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Selection of Water-Saving Plants and Annual Water Consumption Estimation for Garden Green Spaces in Beijing

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Abstract: Currently, the number of urban garden green spaces (GGSs) being constructed in Beijing is increasing, and their high water resource demands contradict the severe water shortage situation in Beijing that is restricting urban construction and economic development. This has created an urgent need to build water-saving GGSs. This study analyzed and compared the daily/annual water consumption of 79 common plants in Beijing, and low-water-consumption (LWC) trees, shrubs and herbs were selected; additionally, the total annual water consumption (TAWC) of all plants in the built-up areas of all 16 districts in Beijing was calculated according to the result of the eighth general survey of landscaping resources in Beijing. The results are as follows: (1) fifteen LWC tree species were selected from among 25 species, and the average daily water consumption (DWC) was <1.09 kg·m^{-2}; (2) nineteen LWC shrubs were selected from among 35 shrubs, and the average DWC was <1.17 kg·m^{-2}; (3) eleven LWC herbs were selected from among 19 herbs, and the AWC was <460.3 kg·m^{-2}; (4) the TAWC of all trees, shrubs and herb plants in the Beijing GGSs was 1.104×10^9, 0.139×10^9, and 0.16×10^9 m^3, respectively. Based on the above results, it was estimated that the TAWC of all plants in the built-up areas of all 16 districts in Beijing is approximately 1.403×10^9 m^3. These findings provide a better understanding of the water consumption of GGS plants in cities in semiarid and semihumid climates and can be used to help select LWC greening plants that can reduce water consumption when expanding green areas in cities.

Keywords: water consumption; herb; shrub; tree; urban; water-savings

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1. Introduction

Water is recognized as the resource that is most critical for human survival, and it is also an important strategic resource for social and economic development and ecological environmental protection [1]. With intensifying global climate change and explosive population growth, industrialization and urbanization, two-thirds of the world's population (approximately 4.0×10^9 people) faces a serious shortage of water resources, nearly half of whom live in China and India [2–4]. The total amount of water resources in China is 2796.26×10^9 m^3, accounting for only 5.1% of the total global water resources. Therefore, the per capita water resources are small, at 2039.25 m^3, accounting for only 25% of the global per capita water resources [5]. The water resource shortages in many Chinese cities have greatly limited the urban modernization process in the country, threatening urban construction, economic development and quality of life [6,7].

As the capital of China, Beijing is its political and cultural center and is located in the western part of the North China Plain. It has a warm temperate monsoon climate, and the rainfall distribution is uneven. For example, the combined precipitation in spring, autumn and winter accounts for less than 30% of the annual precipitation, while summer precipitation accounts for more than 70% of the annual precipitation. At present, the per capita water resources in Beijing are approximately 123 m^3, which is only approximately 1/15 of the national per capita water resources and 1/55 of the global per capita water resources (7500 m^3) [5]; this is far below the internationally recognized lower limit of 1000 m^3 for per capita water resources; thus, Beijing is one of the most water-deficient cities in the world.

Urban garden green spaces (GGSs) are an important component of modern urban ecological civilization construction and are an important indicator of the degree of urban civilization and comprehensive service functions. Therefore, Beijing continues to construct urban GGS. From 2007 to 2017, the number of green trees in Beijing increased from 8.62×10^7 to 1.535×10^8, the GGS area increased from 4.56×10^4 to 8.35×10^4 hm^2, and the green coverage increased from 43.00% to 48.42% [8,9]. The realization of such a large-scale GGS project has improved the urban ecological environment of Beijing. However, to ensure normal plant growth, the amount of water needed for urban GGS vegetation has also increased. According to estimates, the evapotranspiration of Beijing's vegetation reached 667 mm in 2015 [10], which is much higher than the average annual precipitation of 585 mm in Beijing [11]. It is no longer sufficient to rely solely on natural precipitation to meet the needs of Beijing's urban GGS vegetation. The contradiction between the huge water resource demand by vegetation and the actual severe water shortage situation in Beijing has become a major problem that is restricting the city's construction of an ecological civilization and sustainable urban development. Therefore, to balance the water resource shortage and ecological construction of urban GGSs, it is of great importance to study methods for constructing water-saving GGSs to fully utilize urban water resources and promote the sustainable development of urban water resources.

The construction of water-saving GGSs directly involves the theory and practice of selecting water-saving plants, i.e., plants with LWCs and high drought tolerance should be selected. Currently, many scholars have analyzed the leaf anatomy [12] and photosynthetic physiology to determine the plant's water-saving ability [13], but plant screening through the transpiration water consumption law can more intuitively and accurately reflect the plant water consumption. To date, the plant species that have been studied related to plant transpiration and water consumption in Beijing include *Pinus bungeana*, *Fraxinus chinensis*, *Ginkgo biloba*, *Prunus davidiana*, *Lycium chincnse* [14], *Pinus tabulaeformis*, *Platycladus orientalis* and *Quercus variabilis* [15–17]. Shrubs include *Euonymus japonicus*, *Buxus microphylla*, *Euonymus kiautschovicus*, *Kerria japonica* [18], etc. Herbs include *Poa pratensis*, *Festuca arundinacea*, *Lolium perenne*, *Cynodon dactylon*, *Buchloe dactyloides*, *Zoysia japonica* [19], etc.

The difference in plant species will also lead to different water demands for urban GGSs. Therefore, it is necessary to determine the water consumption rules of plants, which is the premise for selecting water-saving plants, reducing GGS water consumption, and building water-saving GGSs. After clarifying the water consumption rules of plants, it is not only possible to select water-saving plants according to their water consumption per unit of time, but also to expand the plant water consumption over time and space and then estimate all plant water consumption in Beijing. From a macroscopic point of view, it is extremely important to determine the amount of water that urban GGSs consume, rationally allocate water resources among various water industries, use water-saving practices when managing GGSs and formulate a water resources strategy for Beijing. The commonly used methods for estimating plant water consumption at the regional scale are remote sensing and the climatological method. The climatological method is based on many related empirical equations, such as the Penman–Monteith [20], Thornthwaite [21], and Makkink equations [22]. The research objects of this method are mostly uniform grassland and farmland crops [23], and a large deviation may occur if it is adopted for the urban GGSs studied in this paper. Remote sensing is the most economical and effective estimation method for performing a large-scale study of transpiration [24,25]. However, urban GGSs have small and fragmented landscape patterns. The classification results from low- and medium-resolution remote sensing images cannot reflect the heterogeneity of plants inside these GGSs, as high-resolution remote sensing images are not accurate at the point and quadrat scales [25]. The data in this study come from a general survey that not only includes an urban green garden space resource survey and determines the number of urban GGS plants in Beijing, but also measures the detailed growth indicators of each plant; thus, the estimates have higher discrimination and greater accuracy. Many studies have used general survey data to estimate the water consumption of GGS plants. In 1998, Chen et al. studied the green level of the 37 most commonly used and representative garden plants in the eight districts of Beijing and estimated that the combined annual water consumption of the green areas of the eight districts of Beijing was 439 million tons by measuring the annual water demand of the leaf area [26]. In 2004, Zhang et al. used the green amount method to calculate the annual water consumption of common trees and shrubs in Beijing with a breast diameter of 15 cm [27]. Che expanded the time and space scales according to the water consumption rules of 35 common garden plants in Beijing and estimated that the annual water consumption of the main vegetation in eight districts of Beijing was 389 million tons [28]. In 2015, a census was again conducted in Beijing. Compared to the previous 10 years, i.e., since 2005, the urban garden green space construction scale had rapidly increased. At the same time, the built-up area of Beijing surveyed also expanded from the previous eight districts to 16 districts. Therefore, calculating the current water consumption of urban greening tree species is crucial for the management and full utilization of Beijing's urban water resources.

In summary, this study will compile relevant research results, analyze and compare the water consumption amounts of common green plants in Beijing, and identify excellent water-saving plants such as native and perennial plants that are suitable for the Beijing urban scape. Moreover, this study will estimate the TAWC of trees, shrubs and herbs of the GGSs in the built-up areas of 16 districts in Beijing based on the results of the eighth landscaping resources survey. The findings will also provide a better understanding of the amount of water GGS plants in semiarid and semihumid climate cities consume and help to select LWC greening plants that can reduce water consumption when expanding green areas in cities.

2. Materials and Methods

2.1. Selecting the Water-Saving Plants to Use in the Green Areas of Beijing

By consulting the relevant literature (in Tables A1 and A2 and Chapters 3.1.3), the water consumption levels of the main plants in Beijing, including trees, shrubs and herbs, are compared and summarized. In the literature, different plants' water consumption amounts are calculated via direct reference or according to equations, such as Equation (1) [15]. Although the studies may differ in their water consumption amounts for the same plant, the average value was obtained from the different research results, and the DWC of a plant was then obtained. Finally, the water consumption amounts of 79 plants (25 trees, 35 shrubs and 19 herbs) were determined, where the water consumption for trees and shrubs was the DWC per unit of leaf area, and the water consumption for herbs was the AWC per area [15,28]. Sorting plants according to the water consumption amount revealed differences in the water consumption capacities of various plants to identify LWC plants.

$$E = \sum_{i=1}^{j}[(e_i + e_{i+1}) \div 2 \times (t_{i+1} - t_i) \times 3600 \div 1000] \times 18 \quad (1)$$

where E is the transpiration water consumption of the plant throughout the day, g; 18 is the molar mass of water; e_i is the instantaneous transpiration rate of the initial measurement point, mmol·m^{-2}·s^{-1}; e_{i+1} is the instantaneous transpiration rate of the next measurement point, mmol·m^{-2}·s^{-1}; t_i is the measurement time of the initial measurement point, h; t_{i+1} is the measurement time of the next measurement point, h; j is the number of measurements; 3600 converts h to s; and 1000 converts mol to mmol.

The water consumption results of certain plants were measured as the AWC per unit of leaf area, and these data were converted into the DWC using Equation (2) [28].

$$\mathrm{W_d} = \mathrm{W_a}/190 \tag{2}$$

where $\mathrm{W_d}$ (g·m^{-2}) is the DWC per unit of leaf area, $\mathrm{W_a}$ (g·m^{-2}) is the AWC per unit of leaf area, and the AWC is calculated over 190 days from the beginning of April to the end of October.

2.2. Estimation of the AWC of the Trees, Shrubs and Herbs in the GGSs in Beijing

The estimated water consumption data were based on the results of the eighth general survey of landscaping resources in Beijing (2013–2015) (which is referred to as the general survey hereafter) [29]. The general survey included two items, i.e., the forest management inventory and the urban GGS resources survey, that were organized by the Beijing Municipal Landscaping Bureau. This general survey was prepared in 2013, and the field survey began in May 2014, and ended in December 2014. A total of 381 investigation teams were formed in built-up areas of 16 districts and counties in the city, with 2403 technicians and nearly 10,000 nonprofessionals directly or indirectly involved in the investigation. These research data mainly came from the survey of urban GGS resources, which is the basic work used to comprehensively and accurately grasp the development status of urban GGSs in Beijing. The method uses sub-compartments of GGSs as the survey units, including green park management units, such as parks and nurseries, or district/county-level administrative areas. In this study, 1,448,321 pieces of data from the urban GGS resource survey were obtained, and calculations and analyses were conducted according to different tree, shrub and herb species.

According to a statistical analysis of the general survey, the spatial scale of plant water consumption was expanded. Through diameter at breast height (DBH) daily water consumption and DBH-leaf area models, the water consumption of 13 tree species was extended to different diameter classes. For coniferous trees, the water consumption of the individual trees in this class of trees was the average water consumption for the individual trees of *P. tabulaeformis* and *P. orientalis*, and the TAWC was estimated in the same manner. The leaf area of individual trees and the AWC per of unit leaf area of broad-leaved trees were calculated as the average for 8 tree species, such as *Ailanthus altissima*, and the TAWC of broad-leaved trees was estimated in the same way. Shrubs were considered according to their leaf area index and green surface area and were mainly divided into the following four categories: deciduous shrubs, hedges, shrub balls, and evergreen coniferous shrubs. The water consumption of herbs was calculated based on the herb area and AWC per area. Finally, the total water consumption of the trees, shrubs and herbs in the GGSs in Beijing was determined. The GGSs in Beijing were mainly found in the built-up areas of 16 districts, including Haidian, Chaoyang, Xicheng, Dongcheng, Fengtai, Shijingshan, Mentougou, Fangshan, Shunyi, Changping, Tongzhou, Daxing, Huairou, Pinggu, Miyun and Yanqing Districts, with a total green area of 83,501.3 hm^2, accounting for 5.09% of the total Beijing city area [10].

2.2.1. Tree Water Consumption Scale Expansion Method

The water consumption amounts of individual trees of different diameters of the five species of *P. tabulaeformis*, *P. orientalis*, *Acer truncatum*, *Ginkgo biloba* and *Robinia pseudoacacia* was calculated using diameter-water consumption models depending on the different diameter classes, as listed in Table 1 [15]. The model in Table 1 directly measures the sap flow rate of the plant sapwood through thermal dissipation sapwood sap flow velocity probe (TDP) technology, and then obtains the transpiration water consumption of the tested single plant. The experimental sites of *P. tabulaeformis*, *P. orientalis* and *A. truncatum* are in the Beijing Botanical Garden. The *G. biloba* and *R. pseudoacacia* experimental sites are on the campus of Beijing Forestry University. The above tree species were continuously observed for two years. Both experimental sites are within the scope of the Beijing urban garden green space (GGS) studied in this paper and are representative. The resulting model is suitable for estimating the water consumption amounts of these trees in the Beijing urban GGS in this study.

Table 1. Diameter-water consumption models of trees.

Species	Diameter-Water Consumption Models	Correlation Coefficient
Pinus tabulaeformis	$W = A \cdot V \cdot T/1000 = 0.594D - 0.009D^2 - 3.685$	R = 0.99
Platycladus orientalis	$W = A \cdot V \cdot T/1000 = 0.542D - 0.006D^2 - 3.488$	R = 0.98
Acer truncatum	$W = A \cdot V \cdot T/1000 = 0.931D - 0.007D^2 - 6.996$	R = 0.95
Ginkgo biloba	$W = A \cdot V \cdot T/1000 = 0.362D + 0.027D^2 - 1.694$	R = 0.95
Robinia pseudoacacia	$W = A \cdot V \cdot T/1000 = 0.118D^{1.533}$	R = 0.99

Note: A is the area of sapwood (cm^2), V is the sap flow velocity ($cm \cdot s^{-1}$), T is the time of day (s), D is the diameter of the tree (cm), W is the daily water consumption (kg), and R is the correlation coefficient.

The trunk sap flow is generally measured from the beginning of April to the end of October. *P. orientalis* experiences normal sap flow throughout April, and *Sophora japonica* experiences normal sap flow only until 1 May, while the sap flow in the other tree species occurs around 20 April. Therefore, when calculating the AWC, that of *P. orientalis* was calculated over one month, i.e., April, while that of *S. japonica* was not determined in April, and that of the other tree species was calculated over 10 days in April [15].

Scale expansion of the water consumption of broad-leaved trees refers to the regression model of the DBH and the leaf area proposed by Chen et al. [26], as summarized in Table 2. In this model, the leaf area of different individual trees was calculated based on the DBH, and the water consumption of the entire tree was then computed based on its water consumption per unit of leaf area and its leaf area.

Table 2. DBH-leaf area models of broad-leaved trees.

Species	DBH-Leaf Area Models	Correlation Coefficient
Koelreuteria paniculata	$S = 13.60D - 62.87$	R = 0.9102
Ailanthus altissima	$S = 14.57D - 101.43$	R = 0.8431
Platanus acerifolia	$S = 22.48D - 38.48$	R = 0.8726
Sophora japonica	$S = 13.56D - 61.87$	R = 0.8939
Populus tomentosa	$S = 10.01D - 64.179$	R = 0.9512
Fraxinus chinensis	$S = 23.89D - 197.60$	R = 0.8437
Salix babylonica	$S = 12.07D - 65.21$	R = 0.8510
Paulownia	$S = 11.57D + 5.10$	R = 0.6708

Note: S for leaf area (m^2); D for diameter (cm); R for correlation coefficient.

The models in Tables 2 and 3 are derived from Chen Zixin's (1998) research [26]. In 1998, Chen Zixin conducted a large number of field measurements on the green quantity of the 37 most commonly used and representative plants in urban garden green spaces in Beijing's eight districts (the number of plants accounted for 81% of the city's total, including 15 trees, 17 shrubs and 5 herbs), for a total of 870,000 plants. According to the correlation between the leaf area of different plants and the diameter at breast height, crown height or crown width, a regression model for calculating the individual leaf area of different plants was established. Therefore, the research area of the relevant model is within the GGSs in the built-up areas of the 16 districts in Beijing in this study, and it is also applicable for estimating the water consumption of related plants in the Beijing urban GGS estimated in this study.

Table 3. Leaf area models of deciduous shrubs.

Species	Regression Equation
Syringa pekinensis	S = 3.8H + 5.02C − 10.34
Prunus triloba	S = 8.2H + 9.42C − 20.17
Hibiscus syriacus	S = 4.31H + 9.47C − 20.9
Lagerstroemia indica	S = 5.62H + 4.24C − 9.7
Kerria japonica	S = 0.98H +1.46C − 2.24
Cercis chinensis	S = 1.31H + 1.99C − 3.03
Cercis chinensis	S = 5.14H + 7.5C − 17.93
Weigela florida	S = 4.37H + 5.91C − 11.11
Forsythia suspensa	S = 1.26H + 1.29C − 2.47
Lonicera maackii	S = 7.09H + 6.08C − 16.31
Rosa cultivars Floribunda	S = 2.29H + 1.66C − 2.18

Note: S for leaf area (m^2); C for crown width (m); H for plant height (m).

According to Equation (3) [28], the water consumption amounts for different diameter classes of each tree species were calculated, and the total water consumption amounts of all diameter classes of each tree species were summed according to Equation (4) [28].

$$Q_i = Q \times N \tag{3}$$

where Q is the AWC of the individual trees in diameter class I, Q_i is the AWC of all trees in diameter class i, and N is the number of all the trees in this diameter class.

$$Qn = \sum_{i=1}^{n} Qi \tag{4}$$

where Qn is the total water consumption of all diameter classes of a certain tree species, n is the number of diameter classes of a certain tree species, and Q_i is the AWC of all trees in diameter class i.

2.2.2. Shrub Water Consumption Scale Expansion Method

To estimate the AWC of the shrubs in the GGSs in Beijing, the shrub water consumption per unit of leaf area was spatially expanded, and the key point was to calculate the leaf area [30]. In urban GGSs, the main shrubs were single plants, hedges, shrub balls, etc., and they were also divided into the categories of deciduous and evergreen shrubs. Therefore, this paper mainly divided shrubs into deciduous shrubs, shrub hedges, shrub balls, and evergreen coniferous shrubs and then estimated the water consumption of all shrubs.

(1) Deciduous shrubs

The water consumption expansion method of deciduous shrubs was similar to that of certain broad-leaved trees, and the water consumption scale was also expanded by the leaf area model of Chen et al. (1998) [26], as summarized in Table 3. According to the model, the leaf area of an individual shrub was calculated, and the annual shrub water consumption per-area was then calculated by using Equation (5) [28], while the TAWC of all deciduous shrubs was determined with Equation (6) [28].

$$Q = Q_d \times 190 \tag{5}$$

where Q ($kg \cdot m^{-2}$) is the AWC per unit of leaf area, and Q_d ($kg \cdot m^{-2}$) is the DWC per unit of leaf area. The number of days in the AWC calculation is 190 days based on the DWC time scale expansion.

$$Q_t = Q \times S_d \times N \tag{6}$$

where Q_t (m^3) is the TAWC of all shrubs, Q ($kg \cdot m^{-2}$) is the AWC per unit of leaf area of the shrub, S_d (m^2) is the plant leaf area of the shrub, calculated with the model in Table 3, and N is the actual number of deciduous shrubs, obtained from the general survey in Beijing.

(2) Hedges

The method for calculating the green surface area of shrub hedges usually follows the cuboid surface area calculation equation, and the green surface area is calculated according to the leaf area index [31]. The product of the green area and leaf area index of the green surface is the total hedge leaf area. The green surface area is the sum of the upper surface area of the hedge and the two side surface areas. The leaf area index is based on the results of Ma et al. [15]. The green surface area and total leaf area of the hedge were calculated with Equations (7) and (8), respectively [28]. Then, the TAWC of the hedge was calculated with Equation (9) [28].

$$S_s = S + 2aS/b \tag{7}$$

where S_s (m^2) is the green surface area of the hedge, a is the hedge height, b is the hedge width, and S (m^2) is the area covered by the hedge. The hedge height is generally 0.6 m, and the width is 0.8 m.

$$S_t = S_s \times K \tag{8}$$

where S_t (m^2) is the total leaf area of the shrub hedge, S_s (m^2) is the area of the actual green surface of the hedge, and K is the leaf area index of the hedge.

$$W = S_s \times K \times W_a \tag{9}$$

where W (m^3) is the TAWC of each hedge, S_s (m^2) is the green surface area of the hedge, K is the leaf area index of the hedge, and W_a is the AWC per leaf area of the hedge.

(3) Shrub balls

The water consumption of the shrub green ball was calculated according to its water consumption per unit of leaf area, leaf area index and surface area, as expressed in Equation (10) [28].

$$W = W_s \times S \times K \tag{10}$$

where W (kg) is the water consumption of a single shrub green ball, W_s ($g \cdot m^{-2}$) is the water consumption per unit of leaf area of the shrub green ball, S (m^{-2}) is the surface area of the shrub green ball, calculated as a hemispherical area, and K is the leaf area index of the green ball, based on the results of Ma et al. (2009) [12] and Che (2008) [16].

The water consumption Q of each green ball was calculated according to Equation (11) [28]. The shrub green ball diameter is 1 m.

$$Q = W \times n \tag{11}$$

where Q (m^3) is the total water consumption of all shrub balls, W (kg) is the water consumption of a shrub green ball, and n is the number of shrub balls.

(4) Evergreen coniferous shrubs

The coniferous shrubs in the GGSs in Beijing are mainly *Sabina procumbens* and *Sabina vulgaris*. The method for calculating the water consumption of these shrubs entails obtaining the total leaf area from the green surface area and leaf area index. The leaf area index was obtained from the results of Ma et al. (2009) [15], and the total water consumption Q was calculated using Equation (12) [28].

$$Q = S \times K \times W \tag{12}$$

where Q (m^3) is the total water consumption of each shrub, S (m^2) is the actual shrub area, K is the leaf area index of a shrub, and W ($kg \cdot m^{-2}$) is the shrub water consumption per unit of leaf area.

2.2.3. Herb Water Consumption Scale Expansion Method

The AWC of herbs was calculated from the herb area and water consumption per-area, as expressed in Equation (13) [28].

$$Q_t = Q_d \times S_t \tag{13}$$

where Q_t (m^3) is the TAWC of each herb, Q_d ($kg \cdot m^{-2}$) is the AWC per unit of herb, and S_t (m^2) is the herb area.

The above research structure diagram is shown in Figure 1.

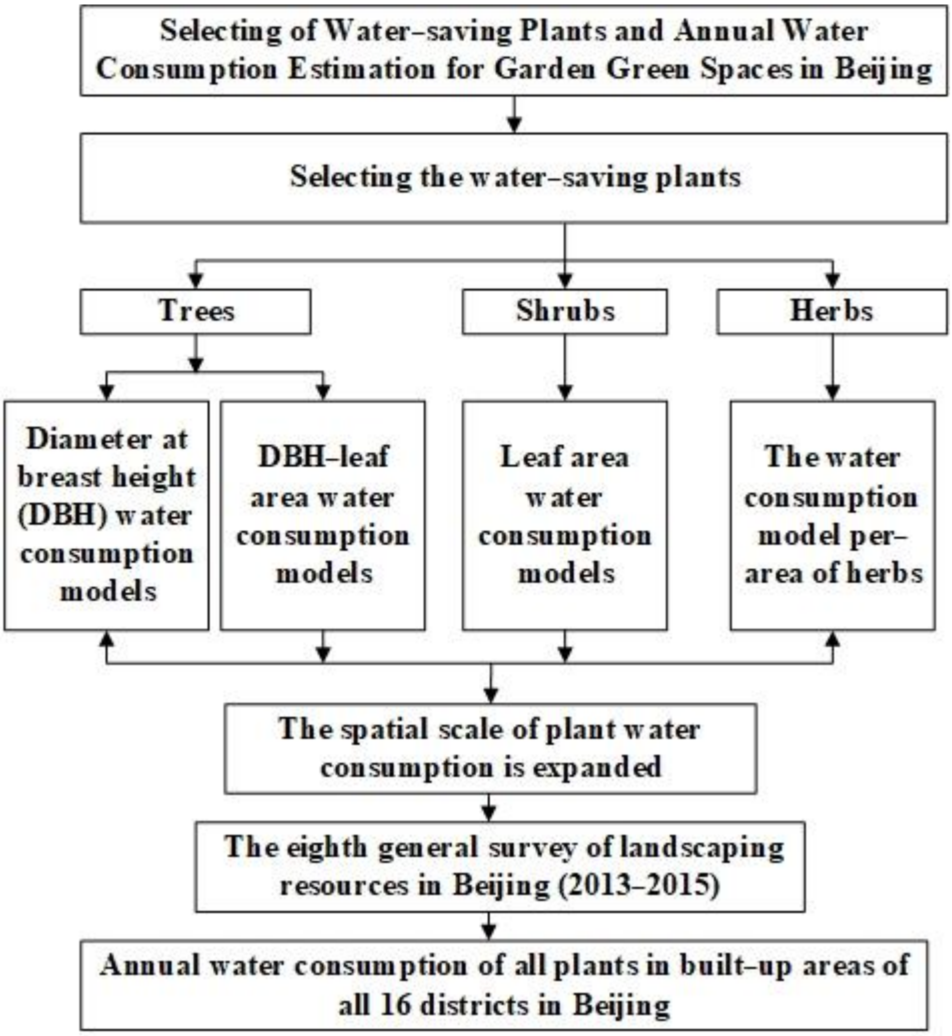

Figure 1. The research structure diagram.

3. Results

3.1. Selecting the Water-Saving Plants

Through a comprehensive comparative analysis of the literature, the water consumption levels of 79 plant species were calculated, where those of trees and shrubs are the DWC per unit of leaf area ($kg \cdot m^{-2} \cdot d^{-1}$) and those of herbs are the AWC per area ($kg \cdot m^{-2} \cdot a^{-1}$).

3.1.1. Selecting LWC Trees

Twenty-five types of common trees in the GGSs in Beijing were selected as research objects for the DWC unit leaf area comparison (Appendix A, Table A1).

The DWC range of 25 trees was 0.49–1.90 $kg \cdot m^{-2}$. The DWC of *M. denudata* was the highest and was 3.88 times that of *P. bungeana*, which had the lowest DWC. The average

DWC of the 25 tree species was 1.09 kg·m^{-2}. Fifteen tree species had lower than average DWCs and are as follows in descending order: *M. micromalus*, *R. pseudoacacia*, *P. acerifolia*, *S. japonica*, *Q. variabilis*, *G. biloba*, *R. chinensis*, *Q. dentata*, *R. Typhina*, *A. altissima*, *P. tomentosa*, *S. chinensis cv. Beijingensis*, *P. bungeana*, *P. tabuliformis*, and *P. orientalis*.

3.1.2. Selecting the LWC Shrubs

According to the literature, the DWCs of 35 shrubs common to Beijing GGSs were selected (Appendix A, Table A2).

The DWC range of the 35 shrubs was 0.27–2.42 kg·m^{-2}, and the average DWC was 1.17 kg·m^{-2}. Nineteen shrub species had a lower than average DWC and were as follows in descending order: *F. suspensa*, *H. rhamnoides*, *C. Korshinskii*, *S. oblata*, *L. chinensis*, *B. thunbergii*, *C. coggygria*, *B. sinica subsp. sinica var. parvifolia*, *S. pekinensis*, *B. megistophylla*, *L. bicolor*, *L. vicaryi*, *W. florida*, *M. dioica*, *S. salicifolia*, *A. fruticose*, *A. davidiana*, *S. vulgaris*, and *S. procumbens*.

3.1.3. Selecting the LWC Herbs

Based on the herb water consumption research results of Zhao et al. (2003), Sun et al. (2004), Ma et al. (2009), Sun et al. (2007), and Guo et al. (2014) [15,19,32–34], the AWC per unit of green space area of 19 common herbs in Beijing are summarized (Appendix A: Table A3).

The average AWC of herbs is 460.3 kg·m^{-2}, and *S. spectabile*, *R. japonicus*, *C. morifolium*, *I. tectorum*, *S. aizoon*, *I. lacteal* var. *chinensis*, *H. fulva*, *F. glauca*, *G. pulchella*, *V. philippica* and *D. chinensis* have a lower than average AWC, making them water-saving herbs.

3.2. Estimated AWC of the Trees in the GGSs in Beijing

3.2.1. Diameter Class Distribution of the Trees

According to the general survey in Beijing, there are 98 main tree species, including 13 coniferous species, and 85 broad-leaved species, and the total number of trees is 46,948,967. Based on the model, this paper estimates the water consumption levels of the two coniferous species (Table 4) and 11 broad-leaved species (Table 5), and estimates the water consumption levels of other coniferous and broad-leaved trees through the above tree species

Table 4. The diameter distribution of coniferous trees in Beijing (strains).

Species	<5 cm	6–12 cm	14–24 cm	26–36 cm	>38 cm	Total
Platycladus orientalis	671,754	2,087,695	505,420	38,173	12,902	3,315,944
Pinus tabulaeformis	217,276	1,372,392	726,589	58,219	9573	2,384,049
Other coniferous trees	639,048	1,221,458	1,246,269	71,957	17,357	3,196,089
Total	1,528,078	4,681,545	2,478,278	168,349	39,832	8,896,082

Table 5. The distribution of broad-leaved trees in Beijing (strains).

Species	<5 cm	6–12 cm	14–24 cm	26–36 cm	>38 cm	Total
Sophora japonica	225,024	1,320,988	1,605,551	310,950	46,351	3,508,864
Populus tomentosa	71,196	387,938	1,002,727	398,742	187,381	2,047,984
Robinia pseudoacacia	327,796	508,314	806,929	138,708	28,909	1,810,656
Ginkgo biloba	215,650	854,082	573,855	42,819	5903	1,692,309
Platanus acerifolia	6884	138,456	175,593	53,038	10,943	384,914
Fraxinus chinensis	334,008	655,826	623,933	48,405	9745	1,671,917
Ailanthus altissima	96,351	112,727	95,769	18,649	4070	327,566
Koelreuteria paniculata	63,453	266,290	152,291	21,090	4372	507,496
Acer truncatum	92,521	298,677	506,928	12,777	1970	912,873
Salix xaureo-pendula	12,650	134,232	119,846	46,631	10,488	323,847
Paulownia	6519	19,209	22,135	13,056	11,071	71,990
Other broad-leaved trees	9,267,797	6,867,882	6,765,066	1,451,843	439,881	24,792,469
Total	10,719,849	11,564,621	12,450,623	2,556,708	761,084	38,052,885

According to the data analysis, the diameter class distribution of coniferous trees is summarized in Table 4. There were 8,896,082 coniferous trees, accounting for 18.95% of the total trees, and *P. tabulaeformis* accounted for 26.80% of the total coniferous trees. The most widely distributed diameter class is 6–12 cm, accounting for 57.57% of the total *P. tabulaeformis*, and the number of trees with diameters above 38 cm is relatively small, accounting for only 0.40%. *P. orientalis* accounted for 37.27% of the total coniferous trees, which was 10.47% more than the number of *P. tabulaeformis.* The most widely distributed diameter class is 6–12 cm, accounting for 62.96% of the total *P. orientalis*, and the number of trees with diameters exceeding 38 cm is relatively small, accounting for only 0.39%. The other coniferous trees accounted for 35.93% of the total number of coniferous trees.

The diameter class distribution of the broad-leaved trees is summarized in Table 5, indicating that the total number of broad-leaved trees in Beijing is 38,052,885, accounting for 81.05% of the total number of trees. The diameter class distribution of the different broad-leaved tree species varies; 63.11% of the total broad-leaved trees are mainly in the 6 to 24 cm diameter class. The numbers of broad-leaved trees in the 26 to 36 cm and larger than 38 cm diameter classes were relatively small, accounting for 6.72% and 2.00%, respectively, of all trees. The number of *S. japonica* trees was the largest, accounting for 9.22% of the total broad-leaved trees, followed by *P. tomentosa* (5.38%), *R. pseudoacacia* (4.76%), *G. biloba* (4.45%), *F. chinensis* (4.39%), *A. truncatum* (2.40%), *K. paniculata* (1.33%), *P. acerifolia* (1.01%), *A. altissima* (0.86%), *S. xaureo-pendula* (0.85%) and *Paulownia* (0.19%). These 11 broad-leaved trees accounted for 34.85% of the total broad-leaved trees, while the other broad-leaved trees accounted for 65.15%.

3.2.2. AWC of the Trees of the Different Diameter Classes

According to the DBH-leaf area regression model in Table 2, the individual tree leaf areas of eight broad-leaved trees, such as *K. paniculata*, *A. altissima*, and *F. chinensis,* were calculated for the different diameter classes (Table 6). Then, the AWC unit leaf area (Table 7) was multiplied by the individual tree leaf area to obtain the AWC of the broadleaf trees of the different diameter classes (Table 8).

Table 6. Leaf area of individual broad-leaved trees in different diameter classes (m^2).

Diameter Class (cm)	10	20	30	38
Koelreuteria paniculata	73.1	209.1	345.1	453.9
Ailanthus altissima	44.3	189.9	335.7	452.2
Fraxinus chinensis	41.3	280.2	519.1	710.2
Platanus acerifolia	186.3	411.1	635.9	815.8
Sophora japonica	73.7	209.3	344.9	453.4
Populus tomentosa	35.9	136	236.1	316.2
Salix xaureo-pendula	55.5	176.2	296.9	393.5
Paulownia	120.8	236.5	352.2	444.8
Other broad-leaved tree	78.9	231.1	383.2	505

Note: the DBH range of the trees in diameter class 10 is 6–12 cm, the DBH range of the trees in diameter class 20 is 14–24 cm, the DBH range of the trees in diameter class 30 is 26–36 cm, and the DBH range of trees in diameter class 38 is greater than 38 cm, as below.

Table 7. Annual water consumption per unit of leaf area of broad-leaved trees (kg).

Species	Annual Water Consumption	Species	Annual Water Consumption
Koelreuteria paniculata	304.7	*Populus tomentosa*	165.9
Ailanthus altissima	174.6	*Salix xaureo-pendula*	327.6
Fraxinus chinensis	327.5	*Paulownia*	278.3
Platanus acerifolia	187.1	Other broad-leaved tree	219.9
Sophora japonica	159.6		

Table 8. Annual water consumption of individual trees in different diameter classes (kg).

Diameter Class (cm)	5	10	20	30	38	Average
Pinus tabulaeformis	167.8	257.5	873.1	1146.7	1119.3	712.9
Platycladus orientalis	154.5	279.7	1039.9	1548.1	1773.2	959.1
Other coniferous trees	161.2	268.6	956.5	1347.4	1446.3	836.0
Ginkgo biloba	527.3	878.9	3105.7	6358.5	9699.5	4114.0
Acer truncatum	184.0	306.6	1676.6	2780.5	3472.1	1684.0
Robinia pseudoacacia	458.9	764.9	2213.7	4121.6	5921.7	2696.2
Koelreuteria paniculata	13,364.1	22,273.5	63,712.7	105,151.9	138,303.3	68,561.1
Ailanthus altissima	4640.8	7734.7	33,156.5	58,613.2	78,954.1	36,619.9
Fraxinus chinensis	8115.7	13,526.1	91,768.3	170,010.4	232,597.6	103,203.6
Platanus acerifolia	20,915.1	34,858.5	76,920.9	118,983.2	152,644.3	80,864.4
Sophora japonica	7057.5	11,762.5	33,404.3	55,046.0	72,362.6	35,926.6
Populus tomentosa	3573.5	5955.8	22,562.4	39,168.9	52,457.5	24,743.6
Salix xaureo-pendula	10,905.8	18,176.3	57,712.8	97,249.3	128,878.5	62,584.5
Paulownia	20,169.3	33,615.5	65,811.8	98,008.1	123,765.1	68,274.0
Other broad-leaved tree	11,387.0	33,615.5	65,811.8	98,008.1	123,765.1	66,517.5

According to the DBH daily water consumption model in Table 1, the individual tree AWCs of the different diameter classes of *P. tabulaeformis*, *G. biloba*, *A. truncatum*, *P. orientalis* and *R. pseudoacacia* were calculated (Table 8).

The general survey divided the tree DBH into five diameter classes. The models in Tables 1 and 2 are not suitable for trees with DBHs smaller than 5 cm, but in the general survey, there were 1,528,078 coniferous trees with DBHs smaller than 5 cm, accounting for 17.17% of the total coniferous trees, and 10,719,849 broad-leaved trees with DBHs smaller than 5 cm, accounting for 28.17% of the total broad-leaved trees. Therefore, the AWC of a single tree with a DBH smaller than 5 cm is calculated as 60% of the individual tree AWC of the 10 cm diameter class (Table 8).

Table 6 indicates that the individual tree leaf areas of the different diameter classes vary greatly. In the same diameter class, the individual tree leaf area of *P. acerifolia* was much larger than that of the other broad-leaved trees. Among them, the individual tree leaf area of *P. acerifolia* was 1.36 times that of the other broad-leaved trees in the 10 cm diameter class. The leaf area of the different broad-leaved trees was positively correlated with the diameter class.

In Table 8, the individual tree AWC is positively correlated with the tree diameter class. For the coniferous trees, the individual tree average AWC of *P. orientalis* was 34.54% higher than that of *P. tabulaeformis*, but the DWC per unit of leaf area of *P. orientalis* was 34.76% lower than that of *P. tabulaeformis* (Appendix A, Table A1). This is due to the sap flow fluctuation of *P. orientalis* that occurred in April, while that of *P. tabulaeformis* occurred over only 10 days in April [15]. Moreover, in the same diameter class, the leaf area of *P. orientalis* was 1.4–1.9 times that of *P. tabulaeformis* [35].

For the broad-leaved trees, the individual tree average AWC of *F. chinensis* in the average-diameter class was the highest (103,203.6 kg), which was 61.29 times that of *A. truncatum*, with the lowest individual tree average AWC in the average-diameter class. The individual tree average AWC of broad-leaved trees is 79.57 times that of coniferous trees and that of broad-leaved trees is considerably higher than that of coniferous trees [17].

3.2.3. AWC of the Trees in the GGSs in Beijing

Based on the above calculations, the AWC of all trees in the Beijing GGSs includes the AWC of the 13 tree species and other coniferous and broad-leaved trees, as listed in Table 9.

Table 9. Annual water consumption of all trees in Beijing (10^3 m^3).

Species	5	10	20	30	38	Total
Platycladus orientalis	104.8	634.3	746.9	59.6	22.8	1568.4
Pinus tabulaeformis	40.9	307.1	448.6	66.4	10.7	873.6
Other coniferous trees	103.0	328.1	1192.1	97.0	25.1	1745.2
Subtotal	248.7	1269.4	2387.5	222.9	58.7	4187.2
Sophora japonica	1588.1	15,538.1	53,632.3	17,116.6	3354.1	91,229.2
Populus tomentosa	254.4	2310.5	22,623.9	15,618.3	9829.5	50,636.7
Robinia pseudoacacia	150.4	388.8	1786.3	571.7	171.2	3068.4
Ginkgo biloba	113.7	750.7	1782.2	272.3	57.3	2976.1
Platanus acerifolia	144.0	4826.4	13,506.8	6310.6	1670.4	26,458.1
Fraxinus chinensis	2710.7	8870.8	57,257.3	8229.4	2266.7	79,334.8
Ailanthus altissima	447.1	871.9	3175.4	1093.1	321.3	5908.8
Koelreuteria paniculata	848.0	5931.2	9702.9	2217.7	604.7	19,304.4
Acer truncatum	17.0	91.6	849.9	35.5	6.8	1000.9
Salix xaureo-pendula	138.0	2439.8	6916.6	4534.8	1351.7	15,381.0
Paulownia	131.5	645.7	1456.7	1279.6	1370.2	4883.7
Other broad-leaved tree	105,532.2	130,340.7	376,136.7	133,899.8	53,457.7	799,367.0
Subtotal	112,075.2	173,006.1	548,827.0	191,179.2	74,461.6	1,099,549.1
All trees	112,323.8	174,275.5	551,214.6	191,402.2	74,520.2	1,103,736.3

The AWC of the coniferous trees in Beijing is 4,187,204.86 m^3 (0.004×10^9 m^3), and the AWC of broad-leaved trees is 10,954,391.29 m^3 (1.100×10^9 m^3). The TAWC of all trees in the Beijing GGSs is 1,103,736,321.14 m^3 (1.104×10^9 m^3). The TAWC of *P. orientalis* among the coniferous trees was 79.53% higher than that of *P. tabulaeformis*, and the TAWC of the broad-leaved trees was 262.60 times that of the coniferous trees. The AWC of the other broad-leaved and coniferous trees accounted for 72.58% of the AWC of all trees.

3.3. Estimated AWC of the Shrubs in the GGSs in Beijing

According to the general survey, the total number of shrubs in the Beijing GGSs is 99,324,466, and the hedge area covers 14,876,207.5 m^2. There were 48 main species of deciduous shrubs, with a total number of 59,222,441, accounting for 59.63% of all shrubs in the GGSs. There were 22,150,424 shrub balls, accounting for 22.30% of all shrubs, mainly including *E. japonicus* and *B. microphylla*, and 17,951,601 coniferous shrubs, accounting for 18.07% of all shrubs, mainly including *S. procumbens* and *S. vulgaris*. The AWC of the shrubs in the Beijing GGSs was estimated based on the regression model of the deciduous shrub leaf area in Table 3 and Equations (5)–(12).

3.3.1. AWC of the Deciduous Shrubs in the GGSs in Beijing

The AWC of the 11 common deciduous shrubs (Table 10) was estimated according to the regression model of the deciduous shrub leaf area in Table 3 and Equations (5) and (6). The individual tree AWC and leaf area of the other deciduous shrubs were estimated based on the averages of these 11 shrubs. The height and crown width of most *Rosa* shrubs are both 0.6–0.7 m, and the height and crown width of the other 10 deciduous shrub species are 1–2 m and 1.2–1.8 m, respectively [28]. Therefore, the height and crown width of the *Rosa cultivar Floribunda* were both calculated as 0.6 m, while the height of the other 10 deciduous shrubs was set to 2 m, and the crown width was regarded as 1.5 m. The specific calculation results are listed in Table 10.

The calculation shows that the total number of the 11 types of deciduous shrubs is 19,984,453, accounting for 33.74% of the total deciduous shrubs. The most abundant type was *R. cultivar Floribunda*, which accounted for 13.41% of the total deciduous shrubs, the least abundant type was *C. chinensis*, accounting for only 0.34% of the total deciduous shrubs, and the other deciduous shrubs accounted for 66.26%.

The TAWC of all deciduous shrubs in the Beijing GGSs is 60,930,420.93 m^3 (0.061×10^9 m^3). The AWC of the 11 deciduous shrubs was 11,992,841.54 m^3 (0.012×10^9 m^3), accounting for 19.68% of the TAWC of all deciduous shrubs. The AWC of the other deciduous shrubs was 48,937,579.40 m^3 (0.049×10^9 m^3), accounting for 80.32% of the TAWC of all deciduous shrubs.

Table 10. Annual water consumption of deciduous shrubs in Beijing.

Species	N	Q ($kg \cdot m^{-2}$)	S_d (m^2)	Q_t (10^3 m^3)
Syringa pekinensis	1,496,059	208.9	4.79	1497.0
Amygdalus triloba	493,124	381.9	10.2	1920.9
Hibiscus syriacus	600,925	342	1.93	396.6
Lonicera maackii	933,508	225.2	6.99	1469.5
Kerria japonica	2,929,891	231.8	1.91	1297.2
Lagerstroemia indica	438,282	351.7	7.9	1217.7
Cercis chinensis	199,948	237.6	2.58	122.6
Sorbaria sorbifolia	674,154	459.6	3.6	1115.4
Weigela florida	1,109,230	152.8	6.5	1101.7
Forsythia suspensa	3,167,744	220.4	1.98	1382.4
Rosa cultivars Floribunda	7,941,588	312.7	0.19	471.8
Other deciduous shrubs	39,237,988	284.1	4.39	48,937.6
Total	59,222,441	-	-	60,930.4

Note: Q represents the annual water utilization per leaf area of shrubs; S_d represents the leaf areas of individual trees of deciduous shrubs; Q_t represents the annual water consumption of all deciduous shrubs.

3.3.2. AWC of the Hedges in the GGSs in Beijing

According to the general survey, the shrub hedges in Beijing mainly include *P. orientalis*, *S. chinensis*, *J. rigida*, *E. japonicus*, *B. microphylla*, *L. vicaryi* and *B. thunbergii*, with a total area of 14,876,207.50 m^2. The total area of *E. japonicus*, *B. microphylla*, *L. lucidum* and *B. purpurea* was 12,585,410 m^2, accounting for 84.60% of the total hedge area. Therefore, the hedge green surface area and total leaf area are calculated with Equations (7) and (8), respectively, and the shrub hedge AWC per unit of leaf area follows the result of Ma et al. [15]. Finally, with the hedge AWC per unit of leaf area and total leaf area, the shrub hedge TAWC can be calculated with Equation (9), as summarized in Table 11.

Table 11. Annual water consumption of hedges in Beijing.

Species	The Area Covered by the Hedge (m^2)	The Green Surface Area (m^2)	Leaf Area Index	The Total Leaf Area (m^2)	The Annual Water Consumption of per Unit of Leaf Area ($kg \cdot m^{-2}$)	The Total Annual Water Consumption (10^3 m^3)
Buxus microphylla	1,242,919.1	3,107,297.8	7.89	24,516,579.3	56.3	1380.3
Euonymus japonicus	7,410,520.0	18,526,300.0	6.2	114,863,060.0	128.3	14,736.9
Berberis thunbergii	1,473,686.0	3,684,216.0	6.81	25,089,511.0	117.9	2958.1
Ligustrum vicaryi	2,458,284.0	6,145,711.0	9.24	56,786,365.0	209.3	11,885.4
Other hedges	2,290,798.0	5,707,539.0	-	-	-	5619.6
Total	-	-	-	-	-	36,580.2

Table 11 reveals that the TAWC of the four major hedges in the Beijing GGSs, *E. japonicus*, *B. microphylla*, *L. lucidum* and *B. purpurea*, is 30,960,653.55 m^3 (0.031×10^9 m^3). Since the total area of these four hedges accounts for 84.60% of the total hedge area, the water consumption of these four hedge shrubs is adopted to estimate the water consumption of all hedges in proportion to their area. Finally, the AWC of all shrub hedges in the Beijing GGSs is 36,580,216.95 m^3 (0.037×10^9 m^3).

3.3.3. AWC of the Shrub Balls in the GGSs in Beijing

There were 22,150,424 shrub balls in the Beijing GGSs, which mainly consisted of 16,548,928 *E. japonicus* shrub balls and 3,375,475 *B. microphylla* shrub balls, accounting for 89.95% of the total shrub balls. Hence, according to Equations (10) and (11), the total water consumption for *E. japonicus* and *B. microphylla* in the Beijing GGSs was 33,902,133.90 and

15,479.64 m^3, respectively. Finally, based on the ratio of the number of these two shrub balls to the total shrub balls in Beijing, the total water consumption of all shrub balls in Beijing was estimated, and the green ball AWC in Beijing is 39,766,926.14 m^3 (0.0398 $\times$ 10^9 m^3), as indicated in Table 12.

Table 12. Annual water consumption of green balls in Beijing.

Species	Quantity	Water Consumption per Green Ball (kg)	The Total Annual Water Consumption (10^3 m^3)
Euonymus japonicus	16,548,928	2048.6	33,902.1
Buxus microphylla	3,375,475	466.6	1575.0
Other green balls	2,226,021	-	-
Total	22,150,424	-	39,766.9

3.3.4. AWC of the Evergreen Coniferous Shrubs in the GGSs in Beijing

The evergreen coniferous shrubs in Beijing mainly include *S. procumbens*, *S. vulgaris*, *S. chinensis*, and *C. macrolepis*. According to the general survey data (Table 13), *S. procumbens* and *Sabina vulgaris* account for 95.84% of the total evergreen coniferous shrubs. Therefore, the AWC of the evergreen coniferous shrubs in the Beijing GGSs is primarily estimated based on these two evergreen coniferous shrubs.

Table 13. Annual water consumption of evergreen coniferous shrubs in Beijing.

Species	Numbers	Actual Area	Leaf Area Index	The Total Leaf Area (m^2)	The Annual Water Consumption per Leaf Area (kg·m^{-2})	The Total Annual Water Consumption (10^3 m^3)
Sabina procumbens	2,024,855	674,951.7	4.0	259,082.7	85.8	231.0
Sabina vulgaris	15,180,380	5,060,127.0	3.7	8,720,301.4	50.4	932.5
Other evergreen coniferous shrubs	746,366	-	-	-	-	35.9
Total	17,951,601	-	-	-	-	1199.3

Through a large number of field investigations, it was found that evergreen coniferous shrubs are mostly planted in clusters in GGSs, and the average planting density of these two shrubs is three plants·m^{-2} [16]. Hence, the actual areas of *S. procumbens* and *S. vulgaris* were calculated to be 674,951.7 and 5,060,127 m^2, respectively. Moreover, the AWC per unit of leaf area was calculated according to the DWC of shrubs (Appendix A, Table A1), and the AWC period was 190 days. According to Equation (12), the AWC of *S. procumbens* was 230,972.74 m^3, and the AWC of *S. vulgaris* was 932,485.20 m^3. Finally, according to the percentages of *S. procumbens* and *S. vulgaris* in the total number of evergreen coniferous shrubs, the total water consumption of the Beijing GGS evergreen coniferous shrubs was 1,199,346.75 m^3 (0.0012 $\times$ 10^9 m^3).

3.4. Estimated AWC of the Herbs in the GGSs in Beijing

Herbs are divided into ground cover plants and lawns. The common ground cover plants in Beijing include *I. tectorum*, *I. lacteal* var. *chinensis*, *Sedum*, and *H. fulva*. The lawns include warm- and cold-season lawns. The warm-season lawns include *B. dactyloides* and *Z. japonica*, and the cold-season lawns include *F. elata*, *P. pratensis* and *L. perenne*.

According to Equation 13, the herb TAWC is provided in Table 14. The water consumption per area of the other warm-season lawns is the average value of *B. dactyloides* and *Z. japonica*, and the water consumption per area of the other cold-season lawns is the average value of *F. elata*, *P. pratensis* and *L. perenne*. The water consumption per area of the other ground cover plants is the average value of *I. tectorum*, *I. lacteal* var. *chinensis*, *Sedum*, and *H. fulva*.

Table 14. Annual water consumption of herbs in Beijing.

Species	The Annual Water Consumption Per Area (kg·m^{-2})	Total Area (m^2)	Total Water Consumption (10^3 m^3)
Festuca elata	783.1	5,757,561.9	4508.7
Poa pratensis	861.7	29,375,821.2	25,313.1
Lolium perenne	850.9	4,895,027.0	4165.2
Buchloe dactyloides	684.2	16,737,691.8	11,451.9
Zoysia japonica	656.8	5,456,846.0	3584.1
Iris tectorum	186.9	1,406,341.7	262.8
Sedum	178.3	776,037.5	138.4
Iris lacteal var.chinensis	207.2	642,555.8	133.1
Hemerocallis fulva	332.4	2,174,142.6	722.7
Other ground cover plants	226.2	54,056,765.4	12,227.6
Other warm-season lawns	670.5	59,572,969.6	39,943.7
Other cold-season lawns	831.9	69,581,629.5	57,885.0
Total	-	-	160,336.4

According to calculations, the lawn TAWC in the Beijing GGSs was 146,851,689.20 (0.147×10^9) m^3, and the ground cover plant TAWC was 13,484,675.65 (0.013×10^9) m^3. Therefore, the herb TAWC in Beijing was 160,336,364.85 (0.16×10^9) m^3.

3.5. TAWC of the Trees, Shrubs and Herbs in the Beijing GGSs

According to the calculation of the AWC of the Beijing GGS trees, shrubs and herbs based on Tables 9–14, the TAWC of all plants was 1,402,549,596.76 (1.403×10^9) m^3. The tree TAWC was 1,103,736,321.14 (1.104×10^9) m^3, accounting for 78.69%. The shrub TAWC was 138,476,910.77 (0.138×10^9) m^3, accounting for 9.83%. The herb TAWC was 160,336,364.85 (0.16×10^9) m^3, accounting for 11.40%. The tree total water consumption in Beijing was 3.70 times the total water consumption of the shrubs and herbs, making trees the main water-consuming species.

Among the GGSs in the built-up areas of 16 districts of Beijing (Table 15), the AWC of the trees, shrubs and herbs in Chaoyang District is the highest, at 335,789,127.76 m^3, or approximately 0.336×10^9 m^3, accounting for 23.94% of the plant TAWC in the Beijing GGSs, and the lowest occurs in Miyun District, at 0.016×10^9 m^3, accounting for only 1.14% of TAWC. The TAWC in the remaining districts are shown in Table 15.

Table 15. Annual water consumption of trees, shrubs and herbs in Beijing (10^3 m^3).

District	Tree	Shrub	Herb	Total
Chaoyang District	271,934.0	34,998.8	28,856.3	335,789.1
Fangshan District	150,816.0	7073.4	11,323.4	169,212.7
Changping District	121,416.0	14,304.0	9286.5	145,006.5
Haidian District	85,851.9	12,966.8	11,816.0	110,634.6
Fengtai District	91,874.5	11,492.1	6792.3	110,158.8
Shunyi District	76,365.3	3996.6	22,317.7	102,679.7
Tongzhou District	83,546.4	8857.6	10,201.3	102,605.3
Daxing District	55,358.1	12,993.5	28,150.7	96,502.3
Shijingshan District	39,964.7	4283.4	6224.0	50,472.1
Huairou District	16,198.4	11,646.7	5546.9	33,392.0
Mentougou District	26,991.3	1499.1	3807.0	32,297.4
Pinggu District	20,614.2	2990.7	7322.5	30,927.3
Yanqing District	27,789.6	408.4	1888.5	30,086.5
Dongcheng District	11,973.0	4696.0	2025.7	18,694.7
Xicheng District	11,186.5	4060.7	2834.3	18,081.5
Miyun District	11,856.5	2209.1	1943.3	16,008.9
Total	1,103,736.3	138,476.9	160,336.4	1,402,549.6

4. Discussion

In this study, according to the transpiration water consumption law of common GGS plants in Beijing, the water consumption capacities of plants were evaluated, which objectively reflect the different water consumption capacities of plants. In the process of selecting water-saving plants, by comparing the water consumption levels of the various plants, 15 species of water-saving trees, 19 species of water-saving shrubs and 11 species of water-saving herbs were finally selected, which can guide the construction of water-saving GGSs in Beijing.

GGS plants can not only beautify the environment but also provide multiple ecological benefits, such as storm runoff regulation, pollutant absorption, solar energy consumption, cool ambient environments and alleviation of the urban heat island effect [36–38]. For example, *P. orientalis*, *R. pseudoacacia*, *U. pumila* and *A. altissima* have strong anti-pollution abilities and have strong abilities to absorb urban car exhaust emissions [39]. *L. vicaryi*, *S. japonicus*, *G. biloba*, etc. have a strong ability to absorb smoke and dust in the urban environment [40]. *R. pseudoacacia*, *P. tabulaeformis*, *P. tomentosa*, etc. have strong resistance to or capacities to absorb heavy metals in urban areas [41]. Additionally, *C. chinensis*, *M. denudate*, *S. oblata*, *B. thunbergii* var. *atropurpurea*, *C. coggygria*, etc. have high esthetic value [39]. Not all of the above tree species are water-saving plants. Furthermore, it should be noted that different plant configuration patterns will have a greater impact on plant water consumption. For example, for the same shrub, the water consumption of the green ball configuration is higher than that of the block configuration, and it is better to arrange shrubs in blocks in garden green spaces [42]. Under the same conditions, compared to composite and single configurations of shrubs, the transpiration rate would be reduced by 30–40% [43]. In a configuration with many types of plants, matching plants with different seasonal water consumption levels can balance the water consumption [44]. Therefore, in the subsequent construction of water-saving gardens and green spaces in Beijing, we must not simply consider the characteristics of the plants themselves, but also the social and ecological benefits of these plants. In particular, we should choose plants that are water-saving, meet people's esthetic requirements and improve the environment. It is also necessary to make a reasonable selection according to the characteristics of the water-saving plants selected, which is of great significance for improving the water use efficiency of Beijing, improving the urban ecological environment, and improving the quality of life of residents.

This study finally concludes that the total annual transpiration water consumption of all trees, shrubs and herbs in the built-up areas of all 16 districts in Beijing GGSs was 1.403×10^9 m^3, accounting for 52.4% of Beijing's total water resources (the total amount of surface and groundwater formed by precipitation in Beijing is 2.676×10^9 m^3) in 2015 and 36.7% of the total water consumption (3.82×10^9 m^3) (BWRB, 2015). The water consumption of plants in Beijing's urban GGSs was very high. In this study, the total water consumption of trees, shrubs and herbs in Haidian District, Dongcheng District (including Xuanwu District), Xicheng District (including Chongwen District), Chaoyang District, Fengtai District and Shijingshan District equals 0.644×10^9 m^3, which is 65.56% higher than the level of 0.389×10^9 m^3 calculated by Che [28] through the fifth general survey of landscaping resources in Beijing. In addition, the highest level of water consumption in 2005 was from 11,361,219 trees, with a water consumption of 0.33×10^9 m^3, accounting for 84.8% of the total water consumption. By 2015, the number of trees was 18,960,002 in the same districts, an increase of 66.88% compared to that in 2005, and the water consumption was 0.53×10^9 m^3. Compared to 2005, the water consumption increased 55.45% and accounted for 79.66% of the total water consumption in 2015. The above results show that the conclusion of this study is reliable and that the choice of garden-greening plant species in Beijing in recent years tends to be water-saving plant species, and the relative increase in water consumption has slowed. Sun et al. calculated the actual AWC of 16 districts in Beijing in 2012 to be 0.809×10^9 m^3, which is 42.33% lower than that in this study. This is mainly due to the rapid economic development of Beijing in recent years [45]. An enormous number of trees have been newly planted, and the water consumption of the Beijing GGS coniferous trees and ground cover plants was not determined at that time, while the shrubs were not divided into shrub balls and hedges. Therefore, there are differences between previous results and the conclusions of this study.

In current estimation methods of plant transpiration water consumption, the difficulties mainly concern scaling up from a single plant to a stand. Normally, the transpiration water consumption of a stand can be obtained by scaling up the relationships between the sap flow and DBH, stem cross-sectional area, sapwood area or leaf area coefficient [46], vegetation density [47], and single-tree area [48]. Relevant research shows that the accuracy of transpiration water consumption scale conversion using the leaf area and DBH is the highest [49]. In this study, tree transpiration water consumption was expanded by the DBH daily water consumption and DBH-leaf area models. In urban gardens, most trees are planted individually, in rows or in pieces, the spacing between the rows is generally relatively large, and most of them are in the form of sparse forest. Therefore, when the scale of the water consumption model is extended, it is not necessary to extend the water consumption per plant to the stand, but only to extend the water consumption per plant to individual plants of different diameter classes [35]. Additionally, the shrub transpiration water consumption was mainly expanded by the leaf area index and green surface area, while the herb transpiration water consumption was accounted for by the herb area and AWC per area. The plant transpiration water consumption models were all reliably expanded and accurately estimated, and this study attains a higher estimation accuracy.

Although the model in this paper does not include related environmental factors such as climate and soil, the relevant plants are commonly used plants in the Beijing urban GGSs, and they are all measured in the Beijing urban GGSs over a long time span. This is equivalent to considering the water consumption of plants under changes in Beijing's urban environment, so the results of this model can be considered to already include the impact of Beijing's environmental factors. Meanwhile, a large number of experiments have shown that when the soil water content is sufficient, the water consumption per plant is linearly related to the leaf area [50], and the leaf area is a group of scalar quantities with extremely high correlations with the trunk diameter and sapwood area [51]. In addition, there is a self-balance between the leaf area and sapwood area. The trunk can provide sufficient water supply to the leaf area, which in turn affects the cross-sectional area of the trunk. This long-term interrelated balance effect leads to mutual adjustment and adaptation between leaf area and sapwood area, so that the two can maintain a similar water potential gradient in the tree. This relationship is relatively stable for the same tree species and does not change with changes in climate and site conditions [52–54]. Since the trunk diameter directly reflects the size of the tree and is also the easiest to observe and there are also many models to calculate leaf area, this study uses the relationship model between the trunk diameter or leaf area and water consumption to predict the water consumption of plants of different diameter classes.

Due to the complex structure of the tree species in urban gardens and the changing environment, it is difficult to estimate the water consumption of GGSs. In this paper, the results of previous water consumption studies are adopted to compare the water consumption of different tree species and to estimate the total water consumption of the trees, shrubs and herbs in Beijing. At present, the research on the scale expansion of plant water consumption is not comprehensive. For the water consumption of many other species, the average value of the same type of species (coniferous trees, broad-leaved trees, deciduous shrubs, herbs, etc.) was adopted, and there was no detailed calculation for each tree species because there were no related models. In addition, errors occur when expanding the water consumption of plants temporally and spatially. Although these errors will not affect the evaluation results of the individual and group water consumption levels of plants, they will affect the design of precision irrigation systems. All these deficiencies need to be addressed and resolved in future research.

5. Conclusions

In this study, by consulting the relevant literature, the water consumption of 79 common plants in Beijing was assessed, and plants with a low water consumption level were identified. Moreover, the AWC of the trees, shrubs and herbs in the Beijing GGSs were estimated.

(1) Forty-five species of water-saving plants were identified, including 15 LWC tree species, i.e., *M. micromalus*, *R. pseudoacacia*, *P. acerifolia*, *S. japonica*, *Q. variabilis*, *G. biloba*, *R. chinensis*, *Q. dentata*, *R. Typhina*, *A. altissima*, *P. tomentosa*, *S. chinensis cv. Beijingensis*, *P. bungeana*, *P. tabuliformis*, and *P. orientalis*, and the DWC was <1.09 $kg \cdot m^{-2}$. Nineteen species of LWC shrubs were identified, i.e., *F. suspensa*, *H. rhamnoides*, *C. Korshinskii*, *S. oblata*, *L. chinensis*, *B. thunbergii*, *C. coggygria*, *B. sinica* subsp. *sinica* var. *parvifolia*, *S. pekinensis*, *B. megistophylla*, *L. bicolor*, *L. vicaryi*, *W. florida*, *M. dioica*, *S. salicifolia*, *A. fruticose*, *A. davidiana*, *S. vulgaris* and *S. procumbens*, and the DWC was <1.17 $kg \cdot m^{-2}$. There were 11 species of LWC herbs, i.e., *S. spectabile*, *R. japonicus*, *C. morifolium*, *I. tectorum*, *S. aizoon*, *I. lacteal* var. *chinensis*, *H. fulva*, *F. glauca*, *G. pulchella*, *V. philippica* and *D. chinensis*, and the average AWC was <460.3 $kg \cdot m^{-2}$.

(2) According to the eighth general survey of landscaping resources in Beijing, there were 98 main tree species, including 13 coniferous tree species (8,986,082 trees) and 85 broad-leaved tree species (38,052,885 trees). The total number of trees was 46,948,967. Based on the diameter and leaf area water consumption expansion models, the AWC of all coniferous trees was 0.004×10^9 m^3, and the AWC of all broad-leaved trees was 1.100×10^9 m^3. The TAWC of all trees was 1.104×10^9 m^3.

(3) The total number of deciduous shrubs was 59,222,441, and the TAWC was 0.061×10^9 m^3. The total area of all green hedges was 14,876,208 m^2, and the AWC was 0.037×10^9 m^3. The total number of all shrub balls was 2,226,021, and the AWC was 0.0398×10^9 m^3. The total number of all evergreen coniferous shrubs was 17,951,601, and the AWC was 0.0012×10^9 m^3. The TAWC of all shrubs was 0.139×10^9 m^3.

(4) The total lawn area was 191,377,547 m^2, and the TAWC was 0.147×10^9 m^3. The total area of ground cover plants was 59,055,843.00 m^2, and the TAWC was 0.013×10^9 m^3. The TAWC of all herbs was 0.16×10^9 m^3.

(5) The TAWC of all trees, shrubs and herbs in the Beijing GGSs was approximately 1.403×10^9 m^3.

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Appendix A Daily Water Consumption (DWC) of Trees, Shrubs and Herbs

Table A1. DWC of trees.

Species	DWC ($kg \cdot m^{-2}$)	Data Sources	Species	DWC ($kg \cdot m^{-2}$)	Data Sources
Acer truncatum	1.13	Ma et al., 2009 [15]; Yang et al., 2007 [55]	*Quercus acutissima*	1.43	Chen et al., 2008 [56]
Ailanthus altissima	0.87	Chen et al., 1998 [15]; Zhou et al., 2002 [57]	*Quercus dentata*	0.92	Yang et al., 2007 [55]; Chen et al., 2008 [56]
Fraxinus chinensis	1.64	Chen et al., 1998 [26]	*Quercus variabilis*	0.93	Yang et al., 2007 [55]
Ginkgo biloba	0.71	Ma et al., 2009 [15]; Lu et al., 2017 [14]	*Rhus chinensis*	0.92	Yang et al., 2007 [55]
Koelreuteria paniculata	1.56	Ma et al., 2009 [15]; Chen et al., 1998 [26]	*Rhus Typhina*	0.8	Zhao et al., 2003 [19]; Zhou et al., 2002 [57]
Liriodendron chinense	1.47	Ma et al., 2009 [15]	*Robinia pseudoacacia*	0.95	Ma et al., 2009 [15]
Magnolia denudata	1.9	Ma et al., 2009 [15]	*Sabina chinensis cv. Beijingensis*	0.61	Ma et al., 2009 [15]
Malus micromalus	1.02	Ma et al., 2009 [15]	*Salix babylonica*	1.61	Chen et al., 1998 [15]
Paulownia	1.46	Chen et al., 1998 [26]	*Salix x aureo-pendula*	1.72	Ma et al., 2009 [15]
Pinus bungeana	0.49	Ma et al., 2009 [15]; Lu et al., 2017 [14]	*Sophora japonica*	0.9	Ma et al., 2009 [15]
Pinus tabuliformis	0.81	Ma et al., 2009 [15]; Zhou et al., 2002 [57]	*Ulmus pumila*	1.2	Kang et al., 2005 [58]
Platanus acerifolia	0.94	Chen et al., 1998 [26]			
Platycladus orientalis	0.53	Ma et al., 2009 [15], Zhou et al., 2002 [57]			
Populus tomentosa	0.83	Zhao et al., 2003 [19]; Chen et al., 1998 [26]			

Table A2. DWC of shrubs.

Species	DWC ($kg \cdot m^{-2}$)	Data Sources	Species	DWC ($kg \cdot m^{-2}$)	Data Sources
Amorpha fruticosa	0.55	Yang et al., 2007 [55]	*Lagerstroemia indica*	1.85	Chen et al., 1998 [26]
Amygdalus davidiana	0.76	Lu et al., 2017 [14]	*Leptopus chinensis*	1.06	Yang et al., 2007 [55]
Amygdalus persica var. *persica f. duplex*	2.09	Li., 2007a [59]	*Lespedeza bicolor*	0.68	Yang et al., 2007 [55]
Amygdalus triloba	2.01	Ma et al., 2009 [15]	*Ligustrum vicaryi*	0.61	Ma et al., 2009 [15]; Li, 2007b [60]
Berberis thunbergii var. *atropurpurea*	1.05	Ma et al., 2009 [15]	*Lonicera maackii*	1.19	Chen et al., 1998 [26]
Buxus megistophylla	0.70	Ma et al., 2009 [15]; Li, 2007b [60]	*Myripnois dioica*	0.87	Yang et al., 2007 [55]
Buxus sinica subsp. *sinica* var. *parvifolia*	0.27	Ma et al., 2009 [15]; Li, 2007b [60]	*Rhamnus davurica*	1.42	Yang et al., 2007 [55]
Caragana korshinskii	1.14	Zhao et al., 2003 [19]; Zhou et al., 2002 [57]	*Rosa cultivars Floribunda*	1.65	Chen et al., 1998 [26]
Cercis chinensis	1.25	Chen et al., 1998 [26]	*Sabina procumbens*	0.45	Ma et al., 2009 [15]
Cotinus coggygria	0.29	Ma et al., 2009 [15]	*Sabina vulgaris*	0.27	Ding et al., 2017 [61]
Deutzia scabra	1.73	Yang et al., 2007 [55]	*Sorbaria sorbifolia*	2.42	Chen et al., 1998 [26]
Euonymus kiautschovicus	1.25	Liu, 2007 [62]	*Spiraea salicifolia*	0.98	Yang et al., 2007 [55]
Forsythia suspensa	1.16	Chen et al., 1998 [26]	*Syringa oblata*	1.1	Chen et al., 1998 [26], Liu, 2007 [62]
Grewia biloba var. *parviflora*	1.31	Yang et al., 2007 [55]	*Syringa pekinensis*	0.66	Ma et al., 2009 [15]

Table A2. *Cont.*

Species	DWC (kg·m^{-2})	Data Sources	Species	DWC (kg·m^{-2})	Data Sources
Hibiscus syriacus	1.8	Chen et al., 1998 [26]	*Vitex negundo heterophylla*	1.46	Yang et al., 2007 [55]; Chen et al., 2008 [56]
Hippophae rhamnoides	1.15	Zhao et al., 2003 [19]; Zhou et al., 2002 [57]	*Weigela florida*	0.8	Chen et al., 1998 [26]
Jasminum nudiflorum	1.64	Chen et al., 1998 [26]	*Ziziphus jujuba* var. *spinosa*	1.98	Chen et al., 2008 [56]
Kerria japonica	1.22	Ma et al., 2009 [15]; Chen et al., 1998 [26]			

Table A3. AWC of herbs.

Species	AWC (kg·m^{-2})	Species	AWC (kg·m^{-2})
Arundinella anomala	812.8	*Iris tectorum*	186.9
Buchloe dactyloides	684.2	*Lolium perenne*	850.9
Calamagrostis brachytricha	524	*Poa pratensis*	861.7
Chrysanthemum morifolium	177.5	*Ranunculus japonicus*	168.8
Dianthus chinensis	432.6	*Sedum aizoon*	195.1
Festuca elata	783.1	*Sedum spectabile*	161.4
Festuca glauca	333.5	*Stipa tenuissima*	642.3
Gaillardia pulchella	340.5	*Viola philippica*	394.8
Hemerocallis fulva	332.4	*Zoysia japonica*	656.8
Iris lacteal var. *chinensis*	207.2		

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