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TOPICAL REVIEW

A review of energy-for-water data in energy-water nexus publications

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Abstract

Published literature on the energy-water nexus continues to increase, yet much of the supporting data, particularly regarding energy-for-water, remains obscure or inaccessible. We perform a systematic review of literature that describes the primary energy and electricity demands for drinking water and wastewater systems in urban environments. This review provides an analysis of the underlying data and other properties of over 170 published studies by systematically creating metadata on each study. Over 45% of the evaluated studies utilized primary data sources (data collected directly from utilities), potentially enabling large-scale data sharing and a more comprehensive understanding of global water-related energy demand. The most prevalent geographic scale of the existing literature was at the individual city scale (39%), limiting comparisons between utilities. Additionally, energy-for-water studies span 34 different countries with 11 countries having at least 4 published studies. The analyzed literature often considered greenhouse gas emissions of energy demand as an important input for life cycle analysis, highlighting the broader impact of the energy-water nexus. As a result of the review, we identify several common practices for filling data gaps, discover that research and data are primarily concentrated in three countries (Australia, China, and the United States), and offer suggestions for the future of the energy-water nexus, specifically regarding energy-for-water.

1. Introduction

Since the mid 1990s, there has been an increasing volume of literature published on the energy-water nexus, specifically quantifying water-related energy or energy-for-water. Gleick [1] provided one of the first assessments of the relationship between energy and water resources. Energy is required to supply, treat, distribute, and reclaim water resources within urban environments [2]. Additionally, there are other types of water-related energy demand in less developed urban environments, such as the energy required for water trucks in Kenya [3] and many other locations globally. As various policies direct water treatment practices and/or set water quality standards, there is a growing demand for energy resources to treat water to policy thresholds [4]. Managing water and energy as joint resources provides further benefits for conservation [5] and can significantly reduce operating costs for a utility [6].

Liu *et al* [7] estimate that water-related energy consumption totals 1.7–2.7% of total global primary energy production. Depending on the inclusion of water end uses in the energy-for-water boundary, previous studies estimate that water demands 12.6% of total primary energy in the United States [8] and 5.8% of total electricity production in Spain [9]. However, the data associated with studying energy-for-water are scattered, scarce, and uncertain. Recently, there have been more efforts to publish energy-for-water data concurrently with research studies, resulting in a discussion on the importance of a broader data collaborative for this component of the energy-water nexus [10–13]. We perform a systematic review of literature related to energy consumption for water resources (at the utility-scale) in urban environments across the globe to determine the source of data, temporal scale of available data, and geographic spread of studies before discussing the implications for a global dataset of energy-for-water data. While there have been several important reviews of this literature space [14–16], these reviews focus on the exact values and statistical ranges of energy demand for water resources and do not investigate the availability and type of data used. Along this vein, our review provides a unique exposition on the state of the literature by focusing on several questions that inform the future of the energy-water nexus:

- Are studies using primary data or do they rely solely on previously published works?
- Where in the world are data for evaluating the energy-for-water demands available?
- What other nexus decisions do the literature address? (i.e. life-cycle assessments, climate, etc)
- How are researchers filling in the gaps when site-specific data are not available?

Recently, there have been several papers that identify the data gap in this field and attempt to collect and compare data from various cities [11, 12, 17]. Answering these four proposed questions provides an important path forward for policy to strengthen the understanding of the energy-water nexus and address data sharing opportunities for cities. This review creates and analyzes metadata of over 170 publications and their underlying data, identifying previously obscured trends that point to the future of the energy-water nexus. Understanding the nexus of resources, including energy and water, and data availability provides important pathways for advancing sustainability and resource management goals [18–20].

2. Methods

We utilized three literature search engines to create a database of journal publications: Web of Science, Scopus, and Google Scholar. We used a set of keywords to identify relevant literature with each search engine; see table S1, which is available online at https://stacks.iop.org/ERL/15/123011/mmedia, for a list of the keywords in the search. Following the stated goal of the manuscript, we only considered peer-reviewed journal literature. Technical reports by state or federal agencies, non-profits, and other agencies (such as the International Energy Agency) were not reviewed or categorized in this manuscript. Additionally, through the review of the literature, there were often studies identified in the introduction and background sections of publications that were not captured in the initial search criteria. These identified studies were then located and included in the analysis. Finally, one significant limitation to the review is that only publications in English were considered. Peer-reviewed articles available online after May 2019 or before 2000 were not considered. We exclude studies before 2000 in the review to discuss trends for the current century. The method resulted in 172 papers, capturing a large amount of the research space. We recognize that it is impossible to be confident in capturing all relevant articles, but we suggest that our data sample is sufficient to make broad statements and analysis of the current state of the field through this systematic review. A list of all the papers included in the review can be found in the supporting information, Text S1.

Kenway and Lam [2] identify four components of the urban water cycle that require energy: (i) water supply, (ii) water end-use, (iii) wastewater, and (iv) non-operational activities. The relationship between energy and water in these four components is shown in figure 1. This review focuses on energy-for-water in water supply and wastewater systems. We limit our review to the municipal scale of energy-for-water, omitting building-scale or residential water end-use. Additionally, we exclude non-operational activities of urban water that would include embodied energy through the life cycle of water system construction. While end-use water-related energy demands can be significant [16], the data are often hidden behind privacy concerns as they relate to individual behaviors. Additionally, the focus on the utility-level is consistent with the literature that often evaluates the four components of energy-for-water separately due to different scopes and objectives of the research. Finally, the energy demand in water end-use varies between residential, commercial, and industrial users that have different water uses and functions. Each of these users pays for their own energy demands associated with water, while utility energy demand is wrapped into the total rate of water. The utility-level scope enforces the goals of the review to expose the challenges in energy management of water resources at a city/urban scale.

To facilitate a uniform review, we analyzed each article using a standardized form. This form included multiple choice, short answer, and check box fields. A team of three researchers read each of these papers over the course of four months. The process, utilizing a standardized form, created metadata for each literature article. The information collected included general citation information, scale and location of each reviewed study, type of energy considered, urban water process (drinking water, wastewater, water reuse), and type of data included. See the supporting information, Text S2, for a list of questions included on the standardized form. These analysis questions were asked of each reviewed study to ensure a systematic and cohesive review of the collected studies in Text S2. Additionally, Dataset S1 provides the evaluation of each included study for generating figures 2–5 in the manuscript.

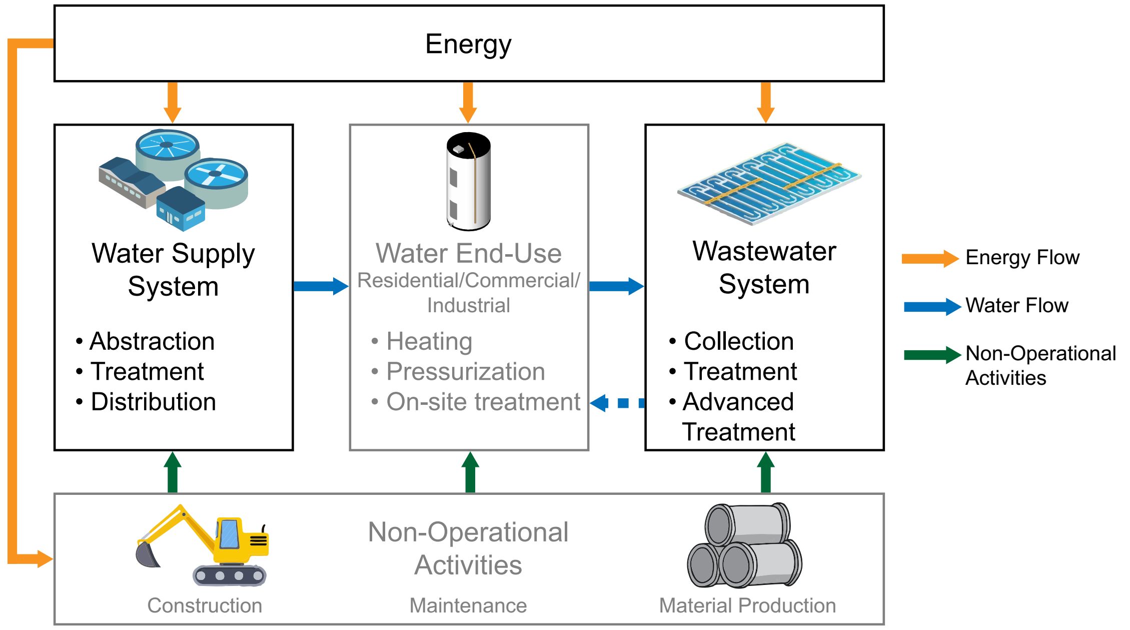

Figure 1. The four categories of water-related energy use include water supply, water end-use, wastewater, and non-operational activities. This review focuses on the systems of water supply and wastewater. Solid blue lines indicate flows of water, with dashed blue lines indicating potential flows. Energy flows are denoted by solid orange arrows. Green lines show the influences of non-operational activities on the systems. [2] adapted by permission of the publisher (Taylor & Francis Ltd, http://www.tandfonline.com).

The type of data utilized within the study were binned into four general categories: primary data, secondary data, modeling, and technical reports. Primary data include data obtained directly by the author(s) related to the utility under investigation through communication with the utility or through their website materials. Secondary data, for the purposes of this review, reference data that were obtained via previously published peer-reviewed literature. Modeled data include estimations generated from EPANET or similar software packages to predict energy consumption and any hydraulic calculations (e.g., depth of groundwater to pump energy). Technical reports represented data that were obtained from large-scale studies performed by state or federal agencies, non-governmental organizations, or other institutions that were published outside the traditional peer-review process. Only data included within individual studies' results or methods sections were included, and studies often utilized multiple types of data.

3. State of the data

3.1. Data sources

Figure 2 displays a histogram of the type of data utilized within peer-reviewed journal papers published between 2000 and 2018. The year 2019 was excluded due to the online publishing cutoff of May 2019. The papers are separated based on geographic scale of each reviewed study. Around 2008–2009, the amount of published papers began increasing much more rapidly than in the first few years of the 21st century. The abundance of orange dots—56 papers total—illustrates the reliance on technical reports for studies, the data for which has not undergone the typical peer review process ($n = 137$). Although not gathered within a formal peer-reviewed framework, technical reports are a common form of presenting data. While primary data are often the preferred data source, these data are not always available or practical to obtain. The other three data sources (technical reports, modeling, and secondary data) each have pros and cons for utilization depending on the scope of analysis.

While technical reports are a common data source, surprisingly, primary data (i.e., data collected directly from utilities) was the most prevalent source of data used, occurring in 62 papers. In comparison, 24 papers used secondary data as a data source. The use of primary data over secondary suggests that there is minimal continuity in the field (i.e., researchers are not using previously published data, potentially due to relevance or inaccessibility). This trend speaks to either the scope of existing studies being somewhat limited and/or the lack of data published in an accessible format. The type of data used in studies varies based on the geographic scale of each reviewed study. Most larger scale studies cite technical reports, and, as the study scale gets smaller, primary data are used more often. In larger studies (regional, country, and multi-country level), technical reports were cited 40 times and primary data cited 19 times. This trend reverses in smaller studies (multi-city and individual city) with primary data cited as the predominant source. Fourteen large geographic scale studies used a

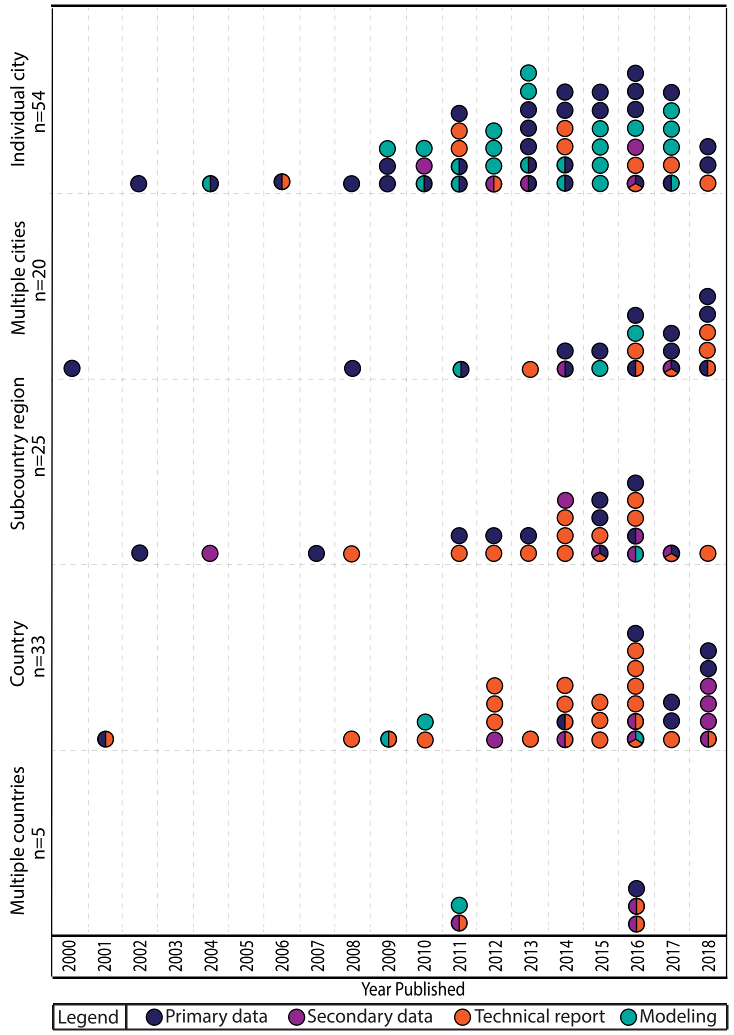

Figure 2. Reviewed studies are grouped by geographical scope and are defined by their data source. A majority of the reviewed studies only analyze a single city as its geographical scale. Each circle represents one journal paper, and the color of the circle corresponds to the type of data used in each reviewed study: primary, secondary, technical report, and/or modeling. Studies that used multiple data types have been split into halves or thirds and show the colors of all data types used.

combination of data sources and 17 studies at a smaller scale used a combination of data sources.

Before 2014, seven papers used modeling in combination with other data; since 2014, modeling has been used alongside other data five times in our literature review set. We define modeled data as estimations generated from EPANET or similar software packages to predict energy consumption and any hydraulic calculations (e.g., depth of groundwater to pump energy). The use of modeling in conjunction with other data sources provides opportunities to validate or enhance the complexity of the energy-water nexus study. Recent studies have utilized regression models [21] or hydraulic models [22, 23] to account for water-related energy demand. However, one of the most common uses of modeling was a calculation of energy to pump water from groundwater depths (see section 6.1).

3.2. Data scale

To illustrate the scale and scope of data utilized in studies, figure 3 shows the type of water system (drinking water, wastewater, wastewater reuse), the energy type, and the temporal scale of the data used within each reviewed journal article. The difference in number of studies within the categories of figures 2 and 3 is due to uncertain or unclassified data sources or types. See Dataset S1 for the detailed metadata on each reviewed study.

Most analyses only evaluated electricity demand as a source of energy-for-water, neglecting natural gas or other primary energy sources. In some cases, the inclusion of only electrical energy is limited by the geographic scale of the study. For example, Ganora *et al* [24] provide a survey of wastewater treatment facilities across Europe and cite the exclusion of non-electrical energy due to the broad scope of the study. This limited scope of energy data is counter to the findings of Chini and Stillwell [11], which demonstrated the large impact of natural gas, especially in the winter months at U.S. utilities. Additionally, as more wastewater facilities adopt biogas or digester gas reclamation technologies to offset

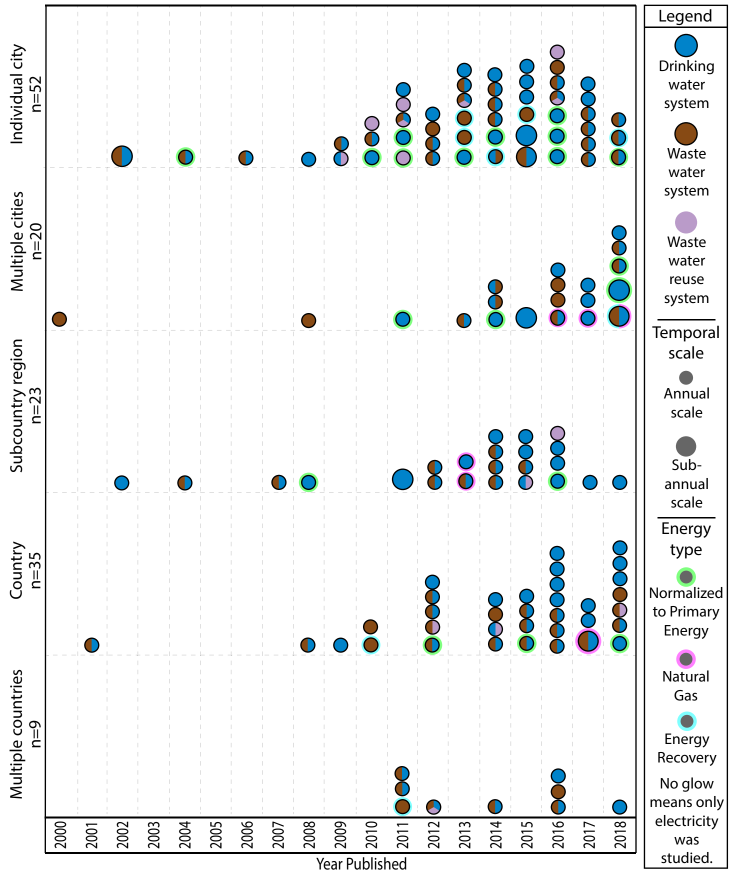

Figure 3. Reviewed studies are grouped by their geographical scope and represented by the system evaluated, temporal scale, and energy type. Nearly all reviewed studies occur at an annual scale, with only eight studies using data of a sub-annual time step. The papers are separated based on geographic scale of the reviewed study, where each circle represents a single article. The color of the circle represents the water system; studies that analyze more than one system are represented by a circle divided into colors for each system. The energy type is shown by a glow (or absence of glow) around the outside of the circle. The size of the circle indicates the temporal scale of the data.

energy demand, it is important to evaluate the opportunity and ensure economic and environmental viability of the technology [25–28]. Better collection of data that includes all energy types consumed will provide better insights to achieve life-cycle greenhouse gas reduction and sustainable development goals.

Based on data collected in this review, 84% of papers included drinking water in their analysis ($n = 139$). Of the papers that studied drinking water, 48% of them studied both drinking water and wastewater, but only 3% of research studies evaluated the full urban water cycle including drinking water, wastewater, and wastewater reuse. Wastewater was included in 59% of all energy-water nexus studies. Wastewater reuse, however, was studied in only 11% of all papers, but the number of papers studying wastewater reuse systems has increased in recent years.

Moving forward, primary data need to be collected and shared across larger geographic and smaller temporal scales. A database on energy-for-water data available to researchers would provide a platform to enable sharing of primary data and increase the amount of reliable secondary data used, supplementing technical reports that reside outside the traditional peer review process. Further, there are opportunities to promote research that studies multiple water systems using data with a sub-annual temporal scale and including all energy required, beyond only electricity. Only eight of the evaluated studies included evaluation of sub-annual variation in the energy-water nexus. Previous research by Chini and Stillwell [11] and Escriva-Bou *et al* [29] illustrate the significant seasonal variation in energy-for-water demand, suggesting a necessary inclusion of these data. Additionally, Slagstad and Brattebø [30] utilize primary data including fuel oil demand and biogas production in their LCA study, while Spang and Loge [31] evaluate energy intensity at a sub-annual timescale for seasonal adaptation and decision-making. In this review, we do not explicitly evaluate the temporal nature of the data beyond cataloging the number of sub-annual analyses due to the relatively small sample size of reviewed studies. Energy reduction goals could be more easily achieved if data from studies with primary sources were more accessible.

3.3. Citing data

During the systematic review, there were three interesting themes associated with sources and citation of data: (i) use of technical reports, (ii) misattribution of sources and data, and (iii) data in review studies. These three themes were common throughout multiple reviewed studies.

First, there was minimal repeated citing of secondary literature. Authors tend to cite their previous papers or major review papers, such as Plappally and Lienhard [16], and not necessarily reference previously published, peer-reviewed literature. Instead, many studies rely upon data from technical reports. The main technical reports cited originate out of three countries: the United States, Australia, and China, corresponding to the countries in which most of the studies have occurred (see figure 4). Table 1 describes the main reports used in energy-for-water studies, their location of origin, and year published. The use of technical reports as a main source of data shows their value to the field of the energy-water nexus. While we did not specifically review technical reports in the systematic review, we evaluate cited technical reports as sources of data for published studies. Technical reports often provide data in a well-constructed and easily identifiable manner. For example, a study that assesses the energy intensity of water across a large region, such as the western United States, would have been substantially more difficult without the utilization of a national report [32], requiring data collection from hundreds or thousands of municipal water utilities.

Additionally, technical reports provide an opportunity to translate data from other languages to an additional audience, such as English. For example, the urban water supply yearbooks of China are published in Mandarin, posing a barrier to access for non-Mandarin literates that is mitigated through subsequent citation and publication in English or other languages. The supplementary information of Lam *et al* [17] similarly shows a number of non-English technical reports made accessible through translation and publication.

While the use of technical reports is prevalent in the field, this type of data comes with its own distinct set of challenges. Data aggregation, which often happens in broad technical reports, reduces data resolution and the distribution of variability in the data. Such is the case for national case studies of data like the Electric Power Research Institute report, table 1. Additionally, these technical reports are location specific and often are not frequently updated, leading to outdated and misapplied data.

Second, through the systematic review of the literature, there were several instances of misattribution of data both through sources and geographical location. Cited data sometimes would not reference the original source and instead reference another paper, which, in turn, referenced the original data. This trend is especially evident in the citation of review papers for data, but was also visible in non-review papers. Misattribution of data was found in several reviewed studies associated with using data from a different geographical region, which could potentially be compounded and distort estimations and the decision-making power of the analysis. There are significant variations of embedded or operational energy in water resources even within a country and using non-country specific data introduces challenges and uncertainties in the results. However, the use of data from another geographic location might be the only viable option for an order of magnitude estimate when no local data are available.

Finally, review papers accounted for 22 of the 172 papers analyzed. It was important to consider review papers as part of this systematic review as they provide important insights into the state of the field and the availability of data. In most fields, literature review papers focus predominantly on reporting and analyzing peer-reviewed literature. However, a significant number of references in the energy-for-water review papers were not from peer-reviewed sources. Approximately 30% of the references in these review papers were from non-peer reviewed sources, including technical reports, data from utility websites, etc. Including technical reports within a review paper provides another pathway for exposing data to researchers, but comes with limitations on data aggregation and misattribution. Through the review papers and the overall systematic review process, we recognize the importance of technical reports in the field of the energy-water nexus.

4. Geographical analysis

As part of this systematic review, we identified the locations where energy-for-water studies are occurring and from where the research is originating. Of the 172 papers that were analyzed, energy-for-water studies occurred in 34 countries with most of the reviewed studies occurring in three countries, figure 4. The United States, China, and Australia were the predominant locations of research, with studies in these countries ranging from the city to the regional and country scale. A few of the articles considered in our analysis evaluated multi-country regions including Europe [33, 24], the Middle East and North Africa (MENA) [34, 35], and Cooperation Council for the Arab States of the Gulf [36]. Several studies also compared cities or regions from multiple countries [17, 37–41]. Lam *et al* [17] is notably comprehensive in comparing 40 cities across 13 countries, including a visualization of annual changes across multiple years for several of these cities.

There were 11 countries that had at least 4 different published energy-water nexus studies. The data sources associated with each of the 11 countries were largely varied. Italy, Norway, Australia, South Africa,

Table 1. The reviewed literature references several common technical reports for data from three main countries.

Location	Name of technical report	Author/organization	Year
Australia	Energy use in the provision and consumption of urban water in Australia and New Zealand	Kenway, *et al*	2008
China	Urban water supply yearbook	China Urban Water Association	2012
United States	US Electricity Consumption for Water Supply and Treatment—The Next Half Century	Energy Power Research Institute	2002
	Energy Index Development for Benchmarking Water and Wastewater Utilities	American Water Works Association Research Foundation	2007
California (US)	California's Water–Energy Relationship	California Energy Commission	2005
	Embedded energy in water studies. Study 1: State-wide and regional water–energy relationship	California Public Utilities Commission	2010

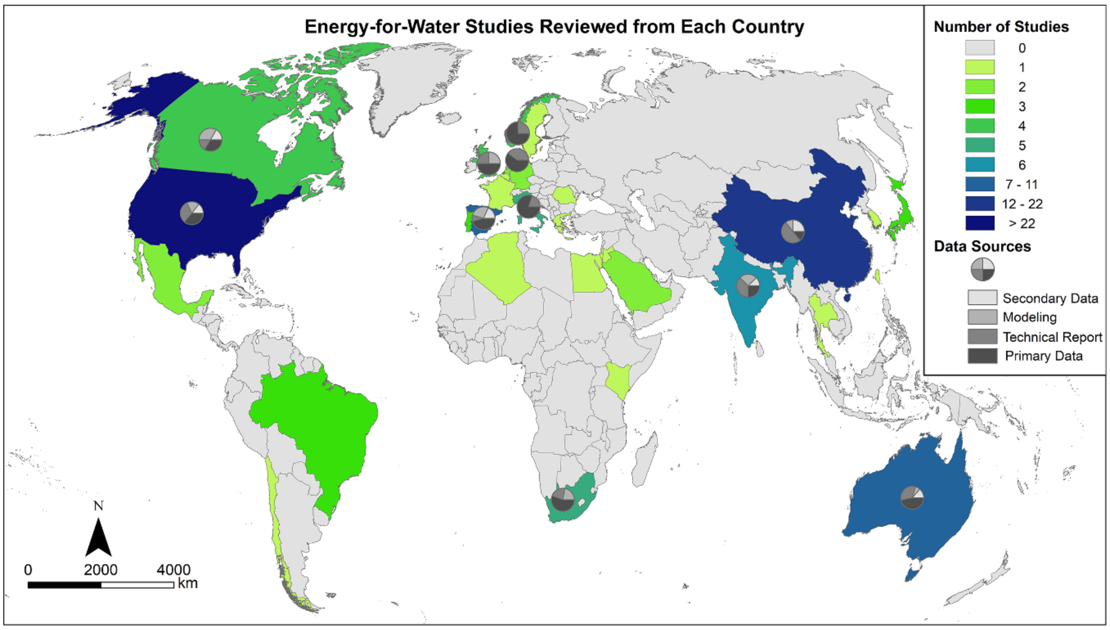

Figure 4. Reviewed studies were geographically spread across the globe with studies evaluating the energy demands of municipal water systems in 34 countries. A majority of the reviewed studies are located in the United States, China, and Australia. Pie charts indicate the relative proportions of available data sources in studies conducted within countries (minimum 4 studies).

and Spain had the largest proportions of primary data utilized within their studies (> 50% of studies). China had the lowest percentage of primary data usage. However, this statistic is slightly misleading as literature often cites country-wide technical reports of reported energy and water usage. Only 24 of the 55 studies (44%) in the United States utilized primary data, with technical reports also being a large source of data.

5. Considering the diverse impacts of the energy-water nexus

There are diverse impacts of urban water systems on the surrounding environment that are not solely captured through a lens of energy [42]. In recognition of these diverse impacts and system interdependencies, literature that describes urban energy-for-water resources often includes other aspects of the urban water cycle. For example, electricity and energy demands of water resources are often used as input for life-cycle assessment studies [43]. Figure 5 showcases the variety of ancillary studies and other nexus components included in the reviewed literature. The intent of this figure is to illustrate the breadth of the energy-water nexus and that utility-scale operations are only part of the discussion.

The most common inclusion was an estimation of greenhouse gas or carbon emissions (GHG on figure 5). This additional consideration often came

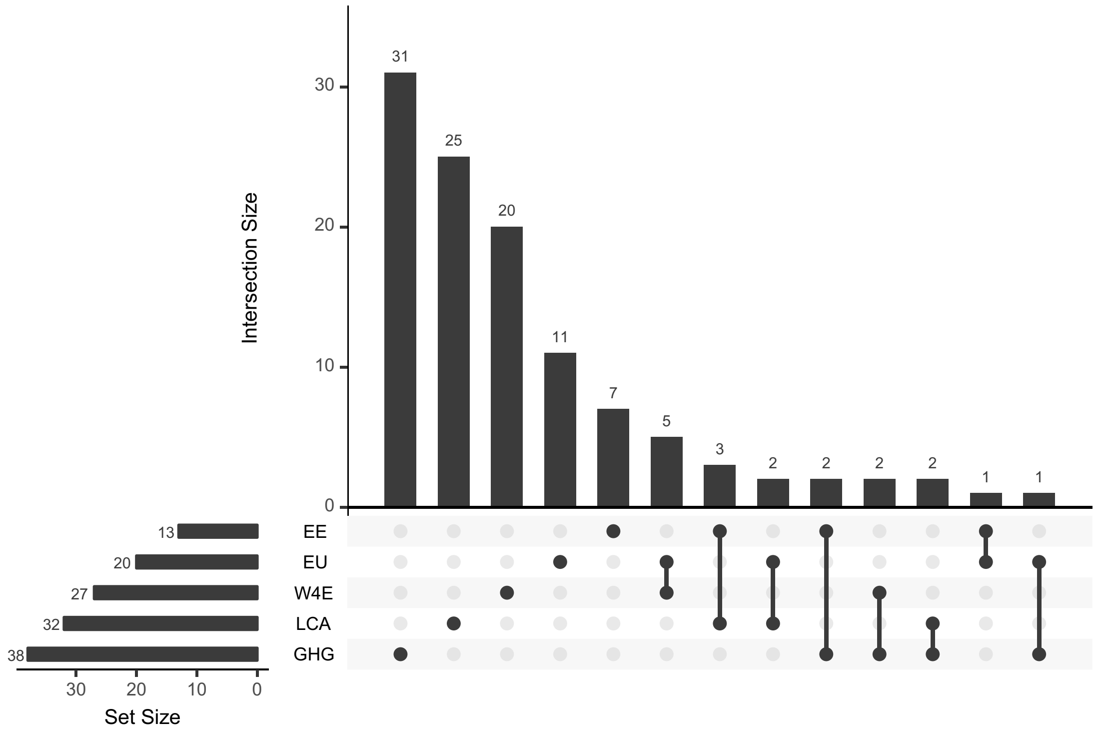

Figure 5. The reviewed studies often included additional analyses, considering a broad range of other interactions, including: embodied energy in the construction phase (EE), end-use energy-for-water demands (EU), water-for-energy (W4E), life-cycle analyses (LCA), and carbon or greenhouse gas emissions (GHG). This figure was constructed using the UpSetR package [44]. The additional analyses are listed in the bottom portion of the figure. The corresponding number of articles that performed these additional analyses are represented in the bar plot. Lines connecting multiple dots show the number of reviewed studies that included multiple additional analyses. The horizontal bar plot shows the total number of reviewed studies that included each additional analysis.

in the form of identifying location-specific carbon intensity factors and applying them to electricity demands [45]. However, this process of assigning carbon footprints to electricity consumption is often challenging due to differences in primary and secondary energy, the interconnected electricity grid, and how renewables are treated. To capture this variability, Siddik *et al* [46] analyze and capture the variability of assigning carbon and water footprints of electricity generation with various attribution methods. We separate this category from another frequently included component, life cycle assessment (LCA), which accounts for other environmental impact factors and, generally, involves a more robust and standardized methodology [47, 48]. For a complete discussion on the use of LCA in water systems, see Byrne *et al* [49]. Only LCA studies that explicitly discuss and break out energy contributions to the system were included in this review. Several reviewed studies also investigated the water demands for energy [35, 50, 51], representing a more holistic view of the energy-water nexus. Not included in figure 5 are inclusions of food or energy intensity for agricultural demand that are part of the broader food-energy-water nexus [52, 51].

Returning to figure 1, there are two commonly included water-related energy demands that were excluded from of this review: embodied energy and end-use water-for-energy. While embodied and embedded energy are often utilized interchangeably throughout the literature, we distinguish between the two terminologies and define embodied energy demands as the indirect energy consumed in either the construction of the urban water system, energy use by maintenance, or in the production of required chemicals. Mo *et al* [53–58] provide a robust description of the role of embodied energy in urban water systems. We, therefore, define embedded energy as the operational energy requirements that are attributed to the production of drinking water or treatment of wastewater resources. Energy demand in end-use water can be found in the industrial, commercial, and residential sectors. This energy demand often comes in the form of water heating [16, 45] and can significantly increase the assessment of water-related energy demand [8].

6. Data challenges

6.1. Filling in missing data

A significant challenge in energy-water nexus studies is a lack of available data. Site-specific, primary data on energy demands for water resources are scarce, even in relatively data-abundant countries

[10]. These data often have to be requested from municipal authorities or other governing bodies and can be associated with concerns over privacy and data sharing [10]. Recognizing these challenges in procuring data, research studies often must turn to other sources for estimating energy demand of water utilities. During the review, we noticed three common practices for filling in missing data: (i) substitution, (ii) estimations, and (iii) cost estimations. Each of these practices is associated with varying degrees of uncertainty but were utilized in the place of site-specific information.

The first practice, substitution, often involved utilizing data from technical reports from different geographic locations. For example, there are two technical reports on energy demands of water resources in California. Both of these reports were heavily cited and were utilized for data in multiple studies. Reviewed studies using these California data ranged from India to Spain [38, 9]. The State of California has been extensively studied with respect to its energy demand for water resources [45, 59–61] and presents an interesting case study. However, there are large water transfer projects for Southern California that inflate energy demands for the region, which could potentially skew results in the subsequent studies. Assuming a singular value for energy intensity of delivered water, especially in arid regions, can be significantly inaccurate if applied generally [61]. Additionally, multiple reviewed studies that compare large numbers of cities show the wide range of embedded or operational energy within even neighboring water systems [11, 12, 17].

Next, estimations are utilized for the purposes of groundwater pumping or conveyance. These estimations are based on the theoretical energy to move a unit of water a vertical distance or through a length of pipe. These modeled values represent best engineering estimates. However, they do not account for varying pipe and pump conditions, potentially propagating uncertainties in subsequent analyses. These assumption do provide the ability to forecast changing energy demands from depleting groundwater resources.

Finally, some reviewed studies estimate energy consumption using operational costs and an assumed price for energy. Several studies cited energy consumption as a significant operational cost associated with water treatment facilities [37, 62]. Therefore, by utilizing a price of electricity towards an operational budget, an estimation of the total electricity consumption can be determined. While 73% of the reviewed studies evaluated only include electricity demand as water-related energy demand, there are other energy demands associated with water treatment, including natural gas [11]. Therefore, this method has considerable uncertainty, especially if the utility has a variable pricing structure for purchasing electricity from the grid, generates their own power, or has significant other operational expenses.

6.2. The challenges and necessity of data normalization

One of the main challenges associated with reporting water-related energy demands comes in the form of normalization. There is no standard approach throughout literature to describe and present the energy demands of water resources. Literature has broken down these energy demands per unit process [48], per capita [48, 17], per user [48], per population equivalent (for wastewater) [24], or without any normalization [63]. The most common means of normalization, however, comes in the form of energy per volume of water treated/distributed [8, 11]. Normalization of data promotes comparison and benchmarking by evaluating the scale of energy demands relative to other locations. However, there are concerns of information loss associated with these strategies. For example, simply normalizing energy demand based on water volume does not indicate efficiencies of scale or give indications on the size of the treatment facility. Similarly, normalizing energy demand on a per capita basis provides an understanding of potential impacts based on population growth, but does not allow for understanding the implications of water conservation. Therefore, while it is important to normalize data for comparison and categorizing impacts, it is also necessary to provide raw data to support these normalizations and allow for the reuse of data in subsequent analyses.

7. Discussion: future directions of the energy-water nexus

There are distinct opportunities available to promote the future of the energy-water nexus, but these goals require actionable decisions, legislative support, and increased data availability. Several studies remark on the strong contribution of literature analyzing California's energy-water nexus [64, 65] to research across the globe. California's contribution is a result of recent legislation and data strategies that have strengthened and supported joint management of the two resources due to the region's water scarcity concerns and large intrastate water transfer projects. Through this analysis on data and the joint management of water and energy in cities, we suggest two main thrusts of research and policy to facilitate the future of the energy-water nexus: (i) creating actionable decisions through scenario analysis and (ii) promoting data for benchmarking and life-cycle assessments.

Nine reviewed studies evaluated future scenarios of energy demand on water resources for their study region. These studies ranged from the United Kingdom of Great Britain and Northern Ireland to South Africa to the United States [66–68] and help inform both energy intensity and carbon intensity changes to water resources. For example, Amores *et al* [69] evaluated the energy intensity of different water supply plans using scenarios. Scenario-based studies provide important decision-making strategies for policy implementation by showcasing future possibilities and potential system or resource vulnerabilities. Future energy-for-water analyses have an opportunity to use various decision-making strategies to influence policy. Additionally, the incorporation of climate uncertainty and energy transitions in scenario-based analyses has the potential to be influential in policy development [70, 71].

Accessible and reproducible data are critical in further benchmarking the energy intensity of urban water resources. Available data have been highlighted throughout this manuscript. However, these data were often challenging to identify within some of the reviewed studies. For example, Mizuta and Shimada [63] considered multiple years and locations of wastewater energy intensity across Japan; however, it was difficult to disaggregate which datum was associated with location. While the analysis and data utilized were robust, the data were minimally reproducible. This relative inaccessibility of published energy data was characteristic across many of the evaluated studies. In certain contexts, these raw data might be perceived as sensitive or critical information [10]. However, there are additional variables that might be used in lieu of primary data to inform energy consumption, such as facility size, treatment processes, quality and type of source water, etc. These benchmarks, in turn, inform decision-makers and reveal potential system inefficiencies. Energy consumption of water and wastewater resources was widely cited as a major contributor to the direct carbon footprints of the facilities. As such, energy data play an important role in developing life-cycle assessments that are widely utilized in assessing the impacts of urban water resources [49]. Additionally, locally-specific data, which are predicated on accessible and refined data, further aid the endeavors of life-cycle assessment and decreasing uncertainty.

In summary, there is a general trend both in literature and policy that a better understanding of energy and water interdependencies is a priority [64]. The breadth of literature available on water-related energy demand suggests a need for further data collection and availability to account for vital urban water resources and their energy requirements [10]. A centralized database or collaborative space for sharing specific energy-for-water data would enable both the advancement of academic research and critical benchmarking for enhanced energy efficiency [11]. There are also possibilities to extend this type of database beyond the utility-scale to include energy demands for the end use of water or non-operational water utilities, as identified in figure 1. Further work on the nexus should facilitate an openness of data where applicable. There are opportunities for researchers to collaborate and promote a centralized repository of these data that fills knowledge gaps around the globe. The future of the energy-water nexus is predicated upon promoting open data and actionable policy suggestions using scenario-based analysis for decision-making support.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

Author contributions

C M C and A S S conceived and developed the study. L E E and C M C performed the systematic review and analyzed the metadata. C M C, L E E, and A S S wrote the manuscript.

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References

[1] Gleick P H 1994 Water and energy *Annu. Rev. Energy Environ.* **19** 267–99

[2] Kenway S J and Lam K L 2016 Quantifying and managing urban water-related energy use systemically: case study lessons from Australia *Int. J. Water Resour. Dev.* **32** 379–97

[3] Sima L C, Kelner-Levine E, Eckelman M J, McCarty K M and Elimelech M 2013 Water flows, energy demand and market analysis of the informal water sector in Kisumu, Kenya *Ecol. Econ.* **87** 137–44

[4] Reiling S J, Roberson J A and Cromwell J E III 2009 Drinking water regulations: estimated cumulative energy use and costs *J. Am. Water Work. Assoc.* **101** 42–53

[5] Bartos M D and Chester M V 2014 The conservation nexus: valuing interdependent water and energy savings in Arizona *Environ. Sci. Technol.* **48** 2139–49

[6] Sowby R B, Jones S C, Packard A E and Schultz T R 2017 Jordan valley water redefines sustainable water supply through energy management *J. Am. Water Work. Assoc.* **109** 38–45

[7] Liu Y *et al* 2016 Global and regional evaluation of energy for water *Environ. Sci. Technol.* **50** 9736–45

[8] Sanders K T and Webber M E 2012 Evaluating the energy consumed for water use in the United States *Environ. Res. Lett.* **7** 034034

[9] Hardy L, Garrido A and Juana L 2012 Evaluation of Spain's water-energy nexus *Int. J. Water Resour. Dev.* **28** 151–70

[10] Chini C M and Stillwell A S 2016 Where are all the data? the case for a comprehensive water and wastewater utility database *J. Water Resour. Plan. Manag.* **143** 01816005

[11] Chini C M and Stillwell A S 2018 The state of U.S. urban water: data and the energy-water nexus *Water Resour. Res.* **54** 1796–1811

[12] Sowby R B and Burian S J 2017 Survey of energy requirements for public water supply in the United States *J. Am. Water Work. Assoc.* **7** 320–30

[13] Sowby R B, Burian S J, Chini C M and Stillwell A S 2019 Data challenges and solutions in energy-for-water: experience from two recent studies *J. Am. Water Work. Assoc.* **111** 28–33

[14] Meng F, Liu G, Liang S, Su M and Yang Z 2019 Critical review of the energy-water-carbon nexus in cities *Energy* **171** 1017–32

[15] Wakeel M, Chen B, Hayat T, Alsaedi A and Ahmad B 2016 Energy consumption for water use cycles in different countries: a review *Appl. Energy* **178** 868–85

[16] Plappally A and Lienhard J 2012 Energy requirements for water production, treatment, end use, reclamation and disposal *Renew. Sust. Energ. Rev.* **16** 4818–48

[17] Lam K L, Kenway S J and Lant P A 2017 Energy use for water provision in cities *J. Clean. Prod.* **143** 699–709

[18] Liu J *et al* 2018 Nexus approaches to global sustainable development *Nat. Sustain.* **1** 466–76

[19] Bleischwitz R *et al* 2018 Resource nexus perspectives towards the United Nations sustainable development goals *Nat. Sustain.* **1** 737–43

[20] Van Vuuren D P *et al* 2019 Integrated scenarios to support analysis of the food–energy–water nexus *Nat. Sustain.* **2** 1132–41

[21] Chhipi-Shrestha G, Hewage K and Sadiq R 2017 Water–energy–carbon nexus modeling for urban water systems: system dynamics approach *J. Water Resour. Plan. Manag.* **143** 04017016

[22] Barker Z A, Stillwell A S and Berglund E Z 2016 Scenario analysis of energy and water trade-offs in the expansion of a dual water system *J. Water Resour. Plan. Manag.* **142** 05016012

[23] Dziedzic R and Karney B W 2015 Energy metrics for water distribution system assessment: case study of the Toronto network *J. Water Resour. Plan. Manag.* **141** 04015032

[24] Ganora D *et al* 2019 Opportunities to improve energy use in urban wastewater treatment: a European scale analysis *Environ. Res. Lett.* **14** 044028

[25] Maktabifard M, Zaborowska E and Makinia J 2018 Achieving energy neutrality in wastewater treatment plants through energy savings and enhancing renewable energy production *Rev. Environ. Sci. Biotechnol.* **17** 655–89

[26] Parravicini V, Svardal K and Krampe J 2016 Greenhouse gas emissions from wastewater treatment plants *Energy Procedia* **97** 246–53

[27] Lorenzo-Toja Y *et al* 2016 Beyond the conventional life cycle inventory in wastewater treatment plants *Sci. Total Environ.* **553** 71–82

[28] Daelman M R, van Voorthuizen E M, van Dongen U G, Volcke E I and van Loosdrecht M C 2012 Methane emission during municipal wastewater treatment *Water Res.* **46** 3657–70

[29] Escriva-Bou A, Lund J R, Pulido-Velazquez M, Hui R and Medellín-Azuara J 2018 Developing a water-energy-GHG emissions modeling framework: insights from an application to California's water system *Environ. Model. Softw.* **109** 54–65

[30] Slagstad H and Brattebø H 2014 Life cycle assessment of the water and wastewater system in Trondheim, Norway—a case study *Urban Water J.* **11** 323–34

[31] Spang E S and Loge F J 2015 A high-resolution approach to mapping energy flows through water infrastructure systems *J. Ind. Ecol.* **19** 656–65

[32] Tidwell V C, Moreland B and Zemlick K 2014 Geographic footprint of electricity use for water services in the Western US *Environ. Sci. Technol.* **48** 8897–904

[33] Svardal K and Kroiss H 2011 Energy requirements for waste water treatment *Water Sci. Technol.* **64** 1355–61

[34] Abbass R A, Kumar P and El-Gendy A 2018 An overview of monitoring and reduction strategies for health and climate change related emissions in the Middle East and North Africa region *Atmos. Environ.* **175** 33–43

[35] Siddiqi A and Anadon L D 2011 The water–energy nexus in Middle East and North Africa *Energy Policy* **39** 4529–40

[36] Al-Saidi M and Saliba S 2019 Water, energy and food supply security in the Gulf Cooperation Council (GCC) countries–a risk perspective *Water* **11** 455

[37] Balmer P 2000 Operation costs and consumption of resources at Nordic nutrient removal plants *Water Sci. Technol.* **41** 273–9

[38] Miller L A, Ramaswami A and Ranjan R 2013 Contribution of water and wastewater infrastructures to urban energy metabolism and greenhouse gas emissions in cities in India *J. Environ. Eng.* **139** 738–45

[39] Venkatesh G, Chan A and Brattebø H 2014 Understanding the water-energy-carbon nexus in urban water utilities: comparison of four city case studies and the relevant influencing factors *Energy* **75** 153–66

[40] Singh P, Kansal A and Carliell-Marquet C 2016 Energy and carbon footprints of sewage treatment methods *J. Environ. Manag.* **165** 22–30

[41] Wang H *et al* 2016 Comparative analysis of energy intensity and carbon emissions in wastewater treatment in USA, Germany, China and South Africa *Appl. Energy* **184** 873–81

[42] Lane J, de Haas D and Lant P 2015 The diverse environmental burden of city-scale urban water systems *Water Res.* **81** 398–415

[43] Pasqualino J C, Meneses M and Castells F 2011 Life cycle assessment of urban wastewater reclamation and reuse alternatives *J. Ind. Ecol.* **15** 49–63

[44] Conway J R, Lex A and Gehlenborg N 2017 Upsetr: an R package for the visualization of intersecting sets and their properties *Bioinformatics* **33** 2938–40

[45] Haley B *et al* 2012 The 2020 emissions reduction impact of urban water conservation in California *J. Water Clim. Chang.* **3** 151–62

[46] Siddik M A B, Chini C M and Marston L T 2020 Urban water and carbon footprints of electricity are sensitive to geographical attribution method *Environ. Sci. Technol.* **54** 7533–41

[47] Barjoveanu G, Comandaru I M, Rodriguez-Garcia G, Hospido A and Teodosiu C 2014 Evaluation of water services system through LCA: a case study for Iasi City, Romania *Int. J. Life Cycle Assess.* **19** 449–62

[48] Loubet P, Roux P, Loiseau E and Bellon-Maurel V 2014 Life cycle assessments of urban water systems: a comparative analysis of selected peer-reviewed literature *Water Res.* **67** 187–202

[49] Byrne D M, Lohman H A, Cook S M, Peters G M and Guest J S 2017 Life cycle assessment (LCA) of urban water infrastructure: emerging approaches to balance objectives and inform comprehensive decision-making *Environ. Sci.: Water Res. Technol.* **3** 1002–14

[50] Stillwell A S, King C W, Webber M E, Duncan I J and Hardberger A 2011 The energy-water nexus in Texas *Ecol. Soc.* **16** 2

[51] Ramaswami A *et al* 2017 An urban systems framework to assess the trans-boundary food-energy-water nexus: implementation in Delhi, India *Environ. Res. Lett.* **12** 025008

[52] D'Odorico P *et al* 2018 The global food-energy-water nexus *Rev. Geophys.* **56** 456–531

[53] Mo W, Nasiri F, Eckelman M J, Zhang Q and Zimmerman J B 2010 Measuring the embodied energy in drinking water supply systems: a case study in the Great Lakes Region *Environ. Sci. Technol.* **44** 9516–21

[54] Mo W, Zhang Q, Mihelcic J R and Hokanson D R 2011 Embodied energy comparison of surface water and groundwater supply options *Water Res.* **45** 5577–86

[55] Mo W, Wang R and Zimmerman J B 2014 Energy–water nexus analysis of enhanced water supply scenarios: a regional comparison of Tampa Bay, Florida and San Diego, California *Environ. Sci. Technol.* **48** 5883–91

[56] Mo W, Wang H and Jacobs J M 2016 Understanding the influence of climate change on the embodied energy of water supply *Water Res.* **95** 220–9

[57] Mo W and Zhang Q 2016 Modeling the influence of various water stressors on regional water supply infrastructures and their embodied energy *Environ. Res. Lett.* **11** 064018

[58] Stang S, Wang H, Gardner K H and Mo W 2018 Influences of water quality and climate on the water-energy nexus: a spatial comparison of two water systems *J. Environ. Manag.* **218** 613–21

[59] Dale L L *et al* 2015 An integrated assessment of water-energy and climate change in Sacramento, California: how strong is the nexus? *Clim. Change* **132** 223–35

[60] Fang A, Newell J P and Cousins J J 2015 The energy and emissions footprint of water supply for Southern California *Environ. Res. Lett.* **10** 114002

[61] Stokes-Draut J, Taptich M, Kavvada O and Horvath A 2017 Evaluating the electricity intensity of evolving water supply mixes: the case of California's water network *Environ. Res. Lett.* **12** 114005

[62] Luna T, Ribau J, Figueiredo D and Alves R 2019 Improving energy efficiency in water supply systems with pump scheduling optimization *J. Clean. Prod.* **213** 342–56

[63] Mizuta K and Shimada M 2010 Benchmarking energy consumption in municipal wastewater treatment plants in Japan *Water Sci. Technol.* **62** 2256–62

[64] Kenway S, Lant P, Priestley A and Daniels P 2011 The connection between water and energy in cities: a review *Water Sci. Technol.* **63** 1965–73

[65] Kenway S, McMahon J, Elmer V, Conrad S and Rosenblum J 2013 Managing water-related energy in future cities–a research and policy roadmap *J. Water Clim. Chang.* **4** 161–75

[66] Walker R V, Beck M B and Hall J W 2012 Water-and nutrient and energy-systems in urbanizing watersheds *Front. Environ. Sci. Eng.* **6** 596–611

[67] Ahjum F and Stewart T J 2014 A systems approach to urban water services in the context of integrated energy and water planning: a city of Cape Town case study *J. Energy South. Africa* **25** 59–70

[68] Shrestha E, Ahmad S, Johnson W and Batista J R 2012 The carbon footprint of water management policy options *Energy Policy* **42** 201–12

[69] Amores M J, Meneses M, Pasqualino J, Antón A and Castells F 2013 Environmental assessment of urban water cycle on mediterranean conditions by LCA approach *J. Clean. Prod.* **43** 84–92

[70] Kasprzyk J R, Nataraj S, Reed P M and Lempert R J 2013 Many objective robust decision making for complex environmental systems undergoing change *Environ. Model. Softw.* **42** 55–71

[71] Raseman W J, Kasprzyk J R, Rosario-Ortiz F L, Stewart J R and Livneh B 2017 Emerging investigators series: a critical review of decision support systems for water treatment: making the case for incorporating climate change and climate extremes *Environ. Sci.: Water Res. Technol.* **3** 18–36