulos [37]. The trend in electricity consumption was then evaluated by applying a least-squares regression model on the α component and the slope (first-order derivative) was computed, which allowed us to understand whether consumption was changing in time. All rates of change reported in this work are obtained from the gradient estimation from the least-squares regression model, where the uncertainty is taken as the standard-error in the model.

2.4. Calculating energy-intensity

Energy-intensity ϵ, measured as the unit energy use per unit of water delivered or wastewater treated (kWh ML^{-1}), is a common metric used globally for assessing the energy intensiveness of a water system [2,23,39]. It should be recognised that this does not necessarily reflect the energy efficiency of the network as other issues also impact this value such as stormwater inputs to the sewer system. Previous works have tended to present ϵ metrics per functional category in a water or wastewater system [23,36]. However, since we did not have time series data on water flows through each of the 395 sites analysed in this work, we could not compute energy-intensity metrics for each site or by functional units. Therefore, ϵ metrics in this work are computed for each of the six water resource zones in the Thames catchment, which were presented in Figure 1. For each water resource zones, ϵ was calculated following Lam *et al.* [19] as:

$$\epsilon_z = \frac{\varphi_z}{\zeta_z} \tag{2}$$

where φ is the electricity consumption per capita (kWh p^{-1}), ζ is the water use per capita (m^3 p^{-1}), and z denotes the specific water resource zone. The per capita use of water and energy are calculated respectively as:

$$\varphi_z = \frac{\sum_{t=1}^{n} f_{t,z}}{P_z} \tag{3}$$

$$\zeta_z = \frac{\sum_{t=1}^{n} w_{t,z}}{P_z} \tag{4}$$

where f is a time series of electricity consumption (kWh) of a specific water resource zone z, ω represents the total water used across the water resource zone within the same time period (m^3), and P

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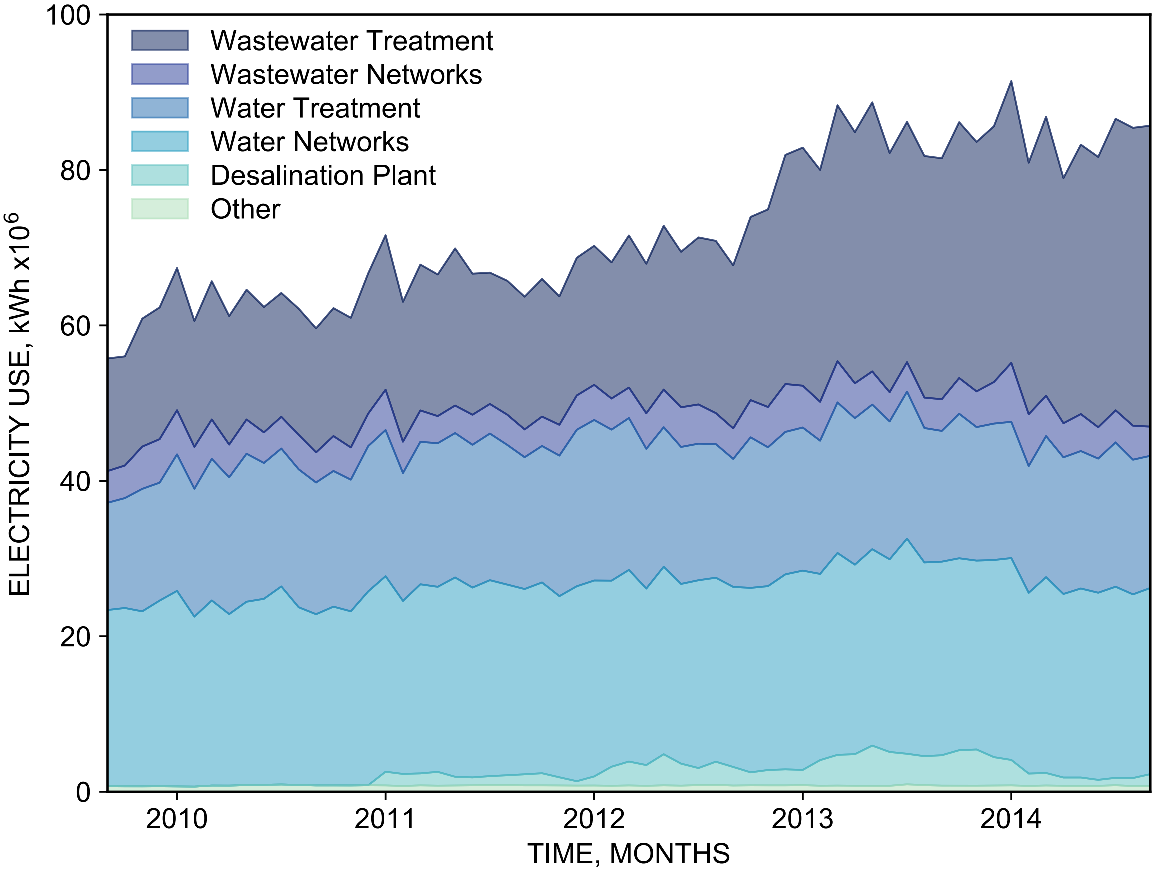

Figure 2. Stacked area chart of electricity consumption (kWh $\times 10^6$) between 2009 and 2014 categorised by functional units.

is the total population (number of persons). Values for the total water used ω and population P in each water resource zone were obtained from Thames Water [40]. The total water use equivalent is the total quantity of water produced, which is the sum of residential and non-household demand, as well as system leakages. These data are summarised in Table 1. The derived metrics for energy-intensity were then compared locally to understand regional spatial variations. We note that this current investigation did not consider wastewater energy-intensity as the required data were not available.

3. Results and Discussion

3.1. Temporal evolution of electricity use

Figure 2 shows the time series of total electricity consumption f_t across the TWUL system between September 2009 and 2014 per functional category. Across the 60-month time-period, the total electricity use in the system was 4426 GWh, which is equivalent to 870 GWh year^{-1} of consumption. This electrical input facilitated the delivery and treatment of 2.5×10^6 m^3 day^{-1} of water and 3.4×10^6 m^3 day^{-1} of wastewater respectively. In descending order, the main contributors to the total energy consumption over the study period were observed to be water networks (33%), wastewater treatment (32%), water treatment (24%), wastewater networks (6%), and desalination (2%). The remainder of consumption (1%) was in other operations such as laboratories, properties, and maintenance work, and is not discussed any further in this work due to the negligible overall contribution of this category. Although the total number of assets in the TWUL system per functional category exceeds the assets for which we have data for (See Section 2.1), we note that those sites that are not considered in this work

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are relatively small facilities, and their energy consumption is not considered material in the context of this study.

In observing the temporal evolution of the total electricity consumption, a consistent increasing trend in electricity usage is evident across the system during the study period. Between the first and last time-period, monthly electricity consumption grew from 56 GWh to 86 GWh. In Figure 3, we can see the observed time series f, trend α, seasonal phase β, and random component γ, which are shown in rows 1, 2, 3, and 4 of the panel plot respectively. In order to ensure the model has adequately captured each phase, we further analysed the γ-phase and observed a random distribution and no autocorrelation. We observe the mean contribution from seasonality β and random effects γ as minor components of the time series f at 0.10% and 0.12% respectively. We assumed constant seasonality across the time series in the decomposition model and it is noted that this might effect the derived results. However, it would not have a large influence in this case since the overall contributions from the β and γ are small. Once the time series has been adjusted for seasonality and random effects, we observe a strong growth in the long-term trend component α during the study period, with an equivalent rate of change of 6.7±0.3 GWh year^{-1} (10.8±0.4 % year^{-1}). More recent statistics from TWUL public reports suggest this growth continued: total electricity consumption across the network was reported to be 941 GWh in 2017-18 [41]. This later reported consumption exceeds the expected value if we were to extrapolate using the rate of change observed over the time slice of the data in this study. This might be attributed to a number of factors including: (1) a significant increase of pumping into reservoirs to meet a sudden increase in summer demand, (2) an unexpected cold wave and increased pipe bursts in February 2018, and (3) the exceptionally hot and dry summer of 2018 [41].

Figure 4 shows the derived trend components from the time series decomposition of each functional category, which have been plotted as the relative change (%) using the first value in the time series as the base value. Here we can clearly observe a strong growth in the electricity requirements for wastewater treatment. Between 2010 and 2012, electricity use in wastewater treatment works grew by approximately 10%, after which it increased dramatically by ∼110% to the end of the time series. After conferring with operations managers from TWUL, we learned that this sudden growth can be attributed to major modifications in five of the utility's largest wastewater treatment works. In order to meet growing demands, as well as stricter effluent quality standards, the plants had the following unit operations added: (1) 12 aeration plants, (2) 2 picket fence thickeners, (3) 2 activated sludge thickeners, (4) 24 final settlement tanks, (5) 5 primary settlement tanks, and (6) 2 inlet pumps. Furthermore, exceptional levels of flooding within this period resulted in larger than normal volumes of stormwater entering the sewer system, which led to additional levels of associated pumping. Across the other functional categories (*i.e.* water networks, water treatment, and wastewater networks), we do not observe any statistical significance trend in the relative energy consumption, and so we conclude the increases in electricity consumption observed across the TWUL system mainly attributed to the modifications in wastewater treatment operations, as well as increased volume of wastewater pumping induced by flooding.

Some of the increasing trends in electricity use can also be attributed to the commissioning of the Beckton Desalination Plant, which is first desalination facility in the United Kingdom and became fully operational in late 2010 [42]. The plant was designed to treat brackish water, which has a lower saline content than seawater, and hence requires less treatment. Beckton is only used at times of drought. Whilst desalination is typically synonymous with high electricity consumption—*e.g.* Sydney's desalination plant consumed 257.7 GWh of electricity in 2010 [43]—the single desalination plant in the Thames catchment is not used frequently. The Beckton Desalination Plant has on average only processed around 23% of its capacity (150 ML day^{-1}) since it came online, and a fairly significant electricity footprint associated with the technology is still observable in the energy use data.

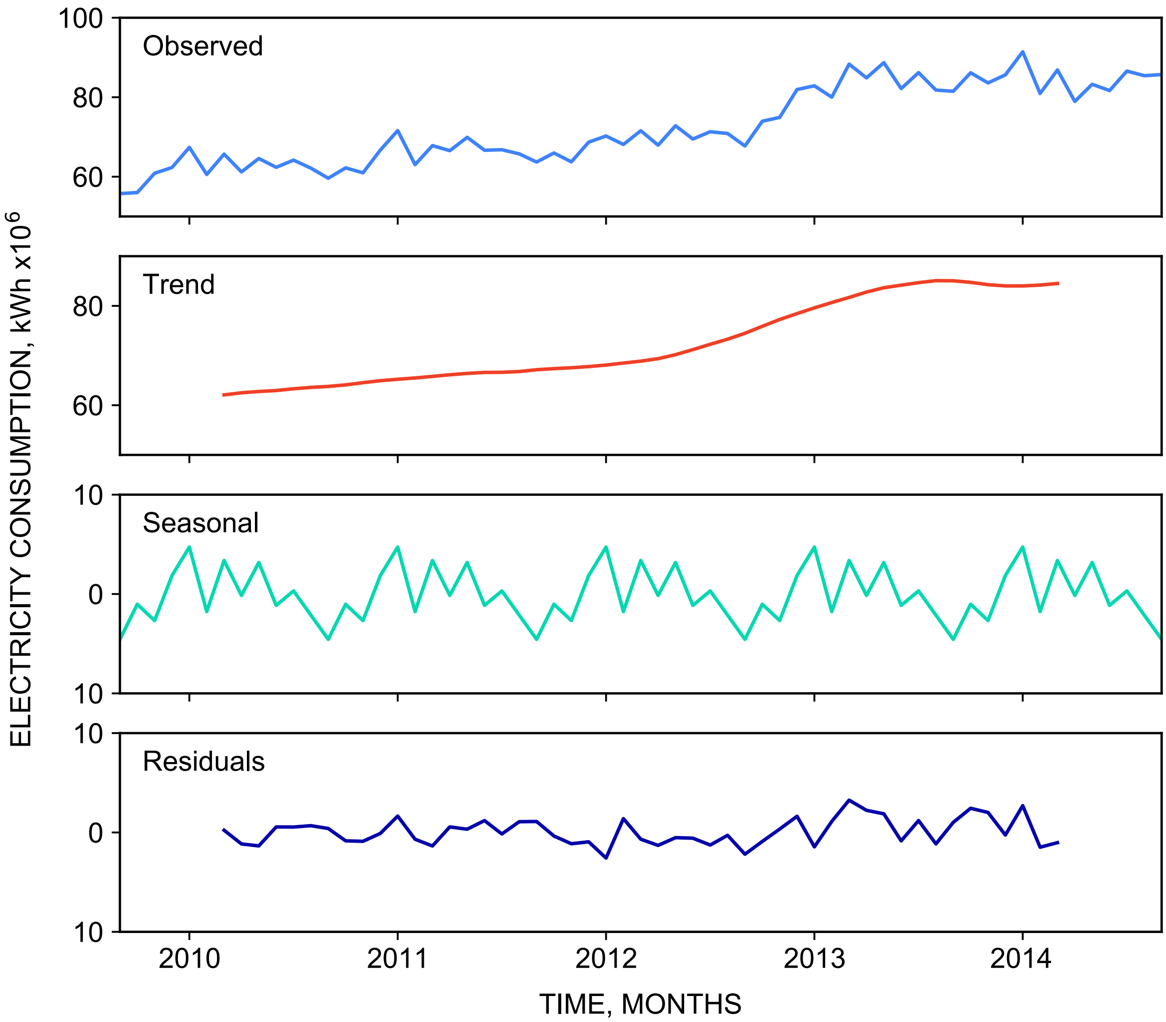

Figure 3. Decomposition of electricity consumption (kWh $\times 10^6$) metrics. The observed time series f, trend α, seasonal phase β, and random component γ are shown in rows 1, 2, 3, and 4 respectively.

As water scarcity pressures enhance in the future, the use of the `Beckton Desalination Plant` could potentially increase if other water resource options with lower energy needs are not developed, which would translate into a higher water-related electricity footprint. Outside of the Thames catchment, there are suggestions that additional desalination plants might be required in the UK [44,45], which would enhance the electricity footprint of water supply across the country, though the feasibility of desalination as a solution elsewhere in England and Wales remains uncertain.

3.2. Electricity use by function

The three most electricity-consumptive functions in the `TWUL` system were observed to be water networks (33%), wastewater treatment (32%), and water treatment (24%). In water supply networks, electricity consumption is primarily a function of water demands, as well as network conditions with respect to hydraulic properties of the pipe (*i.e.* velocity, pressure head, frictional losses, etc.), asset age, and topography. Post-treatment leakages within the `TWUL` system are currently reported to be 26% of the total demand and the company is targeting to reduce this number by 15% in the period between 2020-2025 [33]. This would theoretically result in decreased electricity consumption within the water distribution network as sources of pressure loss are removed and older assets are replaced. In addition, reducing losses in the water network would also lower the throughput needed in water

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Table 1. Summary statistics for each water resource zone as of 2014. Energy use and intensity were calculated in this work, whereas population and water use were obtained from Thames Water [40]. The final row shows a sum for the entire Thames Water system with the exception of the ϵ column, where a mean value is shown.

WRZ	Population [p]	Water Use [ML d^{-1}]	Energy Use [GWh yr^{-1}]	ϵ [kWh m^{-3}]
Guildford	150,136	44.7	10.6	0.65
Henley	49,082	13.1	3.4	0.71
Kennet Valley	389,946	98.4	32.9	0.92
London	6,946,620	2048.1	389.2	0.52
SWA	507,627	135.7	31.4	0.63
SWOX	999,996	261.9	44.7	0.47
Thames Water	9,043,407	2602.0	512.2	0.65

treatment plants, and so reduce the associated electricity use. Though any benefits that are potentially realised here would be offset by population growth.

TWUL predict an increase in the overall water demands as population continues to rise. However, plans to implement smart meters and relatively more water-efficient technologies such as modern dishwashers, washing machines, and low volume toilet cisterns will help to temporarily offset the increases in water demands, by reducing per capita consumption [40].

The most common method for sewage collection across England and Wales is through combined sewage systems, in which sewage from domestic, industrial, and commercial sources is combined with surface runoff, and distributed to local wastewater treatment plants. Combined sewer overflows (CSOs), which is when the total inflows into a combined sewer exceed its capacity causing the discharge of untreated wastewater into local water bodies, have been long recognised as an environmental and public health risk in the Thames catchment, and indeed in other catchments across England and Wales [46,47]. As such, TWUL have targets to reduce overflow events in certain areas. One such project to deal with this issue is the Thames Tideway Tunnel—a 25km-long and 7.2m diameter sewer that is being bored under the River Thames expected to be completed by 2024 at an estimated cost of £4.9bn [48]. The sewer has been designed to reduce the frequency of overflow events from 50–60 to 3–4 per year, which will facilitate the UK Government to become compliant with the EU Urban Wastewater Treatment directive [49]. This project will immediately yield significant public health, environmental, and aesthetic benefits [47,49,50] as overflows events are reduced and more wastewater is directed to local treatment plants. With more water being pumped out of the tunnel and increased inflows into wastewater treatment plants, the electricity use in the wastewater supply chain will increase as a result. It is important to track the energy influence such major implementations as this would form a useful planning guide for other similar projects globally.

3.3. System energy-intensity

Figure 5 shows water-related energy use (kWh p^{-1} $year^{-1}$) against water use (L d^{-1}) in the Thames Water Ltd. system (in colour) compared against other regions in the world (grey) for the review period. We note that this chart shows data for water supply only. Dashed lines in the plot, which indicate linear functions of energy-intensity between 0.5–2.0 kWh m^{-3} have been shown for reference. We observe that the per capita water demands in the Thames catchment are within the average range of the other cities reported. Whilst the observed energy-intensities are generally above the average of all the cities plotted (0.6 kWh m^{-3}), both SWOX and London, where the greatest populations are

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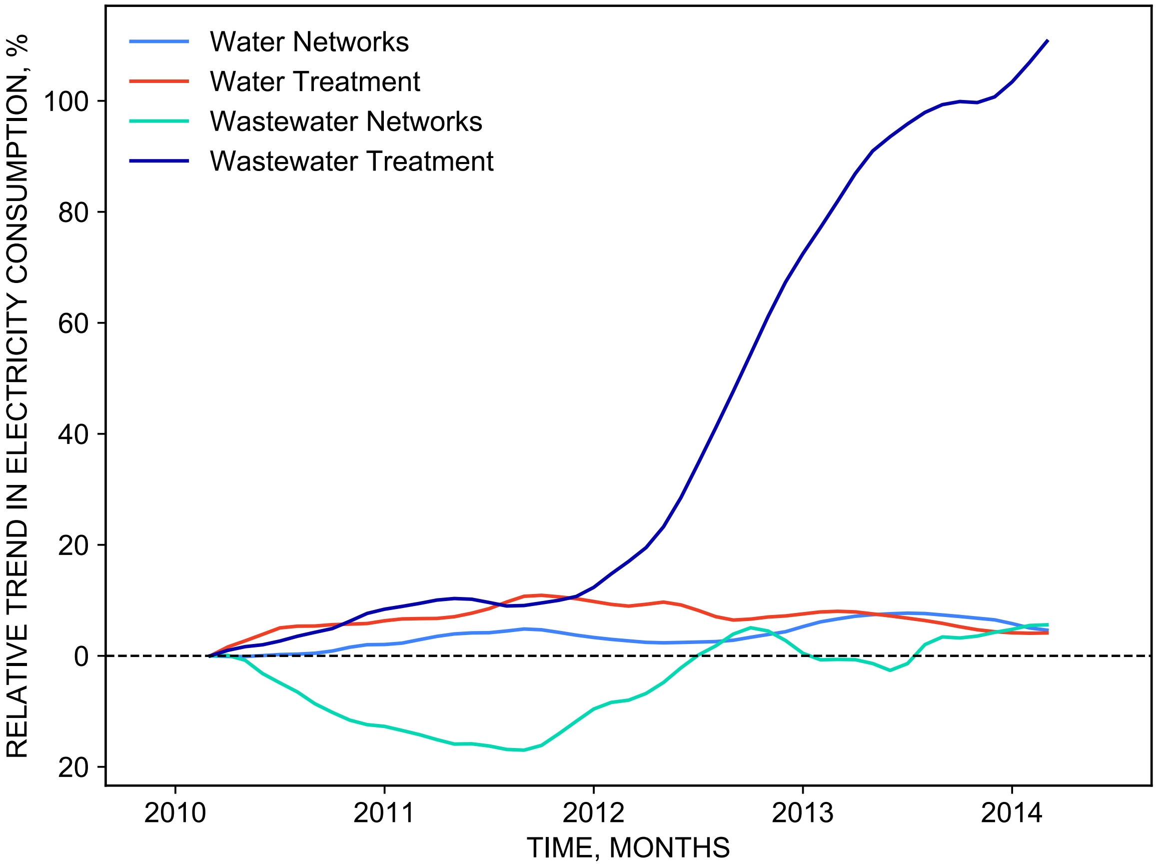

Figure 4. Derived trend components (α) for each functional category: water networks, water treatment, wastewater networks, and wastewater treatment. Shown as relative change (%) using the first term in the time series as the base value.

served, are both below this average value. Further, though we recognise the potential for differences in drinking water quality standards globally and hence treatment requirements, the energy-intensity values derived are higher than those calculated for similarly developed cites, such as Melbourne, Berlin, Sydney, and San Francisco. It should be recognised, however, that the regions studied in this work are water resource zones, and so the spatial extents might vary in comparison to the other regions in the plot, which consider only the city-scale or are an aggregate of all encompassing water supply zones.

Factors that influence the energy-intensity of water-related energy use are known to include climate, topography, water use patterns, and operational efficiency [19,31]. In addition, the initial raw water quality, as well as the required water quality parameters of the final product also influence the electricity requirements of the system. The energy-intensity values derived for the `TWUL` system can likely be explained by two factors: (1) the volume of pumping in the system and (2) low system efficiency attributed to relatively high leakage rates. The `TWUL` system requires relatively high amounts of pumping to convey water between process operations, which is likely due to little topographical variation within water resource zones. Secondly, the energy intensiveness of the `TWUL` system could also be explained by system leakages, which are known to be relatively high across the network [51]. Sections of the supply network are among the oldest in the world and date back to the Victorian era. Further, recent network maintenance reviews revealed the annual asset replacement rates in the network are small-scale in comparison to other parts of the world [52]. Age of a network has been known to correlate with higher leakages in a water distribution network [53], which could explain the relatively high levels of leakages in the `TWUL` system. Leakages in a system can lead to pressure losses

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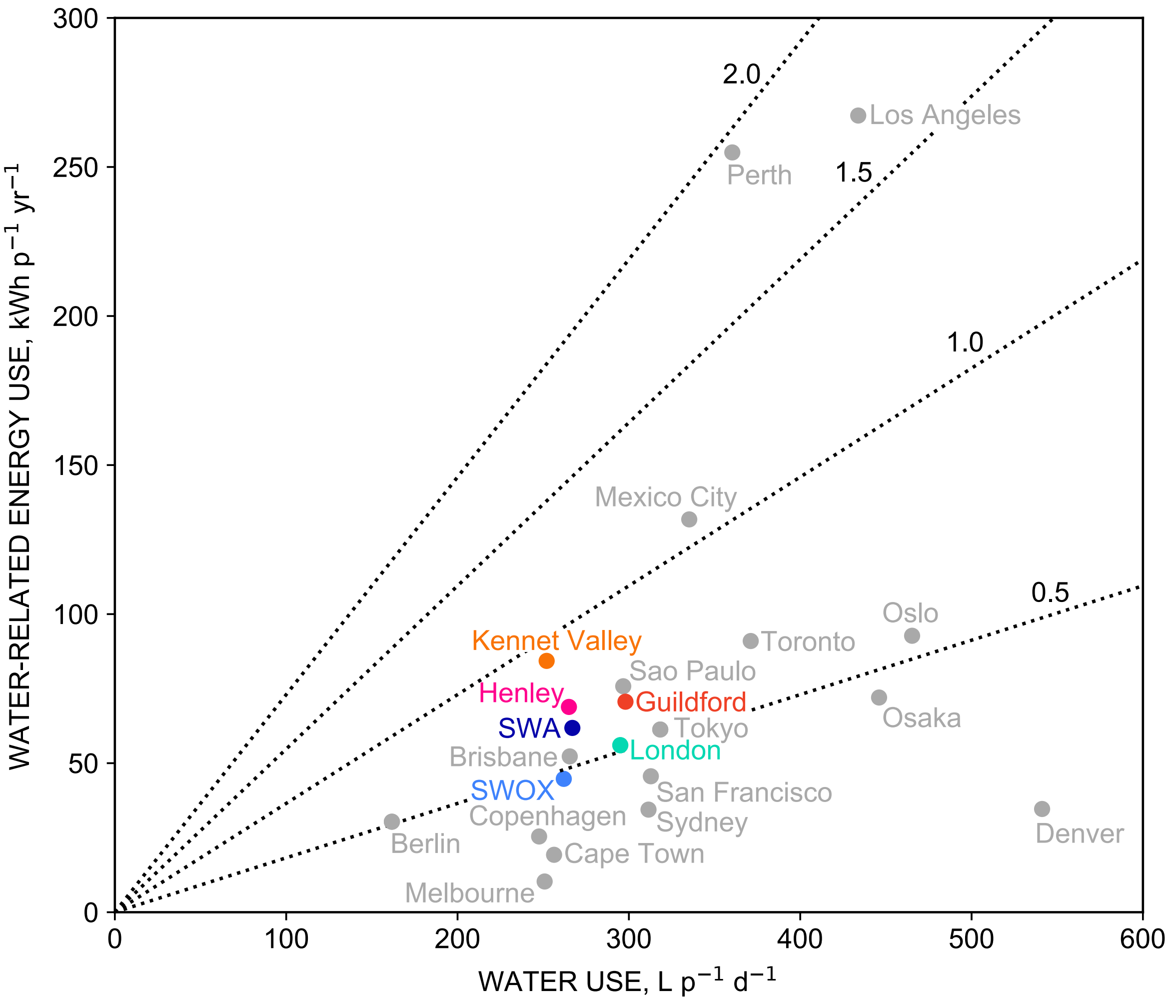

Figure 5. Water-related energy use (kWh p^{-1} $year^{-1}$) against Water use (L p^{-1} day^{-1}) in the Thames Water Ltd. system in 2012 compared against other regions in the world (grey). The dotted lines are plotted for reference and indicate 0.5–2.0 kWh m^{-3} energy intensities. This figure has been adapted from Lam *et al.* [31] and reproduced with permission.

and the need to abstract, treat, and output larger volumes of water into the distribution network, and thus driving up the energy-intensiveness of the system. The utility has targets to reduce leakage rates by fixing or replacing assets within the network, which would yield savings in electricity consumption in the short-term.

Identifying and reducing leakage across the water distribution network has benefits towards an energy efficient system. However, this can come at a significant cost. Figure 6 shows the relationship between capital cost investments and leakage reductions, which is based on an analysis by TWUL [54]. The curve assumes an exponential relationship between leakage reduction and capital cost, in that significant reductions could be realised cost-effectively in the first instance but the economic case decreases after a turning point. The dashed line in Figure 6 represents the targeted leakage reduction by the utility up to 2020: 85 ML d^{-1} with an expected cost of around £340 million. For relative context, this volume of water could meet 96% of the daily demands of the Guildford, Henley, and Kennet Valley water resource zones (589,164 people) [40]. There are a number of benefits of reducing leakages that regulators and utilities in the UK have recognised, and whilst energy savings are also acknowledged they have not yet been quantified in terms of potential reductions in operational expenditure. That is, what would be the unit cost saving for each unit of

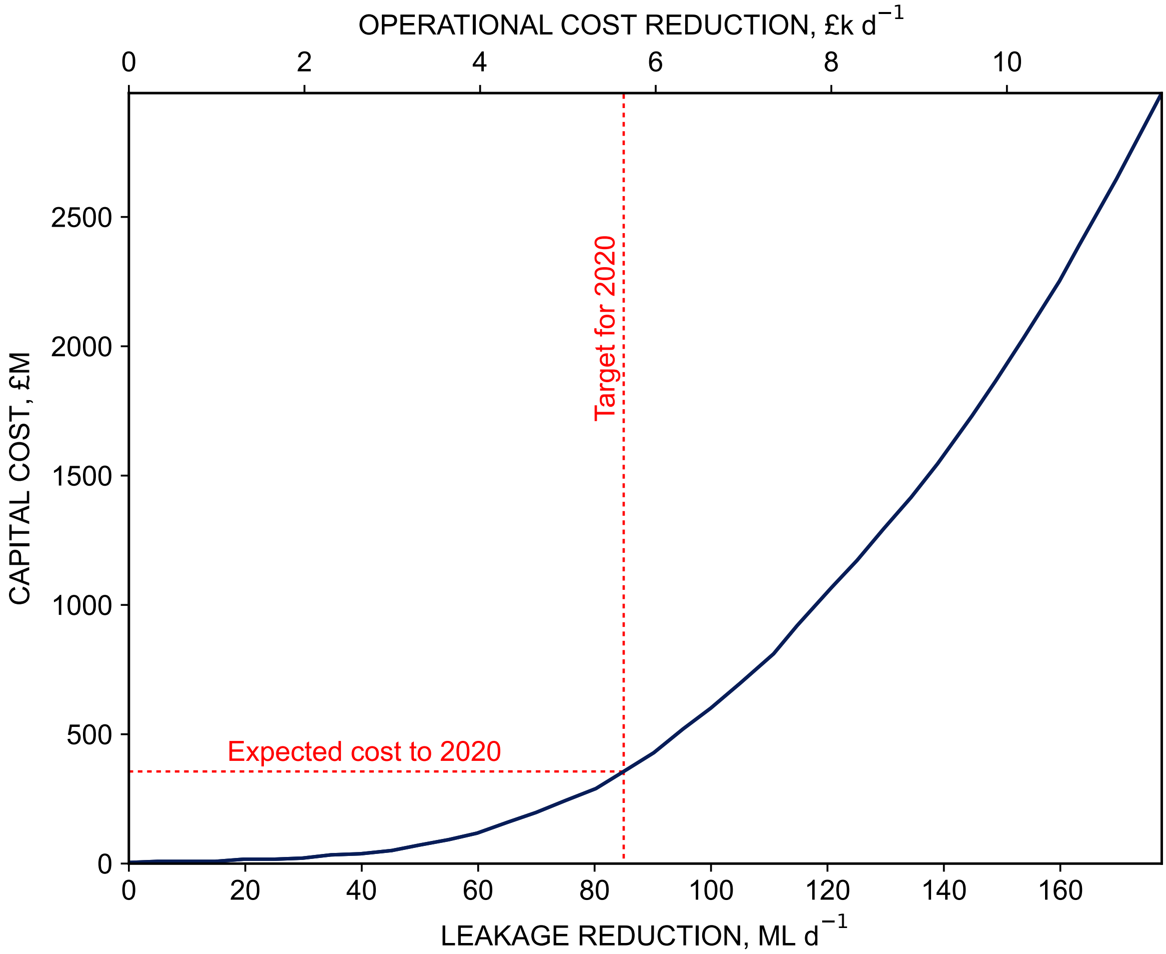

Figure 6. Curve expressing the relationship between capital cost (£ millions), leakage reductions (ML day^{-1}, and reductions in operational expenditures due to electricity consumption (£ 1000s day^{-1}) for the `Thames Water Utilities Ltd.` system. The dashed red lines show the company's leakage reduction targets to 2020 [54].

water leakage prevented? Using the metrics for energy-intensity (kWh m^{-3}) derived in this work, we have expressed this relationship in terms of the energy cost savings that could be realised for every unit reduction in leakage (calculation shown in Appendix A). Should the utility reach its target, this could result in a theoretical reduction of 85 ML d^{-1}, which is roughly equivalent to operational expenditures due to electricity consumption of ∼£2.1 million year^{-1}. However, there is a caveat to this theoretical value as it is derived in the absence of other external pressures such as population growth and demand changes in time. Discourse on the motivations for leakage reductions primarily focus on the environmental benefits of reduced water withdrawals from rivers, as well as the improvement in political and public perception, and less often focuses on the energy-related co-benefits.

4. Conclusions

Electricity consumption in the `TWUL` network increased consistently during the period 2009 to 2014, which was mainly driven by expansions in wastewater treatment works to achieve higher effluent water quality standards and periods of heavy rainfall, which led to more stormwater pumping and treatment, as well as the use of a new desalination plant. As the utility continues to invest in more water supply technologies to meet increasing demands, as well as upgrade its sewer and wastewater treatment capacities, we can reasonably expect this growth in electricity consumption to continue. However, some of this growth could be managed should the planned improvements to water infrastructure efficiency (*e.g.* leakage reductions) be realised. However, the temporary nature of these benefits should be recognised as external pressures such as stricter water quality standards and population growth would offset the potential benefits. With regards to energy use in wastewater operations, regulatory changes require utilities to reduce overflow events in combined sewage networks. Whilst this will reduce the number discharges of untreated wastewater into local water bodies, it will result in increased pumping of wastewater and larger volumes for wastewater utilities to handle, which will increase the associated electricity usage. This highlights the fact that increasing stringency in mandatory effluent standard regulations will generally be associated with higher energy requirements. Through studying the temporal evolution, we have also shown that the energy influence of water-related operations can change rapidly.

When analysing the derived energy-intensity metrics for each water resource zone in the water utility's system, we discovered that energy-efficiency of water supply, in terms of the electricity usage per unit of water delivered, is within the average range when compared against similarly developed cities across the world. Given that TWUL has plans to reduce leakages within their system, the energy-intensity of the network and the operational expenditures associated with electricity could decrease in the short-term as a result, though the benefits would erode in time as a result external factors such as population growth. It has been estimated that customers of TWUL use 7 times more electricity for water-related provisions as compared to the utility's electricity use for their operations.

Temporal studies of the energy influence of water-related operations are rare. Through this study, we have have seen that such studies can be useful in better understanding the energy-related characteristics of a water and wastewater systems. This is particularly important in relation to understanding long-term electricity consumption trends, which can reveal insights on the energy impacts of infrastructure and effectiveness of policy development, and to understand the exogenous seasonal and random influence from the local environment. The information that can be gleaned from such analyses are an important basis for effective energy management programmes in water and wastewater operations.

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Appendix A Cost-benefit analysis

In this section, we discuss the methodology used in the calculations for Figure 6. Data on the capital cost (£) required per megalitre reduction in leakages were produced by TWUL [54]. The benefit in operational expenditure b per unit reduction in leakage was calculated as:

$$b = \mathcal{L} \cdot \bar{\epsilon} \cdot c \tag{A1}$$

where $\mathcal{L}$ is the leakage reduction (ML d^{-1}), $\bar{\epsilon}$ is the mean energy-intensity across the Thames network (kWh m^{-3}), and c is the cost of electricity (£ kWh^{-1}) for TWUL. The $\bar{\epsilon}$ value was calculated in our analysis as 0.65 kWh m^{-3}. The value of c could be calculated based on reports from TWUL, which state that 160.6 GWh of electricity consumption is equivalent to £30 million in operational expenditures to the utility [33].

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