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The role of climate change and decentralization in urban water services: A dynamic energy-water nexus analysis

Masoumeh Khalkhali [a,b], Bistra Dilkina [a,*], Weiwei Mo [b,*]

[a] Computer Science Department at University of Southern California, United States
[b] Civil and Environmental Engineering Department of University of New Hampshire, United States

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ABSTRACT

Urban water services, including drinking water supply and wastewater treatment, are highly energy dependent, contributing to the challenges described under the water-energy nexus. Both future climate change and decentralized water system adoptions can potentially influence the energy use of the urban water services. However, the trend and the extent of such influences have not been well understood. In this study, a modeling framework was developed to quantify both the separate and the combined influences of climate change and decentralization on the life cycle energy use of the urban water cycle, using the City of Boston, MA as a testbed. Two types of household decentralized systems were considered, the greywater recycling (GWR) systems and the rainwater harvesting (RWH) systems. This modeling framework integrates empirical models based on multilinear regression analysis, hydrologic modeling, water balance models, and life cycle assessment to capture the complex interactions among centralized water services, decentralized water system adoptions, and climate parameters for cumulative energy demand (CED) assessment, considering all residential buildings in Boston. It was found that climate change alone will slightly increase the energy use of the centralized systems towards the end of the century, due to the cancelation effect amongst changes in water quality, flow rate, and space and water heating demand. When decentralization is considered alone, we found economically viable decentralized systems may not necessarily produce energy savings. In fact, RWH adoptions may increase energy use. When climate change and decentralization are combined, they will increase the water yield and cost savings of the decentralized systems, while reducing the energy use from the centralized systems. When the centralized systems are further added into the picture, the CED of the entire urban water cycle is projected to increase by 0.9% or 2.3% towards the end of the century under climate change if GWR or RWH systems are adopted by respective cost saving positive buildings.

1. Introduction

Currently, centralized systems are the dominant form of drinking water supply and wastewater treatment in US cities (USEPA 2013). These systems often require a large amount of energy for water acquisition/collection, treatment, and delivery. Approximately 4% of the total US electricity consumption goes to the water and wastewater sector (Mo et al., 2010). Drinking water and wastewater treatment also represents up to 44% of the total public energy cost in a city (Santana et al., 2014; Yonkin et al., 2008). This high dependency of water services on energy is a part of the issues that have been identified under the 'water–energy nexus', which contributes to aggravated system vulnerabilities and resource consumptions imposing system sustainability and resiliency challenges (Nair et al., 2014; Siddiqi and Anadon 2011; Valek et al., 2017). Centralized urban water systems are further challenged by issues related to infrastructure aging (Hasik et al., 2017), lack of resiliency (Leigh and Lee 2019), and vulnerability to natural and manmade threats (Stip et al., 2019). Furthermore, centralized drinking water facilities treat every single drop of water to the highest possible quality, while about 83% of the treated water is used to meet non-potable demands (Hasik et al., 2017). They also rely heavily on traditional ground and surface water resources, which has become increasingly scarce under the rapidly growing demand. To address problems related to the centralized scheme, decentralized systems such as household or community-scale water recycling and rainwater harvesting are increasingly being studied or implemented. Decentralized systems are small scale dispersed facilities that are located near or at the point of use

* Corresponding authors.
E-mail addresses: dilkina@usc.edu (B. Dilkina), weiwei.mo@unh.edu (W. Mo).

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Nomenclature

C	climate model
CED	cumulative energy demand
CED_{Ch}	the changed CED
CED_{O}	the original CED
CED^{C}	the CED of the entire urban water cycle modeled for each climate model C
$CED^{C}_{avoidedCDWS}$	the avoided pumping and treatment CED in the CDWS due to DecS adoption for each climate model C
$CED^{C}_{avoidedCWWS}$	the avoided treatment CED in the CWWS due to DecS adoption for each climate model C
$CED^{C}_{DecS,t}$	the monthly operational, maintenance, and constructional CED associated with the decentralized system for each climate model C
$CED^{C}_{DecS\ net,t}$	the monthly net CED associated with the integration of the decentralized systems into the centralized network for each climate model C
$CED^{C}_{HydroCDWS,t}$	the monthly CED associated with the hydropower generation in the CDWS for each climate model C
CDWS	the centralized drinking water system
CHP	combined heat and power generation
CMIP5	the coupled model intercomparison project phase 5
CWWS	the centralized wastewater system
DecS	the decentralized system
GCMs	the general circulation models
GWR	greywater recycling
$Input_{Ch}$	changed input
$Input_{O}$	original input
j	the indexes of chemicals and energy types consumed or recovered for the CWWS
k	the indexes of chemicals and energy types consumed or recovered for the CDWS
LCA	life cycle assessment
RCP	the representative concentration pathway
RSD	relative standard deviation
RWH	rainwater harvesting
SI	sensitivity index
T	the total number of months in the study period
t	the month index
$V^{C}_{CDWS,t}$	the monthly volume of drinking water demand from the CDWS modeled for each climate model C
$V^{C}_{CWWS,t}$	the monthly volume of wastewater inflow to the CWWS modeled for each climate model C
$VCED^{C}_{CDWS,k,t}$	the monthly volumetric CED associated with the CDWS and chemicals and energy type k for each climate model C
$VCED^{C}_{CWWS,j,t}$	the monthly volumetric CED associated with the CWWS and chemicals and energy type j for each climate model C

(Stang et al., 2021). Decentralized system adoption can reduce potable water demand and avoid extra treatment and pumping through a centralized system (PMSEIC 2007; Stang et al., 2021; Wong and Brown 2008). However, the energy implication of integrating decentralized systems into the existing centralized water and wastewater system network is not well understood on a municipality scale (Retamal and Turner 2010; Sharma et al., 2010), especially considering the uncertain future climate change. Climate change can alter water availability and quality for drinking water supply (Arnell 2003; De Wit and Stankiewicz 2006; Delpla et al., 2009; Haddeland et al., 2014; Khalkhali et al., 2018; Limbrick et al., 2000; Mo et al., 2016; Vörösmarty et al., 2000; Whitehead et al., 2009). It has also shown to have a prominent effect on both drinking water demand and wastewater generation (Khalkhali and Mo 2020; Mo et al., 2016). For instance, drinking water demand in New York City (Protopapas et al., 2000), Nevada (Lott et al., 2013), and Washington (Polebitski et al., 2011) has been reported to increase with temperature rise. Climate change can also affect the decentralized systems, for instance, by altering the amount and pattern of precipitation that is critical to the rainwater harvesting systems (Aladenola et al., 2016; Zhang et al., 2019). Hence, it is important to study the energy implications of both centralized and decentralized urban water services as a whole while considering the potential effect of climate change.

A life cycle perspective is important in obtaining a holistic understanding of the water-energy nexus. Many efforts have been previously made to quantify the life cycle energy associated with individual drinking water or wastewater systems. Some studies have investigated the life cycle energy implications of the urban water services (including both drinking water and wastewater services) as a whole (Amores et al., 2013; Jeong et al., 2015; Lane et al., 2015; Mo et al., 2014; Slagstad and Brattebø 2014; Xue et al., 2019; Xue et al., 2016). These studies have shown the importance of examining an integrated urban water cycle, especially when water recycling is considered (Kim and Chen 2018; Lane et al., 2015; Mo et al., 2014). Other studies have further included decentralized systems as well as their interactions with the centralized systems, and investigated the implications of such integrations on the life cycle energy of the urban water services (Chang et al., 2017; Kavvada et al., 2016; Newman et al., 2014; Stang et al., 2021; Vieira and Ghisi 2016). Some of these studies assumed a constant volumetric avoided energy use from the centralized systems regardless of the scale and pattern of the decentralized system integration (Chang et al., 2017; Newman et al., 2014; Vieira and Ghisi 2016), while others simulated the avoided pumping and treatment energy in the centralized systems based on the spatial pattern and design of the decentralized systems (Kavvada et al., 2016; Stang et al., 2021). The latter studies highlighted the influence of spatial characteristics, such as the adopted decentralized systems' distances from the centralized systems, elevation, as well as user demand and infrastructure characteristics on the life cycle energy of urban water services. Both studies concluded that with proper planning, a reduction of the overall life cycle energy consumption can be achieved. However, neither of these studies further investigated how the energy implication of decentralization might be further influenced by climate change. On the other hand, several studies have investigated the influence of climate change on the life cycle energy consumption of centralized drinking water systems (Mo et al., 2016; Stang et al., 2018), centralized wastewater systems (Khalkhali and Mo 2020; Li et al., 2018), and the decentralized systems (Bixler et al., 2019; Lin et al., 2019) separately. Most of these studies suggested a likely increase in the life cycle energy consumption when individual systems were considered. Nevertheless, to the authors' knowledge, no specific effort has been made to quantify the life cycle energy implication of climate change on the entire urban water cycle, including the potential adoption of decentralized systems. This limits our capability to capture and understand the dynamic interactions across the centralized and decentralized systems when assessing their responses to external stressors, which is important in informing proactive actions in sustainable water and energy system management.

Accordingly, this study presents a dynamic modeling framework to quantify the influences of climate change and decentralization on the life cycle energy consumption of the urban water cycle, using the City of Boston, MA as a testbed. To the authors' knowledge, this is the first attempt to quantify both the effects of climate change and decentralization on the dynamic life cycle energy use of an entire urban water cycle, including the energy use and recovery from both centralized drinking water and wastewater systems. This work aims to answer four key research questions: (1) What is the current life cycle energy consumption of the centralized urban water services? (2) How does climate change influence the life cycle energy consumption of the centralized urban water services? (3) How does decentralized system adoption influence the life cycle energy consumption of the urban water cycle? and, (4) How does climate change and decentralized system adoption combined influence the life cycle energy consumption of the urban water cycle?

2. Methods

Fig. 1 presents the methodological framework adopted in this study, which includes a centralized drinking water system (CDWS) sub-model, a centralized wastewater system (CWWS) sub-model, and a decentralized system (DecS) sub-model. The CDWS sub-model simulates energy consumption associated with drinking water withdrawal, conveyance, treatment, and delivery as well as hydropower generation by the centralized drinking water system. The CWWS sub-model simulates energy consumption associated with wastewater collection, treatment, and discharge as well as energy recovery through combined heat generation and hydropower generation by the centralized wastewater system. Two types of decentralized household water systems were considered in this study: the greywater recycling (GWR) system and the rainwater harvesting (RWH) system. The DecS sub-model estimates GWR and RWH systems' energy consumption as well as their contribution to avoided energy use in the CDWS and the CWWS. The following sections provide the details of the centralized and decentralized systems (Section 2.1), the method for life cycle energy quantification (Section 2.2), the method for simulating the climate change impact (Section 2.3), and the method for sensitivity analysis (Section 2.4).

2.1. System descriptions

The studied Boston, MA CDWS provides around 263 Mm^3/year of

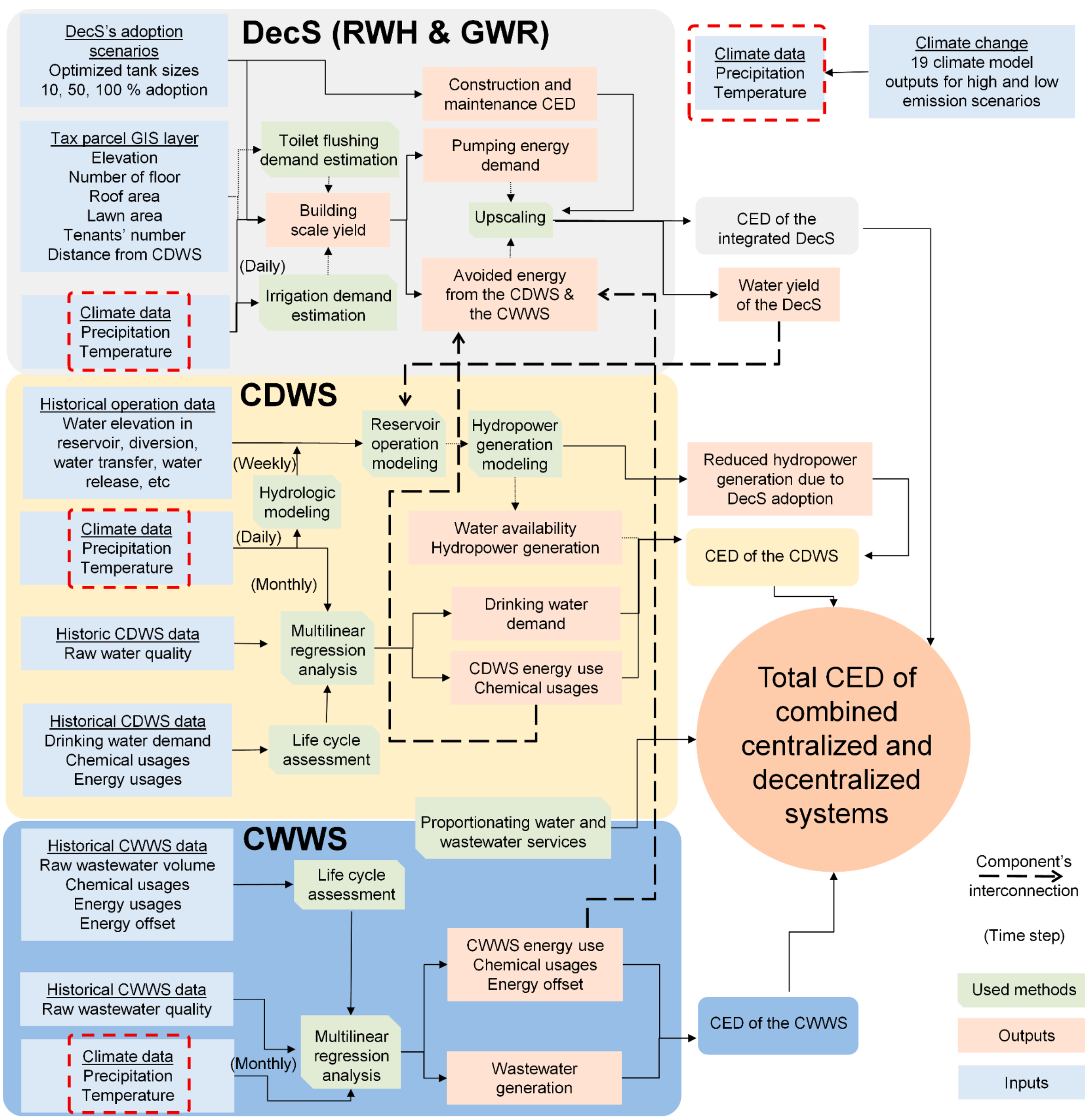

Fig. 1. The modeling framework to estimate the cumulative energy demand (CED) of the urban water cycle under climate change conditions through three sub-models: The CDWS sub-model simulates energy consumption and generation associated with the centralized drinking water system; The CWWS sub-model simulates energy consumption and generation associated with the centralized wastewater system. The DecS sub-model estimates greywater recycling (GWR) and rainwater harvesting (RWH) systems' energy consumption as well as their contribution to avoided energy use in the CDWS and the CWWS.

drinking water and serves a population of 2.8 million (MASSDOCS 2019). The CDWS employs a relatively simple treatment process of ozonation, chlorination, and a final pH adjustment, due to its relatively high raw water quality (Mo et al., 2016; Stang et al., 2018). The system has a much higher elevation than most of its service area, resulting in a relatively low pumping demand for water delivery. Energy generation at the CDWS is practiced through two active hydropower stations. The amount of hydropower generation depends on reservoir operation and water intake by the treatment plant. Historical monthly energy consumption (July 2005-July 2014), chemical use (July 2005-July 2014), and hydropower generation data (September 2007-July 2016) were obtained from the CDWS for estimating its observed CED and for developing future CED estimation models. The Boston, MA CWWS treats around 478 Mm^3/year of combined sewage and serves around 2.6 million population (MASSDOCS, 2019). This CWWS employs a treatment process that consists of primary and secondary treatment, followed by chlorination and dechlorination (Khalkhali and Mo, 2020). Sludge is thickened and anaerobically digested. The generated biogas is used for producing electricity and heat through a combined heat and power generation (CHP) system onsite. The treated wastewater passes through hydroelectric turbines for hydropower generation. Historical monthly energy consumption, chemical use, and energy generation data between July 2006-April 2017 were obtained from the CWWS for estimating its observed CED and for developing future CED estimation models. For consistency, the CDWS service was proportioned to match the serving population of the CWWS.

$$CED^c = \frac{12}{T}\sum_{t=1}^{T}\left(V^c_{CDWS,t} \times \sum_k VCED^c_{CDWS,k,t} + V^c_{CWWS,t} \times \sum_j VCED^c_{CWWS,j,t} - CED^c_{HydroCDWS,t} + CED^c_{DecS\ net,t}\right) \quad (1)$$

In terms of the decentralized systems, the GWR system was assumed to collect greywater from sink, shower, and laundry, treat water by filtration, and then store water in a ground-level tank. The RWH system included a typical design of rooftop rainfall collection, simple filtration treatment, and a ground-level tank. Toilet flushing and residential irrigation were assumed to be the only allowed applications of the collected water for both systems (Sections S-1 and S-2 of the supporting information (SI)). The former was assumed to require pumping energy, while the latter was assumed to be gravity fed. In order to design and simulate the decentralized systems, two dynamic models, one for the GWR system and the other for the RWH system, were developed using Python 3.7, which simulated the water balance, the DecS energy use, the potential energy savings from the centralized systems, and the household economic saving on a daily time step. System water balance was simulated using a "yield after spill" method for both the GWR and the RWH systems. The two models were then run for each of the residential buildings in the City of Boston to identify the building scale optimal RWH and GWR system sizes that maximize life cycle economic savings using 30-year historical climate data between November 1988 and November 2018 (Stang et al., 2021) (Data sources and modeling procedure are provided in Table S-1 of Supplemantary Materials). For the analyses presented in this paper, only households that yield positive life cycle cost savings under the optimal tank sizes were considered for our adoption analysis. Out of the 68,567 residential buildings in the City of Boston, around 8130 buildings resulted in positive life cycle cost savings by installing RWH systems, and all buildings resulted in positive life cycle cost savings by installing GWR systems (Stang et al., 2021). We investigated the CEDs of adoption scenarios where the GWR or RWH systems were installed in the top 10, 50, and 100% of the buildings with positive life cycle cost savings.

2.2. Life cycle energy assessment

A life cycle assessment (LCA) approach was adopted for estimating the energy consumption and generation associated with providing urban water services. All energy types were quantified in terms of cumulative energy demand (CED), which characterizes all energy types in their primary energy form (EIA, 2013; Huijbregts et al., 2006). We classified energy into three types: direct CED, indirect CED, and CED offset. Direct CED refers to the CED that is associated with energy directly consumed onsite of the centralized and decentralized systems (Mo and Zhang, 2012). Indirect CED is the CED associated with providing materials, chemicals, and services for the centralized and decentralized systems (Mo and Zhang, 2012). CED offset accounts for onsite energy generation through approaches such as in-conduit hydropower and combined heat and power generation.

The three types of CEDs were calculated for the operation phase of the existing centralized systems (i.e., CDWS and CWWS), while the construction phase was excluded considering these systems are already in place. Both the construction and operation phases of the decentralized systems were included. The end-of-life phase was not considered for both centralized and decentralized systems because it has been previously reported to be insignificant (Khalkhali and Mo, 2020; Mo et al., 2016). Eqs. (1) and (2) explains how the average annual CED for the integrated centralized and decentralized systems under each climate model was estimated.

$$CED^c_{DecS\ net,t} = CED^c_{DecS,t} - CED^c_{avoidedCDWS,t} - CED^c_{avoidedCWWS,t} \quad (2)$$

Where, CED^C is the CED of the entire urban water cycle modeled for each climate model C, TJ/year; t is the month index; T is the total number of months in the study period, 120 months; $V^C_{CDWS,t}$ and $V^C_{CWWS,t}$ are the monthly drinking water demand from the CDWS and the monthly volume of wastewater inflow to the CWWS modeled for each climate model C, respectively, Mm^3/month; $VCED^C_{CDWS,k,t}$ and $VCED^C_{CWWS,j,t}$ are the monthly volumetric CED associated with the CDWS and the CWWS under each climate model C, respectively, MJ/m^3; k and j are the indexes of chemicals and energy types consumed or recovered for the CDWS and CWWS, respectively; $CED^C_{HydroCDWS,t}$ is the CED associated with the hydropower generation in the CDWS, TJ/month; $CED^C_{DecS\ net,t}$ is the net CED associated with the integration of the decentralized systems into the centralized network, TJ/month; $CED^C_{DecS,t}$ is the operational, maintenance, and constructional CED associated with the decentralized system, TJ/month; $CED^C_{avoidedCDWS,t}$ is the avoided pumping and treatment CED in the CDWS due to DecS adoption, TJ/month; and, $CED^C_{avoidedCWWS,t}$ is the avoided treatment CED in the CWWS due to DecS adoption, TJ/month.

We developed empirical models based on historical data to model the volume of water (V^C_{CDWS}) or wastewater (V^C_{CWWS}) services and the volumetric cumulative energy demand ($VCED^C_{CDWS,k}$ and $VCED^C_{CWWS,j}$, respectively) associated with water/wastewater services under climate change. Given the relatively short periods of historical data that were available for the case study (around 10 years), we used seasonal climate variations as a surrogate to model the influences of future climate change. The process involved three key steps. First, climate indicators (e.g., mean monthly temperature, monthly precipitation) were used as independent variables to predict changes of key water quality indicators (e.g., mean monthly water temperature, chemical oxygen demand). Second, individual regression models were developed for each energy and chemical species to predict their volumetric consumptions based on both climate and water quality indicators. Third, the monthly volumes of water demand and wastewater generation were projected based on climate indicators using either model fitting or multilinear regression. It has to be noted that only regression models with a R^2 value of 0.5 or above were included in our analyses. A detailed description of the regression modeling process for the CDWS and the CWWS can be found in (Mo et al., 2016) and (Khalkhali and Mo, 2020), respectively. The CED associated with hydropower generation in the CDWS ($CED^C_{HydroCDWS}$) is not a linear function of the volume of services. We modelled $CED^C_{HydroCDWS}$ by using an integrated hydrologic, reservoir operation, and hydropower generation model (Li et al. 2018). The hydrologic model simulated the available runoffs entering the source water of the CDWS. Outputs from the hydrologic model were then used in the reservoir operation model to simulate the quantity and duration of water passing through the two hydropower stations based on drinking water demand (V_{CDWS}) and reservoir water storage, which were then used to simulate hydropower generation.

For the DecS, pumping energy used during the operation phase was calculated based on the daily water yield that is allocated to toilet flushing, decentralized system pump efficiency, as well as the required head which depends on the length and friction loss of the pipeline and the building height. The direct and indirect CEDs associated with the construction and maintenance phases were calculated using the EIO-LCA method (CMU, 2018) based on estimated system construction and maintenance costs (Stang et al., 2021). DecS adoption also affects energy consumption and generation in the CDWS ($CED_{avoidedCDWS}$) and the CWWS ($CED_{avoidedCWWS}$). Particularly, RWH systems affect energy consumption and generation in the CDWS, while the GWR systems affect energy consumption and generation in both the CDWS and the CWWS. The avoided treatment energy in the CDWS and the CWWS can be estimated based on the water yield of the DecS multiplied by the average treatment volumetric CED of the CDWS and/or the CWWS. Potential avoided pumping in the CDWS was estimated based on the elevation and distance of each building from the centralized system. In this analysis, we assumed pipelines are aligned with the road network, and the approximate pipeline length between a household and the CDWS was estimated using the Network Analyst toolset in ArcMap 10.6. The influence of the DecS adoptions on the pumping energy for wastewater collection at the CWWS was ignored as the wastewater collection at the CWWS was mostly gravity fed. The DecS adoptions will also influence energy offset through the hydropower generation at the CDWS and the CHP generation and the in-conduit hydropower generation at the CWWS. Such influences were captured as the water flow input changes with the scale and pattern of DecS adoption.

2.3. Climate change scenarios

Outputs from 19 CMIP5 General Circulation Models (GCMs), listed in Table S-2, were obtained from the Bureau of Reclamation (USBR, 2018) for 9 locations (listed in Table S-3) within our testbed area. These 19 climate models have been statistically downscaled to 1/8th degree resolution over the continental United States using the bias-correction and spatial disaggregation techniques (Wood et al., 2002). We investigated two future climate scenarios, RCP 4.5 and RCP 8.5, for each of the 19 climate models. These scenarios are consistent with a wide range of possible changes in future anthropogenic greenhouse gas emissions and have been widely adopted by previous studies (Daniel et al., 2018). Greenhouse gas emissions in the low emission scenario of RCP 4.5 peak around 2040, while in the high emission scenario of RCP 8.5, greenhouse gas emissions continue to rise throughout the 21st century (Collins et al., 2013).

The obtained climate projection outputs were then applied to simulate future system CED as formulated in Eqs. (1) and (2). Future CED was first estimated on a monthly basis for three 10-year period of the early (2027–2036), mid (2057–2066), and late (2087–2096) century. The monthly values were then summed to calculate annual values. The average of all annual values was reported. We also used climate projections to estimate the CED of the water services for the baseline (2007–2016) period under each climate scenarios and compared these values against the observed CED. As the projected CED for the baseline period were close to the observed CED (The projected CED is around 90% of the observed CED), no further bias correction was applied. For consistency, we reported the estimated baseline and future CED values based on projected climate outputs to allow comparison between the two.

2.4. Sensitivity analysis

A sensitivity analysis was conducted to evaluate the effect of input variable changes on the estimated CED of the urban water cycle. Tested variables related to the CDWS and the CWWS include water flow rate, treatment energy intensity, pumping energy intensity, and energy offset intensity. Tested variables related to the DesS are the pumping energy intensity as well as construction and maintenance energy intensity. In addition, sensitivity of the estimated CED to the primary energy convertor of electricity used in the LCA was investigated. Input variables were changed by $\pm$ 50% to represent a reasonable range of possible values. The CED estimations were performed for each of the 19 climate models during the baseline period under both RCP 4.5 and 8.5 climate scenarios. To determine the variables' influence on the outcomes, Eq. (3) was used to create a sensitivity index (SI) (Song et al., 2019). The calculated SIs under all climate models were averaged for each of the RCP scenarios and reported. In addition, relative standard deviation (RSD) amongst all climate models for each SI was reported as a dimensionless measure of dispersion relative to the obtained average SI. The RSD was calculated by dividing the standard deviation of the SIs from all climate models by the absolute value of the averaged SI. Variables were considered highly sensitive if their averaged SIs were greater than one. RSDs lower than 55% represent low variation (StatisticsHowTo, 2020).

$$SI = \frac{(CED_{Ch} - CED_O)/CED_O}{(Input_{Ch} - Input_O)/Input_O} \tag{3}$$

where *SI* is sensitivity index, CED_{ch} is the changed CED, CED_o is the original CED, $Input_{ch}$ is the changed input value, and $Input_o$ is the original input value.

3. Results and discussion

The sections below report 1) the historically observed CED of the centralized services (CDWS and CWWS) (Section 3.1); 2) the influence of climate change on the CED of the centralized services (Section 3.2); 3) the influence of DecS adoption on the CED of the urban water cycle (Section 3.3); 4) the influence of climate change and DecS adoption combined on the CED of the urban water cycle (Section 3.4); and, 5) outcomes of the sensitivity analysis (Section 3.5).

3.1. Observed CED

Fig. 2 presents the results of the observed CED of the combined CDWS and CWWS to provide water and wastewater services to the same serving population under the historical climate condition, breaking down the contributions of each of the two subsystems by direct, indirect and offset CED. Numerical values used to create Fig. 2 are provided in Table 1. The total CED of the combined centralized system is 1483 TJ/year. The CED of the CDWS was estimated to be 345 TJ/year to provide 242 Mm^3 of potable water (1.43 MJ/m^3) and the CED of the CWWS was found to be 1137 TJ/year to collect and treat 478 Mm^3 of wastewater

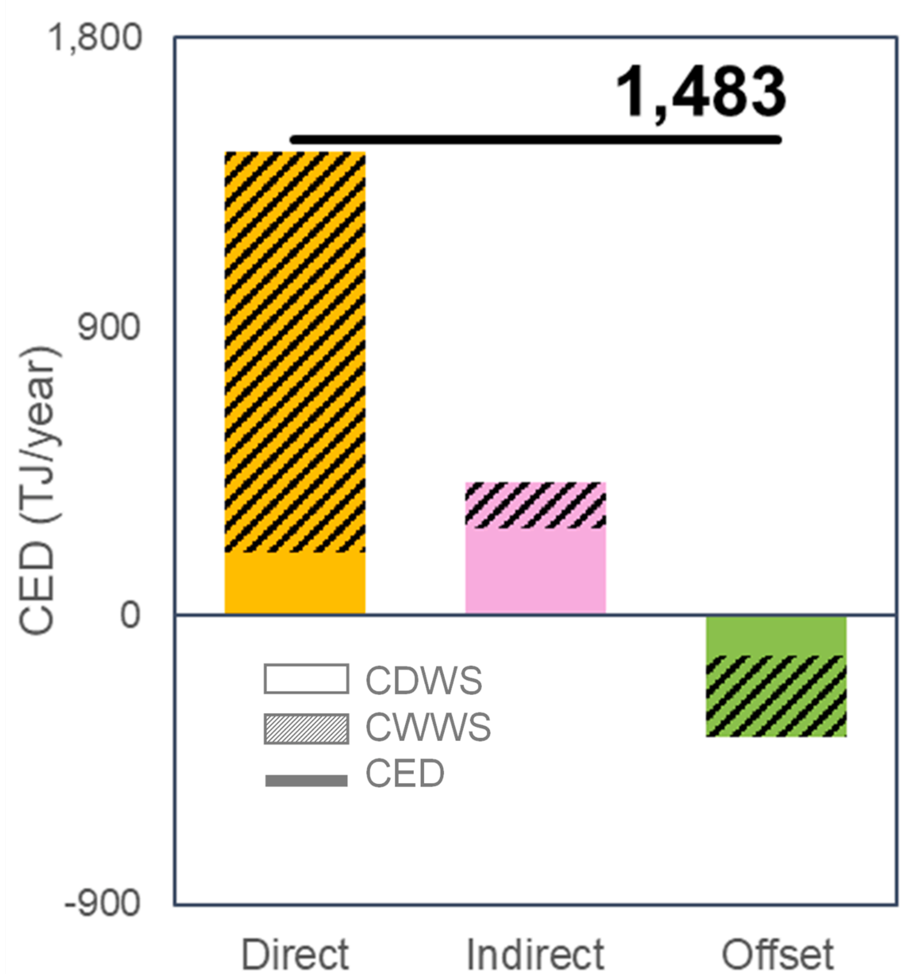

Fig. 2. Historically observed Cumulative energy demand (CED) of the centralized urban water systems showing high contribution of the centralized wastewater system (CWWS) compared to the centralized drinking water system (CDWS).

(2.38 MJ/m^3). These values fall within the broad range of energy intensities for water supply (1.37–12.96 MJ/m^3 with high extreme value of 59 MJ/m^3) and wastewater services (1.15–18.36 MJ/m^3 with high extreme value of 27 MJ/m^3) that have been previously reported in North America (Lee et al., 2017). The CED of the CWWS is about three times that of the CDWS as the wastewater services in this system are more energy intensive and also the volume of wastewater services is about twice the volume of the potable water services (Table 1). However, it has to be noted that the CDWS of the study area benefits from relatively high raw water quality, and the CED could significantly increase in drinking water systems with lower raw water quality (Jeong et al., 2015; Stang et al., 2018). The CWWS has a higher direct CED, which is mainly attributed to the electricity consumption for wastewater collection and secondary treatment (Table 1). The CDWS has a higher indirect CED, which is related to the larger amount and variety of treatment chemicals needed for potable water production. The CWWS has a higher CED offset as the CHP system recovers 17% of the combined system's CED.

3.2. Influence of climate change on the CED of the centralized water services

Fig. 3 presents the average changes in direct, indirect and offset CEDs under RCP 4.5 and 8.5 climate scenarios in the early, mid and late century. Numerical values used to create Fig. 3 are provided in Table 1. The simulated total CED of the combined centralized system at the baseline period is 1341 TJ/year. The CED of the centralized water systems will on average rise by 2% under the two climate scenarios towards the end of the century (1.7 and 2.7% under low and high emission scenarios, respectively), with a steeper slope for late century period under the RCP 8.5 scenario. This overall energy demand increase is due to the increase in both direct and indirect CED consumptions as well as the decrease in the CED offset, as shown in Fig. 3(a). Indirect CED experiences the highest amount of change, which will rise by 2.25% (8.88 TJ/year) as compared to 1.03% (14.06 TJ/year) rise in direct CED and 0.84% (3.56 TJ/year) drop in CED offset in the late century. Indirect CED also presents the highest variation under different climate models, indicating its high uncertainty to climate effects (Tables S-4 and S-5).

When looking individually at the CWWS system, its direct and indirect CED will increase by 15.42 and 1.98 TJ/year respectively, while its CED offset will reduce by 5.44 TJ/year, contributing to a total CED increase of 2.2% or 22.84 TJ/year towards the end of the century (Fig. 3b). It has to be noted that the wastewater inflow to the CWWS under climate change was estimated to decrease by an average of 1.6% as a result of the decrease in groundwater infiltration and stormwater inflow into the wastewater collection network. Despite the reduced wastewater flow rate, the CWWS's overall CED increases because the decrease in groundwater infiltration and stormwater inflow will likely result in a less diluted wastewater influent and hence a higher amount of electricity used for secondary treatment. Meanwhile, the lower wastewater flow rate was predicted to decrease hydropower production and the higher organic concentration is likely to shock the CHP system resulting in less energy being recovered.

The overall CED of the CDWS was estimated to change very little with an average increase of 0.1% towards the end of the century

Table 1
Estimated annual CED of the centralized urban water system for the observed and climate change condition.

CDWS					
Items/Time period	***Observed***	***Climate scenario RCP 4.5***		***Climate scenario RCP 8.5***	
		Baseline	***Late century***	***Baseline***	***Late century***
Direct energy (TJ)	**200**	**203**	**201**	**203**	**202**
Electricity-Distribution	82	83	85	83	89
Electricity-Treatment	89	92	92	92	93
Natural gas	27	26	21	26	18
Diesel	2	2	2	2	2
Indirect energy (TJ)	**270**	**242**	**245**	**242**	**252**
Ammonia	15	16	16	16	17
Bisulfite	14	13	11	13	9
Liquid oxygen	67	70	71	70	73
Ammonia	14	16	16	16	17
Carbon dioxide	56	23	24	23	25
Soda ash	93	94	95	94	99
Hypochlorite	10	10	11	10	12
Energy offset (TJ)	**−124**	**−120**	**−121**	**−122**	**−125**
Hydropower	−124	−120	−121	−122	−125
CED (TJ)	**345**	**325**	**324**	**323**	**329**
Q (Mm3)	242	247	253	247	264
VCED (MJ/m^3)	1.43	1.31	1.29	1.31	1.24
CWWS					
Items/Time period	***Observed***	***Climate scenario RCP 4.5***		***Climate scenario RCP 8.5***	
		Baseline	***Late century***	***Baseline***	***Late century***
Direct energy (TJ)	**1245**	**1183**	**1198**	**1182**	**1206**
Electricity-Collection	352	369	367	368	359
Electricity-Secondary	372	278	297	279	317
Electricity-Primary	161	165	163	165	160
Electricity-Residual	189	196	196	196	194
Electricity-Thermal	101	104	104	104	103
Electricity-Support	70	71	72	71	73
Indirect energy (TJ)	**145**	**153**	**154**	**153**	**155**
Sodium hypochlorite	95	101	101	101	101
Hydrogen peroxide	18	19	20	19	22
Polymer	2	3	3	3	3
Bisulfite	20	21	21	21	20
Ferric chloride	10	10	10	10	10
Energy offset (TJ)	**−253**	**−301**	**−299**	**−301**	**−292**
Hydropower	−42	−49	−48	−49	−47
STG	−211	−253	−251	−252	−245
CED (TJ)	**1137**	**1036**	**1056**	**1036**	**1072**
Q (Mm3)	478	483	480	482	471
VCED (MJ/m^3)	2.38	2.11	2.15	2.11	2.22
CDWS+CWWS					
Items/Time period	***Observed***	***Climate scenario RCP 4.5***		***Climate scenario RCP 8.5***	
		Baseline	***Late century***	***Baseline***	***Late century***
Direct energy (TJ)	1445	1369	1381	1369	1385
	415	394	400	394	407

Table 1 (*continued*)

CDWS					
Items/Time period	***Observed***	***Climate scenario RCP 4.5***		***Climate scenario RCP 8.5***	
		Baseline	***Late century***	***Baseline***	***Late century***
Direct energy (TJ)	**200**	**203**	**201**	**203**	**202**
Indirect energy (TJ)					
Energy offset (TJ)	−377	−422	−420	−422	−417
CED (TJ)	**1483**	**1341**	**1358**	**1341**	**1374**

(Fig. 3c). The main contributing factors here are the reduced direct CED consumption due to the decrease in the natural gas usage for space and water heating within the CDWS (a 0.7% drop), the increased CED offset (by 1.6%) due to increase in water demand and hydropower generation, and the increased indirect CED (a 2.9% rise) consumption due to increase in water treatment needs under climate change conditions.

3.3. Influence of decentralized system adoption on the CED of urban water services

Fig. 4 and Tables S-6 and S-7 present the results on the expected changes in the CED of the urban water cycle due to DecS adoption. Our results show that 100% adoption of the GWR systems (68,567 buildings) will result in a reduction of 11.3 TJ/year of CED (0.8% drop), while a 100% adoption of the RWH systems (8130 buildings) will result in 4.7 TJ/year of increase in CED (0.4% rise) as compared to the baseline of current climate and no DecS adoption (1341 TJ/year). A similar CED benefit provided by integrating GWR systems into the centralized network has been previously reported by Jeong et al. (2018), while the RWH's negative impact on CED consumption has been previously reported by Racoviceanu and Karney (2010) and Lam et al. (2017). One reason for the GWR systems to outperform the RWH systems is because the GWR systems reduce CED consumption from both the CDWS and the CWWS, while the RWH systems only reduce CED consumption from the CDWS (Stang et al., 2021). It is also partly attributed to RWH systems' lower water yield as compared to the GWR systems given their dependence on the intermittent rainfall (Maskwa et al., 2021). Economically positive GWR system adoptions in the city of Boston will result in a 26.66 Mm^3/year of potable water saving from the CDWS, while RWH system adoptions only result in 1.32 Mm^3/year of potable water savings from the CDWS.

3.4. Influence of decentralization and climate change on the CED of urban water services

Fig. 5 shows the implications of both adoption rates and climate change on the CED of urban water services. Numerical values of Fig. 5 are provided in Tables S-6~8. To simulate different adoption rates under baseline climate conditions, the considered buildings were sorted by life cycle cost savings, and the buildings with the highest life cycle cost savings were assumed to adopt the DecS first. More GWR systems adoption results in improvement in all the considered measures, including the overall CED consumption, the water yield, and the cost savings (Fig. 5a). These benefits gradually level with the increase of the adoption rates. When the adoption rate is below 2%, there is a lag in the decrease of the net CED consumption. The reason for this lag is that among the first adopters, there are buildings with high number of floors and occupants. Although these buildings have high water yields and cost savings, they need a high amount of energy to pump water for the GWR systems. Around 96% of the net CED reduction is achieved by only around 50% of the buildings. The flattening of the curve is largely contributed by the reduced hydropower generation at the CDWS as less

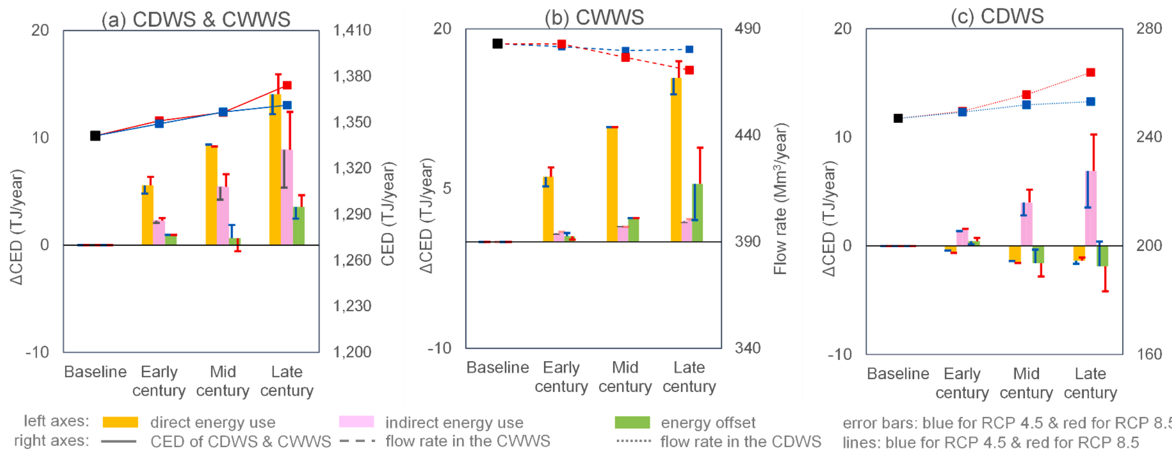

Fig. 3. Centralized system water and wastewater services and their energy implication under climate change conditions in the early, mid and late century. Bar charts (left y axis) represent changes in direct, indirect and offset CED from baseline for (a) the combined CDWS & CWWS, (b) the centralized wastewater system (CWWS), (c) the centralized drinking water system (CDWS); Line charts (right y axis) represent: (a) the combined CDWS & CWWS system annual CED, (b) the annual wastewater volume of the CWWS, and (c) the annual water volume of the CDWS. A positive delta from baseline conditions indicates an increase in either the direct or indirect CED consumptions or an increase in the energy offset, while a negative delta means a decrease in either the direct or indirect CED consumptions or a decrease in the energy offset.

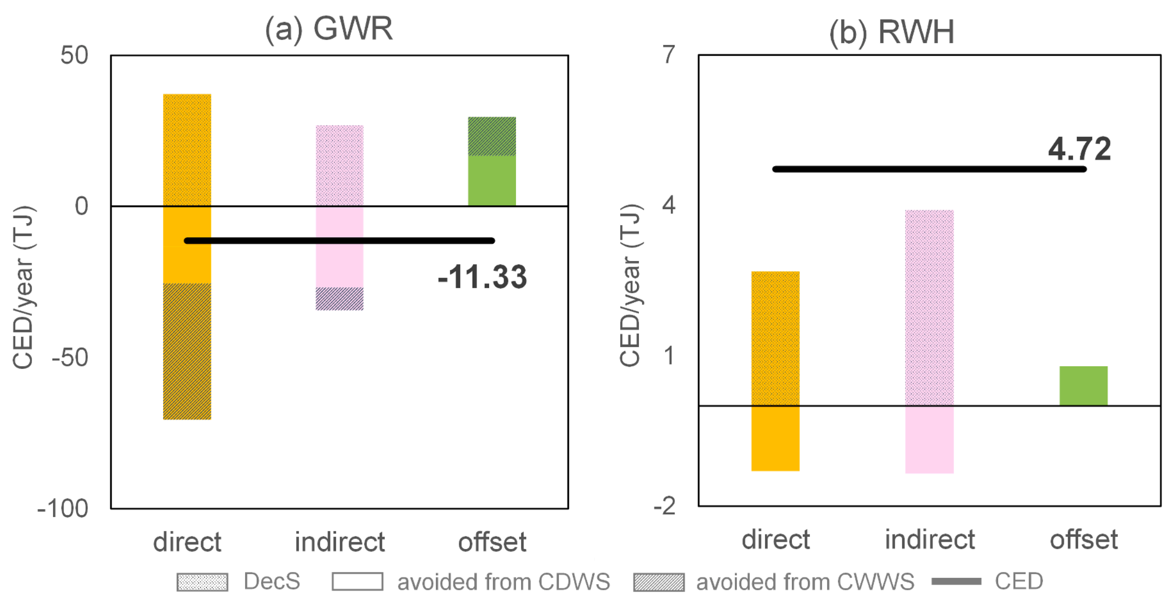

Fig. 4. Energy implications of integrating (a) GWR and (b) RWH systems into the centralized network, showing the avoided direct and indirect energy use and energy offset in the centralized drinking water system (CDWS) and centralized wastewater system (CWWS) as well as the direct and indirect energy use of the decentralized systems.

water flows through the hydropower turbines. The RWH systems have a relatively linear relationship between the adoption rate and the three considered metrics (Fig. 5b). RWH adoption improves water yield and cost saving but worsens the energy performance of the urban water cycle.

Climate change, when added on top of the GWR adoption scenarios (shown as bars in Fig. 5), slightly increases the water yield and cost savings of the GWR systems in general, while significantly reduces the CED consumption of the urban water cycle. This can be explained by the increase in the volumetric energy intensity in the CWWS under climate change. Even though future GWR adoptions will not save more water than what they do now, they might significantly reduce the energy consumption of the urban water cycle given the increased energy demand in the centralized systems. It appears that individual GWR users will not benefit much from this trend as reductions in end users' life cycle cost savings are minimal. However, GWR adoptions has a potentially significant economic benefit to the centralized service providers, in this case, the CWWS. As such, incentives for GWR adoptions may help the centralized systems to better cope with the energy challenges under future climate change. For RWH systems, climate change will also result in an increase in water yield and cost savings, as well as a decrease in the CED consumption, although the decrease in the CED consumption is to a much less extent as compared to the GWR adoptions. As the RWH adoptions do not reduce the wastewater influent to the CWWS, its CED reduction primarily comes from both the more efficient use of the stored water for increased irrigation demand and the larger amount of rainfall to be collected under climate change.

Fig. 6 presents the total CED of the entire water cycle when both climate change and decentralized system adoptions are considered. When centralized systems are further added into the picture, the CED of the entire urban water cycle is projected to increase by 0.9% towards the end of the century under climate change if all households adopt the GWR

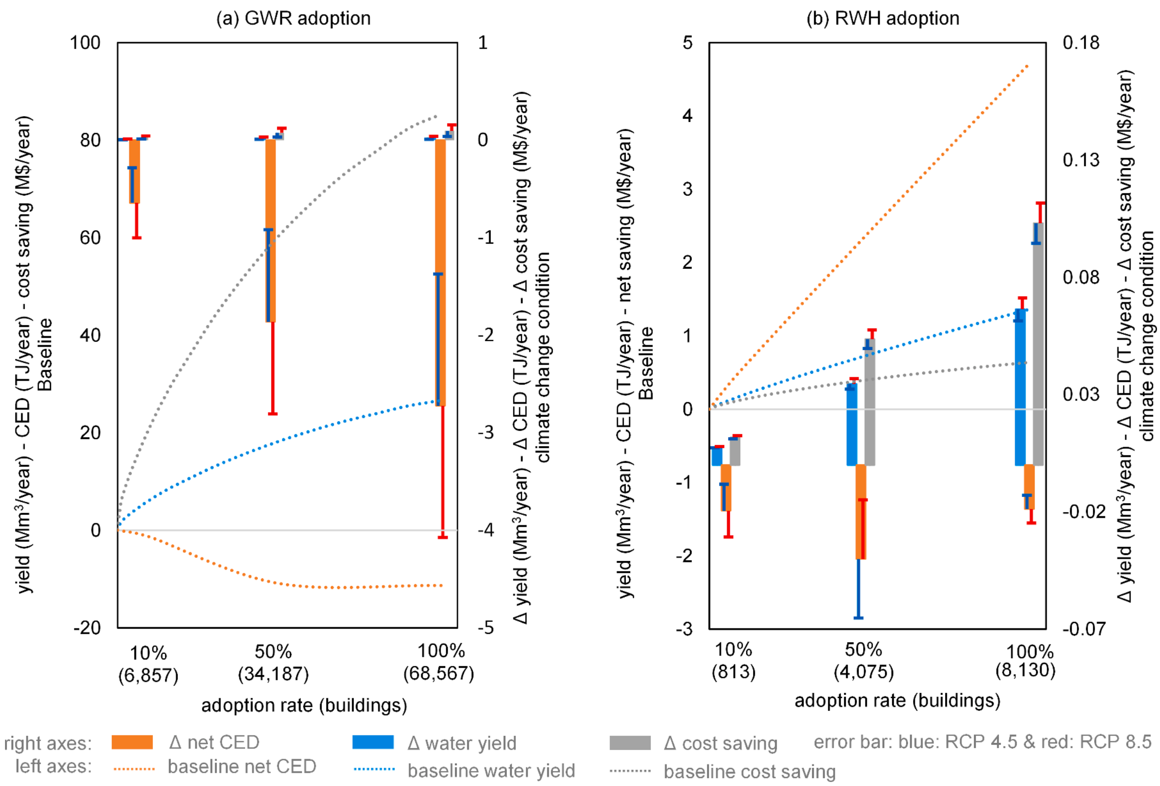

Fig. 5. Decentralized system yield, net CED, and life cycle cost saving under baseline (no climate change considered, lines, left y axis) and climate change (bar charts, right y axis) conditions at different adoption rates of (a) greywater recycling (GWR) and (b) rainwater harvesting (RWH) systems. Line charts show at the baseline more decentralized water system adoption will result in improved energy, water and cost saving for GWR systems but only improved water and cost saving for RWH systems. Bar charts show under climate change decentralized water system adoption will result in more water, cost, and energy savings for both GWR and RWH systems.

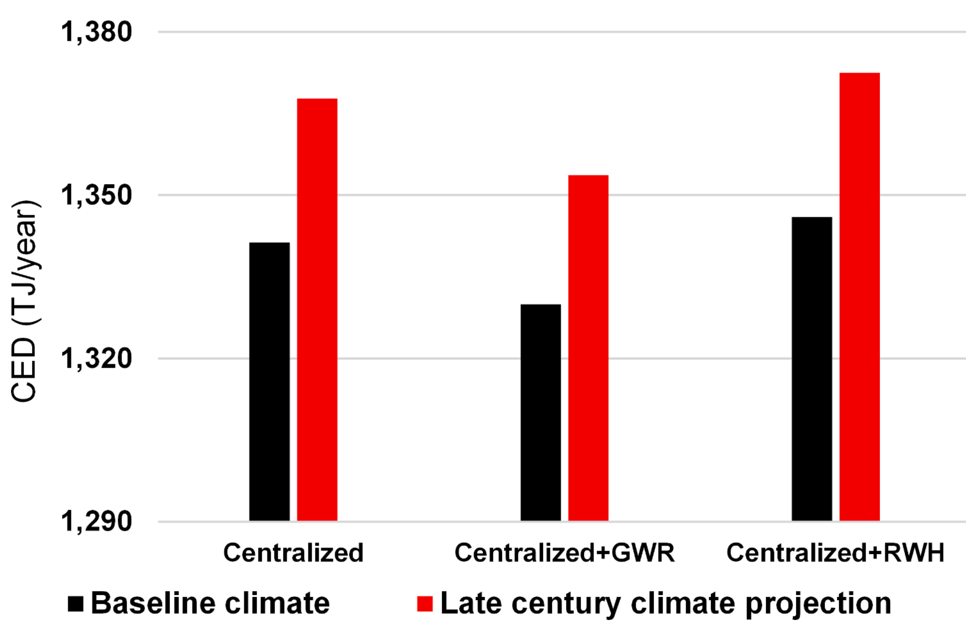

Fig. 6. The cumulative energy demand (CED) of the entire urban water cycle under decentralization and climate change scenarios.

Table 2
Average absolute sensitivity indices obtained for CED estimation of the integrated centralized and decentralized systems under different climate scenarios and models related to the baseline period.

Centralized and decentralized combined system	GWR system integrated								RWH system integrated							
Climate scenarios	RCP 4.5				RCP 8.5				RCP 4.5				RCP 8.5			
Input variable changes (%)	+50		−50		+50		−50		+50		−50		+50		−50	
	Avg	RSD (%)	Avg	RSD (%)	Avg	RSD (%)	Avg	RSD (%)	Avg	RSD (%)	Avg	RSD (%)	Avg	RSD (%)	Avg	RSD (%)
CDWS flow rate	0.19	13.99	0.18	7.98	0.19	10.44	0.18	7.48	0.16	12.71	0.19	2.74	0.16	9.26	0.19	5.04
CDWS pumping energy intensity	0.05	3.99	0.06	5.36	0.05	4.18	0.06	5.27	0.06	3.32	0.07	4.57	0.06	3.51	0.07	4.49
CDWS treatment energy intensity	0.24	0.55	0.24	0.55	0.24	0.81	0.24	0.81	0.27	0.53	0.27	0.53	0.27	0.81	0.27	0.78
CDWS energy offset intensity	−0.08	4.35	−0.08	4.35	−0.08	5.45	−0.08	5.45	−0.09	4.05	−0.09	4.05	−0.09	0.78	−0.09	4.66
CWWS flow rate	0.76	0.43	0.76	0.43	0.76	0.52	0.76	0.52	0.75	0.40	0.75	0.40	0.75	0.46	0.75	0.46
CWWS pumping energy intensity	0.23	2.06	0.23	2.06	0.23	1.96	0.23	1.96	0.23	2.12	0.23	2.12	0.23	2.03	0.23	2.03
CWWS treatment energy intensity	0.72	0.66	0.72	0.66	0.72	0.68	0.72	0.68	0.75	0.64	0.75	0.64	0.75	0.66	0.75	0.66
CWWS energy offset intensity	−0.21	1.12	−0.21	1.12	−0.21	1.62	−0.21	1.62	−0.22	1.10	−0.22	1.10	−0.22	1.61	−0.22	1.61
DecS pumping energy intensity	0.03	0.45	0.03	0.45	0.03	0.62	0.03	0.62	0.00	0.43	0.00	0.43	0.00	0.58	0.00	0.58
DecS construction & maintenance energy intensity	0.03	0.45	0.03	0.45	0.03	0.62	0.03	0.62	0.00	3.01	0.00	3.01	0.00	3.58	0.00	3.58
Primary energy convertor of electricity	0.69	0.44	0.70	0.40	0.69	0.46	0.70	0.49	0.68	0.44	0.69	0.41	0.68	0.47	0.69	0.51

systems. This increase will be 2.3% if all households that can produce a positive life cycle cost saving by installing RWH systems have acted upon it.

3.5. Sensitivity analysis

The CED of the entire water cycle, as shown in Table 2, is not sensitive to changes in any of the tested input variables. The highest sensitivity is related to the flow rate and the treatment energy intensity of the CWWS. The primary energy convertor of electricity in the study region also has high impact on the estimated CED. This aligns with findings from previous studies regarding the key role that the electricity grid mix plays in the life cycle impacts of water infrastructure investments (Jeong et al., 2018; Lam et al., 2015). The calculated Relative Standard Deviation (RSD) of the senstivity indices (SIs) under different climate models are all below 55%, indicating the different climate models have limited influence on the SI outcomes. Out of all studied variables, the CDWS flow rate shows a relatively high RSD values, which is likely a result of the sensitivity of the hydropower generation in the CDWS to the various climate projections.

4. Conclusions

This study investigated the influence of both climate change and decentralized system adoption on the life cycle energy consumption of the urban water cycle. Historically, the studied centralized drinking water and wastewater systems consumed around 1341 TJ/year of cummalitve energy demand (CED), with the centralized wastewater system contributing the most. Climate change is likely to increase the total CED of the centralized systems by 2% towards the end of the century, primarily contributed by an increase in the CED use in the centralized wastewater system due to the predicted worsening of raw wastewater quality. This is primarily contributed by the reduced wastewater dilution by stormwater due to a projected drier climate. The centralized drinking water system is less sensitive to climate change due to the compounded effects of a decrease in space and water heating, an increase in hydropower generation, and an increase in chemical consumptions for water treatment. On the other hand, decentralized system adoption's influence on the urban water services' CED is highly dependent on the type of decentralized system. Grey water recycling (GWR) adoption in all cost saving positive buildings is likely to reduce total CED, while rain water harvestng (RWH) adoption in all cost saving positive buildings is likely to increase total CED. The GWR adoption scenario also has a higher water saving benefit per building basis as compared to the RWH adoption scenario, given its lower dependence on the intermittent rainfall. When climate change and GWR adoptions are combined, they will slightly increase the water yield and cost savings of the GWR systems, while significantly reduce the CED as a result of an increase in the avoided energy from the centralized wastewater system. This trend reveals a potential discrepancy between how individual end users and the centralized systems might benefit from future GWR adoptions, indicating a need for potential incentives to bridge such a gap. RWH adoptions combined with climate change have a similar trend except that the decrease in the CED consumption is to a much less extent. When centralized systems are further added into the picture, the CED of the entire urban water cycle is projected to increase by 0.9 or 2.3% towards the end of the century under climate change if GWR or RWH systems are adopted by their respective cost saving positive buildings. Our findings suggest an overall increasing trend in the CED of the urban water cycle under climate change and decentralized system adoptions, while the magnitude of CED increase is dependent on the type, scale, and pattern of decentralized system adopted, highlighting the importance of proactive decentralized system planning to alleviate future climate challenges. While this study was focused on the energy use of urban water systems under future climate change and decentralization scenarios, there are additional environmental as well as socioeconomic factors that may drive the decision-making surrounding the sustainability and resiliency enhancement of urban water systems, such as water pollution, emergency preparedness, environmental justice, or infrastructure aging. Some of these factors might further influence the urban water-energy nexus, which was not captured in this study. Future studies may expand the modeling framework to multiple cities to investigate how municipal characteristics, such as climate, population, water demand, stormwater/wastewater management, and existing centralized treatment processes might influence the role of climate change and decentralization on urban water-energy nexus.

Declaration of Competing Interest

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

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.watres.2021.117830.

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