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Assessing the Effect of Changing Ambient Air Temperature on Water Temperature and Quality in Drinking Water Distribution Systems

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Abstract: Drinking water distribution systems (DWDS) are affected by climate change and this work aimed to assess the effect of changing ambient air temperature on the water temperature and various water quality parameters in DWDS. A water temperature estimation model was identified and evaluated at seven specific locations in the U.S. and water quality parameters were assessed with a case study for Washington D.C. Preliminary estimation of changes in water temperature and two temperature-related parameters (the chlorine decay rate and bacterial activity) were developed for 91 U.S. cities using local air temperature observations and projections. Estimated water temperature changes in DWDS are generally equivalent to air temperature changes on an annual average basis, suggesting modest changes for the assessed historical periods and possibly more intensified changes in the future with greater increase in air temperature. As higher water age can amplify the temperature effect and the effects of temperature on some water quality parameters can be inter-related, yielding an aggregated effect, evaluation of extreme cases for DWDS will be of importance. In responding to changing climate conditions, assessments of DWDS water temperature changes and resulting impacts on water quality merit more attention to ensure appropriate adaptation of DWDS design and management.

Keywords: climate change; distribution system; drinking water; temperature

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1. Introduction

Climate change poses increasing risk for various types of infrastructure with accelerating evolution of climate conditions, including changes in extreme weather events such as more intense heat waves and heavy rainfalls [1,2]. A challenge for civil and environmental engineers and for society is that much existing infrastructure was designed and is operated based on historical climate conditions and with the assumption that climate is stationary [3]. An emerging responsibility for civil and environmental engineers is therefore to ensure safe, durable, reliable, and resilient infrastructure under the growing challenge of non-stationary climate conditions [3]. Examples of climate change adaptation efforts related to civil and environmental engineering include assessment of bridge scour [4], assessment of water quality in watershed [5], operations in rail networks [6], pavement maintenance [7], and stormwater drainage design [8].

Drinking water supply systems are another type of infrastructure vulnerable to changing climate conditions [9], and changes of drinking water temperature in distribution systems merit particular attention [10,11]. Many installed pipelines for drinking water distribution systems (DWDS) in the U.S. are reaching their functional end of life [12]. As DWDS are renewed, effects of climate change and appropriate adaptation in design should be considered. While overall climate change impacts on DWDS have been addressed to some extent (e.g., by Bondank et al. [13] and water utilities [14]), the effect of air temperature changes on DWDS merits particular attention. Drinking water temperature—a key parameter that influences physical, chemical, and biological processes in DWDS—is greatly affected by ambient air temperature [10]. Although the importance of understanding the water temperature in DWDS is starting to be recognized [10], studies of how changes of ambient air temperature can affect water temperature and quality in DWDS under changing climate conditions are limited.

The investigation of DWDS water temperature changes as a result of air temperature changes and non-stationary climate conditions has been limited and is therefore the focus of this work, while changes related to water temperature, water age, and water quality in premise plumbing of buildings have been examined in a number of studies (e.g., [15–19]). Previous studies [17,18] suggested that water temperature can further increase when the water moves into individual buildings as a result of several factors including the increase in water age in premise plumbing. Results from Salehi et al. [19] showed an average 3.4 °C increase in water temperature from service lines to one studied building in Lafayette, IN. With the urban heat island [20] and subsurface urban heat island effects [21,22], the water temperature in individual buildings can be higher than the air temperature records in nearby weather stations, as results from Bors and Kenway [23] show. Water-saving techniques and green buildings—with a lower water demand—can adversely lead to further increase in water age and water temperature [18] and are of particular concern with respect to degradation of water quality [10]. While the analyses of water temperature and quality in premise plumbing are critical, this study focuses exclusively on the effect of interannual ambient air temperature changes from non-stationary climate conditions on the water temperature and quality of DWDS.

The main objective of this study was to investigate the effects of ambient air temperature changes on water temperature and quality in DWDS. The positive correlation between daily ambient air temperature and daily water temperature in DWDS has been observed and studied (e.g., [10,20,24,25]). This strong correlation between air temperature and DWDS water temperature provides a basis for assessing climate change effects on water temperature and water quality parameters in DWDS. The availability of regional air temperature data in terms of both historical observations [26] and future climate model projections [27] or statistical forecasts and projections [28,29] has substantially increased and can be accessed more conveniently. These regional air temperature observations and future projections have been utilized for climate change impact assessments [30] and therefore provide opportunities to investigate the effects of historical and future regional air temperature changes on water temperature and water quality in the DWDS of particular cities or locations.

The effects of ambient air temperature changes on DWDS water temperature and water quality were evaluated with careful selection and utilization of several techniques in drinking water temperature and water quality estimation. With consideration of general applicability at different locations, separate methods and techniques for estimating water temperature and water quality parameters were selected and linked together to translate changes in ambient air temperature to changes in water temperature and several water quality parameters within DWDS. The parameters considered in this study included chlorine decay, formation of disinfection by-products (DBPs), and bacterial activity. The technique adopted for DWDS water temperature estimation was evaluated for seven different U.S. locations while the methods for estimation of water quality parameters were assessed relative to available data for the city of Washington, D.C. City-level observations and future projections of ambient air temperature were utilized to evaluate both historical and future changes in DWDS water temperature and the selected water quality parameters. Analyses were carried out for Washington D.C., for which some water quality measurements and other information for the DWDS are available, as a case study, and estimates were made for 91 U.S. cities (for which long-term historical air temperature records are available) to assess the spatial variation in the changes of DWDS water temperature and water quality parameters. The estimates of the 91 cities were not calibrated or verified with local measurements and thus have limitations for evaluation of particular cities. The main objective of these analyses was to provide an overview of generally expected changes in DWDS water temperature across different locations and changes in water quality parameters with respect to interannual ambient air temperature changes.

2. Methodology

The methods employed for estimating the effects of water temperature changes on DWDS water temperature and water quality parameters involved three components: regional air temperature observations and projections, estimation of water temperature in DWDS based on air temperature, and estimation of temperature-related water quality parameters. The methods for the individual model components are described subsequently and also summarized in Table 1.

2.1. City-Level Historical Observations and Projections of Ambient Air Temperature

City-level historical observations and projections of ambient air temperature were used to estimate historical and future water temperature in DWDS. The historical daily air temperature records were obtained from the compiled records in Lai and Dzombak [26], while regional air temperature projections were acquired from the G-ARIMA model [29]. The future daily temperature values from the G-ARIMA model were developed based on an integrative technique combining statistical forecasting of city-level historical temperature records [26] and projections from global climate models (GCMs) with different future climate change scenarios (representative concentration pathways, RCPs). The utilized historical observations and projections of air temperature are subject to various limitations, and additional details and descriptions are provided in Supplemental Material Section A as well as in previous work [26,28,29].

Table 1. Summary of the methods used for the individual components of the modeling processes in this work.

Objectives	Models	Methodology and Input	Output	Notes
Ambient air temperature	Historical observations	From the Global Historical Climatology Network-daily; further described in Lai and Dzombak [26]	City-level historical observations	The periods of compiled historical observations start from as early as 1870s.
	Future projections	Using the G-ARIMA model described in Lai and Dzombak [29]	City-level temperature projections	The G-ARIMA model is an integrated technique combining historical-observation-based statistical forecasting and the global climate model (GCM) projections with different representative concentration pathways (RCPs) [29]. Average temperature projections under RCP8.5 were used in this case.
Water temperature	NREL model	$T_{mains,\ day\#} = T_{amb,\ avg} + \Delta T_{offset} + \Delta T_{main} \cdot sin\left[\frac{2\pi}{365}(day\# - 15 - lag) - \frac{1}{2}\pi\right]$ $\Delta T_{main} = \left[k_1 + k_2\left(T^{hist}_{amb,\ avg} - 6.67\right)\right]\frac{\Delta T_{amb,\ max}}{2}$ $lag = k_3 - k_4\left(T^{hist}_{amb,\ avg} - 6.67\right)$ Equation (1)	Daily water temperature estimates $T_{mains,\ day\#}$	$T_{amb,\ avg}$ is annual average air temperature (°C). ΔT_{offset} is an offset value (given as 6 °F or 3.33 °C in Hendron and Engebrecht [31]). ΔT_{main} is an adjustment value considering buried depths. $T^{hist}_{amb,\ avg}$ is the fixed historical annual average temperature of the region; and $\Delta T_{amb,\ max}$ is annual maximum difference in monthly average temperature. The temperature used in original equation is in unit of °F [31].
Water quality parameters	Chlorine bulk decay rate	$C_t = C_0 \cdot e^{-k_b t}$ and $k_b = F \cdot TOC \cdot e^{-\frac{E}{R(T+273)}}$ Equation (2) $ln\left(\frac{k_{b,\ T2}}{k_{b,\ T1}}\right) = \frac{E}{R}\left(\frac{1}{T_1+273} - \frac{1}{T_2+273}\right)$ for only considering temperature effect Equation (3)	Chlorine bulk decay rate k_b and chlorine residuals C_t (considering only bulk decay);or changes in chlorine bulk decay rate	C_t is the chlorine concentration at time t (mg/L). C_0 is the initial chlorine concentration (mg/L). k_b is the bulk decay rate (in units such as hr^{-1} or day^{-1}). F is a frequency factor, E is the activation energy (J/mol), and R is the ideal gas constant as 8.31 J/(mol·K) [F and E/R values were estimated as 1.8×10^6 L/(mg·hr) and 6050 °C [32]]. T is water temperature (°C). $k_{b,\ T1}$ and $k_{b,\ T2}$ are bulk decay rates at temperature T_1 and T_2.
	TTHM formation [1]	$TTHM = k \cdot C_0^a \cdot T^b \cdot TOC^c \cdot pH^d \cdot Br^e$ Equation (4)	TTHM concentration	C_0 is the initial chlorine concentration and T is the temperature (°C) of treated water. TOC, pH, and Br (bromide concentration) are measurements for the water source, and a to e and k are constants determined by model fitting of measurements. The values of a to e and k for the analyses of Washington DC are: 0.64, 0.76, 0.85, 1.30, 1.89, and 0.027, respectively.
	Bacterial activity	$Act(T) = Act(T_{opt})\exp\left(-\left(\frac{T_{opt}-T}{T_{opt}-T_i}\right)^2\right)$ Equation (5) $Act(T,\ C_t) = Act(T_{opt})\exp\left(-\left(\frac{T_{opt}-T}{T_{opt}-T_i}\right)^2\right)\exp\left(-\left(\frac{C_t-C_m}{dC}\right)\right)$ for considering chlorine effect Equation (6)	Bacterial activity levels considering temperature and (or) chlorine effects	$Act(T)$ and $Act(T,\ C_t)$ are bacterial activity at temperature T (°C) or with chlorine concentration of C_t at time t. T_{opt} is the optimal temperature for the bacteria community, and T_i is a shape parameter. $T_{opt} = 40 - (20 - T)/2$ and $T_i = 18 - (20 - T)/2$ when seasonal changes of temperature are considered [33]. C_m is a threshold concentration, and dC is a coefficient (C_m and dC were given as 0.1 and 0.25 mg/L for fixed bacterial [34]).

[1] The analyses of TTHM formation were applied for Washington D.C. based on the available measurements (TTHM concentrations for the treated water were used). Evaluation of TTHM formation was not further assessed for the 91 cities.

2.2. Estimating Water Temperature in DWDS

Water temperature in a DWDS can be estimated with air temperature records because the water temperature in a DWDS is strongly affected by soil temperature [10], which can be estimated using ambient air temperature records [35]. A mechanistic model has previously been developed by Blokker and Pieterse-Quirijns [36] to estimate water temperature in distribution mains considering the heat exchange between ambient air, soil, pipelines, and water in the pipes. Simulations with this mechanistic model [36] indicate that the amount of time for water temperature to reach the equilibrium with soil temperature (at the depths of pipelines) is generally shorter than water residence time in a DWDS, indicating that soil temperature at the buried depth of water mains can be used to predict water temperature. As soil temperature can be determined by air temperature [35], DWDS water temperature is consequently correlated to ambient air temperature records. Such a positive correlation has been observed in many locations, e.g., Arlington, VA [37]. Bors and Kenway [23] and Kaufmann [38] have constructed regression models to provide DWDS water temperature estimates based on air temperature records from local weather stations.

The type of water source will likely have a limited effect on water temperature in a municipal DWDS, although evaluation of different water sources (i.e., surface water or groundwater as sources) was not performed in this work because of limited available data. Additional investigations are needed. Considering that water temperature tends to reach equilibrium with soil temperature within the water residence time in a DWDS, as demonstrated by Blokker and Pieterse-Quirijns [36], it is expected that water temperature in a DWDS is relatively independent of the type of water source. Water temperature measurements from four residential sites at which individual wells are used, from Abrams and Shedd [24] (some of their water temperature data were used in this work), also provide insight into the effect of water source on DWDS water temperature. Specifically, the measured water temperatures at two well-supplied sites studied by Abrams and Shedd [24] exhibit limited seasonal changes because the wells are adjacent to the residential sites, while the measurements at the other two well-supplied sites exhibit stronger seasonal changes similar to those of a municipal system, likely caused by the routing of piping from the wells to the residential sites which provides opportunity for heat transfer with surroundings, as discussed by Abrams and Shedd [24]. It is possible that when groundwater is used as the main water source for a DWDS, a particular location that has relatively short water residence time can exhibit water temperature independent from the air temperature. Because the main objective of this work was to provide a preliminary assessment of the effect of interannual temperature changes on water temperature in DWDS, and data for water temperature in DWDS using different types of sources are very limited, additional assessments of the effect of different water sources were not performed.

A water temperature estimation model with general applicability to different cities—similar to the models used for estimating soil temperature—was used in this work. This water temperature model was developed by the National Renewable Energy Lab (NREL [31]) and subsequently utilized for cold water temperature estimation in the Building America Research Benchmark and the EnergyPlus model [39]. The equations for the NREL model are presented in Equation (1) of Table 1. While a mechanistic model such as that developed by Blokker and Pieterse-Quirijns [36] could be constructed and utilized to estimate DWDS water temperature, a substantial amount of information on the DWDS is required and the development of such models can be "impractical" [40], especially for general use and application in different regions.

Similar to the soil temperature estimation models or the Kusuda equation for estimating soil temperature [35], the obtained daily water temperature from the NREL model exhibits a sinusoid shape and a lag to ambient temperature change. As distribution mains are installed below local frost lines [41], buried depths of drinking water pipelines are different in different regions. To simplify the calculations and also allow water temperature estimation for different cities, the annual average air temperature is utilized in the NREL model as a surrogate for the buried depth of water mains [40]. A lower average temperature value suggests a colder climate and consequently indicates a greater required depth for a water pipeline. Several other methods for estimating water temperature by using air temperature records (similar to the NREL model) are also available [42]. Results from Chmielewska [42] and a preliminary assessment of alternative methods indicated that the NREL model provides daily water temperature estimates with a better alignment to water temperature measurements.

In addition to using the standard parameters provided by the NREL model, the water temperature estimation accuracy can be improved for a particular location by optimizing the parameters based on water temperature measurements for the locality. Żukowski [25] implemented the NREL model for estimating cold water temperature for one location in Poland and used water temperature measurements spanning a period of three years for calibration. According to the results of Żukowski [25], the root mean square errors (RMSEs) were reduced by more than 50% by modifying the parameters of the NREL model. Therefore, both standard parameter values of the NREL model and the parameter values with further calibration were used and assessed in this work (for the seven locations with water temperature measurements). The calibration was applied for the five parameters (k_1, k_2, k_3, k_4, and ΔT_{offset}) presented in Table 1 by minimizing the RMSE using a numeric optimization algorithm (the Broyden–Fletcher–Goldfarb–Shanno algorithm [43]). The analyses were applied for the seven locations including Washington D.C. and the results are discussed in Section 3.

The water temperature measurements at different locations of a system are expected to vary from the system-wide water temperature estimates obtained from the NREL model due to factors including urban heat island and subsurface urban heat island effect. The water temperature is expected to have a ± 5 °F (or approximately ± 2.7 °C) temperature variation from the estimates provided by the NREL model with the standard parameters [40]. A substantial variation of water temperature measurements for one system in the same day has been observed by Bors et al. [20], indicating the potential urban heat island or subsurface urban heat island effect. For example, Benz et al. [21] suggested that the subsurface urban heat island effect can lead to an increase in groundwater temperature and can thus likely affect the DWDS water temperature [10]. Although applying the NREL model with its standard parameters can potentially lead to large errors for particular locations, using the temperature measurements of the studied locations and additional calibration can reduce such errors as has been shown in Żukowski [25].

2.3. *Estimating the Effect of Water Temperature on Drinking Water Quality Parameters*

Estimation of the effect of water temperature on drinking water quality parameters was conducted by identifying the input of water temperature information in the typical calculation processes for these parameters, which in this study included the chlorine bulk decay rate, total trihalomethane (TTHM) formation, and bacterial activity, as presented in Table 1. As the estimation of water quality-related parameters often requires some other information or parameter values in addition to temperature, the analyses were carried out for Washington D.C. (for which some measurements of water quality parameters and other information about the water quality in the DWDS are available) as a case study and also for the 91 U.S. cities (for which some general effects of water temperature changes on chlorine decay and bacterial activity were assessed). The methods for estimating the water quality-related parameters using temperature estimates are discussed in Sections 2.3.1–2.3.4 while the approach applied for the analyses of Washington D.C. and the 91 cities is further discussed in Section 2.4.

2.3.1. Change in the Chlorine Bulk Decay Rate

Temperature is a key factor in determining chlorine decay in DWDS and the modeling of chlorine decay commonly considers the decay in bulk water and decay on pipeline walls [44]. The chlorine bulk water decay rate can be determined with bottle tests [45] for particular drinking water systems, while decay on the wall can be estimated with the aid of hydraulic calculations using models such as EPANET [46]. The chlorine bulk decay rate as a function of water temperature was assessed in this work. Chlorine decay on the wall is potentially affected by biofilm activity [47] and thus by water temperature as well, but was not considered and studied explicitly here. The chlorine bulk decay rate is affected by several water quality parameters [48] including temperature, initial chlorine concentration, and total organic carbon (TOC). As these parameters can be location specific, reported chlorine bulk decay rates vary among different DWDS, e.g., the test results of bulk decay rates in five utilities from Vasconcelos et al. [49] showed a range of values from 0.1 to 17.7 day^{-1}. With water temperature estimates, on-site measurements of initial chlorine concentrations and TOC, and water ages, a commonly used first-order bulk decay model as presented in Equation (2) of Table 1 [48], were utilized to estimate the effect of water temperature changes on the chlorine residual levels (when only bulk decay is considered) for Washington D.C. In addition, the derived relationship between the first-order bulk decay rate and water temperature (as presented in as presented in Equation (3) of Table 1) was used to provide general estimates for the 91 cities.

2.3.2. Change in TTHM Concentration

Water temperature can affect the rate of various reactions in drinking water between chlorine and substances such as natural organic matter and inorganic compounds (e.g., ammonia, Fe^{2+}, and Mn^{2+}), which can lead to formation of various DBPs, including trihalomethanes, haloacetic acids (HAAs), and other known and unknown products [50]. Water temperature estimates can thus be used to assess the effect of water temperature change on DBP formation, in this case for TTHM. For estimating TTHM concentrations, although further development is needed [50,51], many empirical predictive models have been developed in addition to mechanistic models [44,51]. In general, the predictors in the empirical predictive models for TTHM concentration include chlorine dosage, temperature, and reaction time (water age) in treatment processes and distribution networks; and organic content (typically using surrogate parameters such as TOC and ultraviolet absorbance UV_{254}), pH, and bromide concentrations of water source [52]. A similar empirical predictive model was utilized in this work to predict TTHM concentrations in the treatment plants of Washington D.C., using initial chlorine concentration, water temperature, TOC, pH, and bromide concentrations as predictors, as presented in Equation (4) of Table 1 (the predictors were selected based on the available measurements). As the estimated coefficients for the empirical predictive models may not be applicable for other locations, the effect of water temperature changes on TTHM concentrations was not further assessed for the 91 cities.

2.3.3. Change in Bacterial Activity

Similar to chlorine decay and TTHM formation, water temperature is a key parameter for bacterial activity [53] and an increase in water temperature can promote bacterial regrowth in water and biofilms within DWDS [54], leading to degradation of water quality. While heterotrophic bacteria levels in drinking water alone are not typically considered as a human health concern [55], limiting the exposure to heterotrophic bacteria can reduce the risks of waterborne pathogens [53]. One example of such opportunistic pathogens is Legionella. A more than five-fold increase in the cases of Legionnaires' diseases has been reported in the U.S. from 2000 to 2017 [56]. The World Health Organization recommends that cold water temperatures in DWDS be below 25 °C [57] to reduce Legionella risk. Simmering et al. [58] also showed the dependence of the number of Legionella cases on warmer and more humid weather conditions. Consequently, climate change impacts and the effect of increasing temperature on waterborne diseases (including Legionnaires' diseases) are of particular concern [59].

Although assessing the likelihood of occurrence of a particular pathogen such as Legionella with water temperature estimates can be conducted using information from studies such as LeChevallier [60], a more general approach of modeling of heterotrophic bacteria regrowth in DWDS was utilized in this work to assess the overall effect of water temperature change on bacterial activity. Empirical models with several water quality parameters as predictors (similar to the one use for modeling TTHM formation) as well as mechanistic models with descriptions of several biochemical processes have been developed in the literature [53]. Because the parameters and their coefficients vary in the various available empirical models [53], a commonly used expression in the mechanistic models as presented in Equations (5) and (6) of Table 1 (based on the Monod equation; such as in [34,61–63]) for describing the effect of water temperature on bacterial activity was utilized for the analyses of Washington D.C. and the overview of the 91 cities.

2.3.4. Effects of Water Temperature on Other Parameters and the Aggregate Temperature Effect

Changes of water temperature can affect several other temperature-related water quality parameters during treatment processes or in DWDS, including ozone solubility, corrosion, and water discoloration. For example, ozone is used by approximately 7% of surveyed utilities in the U.S. [64] as an alternative disinfectant and an increase in water temperature can reduce ozone solubility, leading to an increase in required ozone dosage, as studies of treatment plants in Boston and Tampa have indicated [65,66]. The Henry's law coefficient for ozone solubility at different water temperatures can be determined using the results such as from Biń [67]. Pipe corrosion is another factor related to water temperature. A positive correlation between water temperature and corrosion rate has been observed [68], although the effect of water temperature on the rate of corrosion is inter-mixed with several processes including hydraulics, other water quality parameters, and biological activity [69]. Additionally, some preliminary work on discoloration-related customer reports and water temperature by Van Summeren et al. [70] showed an increase in water temperature can lead to discoloration and reduced aesthetic quality.

Several other aspects of temperature effect on water quality are of particular importance including the aggregate temperature effect on different parameters and the amplification of the temperature effect with greater water age. One example of the aggregate temperature effect is the inter-mixed processes between chlorine decay, DBP formation, and bacterial activity. Chlorine dosage is a key parameter for determining TTHM formation and limiting bacterial activity [62], while an increase in biofilm activity can lead to greater TTHM formation [63] and acceleration of chlorine decay on the pipe wall [47]. As a result of increasing water temperature, both chlorine decay and bacterial activity can be accelerated, leading to potential higher chlorine dosage requirement or higher TTHM formation when dosage is increased. If the chlorine dosage remains the same, bacterial activity can be further increased with a higher chlorine decay rate. Further, while the maximum water age in a DWDS is generally below 10 days [64], an increase in water age can amplify the effect of increased water temperature [61]. This is especially of concern for some premise plumbing for which a prolonged water age may exist, as discussed previously [15,17,56].

2.4. Applied Case Study of DWDS Water Temperature and Water Quality

The water temperature estimation model was implemented and evaluated with water temperature measurements for seven U.S. locations. The measurements, except for the measurements for Washington D.C., were obtained from Abrams and Shedd [24]. The measurements from Abrams and Shedd [24], which were made within the water supply piping of residential sites in the period 1994–1995, were averaged into weekly values at 12 residential sites. Four sites from Abrams and Shedd [24] (data for a total of 16 sites are provided) were excluded from the analyses because the water sources for these four sites were identified as individual wells. The 12 sites include nine single-family detached homes, two laundry rooms of apartment complexes, and one apartment building (additional information can be found in Abrams and Shedd [24]). The water sources (i.e., surface water or groundwater) for these municipal DWDS sites are unclear, however. Water temperature measurements for Washington D.C. were obtained in the two treatment plants associated with the Washington Aqueduct [71] and were compared with reported

DWDS water temperatures from the DC Water drinking water quality reports [72]. Water temperature of the DWDS in Washington D.C. was assessed because some measurements of and information about water temperature and quality parameters are available.

The methods for estimating the effects of temperature on the three water quality parameters (as presented in Table 1) were applied for Washington D.C. as a case study. The analyses utilized the records of ambient air temperature for two historical periods (1951–1968 and 2001–2018) and for a future projected period from the G-ARIMA model results (2051–2068) to estimate the corresponding historical and projected changes (i.e., from the 1951–1968 level to the 2001–2018 level; and from the 2001–2018 to the 2051–2068 level) on water temperature and the three quality-related parameters. These three periods were selected because the monthly measurements of water temperature and some quality-related parameters for the treated water are available for Washington D.C. [71] during the period 2001–2018 and the other two periods were used for assessing historical and future changes.

An assessment of water temperature estimates, historical and projected changes of water temperature, and the effect of temperature changes on two selected water quality parameters (the chlorine bulk decay rate and bacterial activity) was performed for the selected 91 U.S. cities. Historical ambient air temperature records were utilized to estimate average DWDS water temperature for two historical 20-year periods (1951–1970 and 2001–2020), while the air temperature projections from the G-ARIMA model (2051–2070) were used to evaluate future changes. The standard parameters of the NREL model were used to estimate water temperature for the 91 cities. As discussed previously, because the analyses of the 91 cities with the NREL model were not evaluated with local water temperature measurements, the estimates of the water temperature and the two water quality parameters are subject to limitations and likely large uncertainty. The annual average estimates of water temperature and water quality parameters and their changes on an annual average basis were assessed and are presented in this work, because these estimates are more directly related to the annual average air temperature (according to the NREL model) and are likely subject to less uncertainty. The goal of these analyses was to assess the general historical and future changes in drinking water temperature and water quality parameters, and across a range of geographical areas and climate conditions. It was not intended to develop accurate estimates for particular locations and systems, although further detailed evaluation on specific locations (if local measurements are available) can be applied and provide additional valuable information such as possible extreme water temperature.

3. Results

3.1. Estimated Historical and Future Changes in DWDS Water Temperature

3.1.1. Water Temperature Estimates from the NREL Model

Water temperature in a DWDS is correlated to the ambient air temperature, which is evident in an example comparison between measured water temperature and ambient air temperature data for Washington D.C., presented in Figure 1. A surface water source is used for the two treatment plants in Washington D.C. [71] and both the temperature measurements of treated water [71] and of water in the DWDS [72] were acquired and are presented in Figure 1. While the temperature measurements from the DWDS for Washington D.C. are limited, the temperature of the treated water exhibits an annual variation similar to the water temperature measurements in the DWDS and also similar to the air temperature records from the local weather station. As presented in the bottom right graph of Figure 1, the monthly water temperature measurements of the treated water are similar to the monthly air temperature records, with the exception that the water temperature in the winter months are greater and above 0 °C. The reported water temperature for the DWDS exhibits an annual range comparable to that of the air temperature, while one notable difference between the reported water temperature for the DWDS and the air temperature records is that the maximum temperature measurements obtained in the DWDS of Washington D.C. (presented as the higher blue shaded bar in Figure 1) are greater than the annual maximum daily mean air temperature from the Reagan National Airport (i.e., the weather station) as presented in Figure 1, potentially caused by the urban heat island or subsurface heat island effect as previously discussed. Because the monthly temperature measurements of treated water are comparable to the measurements in the DWDS and the results of water temperature in the DWDS of Washington D.C. from drinking water quality reports are limited, the measurements for the treated water were used to verify and further calibrate the NREL model for water temperature estimates of the Washington D.C. DWDS. Additional information and measurements for the water temperature in the Washington D.C. DWDS, if available and applied, are expected to improve the analyses.

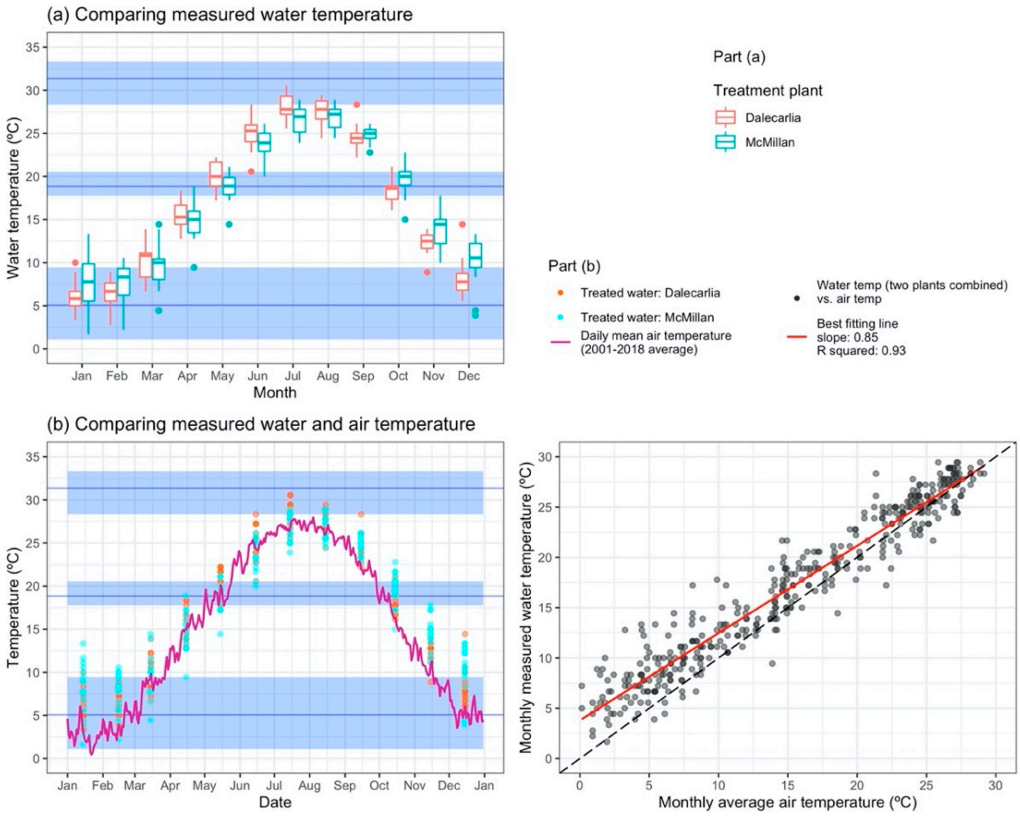

Figure 1. Water temperature measurements and air temperature records from the local weather station (Reagan National Airport) for Washington D.C., with (**a**) boxplots of monthly average temperature measurements of treated water (water entering the distribution system) in the two treatment plants of Washington Aqueduct [71] during the period 2001–2018 (each boxplot shows values across the period 2001–2018) and annual water temperature results in the DWDS provided by the DC Water drinking water quality reports [72] for the period 2003–2017; and (**b**) comparison with the air temperature records from the weather station (with the bottom left graph presenting the seasonal variations and the bottom right graph presenting the scatter plots of monthly measured water temperature of treated water vs. monthly average air temperature). In part (**a**), the three shaded bars present the reported annual maximum, average, and minimum water temperature in the DWDS from the drinking water quality reports [72] for the period 2003–2017 (with the bounds and bold lines representing the highest, lowest, and mean values reported every year between 2003 and 2017). Monthly temperature measurements for the treated water are presented as points in part (**b**), instead of boxplots as in part (**a**).

The results of water temperature estimation using the NREL model for Washington D.C. and the other six locations are presented in Figure 2 using both standard parameter values and calibrated parameter values. The water temperature measurements for the other six locations (with 12 residential sites; some sites are within close proximity and were thus combined) were collected by Abrams and Shedd [24] during the period 1994–1995. As previously discussed, the temperature measurements for the other six locations are the recorded water temperature in the supply piping of the residential sites. As presented in Figure 2 (and in Figure 1 for Washington, D.C.), seasonal changes of water temperature records throughout the year can be observed across all seven locations (although the water sources for the measurements provided by Abrams and Shedd [24] are unclear) and are consistent with the assumption that the water temperature exhibits sinusoidal variation with time. Thus, the use of air temperature to provide water temperature estimates with similar sinusoidal, seasonal variation in the NREL model is appropriate. Similar to the findings of Żukowski [25], using the standard parameters of the NREL model provides reasonable estimates of the measured water temperature, with the exception of Texarkana, AR for which the estimates show greater seasonal changes. After application of numeric optimization for further calibrating the NREL model (calibration of the parameter values for individual assessed locations), RMSEs were (averaged across all locations) reduced from 1.98 to 1.01 °C. The reduction in the RMSE by approximately 50% is consistent with the results of Żukowski [25]. As the different sites within each location (or city) also exhibit variations from the average estimates for that city (e.g., at different sites of Tulsa in Figure 2), the NREL model can be further calibrated to the individual sites to provide better estimates. If additional site-specific measurements are available, the NREL model can thus likely be improved to provide location-specific water temperature estimates.

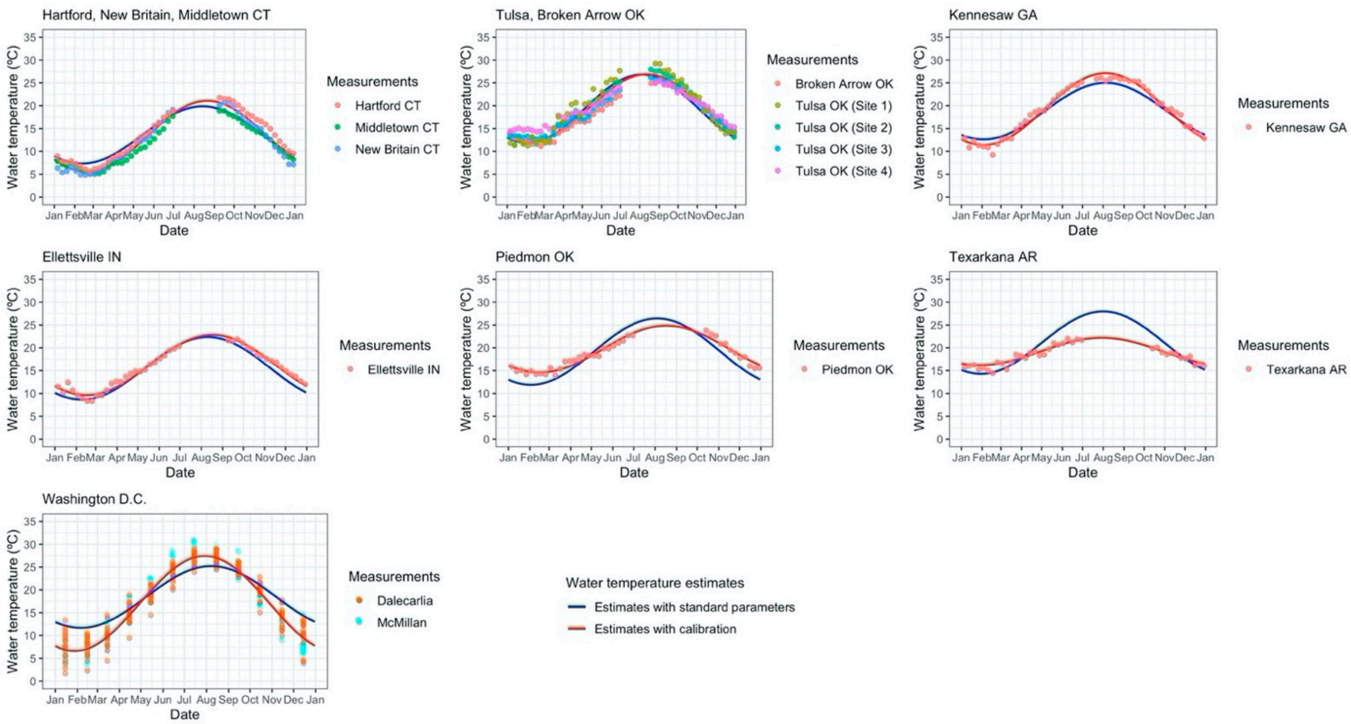

Figure 2. Comparisons between water temperature measurements and the water temperature estimates from the NREL model. The water temperature measurements (with the exception of Washington D.C.) were obtained from Abrams and Shedd [24] and were recorded in the water supply piping of 12 residential sites during the period 1994–1995. For the further calibration of the NREL model, the root mean square errors (RMSEs) were calculated between the measurements and the corresponding weekly or monthly averages of water temperature estimates. Station information for the air temperature records used for the seven locations can be found in Supplemental Materials Section B.

3.1.2. Historical and Projected Changes in Water Temperature Estimates

As water temperature can be estimated using ambient air temperature records in the NREL model, historical and future projected changes in the water temperature estimates can be analyzed by utilizing historical air temperature records and future temperature projections. The results of applying the NREL model for water temperature estimation in Washington D.C. with the air temperature records of two different historical periods (i.e., 1951–1968 and 2001–2018) and a projected period (2051–2068) are presented in Figure 3.

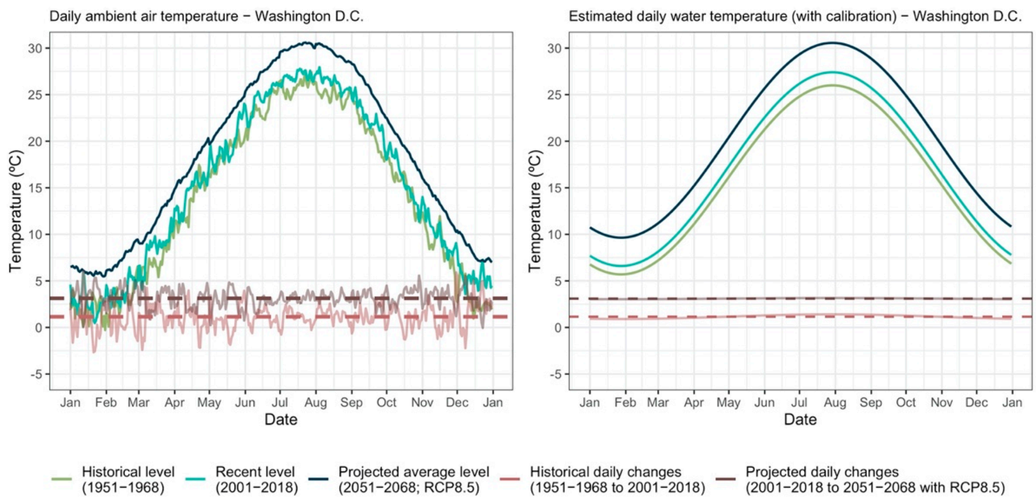

Figure 3. An assessment of daily air temperature records and projection and daily water temperature estimates between a historical period (1951–1968), a recent historical period (2001–2018), and a projected future period (2051–2068) for Washington D.C. The results of the daily air temperature in the two historical periods are the averaged daily values for the two periods, while the presented air temperature projection is an average projection in daily resolution from the G-ARIMA model (and consequently exhibits less daily variations compared to the two historical levels). The three periods were assessed because of the avaialable measurements for the period 2001–2018. Daily water temperature estimates were calculated based on the air temperature of these three periods. The results of the daily changes and their annual averages (presented as the dashed lines) are based on the differences of the daily water temperature estimates between the three periods.

The results of Figure 3 suggest that the estimated changes of water temperature at annual average level from the NREL model are equal to the changes of air temperature records at the annual average level. Water temperature estimates increase by approximately 1.2 °C from the 1951–1968 to the 2001–2018 level and by 3.1 °C from the 2001–2018 to the projected 2051–2068 (with a higher climate change scenario RCP8.5) level in terms of annual average. While the daily differences between the different periods of air temperature records exhibit large variations, the water temperature was estimated to have a sinusoid shape and consequently the daily differences have less variation and are similar to the annual average levels. Additionally, the further calibration of the NREL model (with modification of some parameter values), which can improve the seasonal estimates as presented in Figure 2, does not affect the estimated changes in water temperature for different periods in Figure 3 at the annual average level (equivalent to the changes in air temperature according to the NREL model). Therefore, based on the NREL model, an assessment of air temperature changes at particular cities can provide reasonable estimates of DWDS water temperature changes for those cities.

The estimation of DWDS water temperature was then conducted for 91 cites and historical and future projected changes were calculated. The results are presented in Figure 4. As previously discussed, the presented results of annual average water temperature estimates and the estimated changes in water temperature were mainly determined by the annual averages of air temperature records at these cities. The results of Figure 4 (i.e., when averaged across all cities, an approximately 0.8 °C increase from the 1951–1970 to 2001–2020 level and 2.3 °C increase from the 2001–2020 to 2051–2070 level under RCP8.5) are consistent with the estimated air temperature change for the U.S. (e.g., a 0.7 to 1.0 °C increase from the 1901–1960 to 1986–2016 level and a further 3.0 to 6.1 °C increase under RCP8.5 in the late 21st century relative to the 1986–2015 level [1]). Calculation of the changes in annual average air temperature can thus provide an efficient estimate of the changes of water temperature in DWDS. Further calibration of the NREL model with modification of the parameter values for particular locations can increase the alignment of estimated water temperature to the seasonal variation of observed water temperature but it does not alter the results of estimated changes in water temperature on an annual average basis.

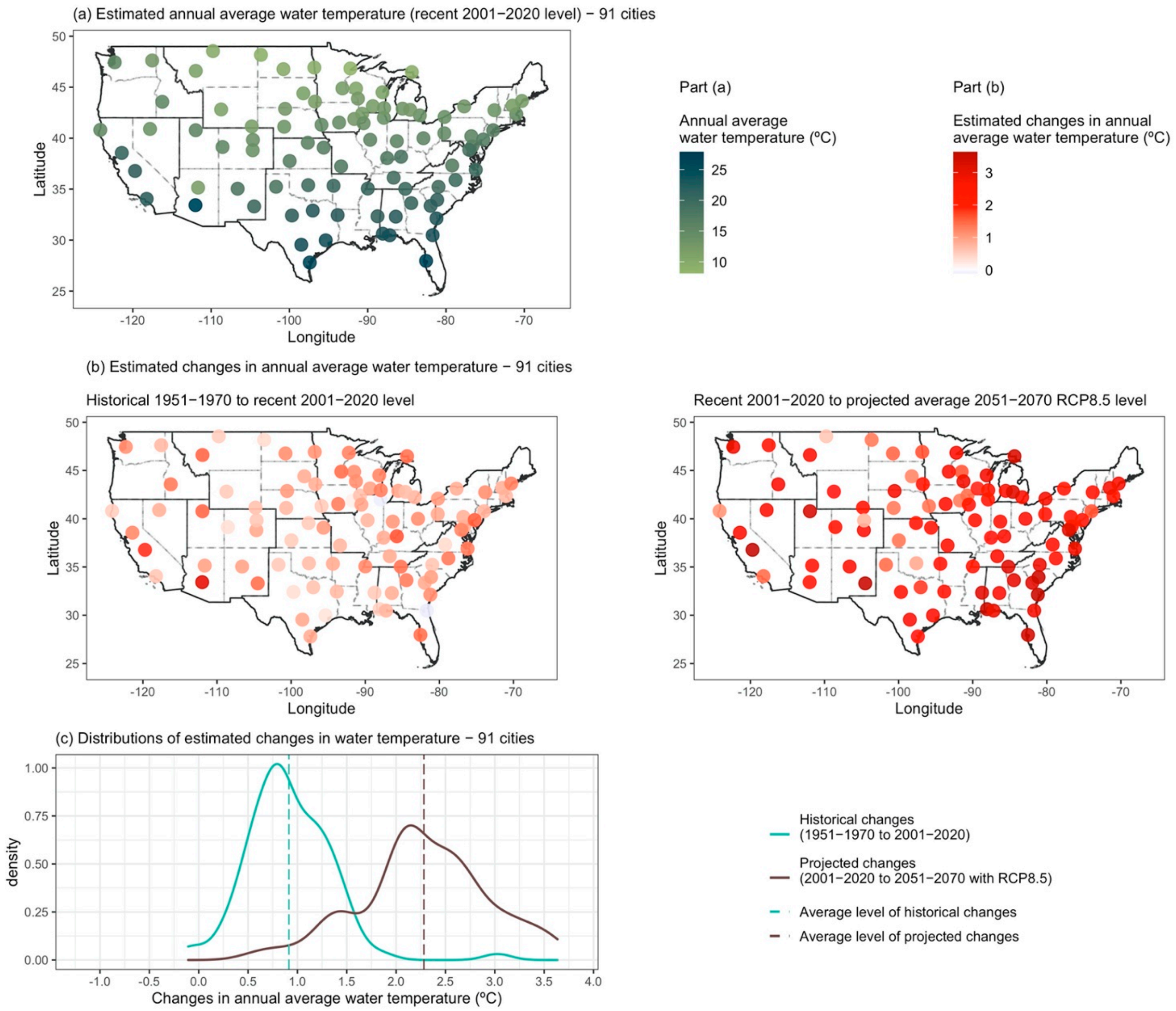

Figure 4. Annual average DWDS water temperature estimates and estimated water temperaure changes (with three separate 20 year periods) for the 91 U.S. cities with (**a**) the spatial distributions of the annual average water temperature estimates for the 91 cities (2001–2020 level); (**b**) the spatial distributions of the estimated changes in annual average water temperature between the two historical levels and from the recent 2001–2020 level to the projected 2051–2070 level; and (**c**) probability density functions (PDFs) of the estimated changes among the 91 cities. The standard parameter values of the NREL model were used. Solid lines around the boundaries of states in parts (**a**) and (**b**) show the nine NOAA climate regions [73].

It is important to note that the analyses of Figure 4 aimed to provide a general evaluation of the expected average changes in drinking water temperature in the DWDS and the results are directly based on the historical and projected air temperature. Further discussion of the historical air temperature records and projections used and the corresponding changes are provided in Supplemental Material Section A.

3.2. Estimated Historical and Future Changes in Temperature-Related Water Quality Parameters in DWDS

Temperature-related water quality parameters and changes of these parameter values caused by air temperature changes can be assessed with the input of water temperature estimates. Washington D.C. was further assessed as a case study, with the analyses on TTHM concentrations based on the availability of measurements. Seasonable variations of the other two parameters (chlorine decay and bacterial activity) for Washington D.C. and average historical and projected changes of the chlorine decay rate and bacterial activity for the 91 cities were also evaluated and are presented. The objective of these analyses was to provide a general assessment of the effect of water temperature (i.e., air temperature) changes on the water quality of DWDS.

3.2.1. Analyses of the TTHM Concentrations for Washington D.C.

The measured TTHM concentrations and the results for the predicted TTHM concentrations from the empirical predictive model are presented in Figure 5. The monthly measurements of TTHM concentrations are from the Washington Aqueduct for the period 2001–2018 [71], and facilitate a more detailed assessment compared to the other two parameters addressed in the subsequent section. It is important to note that the measurements of TTHM concentrations presented in Figure 5 were obtained for the treated water at the two treatment plants of Washington D.C. Some information about the measured TTHM concentrations in the DWDS of Washington D.C. was obtained from DC Water [74] and compared with the TTHM measurements for the treated water, which suggest that the TTHM measurements for the treated water are generally comparable to the reported TTHM concentrations in the DWDS. The results in Figure 5, as further discussed, suggest that the use of estimated water temperature from the NREL model (which was calibrated using the water temperature measurements of the treated water in Washington D.C.) instead of measured water temperature did not lead to substantial differences in estimating TTHM. Water temperature and TTHM measurements in the DWDS, if available and utilized, can improve the analyses, while the analyzing method is expected to be applicable.

According to Figure 5, the measured TTHM concentrations exhibit seasonal variation which can be estimated by the empirical predictive model and the NREL model-estimated water temperature. The TTHM measurements exhibit the highest level during the summer months—similar to the seasonal changes of temperature in the previous figures—and are likely attributable to the higher water temperature and TOC during these warmer months. The measured TTHM concentrations also exhibit greater variations in summer months than the two prediction series, indicating limitations with respect to the empirical predictive model (e.g., some other factors can contribute to higher TTHM concentrations in summer months and were not considered). The use of daily water temperature estimates from the NREL model provided daily TTHM concentrations (rightmost graph of Figure 5a) comparable to the prediction using measured water temperature (middle graph of Figure 5a), suggesting that the water temperature estimation model does not contribute to significant errors. For example, using the monthly water temperature measurements, the TTHM concentrations were predicted with an average absolute error of 6.76 ppb, as presented in the bottom left graph of Figure 5b. If the estimated water temperature from the NREL model was used (all other water quality parameters kept the same), the prediction is similar, with an average absolute error of 6.64 ppb in the bottom right graph of Figure 5b. Combining the techniques for estimating water temperature and predicting TTHM concentrations therefore provides an approach for assessing historical and future changes in average TTHM level that are caused by interannual changes in water temperature.

3.2.2. Estimated Changes in Water Quality Parameters for Washington D.C.

Similar to the estimation of daily TTHM concentrations in Figure 5a, the estimation of daily values of other water quality parameters and historical changes of these parameters as a result of the changes in water temperature (or air temperature) were assessed. The results are presented in Figure 6. These analyses were based on the equations presented in Table 1, which enable an efficient preliminary assessment of the effect of water temperature changes (both seasonally and interannually). The aggregate effect of water temperature changes on inter-related water quality parameters was also evaluated in a similar manner with the example of assessing bacterial activity, as presented in part Figure 6d.

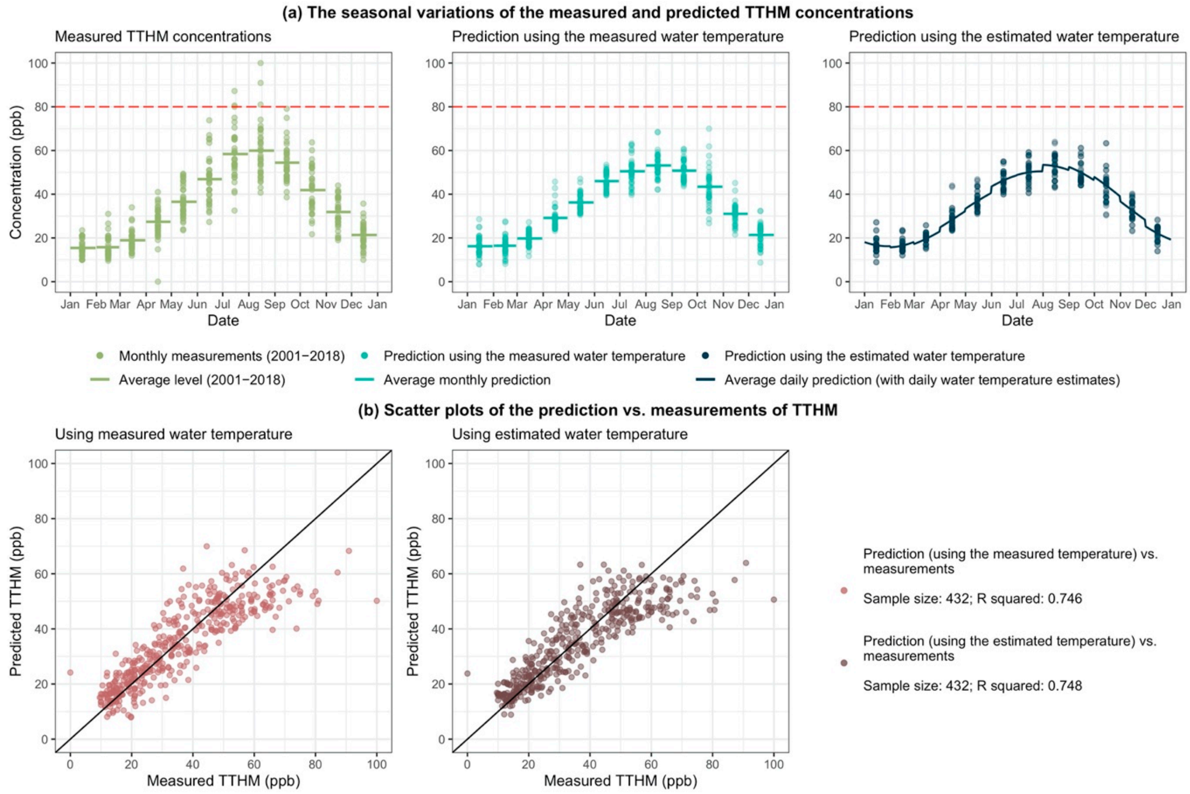

Figure 5. The measured and predicted TTHM concentrations for Washington D.C. with (**a**) seasonal variations of the monthly measured and predicted (using measured or estimated water temperature) TTHM concentrations for the same period 2001–2018; and (**b**) the comparisons between the predicted TTHM concentrations (with the use of measured or estimated water temperature) and the measured monthly average TTHM concentrations. The predictions were obtained using the empirical model presented as Equation (4) of Table 1. The measurements of TTHM concentrations were obtained from the treated water (measurements of TTHM in the DWDS are limited). As monthly measurements of other required parameter values were kept the same and used for the daily calculation in the rightmost graph of part (**a**), the daily estimates exhibit sudden shifts in different months. The red dashed lines in part (**a**) present the regulated level (80 ppb) for TTHM concentrations [75].

The estimated water quality parameters exhibit seasonal variations in similar sinusoidal patterns consistent with the seasonal changes in water temperature. Specifically, although site-specific water age information for the DWDS in Washington D.C. was not utilized, use of 30 and 75 h (based on the general water age information from a number of utilities [64,76]) yielded monthly chlorine residual levels similar to those available (the provided monthly median and 10th percentile level in the DWDS) from DC Water [77]. The seasonal variations in these parameters, as the previous analyses of TTHM concentrations suggested, are likely related to multiple factors including the higher temperature and the changes of other parameters such as higher TOC in summer months.

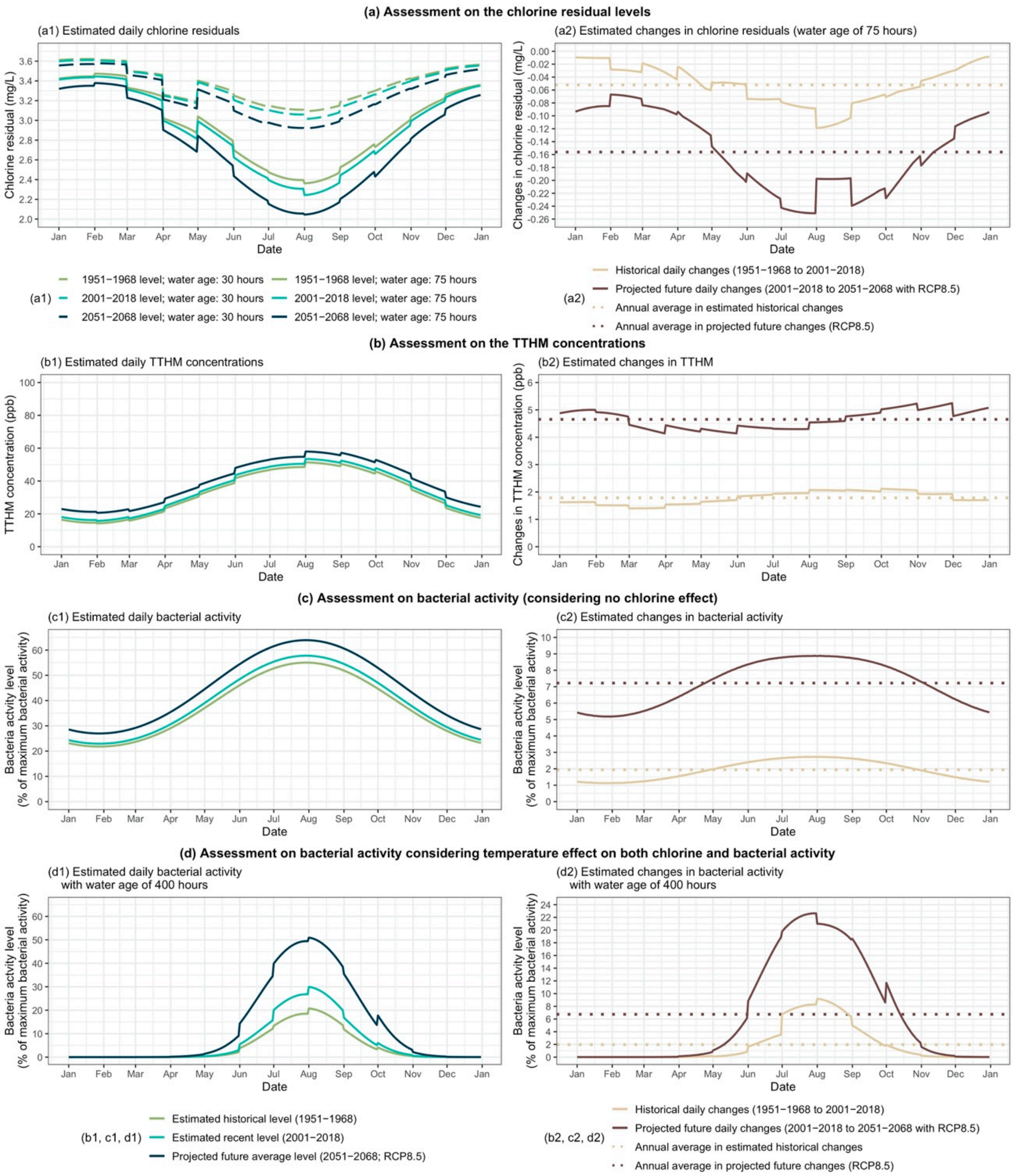

Figure 6. Estimated historical and projected water quality parameters and their changes for Washington D.C. with respect to daily (**a**) chlorine residuals with 30 h and 75 h water age values (considering only bulk decay); (**b**) TTHM concentrations in treated water; (**c**) bacterial activity (for fixed bacteria) considering no chlorine effect; and (**d**) bacterial activity (for fixed bacteria) considering the aggregate temperature effect on bacterial activity and chlorine residual (for a hypothetical location and an extreme case with a 400 h water age value). As monthly measurements of other required parameter values were kept the same and used for the daily calculation, the daily estimates exhibit sudden shifts in different months. The results of estimated bacterial activity are higher in part (**c**) than part (**d**) is because part (**c**) assumes no effect of chlorine.

The overall interannual changes of water quality parameters caused by the increase in ambient air temperature are not substantial during the assessed historical periods but can be intensified with higher air temperatures in the future. Several findings from Figure 6 merit particular attention. As presented in part Figure 6a–c, the estimated changes in the assessed water quality parameters are not substantial between the two historical levels, while further and greater changes are projected with the greater increase in air temperature. For example, the annual average chlorine residual with 75 h water age is approximately

2.8 mg/L, the average decrease in chlorine residuals between the two historical levels is approximately 0.05 mg/L and for the future, the chlorine residual is projected to further decrease by approximately 0.15 mg/L in annual average under RCP8.5. The effect of water temperature changes can be amplified with greater water age, as the comparison between the results of 30 h and 75 h water age suggest, and locations with high water age values can thus be more vulnerable to temperature changes. Additionally, a hypothetical extreme case (with a water age of 400 h throughout the year; more than 400 h of maximum water ages have been observed for some systems in the U.S. [64,76]) was assessed in part (d) of Figure 6, which provides some notable findings on the possible aggregate temperature effect. Specifically, a combination of temperature effects on chlorine residuals and bacterial activity yielded an increase of 8–9% of maximum activity during summer months from the 1951–1968 level to the 2001–2018 level and an increase of 20–23% from the 2001–2018 level to the projected 2051–2068 level for this hypothetical location.

3.2.3. Historical and Projected Changes in Water Quality Parameters across the 91 Cities

Using the water temperature estimates for the 91 U.S. cities, the historical and projected changes in the water quality parameters resulting from interannual ambient air temperature changes were evaluated and are presented in Figure 7. Two water quality parameters (the chlorine bulk decay rate and bacterial activity) were assessed.

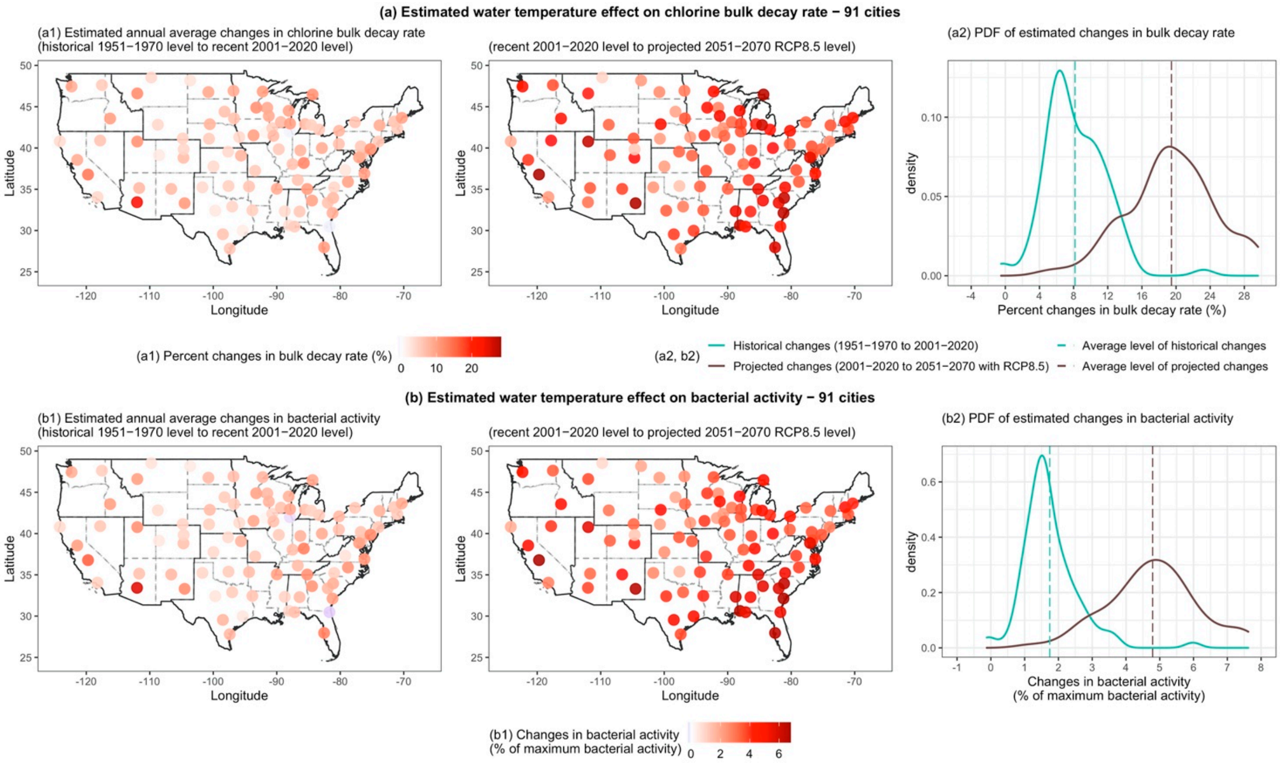

Figure 7. The estimated changes in (**a**) the chlorine bulk decay rate and (**b**) bacterial activity in DWDS for the 91 cities as a result of interannual water (or ambient air) temperature changes. The changes from the 1951–1970 level to the 2001–2020 level and from the 2001–2020 level to the projected 2051–2070 level (under RCP8.5) are presented. The percent changes in the chlorine bulk decay rate were calculated and are presented in part (**a**), while the results of the bacterial activity changes in part (**b**) are presented as absolute differences in percentages of maximum activity (similar to the differences in y-axis between two lines presented in plot Figure 6(c1)). Similar to part c of Figure 6, part b assumes no chlorine present or a chlorine level below the threshold concentration of suppressing bacterial activity. Solid lines around the boundaries of states in part (**a1**) and (**b1**) show the nine NOAA climate regions [73]. Similar to Figure 4, the results are directly based on the calculation of historical and projected air temperature and the interpretation of results for particular cities is subject to uncertainty. Further details are offered in Supplemental Material Section A.

The results in Figure 7 suggest that the estimated changes in the two water quality parameters are consistent with the estimated changes in water temperature. Notably, comparing Figures 4 and 7, the shapes of the PDFs among the 91 cities are similar for the changes in DWDS water temperature estimates and the changes in the two water quality parameters. Similar to water temperature, the overall effect from the interannual ambient air temperature changes on the water quality parameters is not substantial between the two historical levels, while the changes are projected to increase in the future. Results from Figure 4 suggested that a 1 °C increase in annual average ambient air temperature leads to a 1 °C increase in the annual average water temperature as estimated from the NREL model. As the temperature effect generally follows the Arrhenius expression for rate of reaction (for which, a 10 °C increase in temperature approximately doubles the reaction rate), the general expectations for the changes of water quality parameters can be obtained. The 91 cities on average exhibit an increase in water temperature of approximately 0.8 °C from the 1951–1970 level to the 2001–2020 level (Figure 4), and this increase in water temperature leads to an approximately 8 percent increase in the chlorine bulk decay rate (Figure 7). Considering that the U.S. average temperature is projected to increase (relative to the 1986–2015 level) 1.3–3.7 °C for a lower RCP scenario or 3.0–6.1 °C for a higher RCP scenario in the late 21st century [1], the magnitude of temperature changes is projected to be intensified, as also suggested by the results of Figure 7. Additionally, other factors such as high water age values at particular location of a DWDS and the aggregate temperature effect on multiple parameters can also amplify the effect of ambient air temperature changes and lead to potentially greater risks, as discussed in the previous sections.

3.3. Other Potential Assessments Using DWDS Water Temperature Estimates

In addition to drinking water quality, water temperature estimates for DWDS provide valuable information for several other processes related to DWDS, e.g., water main breaks and energy consumption in cold-water heating. Notably, many existing studies of water temperature in DWDS—including development of the NREL model [31] utilized in this work for water temperature estimates—were performed with a focus on energy. An increase in DWDS water temperature can likely yield benefits in energy savings from heating water and from fewer water main breaks for cities in colder regions. Because an increase in water temperature in DWDS can potentially reduce the amount of energy required for heating cold water, the increase in air temperature can thus lead to energy savings [20]. A comprehensive assessment of the water temperature profile in DWDS and potential future changes in water temperature can identify opportunities for system-wide drinking water management to increase energy efficiency [20]. Furthermore, DWDS water temperature, which is highly correlated with ambient temperature, as discussed previously, is also a critical factor in determining the number of water main breaks [37,41,78]. Specifically, the number of water main breaks increases when ambient air temperature decreases in winter months [37]. Although water temperature will generally increase as a result of increasing ambient air temperature, using future water temperature information and a comprehensive analysis of the water temperature profile of a particular DWDS can potentially facilitate identifying the most vulnerable water mains and optimizing resources, especially in the context of the challenges posed by the aging of drinking water infrastructure [79].

4. Summary, Conclusions, and Recommendations

Increasing challenges have been presented to many types of infrastructure by changing climate conditions, among which the effect of air temperature changes on drinking water temperature and water quality in DWDS merits some particular attention. As water temperature is a key parameter affecting chemical, physical, and biological processes in DWDS and is correlated with local air temperature, the main objective of this work was to assess in a preliminary manner the possible effects of increasing ambient air temperature on drinking water temperature and on temperature-related water quality parameters.

An existing water temperature estimation model, the NREL model, was identified and used to assess the water temperature changes in DWDS based on local ambient air temperature records. From the analyses for seven different locations including Washington D.C., the use of the standard parameter values for the NREL model can provide reasonable estimates of DWDS water temperature, and calibrating the parameter values of the NREL model for particular locations can improve the water temperature estimates especially in capturing the seasonal variations of daily water temperature.

The NREL model was utilized to evaluate DWDS water temperature changes between two historical periods and between a recent historical period and a future projected period for 91 U.S. cities. As the estimated changes in annual average levels of water temperature are determined by the average changes in air temperature in the NREL model, the estimated water temperature changes in annual average for the 91 cities are equivalent to their local air temperature changes, i.e., an approximately 0.8 °C increase from the 1951–1970 level to the 2001–2020 level or 2.2 °C increase from the 2001–2020 level to the projected 2051–2070 level under a higher scenario RCP8.5 (averaged across the 91 cities).

The water temperature estimates were then used to evaluate several temperature-related water quality parameters in DWDS. Analyses were performed for chlorine residuals, TTHM concentrations, and bacterial activity for Washington D.C. as a case study, while some preliminary evaluations of the historical and projected changes for two water quality parameters (the chlorine bulk decay rate and bacterial activity) were conducted for the 91 cities. Similar to the estimated changes in water temperature, the results suggest modest changes in the assessed temperature-related water quality parameters between the two historical periods, while the changes can continue to a greater extent in the future. Given the estimated changes in DWDS water temperature, the changes in the assessed water quality parameters are consistent with the general expectations from the Arrhenius expression for the effect of temperature on rate of reaction.

Several findings from the analyses merit particular attention. One notable finding is that an increase in water age can amplify the effect of water temperature changes. The aggregate effect from increasing water temperature on inter-related aspects of water quality such as chlorine decay, DBP formation, and bacterial activity can also lead to higher risks than the results from assessing individual parameters. Therefore, an assessment of extreme cases (e.g., with the highest water temperature in a year and at system locations with greatest water age, or considering the combination of effects) can be informative in providing safe drinking water. In addition to water quality, knowledge of the DWDS water temperature changes can provide valuable information and opportunities for DWDS management including the possible benefits from less energy required for heating water.

To advance understanding of the challenges and opportunities related to higher water temperature in DWDS as a result of increasing air temperature, additional assessments and development are needed. Possible pathways for future development include use of more comprehensive location-specific measurements of water temperature and water quality parameters in the DWDS for improving water temperature and water quality parameter estimation, incorporating an efficient mechanistic model for describing drinking water temperature applicable at different locations, and integration of distribution system modeling such as the use of EPANET-MSX [80], with regional climate projections and water temperature estimation.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/w13141916/s1, Supplementary Materials Section A: Ambient air temperature observations and projections, Section B: Estimating drinking water temperature, and Section C: Estimating temperature-related drinking water quality parameters.

Author Contributions: Conceptualization, Y.L. and D.A.D.; methodology, Y.L. and D.A.D.; formal analysis, Y.L.; writing—original draft preparation, Y.L.; writing—review and editing, D.A.D.; visualization, Y.L.; supervision, D.A.D.; funding acquisition, D.A.D. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: Data available in a publicly accessible repository: The historical air temperature data presented in this study are openly available in Carnegie Mellon University KiltHub repository at https://doi.org/10.1184/R1/7890488 (accessed on 6 January 2021). Third-party data restrictions apply to the availability of these data: Measurements of drinking water temperature and water quality parameters for Washington D.C. were obtained from the U.S. Army Corps of Engineers Washington Aqueduct and are available at https://www.nab.usace.army.mil/Missions/Washington-Aqueduct/Water-Quality (accessed on 11 August 2019). Measurements of the water temperature for the other six locations were obtained from Abrams and Shedd [24]. The GCM simulation results for the use of the G-ARIMA model can be accessed through the World Climate Research Programme's Working Group on Coupled Modelling [81].

Conflicts of Interest: The authors declare no conflict of interest.

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