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Estimating Urban Green Space Irrigation for 286 Cities in China: Implications for Urban Land Use and Water Management

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Abstract: Urban green space has increased significantly in many cities in China as a result of rapid urbanization. Despite various environmental and societal benefits of urban green space, its irrigation water use has become an important yet under-researched issue in urban water management. Using a newly developed green space evapotranspiration and soil water budgeting model coded in Python, this research estimated the irrigation water requirement of urban green space for 286 cities at the prefecture level and above in China, with daily meteorological data in 1986–2011, the distribution and areas of urban green space from the 30 m resolution "Essential Urban Land-Use Categories in China" database, and green space types from the 10 m resolution "10 m resolution global land cover" database. The estimated annual average irrigation water requirement of urban green space for these 286 cities was 8.7 billion m^3, accounting for over 20% of residential water consumption in the cities where data on residential water use were available. We also investigated the spatiotemporal variation of urban green space irrigation water requirement and the factors that influence such variations. To the best of our knowledge, this study develops the first set of results of urban green space irrigation for all major cities in China, thus providing useful insights for green space irrigation and urban water man-agement in the context of rapid urbanization and sustainable water management.

Keywords: urban green space; irrigation; evapotranspiration; remote sensing; water consumption

Citation: Pan, L.; Zhao, Y.; Zhu, T. Estimating Urban Green Space Irrigation for 286 Cities in China: Implications for Urban Land Use and Water Management. *Sustainability* **2023**, *15*, 8379. https://doi.org/10.3390/su15108379

Academic Editor: Giovanni De Feo

Received: 10 March 2023
Revised: 21 April 2023
Accepted: 18 May 2023
Published: 22 May 2023

1. Introduction

The urbanization rate in China reached 65% in 2022, and it is expected to continuously grow in the years to come [1]. The rapid development of the urban economy and increased urban population have led to a rapidly growing urban water requirement, aggravating the problem of urban water shortage in many cities [2,3]. As an important component of the urban environment, urban green space such as parks, forests, and residential greenery play an important role in promoting environmental sustainability, ecological integrity, and public health. Previous studies found that urban green space has crucial ecological benefits in protecting the urban environment [4], such as alleviating the heat island effect [5,6], reducing air pollution [7], and improving the urban microclimate [8]. In addition, urban green space also provides suitable places for outdoor activities of different age groups, which contributes to the physical and mental health of urban residents [9]. Nevertheless, to ensure the normal growth of green space vegetation, a large amount of irrigation water is needed every year, which brings great pressure to urban water supply and may exacerbate urban water shortage [10]. With the increase in urban green space rate and per capita green space area year by year [11,12], the contradiction between the shortage of urban water resources and increase in irrigation water requirement of urban green space is becoming increasingly prominent.

In recent years, studies have been conducted on water utilization in urban green space irrigation [9,13,14]. However, the heterogeneity in the spatial distribution of the vegetation and soil texture of urban green space makes it difficult to accurately estimate wide-ranging regional green space irrigation water requirement. Therefore, most existing studies focused exclusively on humid regions or only a few cities in arid regions. For instance, in the arid metropolitan area of Santiago, the Integrated Hydrological Model at the Residential Scale (IHMORS) hydrological model was used to simulate the irrigation water requirement of green space [13]. In the humid region of the Yangtze River Delta in China, a model was developed to quantify the irrigation water requirement of green space in 16 cities [14]. However, so far, a green space irrigation study that covers major cities in different climate zones across China has yet to be conducted. Such a study can help understand the difference in urban green space irrigation consumption under different climatic and soil conditions, as well as provide a big picture of irrigation water use for urban green space in the entire country.

On the one hand, to quantitatively estimate the irrigation water requirement of green space within a city, determining the total area of different types of green space is a prerequisite [15], and a variety of methods have been used for such purposes. For example, Google Earth Map is widely used to estimate urban vegetation coverage [16]. Using the "add polygon ruler" and "show rule" functions in Google Earth Map, Shi et al. [14] calculated the coverage ratio of trees/shrubs versus bare grassland, and the area data of urban green space reported in the China Urban Statistical Yearbook were adopted to obtain the areas of different types of green space vegetation [17]. Reyes-Paecke et al. [13] utilized high-resolution remote sensing data of land cover to extract the extent of green space and subsequently categorized urban green space into various types on the basis of their functional distinctions. Generally, these methods all used high-resolution land-use/cover remote sensing data to determine the scope and area of urban green space, only with differences in the methods of further distinguishing the type of green space vegetation.

On the other hand, the accuracy of the method also needs to be improved. In contrast to the distribution of a single crop in a large range of farmland, green space vegetations are more complex: they are usually mixed with trees, shrubs, and turfgrasses with different water requirements in a small range [18]. Although the methods of estimating crop irrigation water requirement have been well established, there are relatively few studies on the irrigation of urban green space vegetation. In addition, existing studies focused more on the irrigation of turfgrass [19,20], and the applicability of their approaches was limited by regions and climate [20]. So far, the Water Use Classification of Landscape Species (WUCOLS) approach proposed by Costello and Jones [21] is the most widely used for estimating irrigation water requirements of green space vegetation. It uses the vegetation coefficient to integrate the effects of species, density, and microclimate. WUCOLS can provide an initial estimate of irrigation requirement, which ideally should be further refined on the basis of conditions such as the health and aesthetics of urban green space vegetation. Other studies believed that green space irrigation water requirements mainly include plant evapotranspiration, vegetation growth water requirement, and soil moisture for maintaining vegetation survival. According to the principle of water supply and requirement balance, green space irrigation water requirement is the difference between the vegetation's total water requirement and effective rainfall [22]. The abovementioned IHMORS model was used to continuously simulate the soil moisture balance, including rainfall–runoff conversion, and irrigation requirements were estimated for green space in San Diego [13]. Given that the planning of green space varies vastly from city to city in China, and that the planting density and microclimate of different types of green space vegetation in the same city also vary greatly [21], those methods are relatively inappropriate for this study.

To address the above two research gaps, in this paper, we extracted and processed high-resolution land-use/land-cover remote sensing data and the data of areal distribution of urban green space vegetation for 286 selected cities at a prefecture level and above. A daily soil water balance model was set up to calculate urban green space irrigation water requirement for each city using long-term daily meteorological data, as well as green space areas, types, and distribution data that reflect the condition in year 2018. To the best of our knowledge, this is the first nationwide study on irrigation water requirement for urban green space; hence, it provides the first set of results for urban green space irrigation of major cities in China. By analyzing the temporal and spatial distribution of green space irrigation water requirement, this study revealed the diversity in urban green space water uses and identified the main factors influencing irrigation water requirement. The findings from this study can potentially be used to inform urban green space planning and management and urban water management.

2. Study Area

Our study estimated the irrigation water requirement of green space in 286 major cities. There are 297 cities at the prefecture level and above in mainland China; however, due to the lack of meteorological data and remote sensing data, 11 prefecture-level cities are not included in this study. Among the selected cities, Beijing, Shanghai, Tianjin, and Chongqing are the four major municipalities directly under the Central Government of China, while the remaining cities are distributed in 22 provinces and five autonomous regions. These 286 cities span across various climatic zones and cover a large geographical domain in China, with longitude ranging from 84°44′ E to 131°09′ E and latitude ranging from 18°09′ N to 50°11′ N. The 400 mm isohyets line is a geographically significant demarcation line between wet and dry areas, which is the boundary between semi-humid and semi-arid areas in China. Out of the 286 cities, 258 cities are located in humid or semi-humid areas, with the average annual rainfall from 1986 to 2011 ranging from 405 mm to 2671 mm; the remaining 28 are located in arid and semi-arid areas, with the average annual rainfall in 1986–2011 ranging from 16 to 394 mm.

3. Materials and Methods

3.1. Materials

Seven different categories of data were used in this study, as listed in Table 1. To determine the area of different types of green space vegetation, we further conducted data processing in the ArcMap software. First, the areas of turfgrasses, shrubs, and trees in urban green space were extracted from the "Essential Urban Land-Use Categories (EULUC) in China Dataset". The EULUC dataset was generated using 10 m satellite images, OpenStreetMap [23], nighttime lights, point of interest, and Tencent social big data in 2018 as input features, with training and verification datasets collected through crowdsourcing [24]. Lastly, the results of the basic categories of urban land use in China were generated on the basis of the input characteristics obtained in 2018. This is a secondary classification system, with an overall accuracy of 61.2% for Level I and 57.5% for Level II, verified by independent validation datasets. Parks and green space in EULUC determine the scope of urban green space.

Table 1. Data used in this study.

Category	Data	Period	Resolution	Source
Meteorology	Air temperature Air pressure Precipitation Relative humidity Wind speed Sunshine hours	1986–2011	Daily	[25]
Urban green space area composition	Scope of urban green space Proportion of green space area of turfgrass, shrubs, and trees	EULUC (2018) GLC (2017)	Area (30 m) Proportion (%)	[24] [26]

Table 1. *Cont.*

Category	Data	Period	Resolution	Source
Urban green space area	Area of green space (districts within a City)	2018	/	[17]
Soil hydraulic property	Field capacity/permanent wilting point	2019	30 arc s	[27]
Soil texture	Sand content Silt content Clay content	2018	/	[28]
Climatic region	400 mm isohyet	/	/	[29]
District boundary	Boundary of the district of the city	2018	/	[30]

The "Datav.GeoAtls" dataset provided by the Aliyun data visualization platform provided the boundaries of administrative districts in the 286 cities of this study [30]. The GLC 2017 dataset, of which the full name is "stable classification with limited sample: transferring a 30 m resolution sample set collected in 2015 to mapping 10 m resolution global land cover in 2017", provides 10 categorical indicators of land use in raster format, including grassland, shrubs, and trees under three plantations [26]. Furthermore, we also collected urban green space area data from the China City Statistical Yearbook [17]. Urban green coverage area is the vertical projection area of all plants within a certain land area, and the overlapping area of various plants is not double-counted.

To determine the shares of turfgrasses, shrubs, and trees in total urban green space area of each city, we processed the data in three steps:

(1) Determine the scope of urban green space using the "park and green space" item from the EULUC dataset.
(2) Use district boundary data of each citytaken from the "Data.GeoAtlas" database of Alibaba to determine the area of districts within each city.
(3) In ARCMAP, use the GLC2017 and EULUC land-use data as a mask to extract the area shares of turfgrass, shrubs, and trees within the green space area of each city.

3.2. Methods

3.2.1. Green Space Irrigation Water Requirement Model

The net irrigation water requirement for green space was computed using ET_0 and a soil water budgeting model, for each type of green space vegetation. Figure 1 illustrates the procedures of spatial data extraction and processing, as well as the steps to compute the net irrigation water requirement of urban green space. The volumetric irrigation water requirement was estimated according to the area of green space and net irrigation water requirement, for each type of green space in each of the 286 cities.

The SLIDE rules are a set of guidelines that leverages scientific assumptions regarding vegetation and the physical complexity of urban environments to estimate the watering needs of green spaces. The guidelines are conceptually accessible and operationally useful for estimating water requirement for a wide range of vegetation in urban green space vegetation type [20]. Moreover, they define a science-based regulator plant factor. Compared with the WUCOLS method for estimating water requirement of urban green space vegetation, SLIDE eliminates the comprehensive factors such as vegetation species, plant density, and microclimate factors as a function of a specific area proposed in the WUCOLS method, which greatly simplifies the calculation process and eliminates the computational complexity. Therefore, this paper used SLIDE to calculate the evapotranspiration of urban green space.

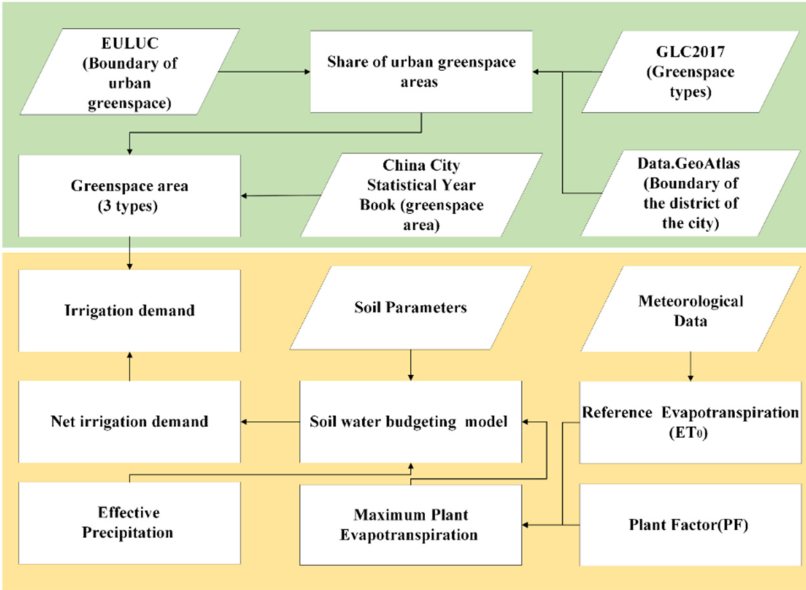

Figure 1. Flowchart illustrating the procedures of data processing and irrigation water requirement estimation.

This study used climatological methods to estimate the water consumption for green space irrigation in 286 cities at the prefecture level and above in China [15,31]. The calculation of the reference evapotranspiration of urban green space was based on the Penman–Monteith method [21], and the soil water balance method [31] was used to calculate the net irrigation water requirement, as shown in the following equation:

$$I_i(t) = (ET_{c,i}(t) - P(t) + RO(t) - D_{r,i}(t) + D_{r,i}(t-1)) \times A_i \ \forall t, \tag{1}$$

$$ET_{c,i}(t) = PF_i(t) \times ET_{0,i}(t) \ \forall t, \tag{2}$$

where t is a specific time period set by the calculation process. In our study, a daily timestep was adopted. The meteorological data came from the "China Surface Climate Data Daily Value Dataset (V3.0)" of the National Meteorological Science Data Center, and we used the daily data from 1986 to 2011. The subscript i represents different vegetation types, and we only considered three urban green space types: trees, shrubs, and turfgrasses. $I_i(t)$ is the net irrigation water requirement ($m^3 \cdot day^{-1}$) of green space i on day t. A_i is the green space coverage area of the urban built-up area. $ET_{0,\,\mathrm{i}}(t)$ is the reference evapotranspiration of vegetation. The FAO Penman–Monteith method was used to calculate reference evapotranspiration, using meteorological data. $ET_{c,i}(t)$ corresponds to the evapotranspiration of vegetation under standard conditions, which refers to crops grown in large fields under excellent agronomic and soil water conditions. The effects of various climatic conditions on evapotranspiration are included in ET_o, and the plant factor PF_s can accurately adjust the reference evapotranspiration to estimate vegetation evapotranspiration in different landscapes.

Runoff generation, $RO(t)$, was determined using the SCS curve number method, as follows:

$$CN = \frac{1000}{10 + 0.394S}, \tag{3}$$

$$RO(t) = \frac{(P(t) - 0.2S(t))^2}{P(t) + 0.8S(t)}, \ P > 0.2S \ \forall t, \tag{4}$$

where $RO(t)$ is the soil surface runoff, estimated by the SCS CN model. $S(t)$ is the maximum retention; after simplifying the model, max retention S is determined by and only by the curve number (CN). We used the "Spatial Distribution Data of Soil Texture in China" dataset of the Chinese Academy of Sciences to determine the soil type that accounted for the largest proportion in different cities. This study assumed that each city had its main soil type: sand was the main soil type in North China, Northwest China, and Northeast China, but sandy soil was the main soil type in Tibet; clay was the main soil type in South China; silty soil was the main soil type in East China and Central China. Lastly, the CN value of urban green space under different soil qualities was derived to estimate runoff [32].

The other variables related to the calculation of the net irrigation water requirement of urban green space were as follows:

$$TAW = 1000(\theta_{FC} - \theta_{WP})Z_r, \quad (5)$$

$$D_{r,i-1} = 1000(\theta_{FC} - \theta_{i-1})Z_r, \quad (6)$$

$$RAW = pTAW, \quad (7)$$

$$p = p_{table} + 0.04(5 - ET_c), \quad (8)$$

where TAW is the total available soil water in the root zone (mm), θ_{FC} is the water content at field capacity, θ_{WP} is the water content at wilting point, Z_r is the rooting depth (m), $D_{r,i-1}$ is the water content in the root zone at the end of the previous day ($i-1$, mm), θ_{i-1} is the average soil water content for the effective root zone, RAW is the readily available soil water in the root zone (mm), and p represents the p-average fraction of soil available water that can be consumed by roots before water stress occurs [0–1]. We first needed to determine the field capacity data and wilting coefficient of the soil planted with green space in each city. We used the "China Soil Hydrology Dataset for Land Surface Process Models" provided by the National Glacier, Permafrost, and Desert Science Data Center, which uses the pedotransfer function to estimate soil hydrological parameters with sand, silt, clay, organic matter, and bulk density as inputs, including the required field capacity and wilting coefficient data. The maximum effective soil depth Z_r of turfgrasses, shrubs, and trees was 0.3 m, 0.6 m, and 1.2 m, respectively [14]. This study assumed the arithmetic mean of field capacity and wilting coefficient as the mean value of effective soil water content in the root zone θ_{i-1} to initialize the water balance in the root zone. The part of TAW vegetation that can be extracted from the root zone without being subjected to water stress is the readily available soil moisture $RAW = pTAW$, and p varies with crop type. In this paper, the initial values of p for turfgrass, shrubs, and trees were all 0.5 [31]. The value of p can be adjusted according to $p = p_{table} + 0.04(5 - ET_c)$ which is affected by ET_c.

The soil water stress reduces the potential energy of soil moisture, making it more difficult for plant roots to absorb water. In moist soils, water has a higher potential energy and is more readily absorbed by plant roots. In dry soils, the potential energy of water is low, and it cannot be easily absorbed by crops; when the potential energy of soil water drops below a threshold, crops will experience water stress. The effect of soil water stress can be described by the crop water stress coefficient K_s [31]. The same goes for urban green space vegetation. To ensure the healthy growth of urban green space, we formulated an irrigation strategy that keeps the green space free from soil water stress; that is, we irrigated the green space vegetation to make the soil water reach the field capacity before soil water stress occurs. When it rains, if the sum of soil water deficit relative to the field capacity $D_{r,i-1}$ and maximum evapotranspiration of the vegetation i on that day $ET_{c,i}(t)$ is less than the sum of the readily available water in the soil $RAW_i(t)$ and the rainfall amount P_t in that day, irrigation is not needed; otherwise, if the sum of $D_{r,i-1}$ and $ET_{c,i}(t)$ is greater than the sum of $RAW_i(t)$ and P_t, irrigation is applied until the soil moisture reaches field capacity. However, in the absence of rainfall, when the soil water deficit relative to the field capacity $D_{r,i-1}$ and the maximum evapotranspiration $ET_{c,i}(t)$ is less than the readily available water in the soil $RAW_i(t)$, there is no need to irrigate the green space on that day; otherwise, irrigaiton is applied to bring soil moisture to the field capacity at the beginning of the day.

3.2.2. Mann–Kendell Trend Test

The Mann–Kendall nonparametric trend test method was used to detect the trend of annual net irrigation requirement for urban green space. Compared with the traditional parametric statistical method, this method is more suitable for analyzing the trend of data with non-normal distribution and deleted sequence data in hydrology and meteorology.

The principle of the Mann–Kendall nonparametric test method is to determine whether there is a trend change by calculating the permutation and combination of existing data, with the following steps:

Firstly, arrange the tested time series data $\{x_1, x_2, x_3, \ldots, x_n\}$ in the time order of their occurrence to form a strictly increasing sequence $\{x_1 < x_2 < x_3 < x_n\}$.

Then, calculate the permutation and combination of each pair of data in the time series, denoted as (x_i, x_j), where $i < j$, $i = 1, 2, 3, \ldots n-1$, $j = 1, 2, 3, \ldots n$.

Next, calculate the sum obtained by all permutations and combinations, and record it as S, i.e., $S = \sum(i,j)\ (xi - xj)$.

Lastly, compare the S value calculated by the Mann–Kendall test null hypothesis $S = \sum(i,j)\ (xi - xj)$ with S_0, where S_0 is the theoretical expected value of S in the case of no trend. If the actual value S is greater than S_0, the time series data are considered to have a positive trend; if the actual value S is less than S_0, the time series data are considered to have a negative trend. Otherwise, if the actual value S is equal to S_0, the time series data are considered no clear trend change.

4. Results

4.1. Urban Built-Up Area Green Space

Our research shows that the average green space area of all prefecture-level and above cities was 69 km^2, among which Longnan city had the smallest green space area, with only 3.22 km^2, since Longnan city has the lowest green coverage rate of only 23%, far below the average green coverage rate of all cities of 40.5%. Beijing had the largest green area of 712 km^2, which was directly related to its large urban built-up area and high green coverage rate of 48.44%. It is worth noting that Jingdezhen had the highest green coverage rate of 51.61%, far more than other cities, even though its green area was only 31.5 km^2. This shows that the area of green space is not completely related to the green coverage rate, and cities can maximize the use of limited green space resources to achieve a high green coverage rate through rational planning and design. In general, among the 286 cities at a prefecture level and above, 25% had an urban green space coverage less than 38.7% and a green space area smaller than 24.0 km^2, 75% had an urban green space coverage larger than 43% and a green area less than 69.6 km^2, and 50% had a green coverage greater than 41% and a green area larger than 36.5 km^2.

The 286 cities included in this study are distributed in 22 provinces, five autonomous regions, and four municipalities directly under the Central Government of China, with a total of 31 first-level administrative regions. Our study showed that Guangdong Province ranked first with 2524 km^2 of green space, 817 km^2 more than that of second place Shandong Province. This was largely related to the high green coverage in Guangdong Province, with an average of 45.14%, ranking third among the 31 first-tier administrative regions. In general, among the 31 first-level administrative regions, the average provincial built-up green area was 634 km^2, and, for 25% first-level administrative regions their weighted green coverage rate was less than 39.5%, with provincial green space area less than 348 km^2. In addition, 75% of the first-level administrative districts had a weighted green coverage of less than 42% and a green area of less than 750 km^2, while 50% of the first-level administrative districts had a weighted green coverage rate of more than 41% and a green area of more than 557 km^2.

4.2. Irrigation Water Requirement of Urban Green Space

4.2.1. Total Irrigation Water Requirement

For all the prefecture-level and above cities in this study, the average reference evapotranspiration was 1239 mm/year, the average annual precipitation was 977 mm/year, and the average net irrigation water requirements for turfgrasses, shrubs, and trees were 476, 392, and 334 mm/year, respectively. Therefore, it is necessary to reasonably select the type and quantity of green space vegetation according to different uses and needs, so as to save water and protect water resources to the greatest extent. Figure 2 shows the spatial distribution of the net irrigation water requirement for turfgrasses under different precipitation and evapotranspiration in all cities. Most cities in Northwest China were located in dry regions, with the lowest annual precipitation of 370 mm, while the evapotranspiration of urban green space was very high, resulting in the average net irrigation water requirement of green space in these cities being very large. For instance, the average net irrigation requirement in Turpan and Karamay even exceeded 1000 mm/year. However, in East and South China, where the climate is humid, the average net irrigation water consumption of most urban green space was less than the average of 476 mm/year. This highlights the climatic control of water requirement for green space irrigation.

(**a**)

(**b**)

Figure 2. Net irrigation requirement of turfgrass estimated with precipitation (**a**) and reference evapotranspiration (**b**) in 2018.

Among all the first-level administrative regions, the average irrigation water requirement of green space was 280 million m^3/year, with 25% of them being less than 162 million m^3/year, 50% being less than 216 million m^3/year, and 75% being less than 308 million m^3/year. Considering the number of prefectural cities with complete data in each province, Guangdong, Shandong, and Jiangsu provinces ranked top three in terms of irrigation water consumption of green space, at 1063 million m^3/year, 943 million m^3/year, and 581 million m^3/year, respectively. The main reason is that the GDP and built-up green space area of these three provinces ranked top three in China, making the total amount of water needed for irrigation of green space the largest. Among the four municipalities directly under the central government, Beijing, Shanghai, Tianjin, and Chongqing used 491 million m^3, 186 million m^3, 259 million m^3, and 110 million m^3 of irrigation water respectively, and their green coverage rates were 48%, 39%, 38%, and 40%, respectively. The average annual rainfall of cities in South China and East China exceeded 1100 mm. However, the average annual rainfall of cities in North China was only 448 mm; thus, the green space coverage rate and annual rainfall were the main factors influencing the green space irrigation water requirement. Therefore, it is necessary to rationally plan and allocate green space area to achieve sustainable urban development.

The total water demand for green space irrigation in the 286 cities was estimated to be 8.7 billion m^3 for the year 2018, equivalent to 10% of the national domestic water consumption in the same year [33]. This confirms that urban green space is a major consumer of urban water supply, as found by other studies for individual cities [31,34]. In addition, from the simulation results, we found that, among the three urban green space types, the irrigation frequency of turfgrasses is the highest, with an average interval of 19 days between two irrigation events, followed by shrubs with an interval of 50 days and trees with an interval of 141 days. However, considering the amount of irrigation each time, trees used the highest irrigation water amount, averaged at 91 mm per irrigation, followed by shrubs (45 mm per irrigation) and grassland (22 mm per irrigation).

4.2.2. Intra-Annual Distribution of Irrigation Water Requirement

With the urban built-up green space area of each city fixed at the year 2018 level, we summarized the monthly average net irrigation water requirement of first-level administrative regions distributed in seven geographical regions from 1986 to 2011, in order to explore the influence of climate factors on the irrigation water requirement of urban green space in time and space. Figure 3 shows that, except for South China, cities in the other six regions generally reached peak irrigation water requirement in April, and the minimum values occurred in January or December. In South China, the irrigation water requirement basically peaked in November, and the minimum occurred in June. Additionally, for many cities, more than half of the annual irrigation water requirement was concentrated in 4 months. These results indicate that the irrigation water requirement of urban green space is affected by various spatiotemporal and climatic factors. In addition to climatic factors, urban green space coverage and irrigation efficiency are important factors influencing urban green space irrigation water requirement.

4.2.3. Interannual Distribution and Climate-Driven Trends of Irrigation Water Requirement

In terms of the irrigation water requirement of built-up green space, in descending order, East China, South China, Central China, North China, Southwest China, Northeast China, and Northwest China accounted for 30%, 16%, 14%, 13%, 11%, 10% and 6% of the total irrigation water requirement of built-up green space, respectively. In terms of the mean annual rainfall of cities in each region, South China, Central China, East China, Southwest China, Northeast China, North China, and Northwest China ranked from first to seventh with values of 1729, 1207, 1105, 1024, 602, 448, and 370 mm/year, respectively.

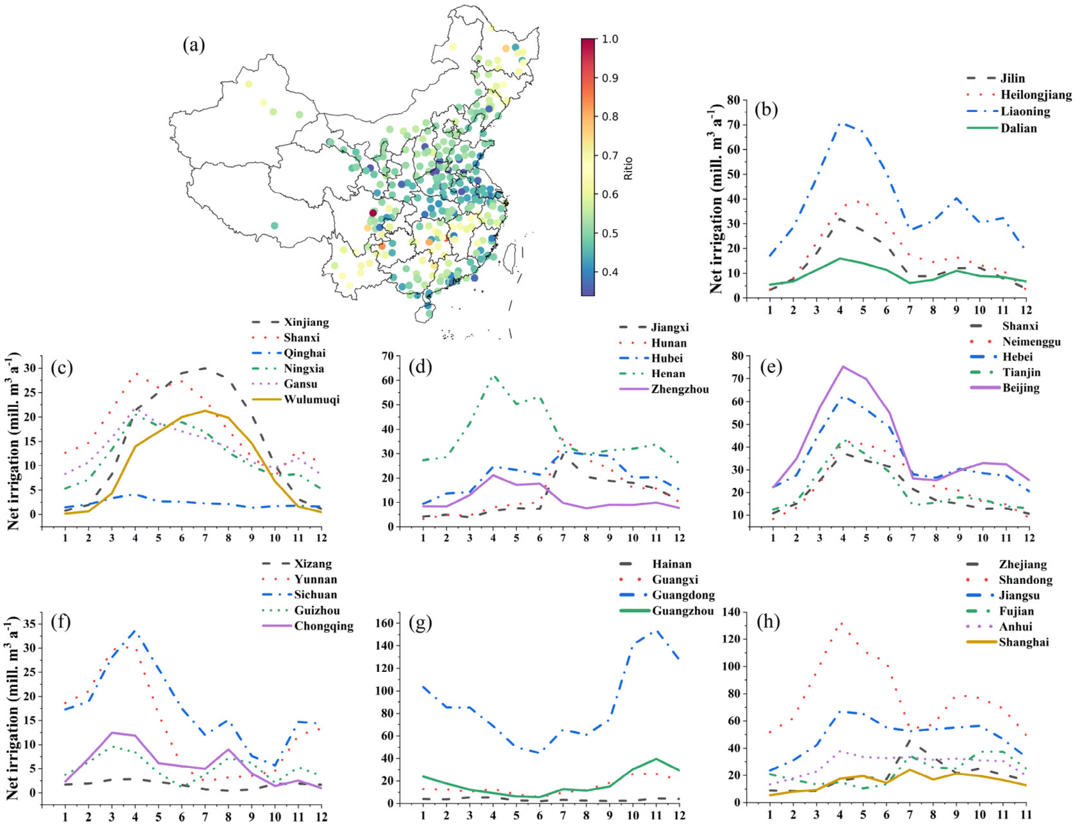

Figure 3. Monthly net irrigation water requirement in urban green space. The ratio of the largest value of total urban green space irrigation requirements in four consecutive months to that of average annual requirement of each city reflects the intra-annual concentration (**a**). The 31 primary administrative regions are distributed in seven major regions in China: East China (**b**), North China (**c**), South China (**d**), Central China (**e**), Northeast China (**f**), Northwest China (**g**), and Southwest China (**h**), ranked in descending order by built-up area. They accounted for 29%, 19%, 15%, 12%, 10%, 8%, and 6% of the total built-up area in the country, respectively.

With the green space area of each city fixed at year 2018 level, we summarized the net irrigation water requirement of first-level administrative regions in seven geographical regions from 1986 to 2011, so as to explore the temporal and spatial characteristics of annual green space irrigation water requirement in cities in different regions. On the basis of the net irrigation water requirements from 1986 to 2011, we analyzed the trends of 286 cities at the prefecture level and above in China. It is worth noting that these trends were exclusively climate-driven because the green space data were fixed at the 2018 level. In the nonparametric Mann–Kendall test, the trend of net irrigation water requirement for each city from 1986 to 2011 was calculated, and Sen's slope value was calculated, as shown in Figure 4.

In the Mann–Kendall test, Z_c statistics revealed the variation trend of urban net green space irrigation water requirement of 286 cities from 1986 to 2011. Without considering the sequence correlation, the results of the Mann–Kendall tests are shown in Figure 4. Among 286 cities, 14 cities showed a significant upward trend at the 5% confidence level, seven cities showed a significant downward trend at the 5% confidence level, and other stations showed no obvious trend. This means that the changing trend of water requirements for green space irrigation in most cities was not significant. However, that does not mean that these cities can ignore the vast water resources needed to irrigate urban green spaces. On the contrary, more attention should be paid to the selection and layout of green spaces in urban planning to reduce the water requirement of urban green space. Therefore, the Mann–Kendall test can provide useful information for urban planners and decision makers to make informed decisions in water management and urban planning. It helps identify those cities with significant trends in water requirement, enabling appropriate measures to mitigate the impacts of urbanization on water resources.

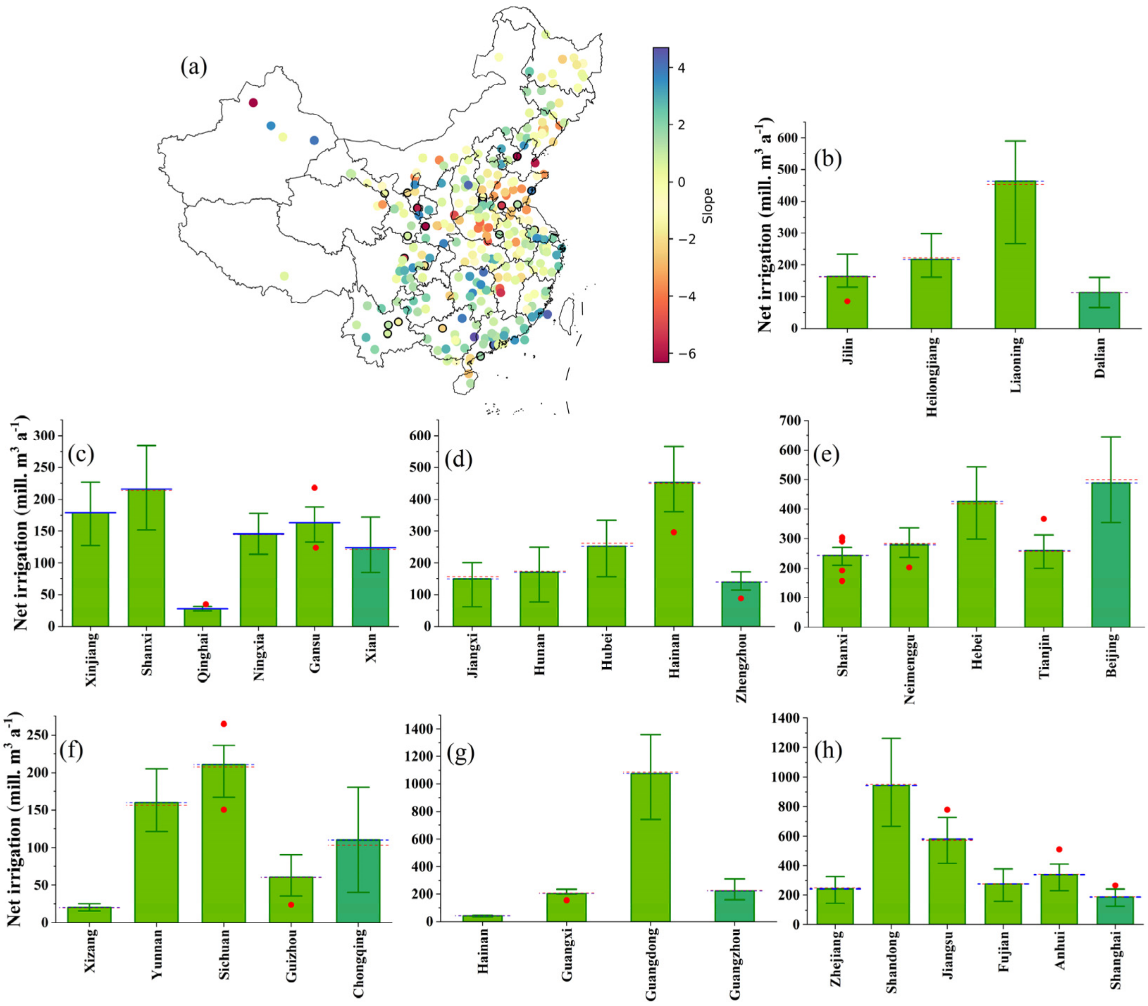

Figure 4. Net irrigation water requirement in urban green space: climate-driven trends of annual irrigation water requirement in each city (**a**) and interannual distribution of irrigation water requirement by province (**b**–**h**). The red dots indicate the presence of outliers; the bright green indicate different provinces located in the same geographic region, and the light green indicates a typical city in the region.

5. Discussion

Urban green space irrigation plays an important role in urban water management. It is also a vital indicator to measure urban water use sustainability. With rapid urbanization in China, urban green space will likely continue to expand [34]. Our study indicated that irrigation water requirement of urban green space is influenced by various factors such as climate, soil, vegetation type and the coverage and efficiency of irrigation systems. Although the Mann–Kendall test showed that the irrigation water requirement trend of most cities' net urban green spaces was not significant, it is necessary to recognize the enormous amount of water required for irrigating urban green space. Therefore, in urban planning and green space design, urban planners and decision makers need to consider the factors that influence the irrigation water requirement. We suggest using more efficient irrigation technologies to reduce water usage and alleviate the impact of urban green space on water resources. Urban green space irrigation technologies include sprinkler irrigation, drip irrigation, seepage irrigation, and irrigation with rainwater harvesting.

When choosing irrigation technologies, a comprehensive analysis of various factors such as green space type, tree species, soil conditions, and sources of irrigation water supply should be considered. For example, in arid and water-scarce areas, drip irrigation and seepage irrigation technologies can be used because they can reduce irrigation water losses to percolation and evaporation. In areas with high rainfall, rainwater harvesting technology can be used to store rainwater for green space irrigation. In addition, irrigation automation can adjust the applied irrigation water amount according to requirements, achieving water conservation and irrigation efficiency improvement. Therefore, when selecting urban green space irrigation technologies, multiple factors need to be considered to achieve the goal of conserving water resources, improving irrigation efficiency, and protecting the environment. Furthermore, this study emphasized the importance of selecting appropriate types of green space on the basis of local climatic and soil factors to achieve a balance between the ecological and economic benefits of urban green space irrigation, thereby promoting sustainable development and management of urban green space [35].

"The Code for Design of Outdoor Water Supply" stipulates that the irrigation water for urban green space is 1.5–2.0 L·m^{-2} each time [36]. In this paper, we defined irrigation frequency as the average number of days between two adjacent irrigation events. Simulated irrigation frequency depends on local climatic condition and the specific conditions of urban green space such as rooting depth and soil properties. The irrigation efficiency was computed for each city and green space type as a function of the inter-irrigation event duration from 1986 to 2011. Compared with Beijing's green space irrigation frequency of 66 times per year from previous literature, among the 286 prefecture-level cities, the calculated annual green space water consumption in most cities was far lower than the simulated value according to the soil water budget model in this study, indicating that almost all cities do not have enough water for green space irrigation to maintain the normal green space growth. In the long run, many ecological functions of urban green space will be greatly reduced. Therefore, the irrigation frequency of different green space and the minimum irrigation water determined by the soil water budget model could provide a reference for urban green space irrigation management, which is conducive to the sustainable irrigation of urban green space, while promoting the utilization of urban water resources and management [37].

By calculating the water requirement of urban green space irrigation, we found that the share of urban green space water requirement in total urban water consumption was significant, which provides a better basis for urban water utilization and management. Urban water conservation is critically important in China given the water-scarce situation in many places across the country. Therefore, cities should take the efficiency of urban water resource utilization into consideration when planning water supply and demand. The cities can improve the urban water resources utilization efficiency and promote the sustainable development of urban water resources by adopting measures such as reuse of reclaimed water, rainwater utilization, improved sewage treatment efficiency, and improved urban green space vegetation distribution and irrigation efficiency.

6. Conclusions

This paper quantitatively estimated the irrigation water requirements of green space in 286 cities at a prefecture level and above in China using detailed information of the scope, type, and spatial distribution of green space taken from high-resolution remote-sensing products. The estimated annual average irrigation water requirement of urban green space for all these 286 cities was 8.7 billion m^3, according to greenspace type, area, and distribution data obtained for 2018, as well as long-term daily meteorological data. To our best knowledge, this is the first set of results of urban green space irrigation requirement for all major cities across the country. Irrigation requirement was high in cities of an arid and semi-arid climate, where evapotranspiration is well above effective rainfall; in humid and semi-humid areas, however, green space irrigation was generally concentrated in months with low rainfall.

To improve urban water management, or for sustainable urban green space management per se, it is necessary to design effective water resource utilization and management schemes for urban green spaces, including the selection of appropriate green space types according to local conditions, improvement of rainwater utilization, and enhancement of public awareness about sustainable green space water uses. With country-wide results of urban green space irrigation, this study provides useful insights for future green space planning, especially for cities confronted with existing or emerging water scarcity.

Author Contributions: L.P., conceptualization, methodology, data curation, software, investigation, visualization, formal analysis, writing—original draft, and writing—review and editing; Y.Z., validation and writing—review and editing; T.Z., supervision, conceptualization, methodology, resources, writing—original draft, writing—review and editing, and funding acquisition. All authors have read and agreed to the published version of the manuscript.

Funding: This study was supported by the National Key Research and Development Program of China (2020YFA0608603) and the "Water–Energy–Food–Ecosystem Nexus in the Yangtze River Delta" project funded by Jiaxing City of Zhejiang Province, China. This study was also partially supported by the Dynamic Research Enterprise for Multidisciplinary Engineering Science of the ZJU-UIUC Joint Research Center through the "Center for Infrastructure Resilience in Cities as Livable Environments (CIRCLE)".

Data Availability Statement: All data used in this study are publicly available online, with sources provided in Table 1.

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

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