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Research on a zero water consumption operation model and feasibility for office buildings

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ABSTRACT

According to Taiwan's government policy on net zero emissions by 2050, building designs are moving toward zero energy and zero water consumption to achieve these goals. Among these goals, establishing an independent water cycle within building systems is a primary objective. The present study examined office buildings as the research subject due to their crucial water usage characteristics, which can serve as a reference for other building types. We developed a water-use estimation model by conducting a literature review and data collection from existing green office building cases in Taiwan. The methods involved calculating the median annual water consumption per unit building area and discussing the current water-saving design status and water-saving rate. The findings indicate a median water-saving rate of 53%, which is far short of the goal of achieving a zero water building. This finding is primarily attributed to the infrequent use of water compensation in building designs. The feasibility of a zero water building is validated and determines its crucial operation. Consequently, design engineers can employ this methodology to compute water conservation rates for their designs, aiming for the construction of a zero water consumption building.

Key words: green building, near-zero water building, office building, sustainable buildings, water resource

HIGHLIGHTS

- Discussion on equipment water, additional water, and compensatory water.
- Establishing water assessment methods.
- In-depth study of the water characteristics of individual buildings.
- Rainwater recycling and reclaimed water are two of the options to reduce the impact of climate change.
- Future policy and research directions are suggested.

1. INTRODUCTION

Toward sustainable development goals (SDGs) and the goal of achieving net-zero emissions by 2050, Taiwan officially unveiled its 'Taiwan 2050 Net-Zero Emissions Pathway and Strategy Overview' in March 2022. This comprehensive plan outlines development objectives for each phase of the planning period and the promotion strategies for different sectors. In January 2023, the Climate Act was passed, which includes a net-zero emissions target for 2050. In the field of architecture, for example, the United States, Canada, the United Kingdom, Japan, and other countries (International Energy Agency) are moving toward the goal of zero- or near-zero-energy buildings. The concept of zero- or near-zero-energy buildings aims to reduce energy consumption and carbon

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emissions while promoting sustainable development. In fact, water efficiency is like energy efficiency. Water efficiency is a key metric in evaluating building sustainability (Sharma *et al.*, 2009). Across the globe, water security is already being directly and indirectly affected by climate change. The effects of climate change on water security vary significantly both within and between regions due to varying levels of vulnerability (Ayanlade *et al.*, 2023). According to the 2019 World Water Development Report, it is projected that by 2050, over 2 billion people will reside in regions experiencing severe water shortages, and approximately 4 billion people will endure severe water shortages for at least one month annually (Niu *et al.*, 2022). Water usage in buildings represents a significant portion of water resource consumption and carbon emissions. In recent years, water scarcity issues in Taiwan have become increasingly apparent and severe despite Taiwan having an annual rainfall of about 2.5 times the global average. In response to these environmental issues, it is essential to adopt sustainable practices in building design. Adopting sustainable practices such as rainwater harvesting and greywater recycling can reduce water usage in buildings while promoting SDGs and global sustainability (Cheng *et al.*, 2016). Zero water consumption buildings are characterized by low water usage neutralized by rainwater harvesting systems or regenerated water in building design. They can achieve self-sufficiency through rainwater and reclaimed water circulation systems. Offsetting between these sources can facilitate water consumption approaching zero (Pimentel-Rodrigues & Silva-Afonso, 2019). These buildings primarily follow two main directions: sourcing and conservation. Sourcing involves using reclaimed water, such as rainwater and treated wastewater, to offset the original water usage (e.g., flushing toilets and irrigation), achieving the goal of recycling. On the other hand, conservation entails using water-saving devices such as toilets, urinals, and faucets, to fundamentally reduce water consumption. The present study adopted office buildings as the research subject due to their crucial water usage characteristics. The research was conducted to investigate water consumption in these buildings and assess the viability of utilizing performance-based data for the establishment of a water benchmarking system (Bint, 2012). A water-use estimation model was developed by conducting a literature review and collecting data from existing green office building cases in Taiwan.

2. RESEARCH BASIS AND LITERATURE REVIEW

Studies on water reuse around the world indicate that the successful implementation of new water reuse technologies is heavily dependent on the establishment of robust institutional arrangements (Marks & Zadoroznyj, 2005; Bixio *et al.*, 2006; van Lier & Huibers, 2010; Marome & Pholcharoen, 2019; Wakhungu 2019). To achieve the goal of zero water consumption in buildings, it is necessary to focus on three main areas: equipment water usage, additional water usage, and compensatory water usage. Analyzing water usage rates in these areas is crucial. Besides equipment water conservation, rainwater harvesting, and the use of recycled water will also play key roles in determining whether a building can achieve zero water consumption.

2.1. Zero water building concept

A zero-impact building aims to achieve optimal efficiency in managing combined resources and maximizing the generation of renewable resources. The building's resource management focuses on the practicality of utilizing renewable resources such as energy and water, while striving for a closed-loop system that minimizes overall material and land use (Attia, 2016). A near-zero water system is characterized as a water and wastewater management system that operates within its designated service area, ranging from individual residential lots to expansive urban water districts, without significant withdrawals or releases of water outside this defined boundary (Englehardt *et al.*, 2016). The implementation methods for buildings with near-zero water consumption should comprehensively address both water-saving measures and water reclamation systems (Li Cheng & Kawamura, 2023). Effective strategies include the integration of high-efficiency fixtures and appliances to minimize water use, as well as the adoption of advanced technologies for capturing and treating greywater and rainwater. Additionally, the design should incorporate systems for on-site water treatment and recycling, enabling the reuse of water for non-potable purposes. Rainwater and greywater are two common alternative water sources that can be reused in buildings because several water uses do not require high-quality water, such as toilets (Penn *et al.*, 2013), urinals (Sahin & Manioğlu, 2019), and irrigation (Devkota *et al.*, 2015; Unami *et al.*, 2015; Fonseca *et al.*, 2017). These efforts collectively contribute to reducing the overall water footprint of the building, ensuring sustainable water management practices are in place. By prioritizing both conservation and reclamation, buildings can achieve near-zero water consumption and significantly lessen their environmental impact.

2.2. Classification of water use and water saving in office buildings

The existing water consumption data in Taiwan is primarily based on the residential water supply provided by water utility companies. The primary measure is the daily per capita water consumption obtained from the total residential water consumption calculated based on the total population. Residential water usage encompasses water consumption in ordinary households, commercial establishments, military dependents' residences, institutional buildings, and daily office water consumption. According to statistics from the Water Resources Agency of the Ministry of Economic Affairs in Taiwan, the average daily per capita residential water consumption in Taiwan was 282 L in 2021. This study presents a graphical representation of the daily per capita residential water consumption over the past 10 years. This information is based on the Water Resources Agency's statistics on residential water consumption from 2012 to 2021. The long-term trend indicates a rise in water consumption, as shown in Figure 1.

2.3. Green building and water-use intensity

In the literature review and practical applications, the estimation of building water usage is frequently associated with the scale and occupancy of the building. Typically, building water usage is estimated by converting the

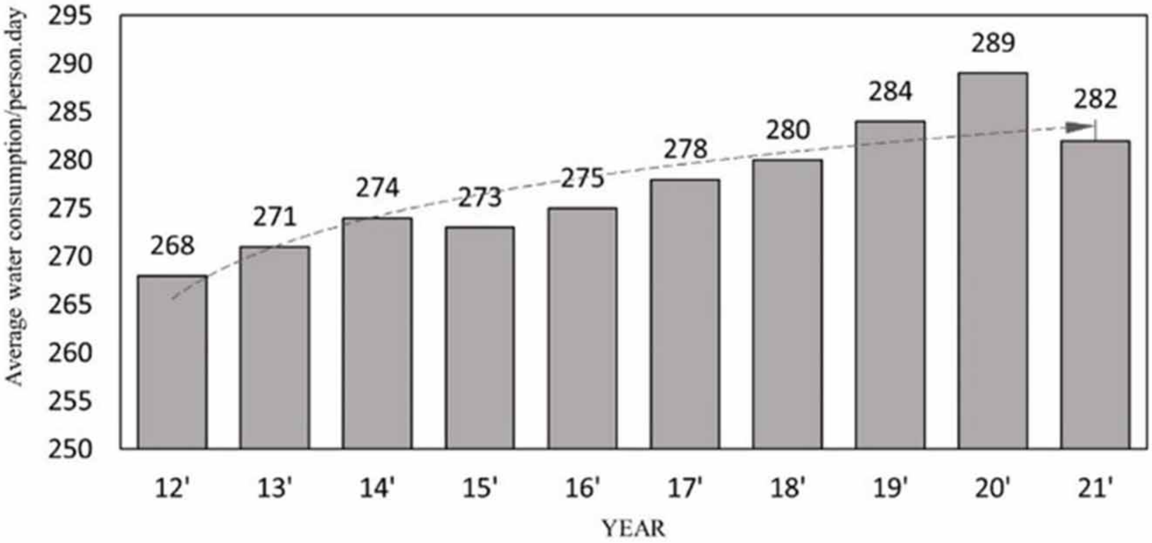

Fig. 1 | Statistics on per capita daily water consumption over the past 10 years. Data Source 2001–2021. Taipei City: Taipei Water Supplies Department.

building floor area into an equivalent number of occupants, and then designing and calculating water facilities based on this occupancy rate (Li Cheng & Kawamura, 2023). The annual water usage per unit of building area (m^3/m^2·year) serves as the benchmark for water consumption. We established formulas, and calculations were performed accordingly. The information was derived from a publication by the Society of Air Conditioning, Heating, and Sanitary Engineers in Japan in 1997. The standards for personnel density in building areas primarily reference the (ASHRAE 2004) and the parameters for estimating water usage in office building spaces were standardized through the California Title 24 Alternative Calculation Method. The parameters for calculating water usage in office building spaces are illustrated. The building unit area annual water usage (water-use intensity (WUI), m^3/m^2·year) calculation was estimated through the average building area density (P_{di}, people/m^2), the baseline for annual water usage per person (Q_{wi}, m^3/person), and the facility utilization rate (F_{ri}). The standardized annual water usage per unit area for office buildings was determined to be 2.63 (m^3/m^2·year), as shown in Table 1.

The Taiwan Green Building Evaluation (EEWH) system, which stands for 'Ecology, Energy Saving, Waste Reduction, and Health,' emphasizes water conservation as a key priority to safeguard water resources through building equipment design in Taiwan (Cheng, 2002). This initiative has introduced a water conservation index that employs quantitative methods and validation procedures. The assessment index is based on standardized scientific quantification, allowing its implementation in the initial design phase to attain desired results. Furthermore, this metric is supported by crucial research tailored to Taiwan, guaranteeing its relevance and usability. The Taiwan Green Building Certification system and the contents provided in the assessment manual indicate that the reference standard W_f for unit area water consumption in the water resource indicator was initially established to confirm the calculation parameter of rainwater harvesting efficiency. This is represented by the domestic water replacement rate. Building types were roughly categorized into seven major types, including offices, department stores, hotels, hospitals, schools, dormitories, residential, and others. Among these, the office type, relevant to this study, was further divided into general and mixed-use, with unit area values of 7 and 9 (liters/m²·day), respectively. The unit area water consumption reference standard W_f was roughly summarized based on the density of use. This provided a simplified assessment basis for the planning and design of rainwater utilization in green buildings. The formula for calculating the total water consumption of a building is as follows:

$$W_t = W_f \times A_f \tag{1}$$

W_t is the total water consumption for the entire building (liters/day), W_f is the water consumption per unit area (liters/m²·day), A_f is the effective total floor area (m²).

2.4. Rainwater and recycled water utilization

The usage of reclaimed water is an effective choice worldwide for the conservation of water resources, which reduces effects on the environment in addition to reducing the expenses and energy needed for water source

Table 1 | Parameters for calculating water usage in standardized office building spaces.

Building type	Groups	Category	P_{di} (p/m^2)	Q_{wi} (m^3/P)	F_{ri}	WUI (m^3/m^2·year)
Type G (Office, service)	G-1 Finance and Securities	G11	0.15	25	0.7	**2.63**
	G-2 Office space	G21	0.15	25	0.7	**2.63**

Bold text is used solely to enhance readability for the reader.

management (Takeuchi & Tanaka, 2020). One of the alternatives that can be practiced is to use reclaimed water. Water reuse entails repurposing cleansed wastewater for usable purposes (Bachi *et al.*, 2023). In recent years, rainwater harvesting has become a common method for buildings to recycle water resources. This method provides a substantial alternative benefit that surpasses other sources of recycled water with the characteristic of relatively lower installation costs. Rainwater collection and utilization systems are employed in different settings, including buildings, parks, and green spaces, based on roof and ground collection methods. Typically, buildings are more suitable for roof-based collection methods, whereas larger areas such as parks and green spaces often require ground-based collection strategies. According to the annual average rainfall data from the Water Resources Agency of the Ministry of Economic Affairs in Taiwan from 1949 to 2020, the average annual rainfall is 2507 mm. Each square meter of rainwater collection area can collect approximately 6.87 L of rainwater per day. Adopting rainwater harvesting is gaining increasing attention in building practices, underscoring the growing importance of achieving zero water buildings. The primary sources of recycled water in office buildings encompass toilet flushing, plant irrigation, cleaning, air conditioning, cooling water circulation, fire protection, and other uses. Encompass five primary components: collection, conveyance, purification, storage, and power. However, the water sources collected by water recycling systems often have higher pollution levels. As such, the purification equipment associated with these systems is generally more intricate and expensive than rainwater recycling systems. Despite the increased complexity and cost of designing a water recycling system, these systems offer the advantage of a consistent water recovery volume unaffected by weather conditions. This feature makes it suitable for deployment in various locations, including residential areas, educational institutions, office buildings, and precision factories. Incorporating water recycling systems into building design is crucial to achieving near-zero water consumption objectives.

2.5. The Monte Carlo simulation method

The basic principle of the Monte Carlo method is to repeatedly obtain random numbers to simulate the results. The input parameters are divided into intervals, and one value is randomly selected from each interval. Sets of inputs are then randomly generated for each of the selected values (Kang *et al.*, 2009). During operation, the likelihood of all possible results is defined as a probability density function; the probability density function is accumulated into a cumulative probability function with an adjusted value. The maximum value is 1, and a numerical simulation of a standard normal distribution can be conducted. In simulations, the normalized normal distribution accurately represents the probability characteristic reflecting the cumulative occurrence of all events with a probability of 1. It establishes a connection with the actual problem simulation through random number sampling. The management of water resources is a complex and dynamic field, often characterized by uncertainties and variability in key parameters such as precipitation, population growth, and water demand. The Monte Carlo simulation method has become increasingly prominent in recent years as a robust tool for evaluating and forecasting water resource dynamics. Uncertainty parameters are generated with a membership function as a fuzzy number. Generally, the Monte Carlo Simulation (MCS) and fuzzy method are the most used among the others. This present study used the Monte Carlo method to improve the accuracy of probability simulations. It randomly selected 73 cases of office buildings that have been awarded green building labels. Initially, water consumption from equipment, additional water consumption, and compensatory water consumption of the cases were computed individually. Subsequently, 10,000 data points were simulated using the Monte Carlo simulation method to investigate their water-use ratio. The data were used to calculate the water-saving rate and analyze the current distribution of water-saving rates in the design of green office buildings (see Figure 2).

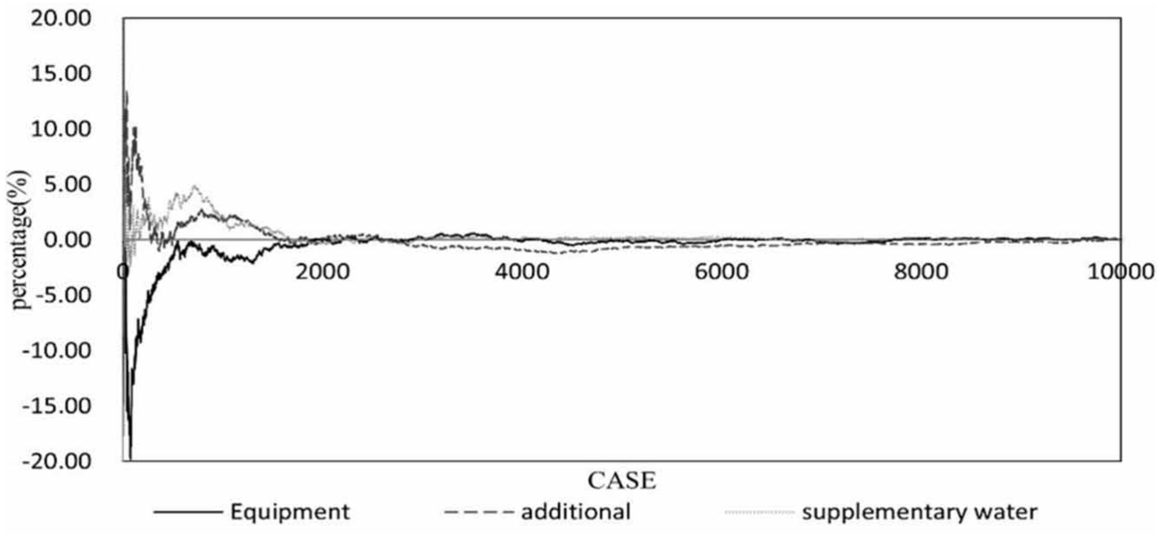

Fig. 2 | Monte Carlo data simulation analysis and validation.

3. METHODOLOGY

This study categorized water usage and conservation in office buildings into three groups according to the building's current design: equipment water usage, additional water usage, and compensatory water usage. Subsequently, we developed assessment formulas and calculations for water usage and conservation in office buildings and calculated the daily equipment water consumption per person for 73 office buildings, which were computed based on this classification. Additionally, the potential for achieving zero water consumption was investigated using calculation methods, as shown in Table 2.

3.1. Standard water consumption and maximum water saving for office building facilities

Water consumption in office buildings primarily involves activities such as toilet flushing, handwashing, cleaning, and drinking water. Water fixtures include faucets, urinals, toilets, water dispensers, and similar equipment. In accordance with water usage habits, this study employed a flushing duration of 10 s multiplied by four times for each toilet flush. The water usage for dishwashing and cleaning was also considered based on personal habits, and handwashing was set at 1.5 min. Regarding water dispensers, considering variations in personal

Table 2 | Classification of water use and water-saving in office buildings.

Office buildings

Equipment water usage		**Additional water usage**		**Compensatory water usage**	
a.	Toilet	a.	Irrigate	a.	Rainwater recycle
b.	Urinal	b.	Pool	b.	Graywater recycles
c.	Faucet	c.	Cooling tower	c.	Condensed water
d.	Water dispenser			d.	Reverse osmosis water

drinking habits and working hours, this study used half of the daily recommended water intake of 2 liters per person, set at 1 liter per person per day. In addition to regular water dispensers, a reverse osmosis (RO) water dispenser was included in the settings with a wastewater generation rate of 1:2.5. The produced wastewater can be recycled for cleaning, toilet flushing, and irrigation.

3.2. Calculation method for additional water consumption and water saving

According to the nature of office buildings, water usage can be divided into the following categories: irrigation for green landscaping, water usage for landscape ponds, and cooling circulation water for central air conditioning. However, many office buildings do not include design plans for swimming pools. In addition to the replacement water for the pool itself, the overall water consumption of a swimming pool encompasses users' bathroom facility usage behaviors. Many existing studies regard this as independent water usage. Therefore, this study excluded swimming pool spaces from examining water usage in office buildings.

3.2.1. Irrigation water

The calculation for irrigation water was based on 5 liters per square meter per day. The calculation for irrigation systems equipped with rain detection for water conservation was based on an allocation of 3.5 liters per square meter per day. Moreover, using a smart water-saving irrigation system can result in a 50% reduction in irrigation water consumption, as indicated by data from the United States Environmental Protection Agency. The formula for annual irrigation water consumption per unit area was derived based on an annual average of 251 working days, as shown in the following formula.

$$W_g = A_g \times C_g \times S_g \times 365 \div A_f \tag{2}$$

W_g is the annual irrigation water consumption per building unit area (m³/m²·year), A_g is the planting area (m²), C_g is the daily irrigation volume per square meter (m³/m²), S_g is the irrigation water conservation rate, A_f is the building floor area (m²).

3.2.2. Pool water usage

The pool water usage calculation was based on the specified pool volume and involved multiplying the volume by the water replacement frequency. If the design specifications do not specify the replacement frequency, it is recommended to assume a frequency of once a week (approximately 52 weeks in a year). Furthermore, it is recommended to incorporate a daily replenishment of 0.5% to offset the evaporative loss, as shown in the following formula.

$$W_p = V_p \times 53.825 \div A_f \tag{3}$$

W_p is the annual pool water consumption per building unit area (m³/m²·year), V_p is the pool volume (m³), A_f is the building floor area (m²).

3.2.3. Cooling tower circulating water

In typical office buildings, an air conditioning system operates primarily during working hours, approximately 10 h per day. The annual usage frequency may vary depending on the region or usage habits. Therefore, this study referred to the monthly average temperatures from April to October, which are comparatively elevated, comprising 7 out of 12 months. This statement forms the foundation for the calculation formula of daily cooling tower water usage per person, as shown in the following formulas.

$$W_a = (Q_{sd} + Q_e + Q_b) \times 87.85 \div A_f \tag{4}$$

$$Q_{sd} = L_c \times 0.05\% \tag{5}$$

$$Q_e = L_c \times 0.83\% \tag{6}$$

$$Q_b = Q_e \div 3 - Q_{sd} \tag{7}$$

W_a is the annual cooling tower water consumption per building unit area (m³/m²·year), Q_{sd} is the water loss due to splashing per minute (LPM), Q_e is the water loss due to evaporation per minute (LPM), Q_b is the Water Loss due to Discharge per Minute (LPM), L_c: Cooling Circulating Water Volume per Minute (LPM), A_f: Building Floor Area (m^2).

3.3. Calculation method for additional compensatory water volume

This study classified reused water from water resources as additional compensatory water volume. Currently, recorded and quantifiable items allow for a rough categorization into rainwater harvesting, reclaimed water reuse, and condensate water recovery. We distinguished the calculation method for condensate water recovery from that of reclaimed water reuse due to its unique characteristics, according to the water usage patterns in office buildings. Regarding rainwater harvesting and reuse, typically, the roof area is the collection area. We calculated the daily average of collected rainwater and multiplied it by 365 days to determine the annual usable rainfall, as shown in the following formula.

$$W_r = R \times A_r \times 365 \div A_f \tag{8}$$

W_r is the annual usable rainfall per building unit area (m³/m²·year), R is the daily average rainfall (m³/m²), A_r is the collection area (m²), A_f is the building floor area (m^2).

3.3.1. Reuse of reclaimed water

The primary origin of this type of water is derived from domestic wastewater, which includes activities such as bathing, personal hygiene, laundry, kitchen use, and cooling tower water. This type of water is also known as reclaimed water. In the context of water consumption in office buildings, tap water usage in sanitary facilities can be considered a potential source of reclaimed water. The measurable amount of reclaimed water available per individual per day encompasses tap water usage and wastewater from RO water dispensers, as shown in the following formula.

$$W_g = W_{\mathrm{col}} \times 365 \div A_f \tag{9}$$

W_g is the annual usable reclaimed water per building unit area (m³/m²·year), W_{col} is the daily collected reclaimed water volume (m³), A_f is the building floor area (m^2).

3.3.2. Condensate water recovery and reuse

The quantity of recoverable condensate water is typically affected by factors such as humidity, peak load of the unit, air density, and operating duration. In typical conditions, approximately 0.4 L of condensate water can be produced per hour for each 1 kW of cooling load. In scenarios with a higher latent heat load, approximately 0.8 L of condensate water can be generated per hour. For the subsequent calculation of condensate water volume, this study adopted an average value of 0.6 liters per hour. The frequency of annual usage may differ depending on regional or usage patterns. Therefore, this study examined the monthly average temperatures from April to October, comprising 7 out of 12 months, as shown in the following formula.

$$W_c = Q \times 32.07 \div A_f \tag{10}$$

W_c is the annual usable condensate water volume per building unit area ($m^3/m^2 \cdot year$), Q is the cooling load (kW), A_f is the building floor area (m^2).

3.3.3. Compensatory water usage rate

Projected water usage is linked to an architect's strategies for water conservation design. This can involve the use of recycled water for the building and identifying specific areas of water consumption that necessitate offsetting. The amount of compensatory water gathered is affected by variables such as the area of collection, air conditioning system design, and equipment selection. Using these alternative water sources is a crucial strategy for achieving nearly zero water consumption in sustainable office buildings, as shown in the following formulas.

$$S_{\mathrm{wr}} = WR_{\mathrm{use}} \div WR_{\mathrm{max}} \times 100\% \tag{11}$$

$$WR_{\mathrm{max}} = W_r + W_c + W_g \tag{12}$$

S_{wr} is the compensatory water usage rate, WR_{max} is the annual compensatory water collection per building unit area ($m^3/m^2 \cdot year$), W_r is the annual usable rainfall per building unit area ($m^3/m^2 \cdot year$), W_c is the annual usable condensate water volume per building unit area ($m^3/m^2 \cdot year$) and W_g is the annual usable reclaimed water per building unit area ($m^3/m^2 \cdot year$).

This study employed calculation methods from existing literature and regulations, coupled with the reasonable frequency of water usage in office buildings, to develop the following: an estimation method for water consumption, water-saving practices related to office building equipment, additional water use, and a calculation method for compensatory water. The goal was to investigate the water consumption and water-saving benefits of green buildings. Formulas (12)–(15) were used to calculate the total annual water consumption per unit area for each designed case of green office buildings. This calculation can facilitate subsequent discussions on the water distribution design in current green office buildings.

$$W_{\mathrm{total}} = WE_{\mathrm{use}} + WA_{\mathrm{use}} - WS_{\mathrm{use}} \tag{13}$$

$$WE_{\mathrm{use}} = W_t + W_u + W_f + W_d \tag{14}$$

$$WA_{\mathrm{use}} = W_i + W_p + W_c \tag{15}$$

$$WS_{\mathrm{use}} = WS_r + WS_g + WS_c + WS_o \tag{16}$$

W_{total} is the total annual water consumption intensity per unit area of the building ($m^3/m^2 \cdot year$), WE_{use} is the annual water consumption intensity per unit area of the building equipment ($m^3/m^2 \cdot year$), WA_{use} is the annual water consumption intensity per unit area of the building – additional ($m^3/m^2 \cdot$year), WS_{use} is the annual water consumption intensity per unit area of the building – compensatory ($m^3/m^2 \cdot$year), W_t is the annual water consumption intensity per unit area of toilet use ($m^3/m^2 \cdot$year), W_u is the annual water consumption intensity per unit area of urinal use ($m^3/m^2 \cdot$year), W_f is the annual water consumption intensity per unit area of faucet use ($m^3/m^2 \cdot$year), W_d is the annual water consumption intensity per unit area of water dispenser use ($m^3/m^2 \cdot$year), W_i is the annual water consumption intensity per unit area of irrigate use ($m^3/m^2 \cdot$year), W_p is the annual water consumption intensity per unit area of pool use ($m^3/m^2 \cdot$year), W_c is the annual water consumption intensity per unit area of cooling tower use ($m^3/m^2 \cdot$year), WS_r is the annual water consumption intensity per unit area of rainwater recycle save ($m^3/m^2 \cdot$year), WS_g is the annual water consumption intensity per unit area of graywater recycle save ($m^3/m^2 \cdot$year), WS_c is the annual water consumption intensity per unit area of condensed water save ($m^3/m^2 \cdot$year), WS_o is the annual water consumption intensity per unit area of RO water save ($m^3/m^2 \cdot$year).

The total water-saving rate calculated by Formula (12) includes the amount of water used for equipment, additional water, and compensatory water. Compared to the previous discussion of the water-saving for equipment alone, the water-saving design of a building can be discussed more in depth. While it is an office building, it may be due to factors such as the owner and the environment in establishing additional water consumption. The maximum water consumption of each case will differ due to reasons such as the site area and design strategy. The utilization rate of making up for water will also affect the building's total water consumption. Incorporating it into the calculation of the water-saving rate can lead to a more accurate understanding of the distribution of the total water-saving rate of green office buildings to explore whether there is room for a near-zero water consumption building, as shown in the following formula.

$$S_{\text{rc}} = \left(1 - \frac{W_{\text{total}}}{WE_{\max} + WA_{\max}}\right) \times 100\% \tag{17}$$

S_{rc} is the total water-saving rate, $WE_{\max}$ is the maximum annual water consumption intensity per unit area of the building – equipment ($m^3/m^2 \cdot$year), $WA_{\max}$ is the maximum annual water consumption intensity per unit area of the building – additional ($m^3/m^2 \cdot$year).

4. EMPIRICAL ANALYSIS AND FEASIBILITY

Water usage in office buildings can be divided into two main categories: equipment water usage and additional water usage. Necessary facility water usage refers to the water consumed for basic daily life facilities, while other water usage encompasses water-related elements designed to meet specific needs. This study calculated the daily equipment water consumption per person for 73 office buildings. The distribution of water consumption for these cases, sorted by total equipment water usage, revealed an average value of 34.69 liters per capita per day, as shown in Figure 3.

The scale can be generally divided into small-scale office buildings with a total floor area below 10,000 m^2 and large-scale office buildings with a total floor area above 10,000 m^2. Therefore, in this study, a scatter plot was created (as shown in Figure 4) to illustrate the relationship between building floor area and water usage. The study investigated whether water consumption is directly correlated with building size. Figure 5 shows that the water usage of building equipment does not necessarily increase with the rise in building floor area. Instead, it appears to be more closely related to the design strategies used by designers.

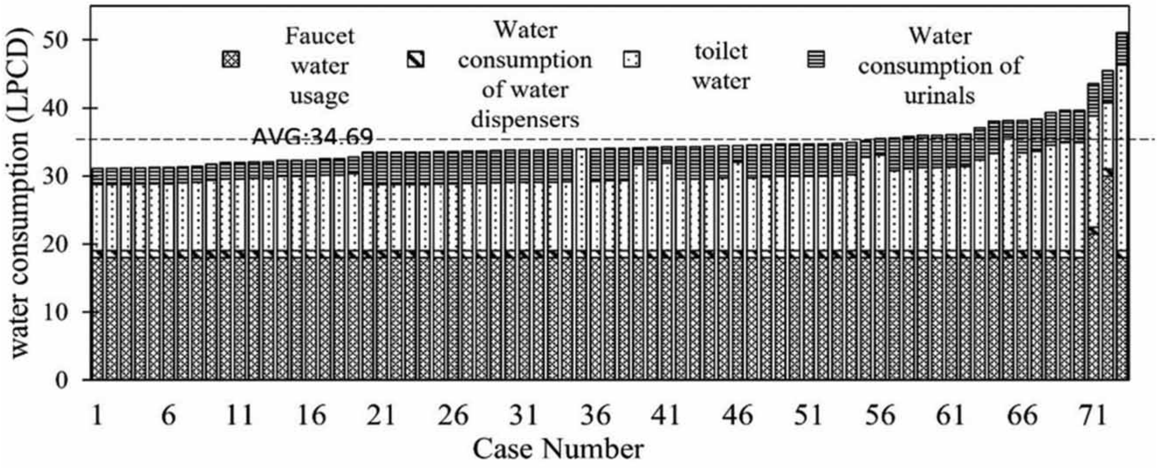

Fig. 3 | Distribution of equipment water usage per person per day.

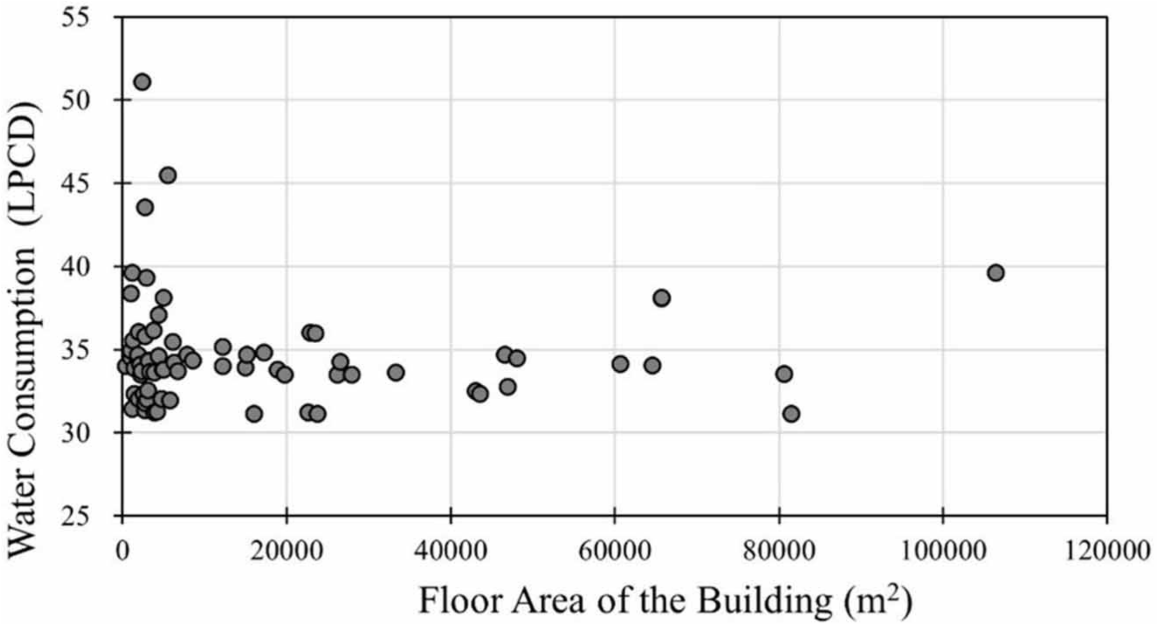

Fig. 4 | Scatter plot of building floor area/water usage.

4.1. Distribution of basic equipment's water consumption

The essential water facilities required for daily use include toilets, urinals, water taps, and drinking fountains. The designed range for the annual water consumption per unit area, known as the WUI, was between 0.72 (m^3/m^2·year) and 1.79 (m^3/m^2·year). The median actual water consumption was 0.86 (m^3/ m^2·year), and the

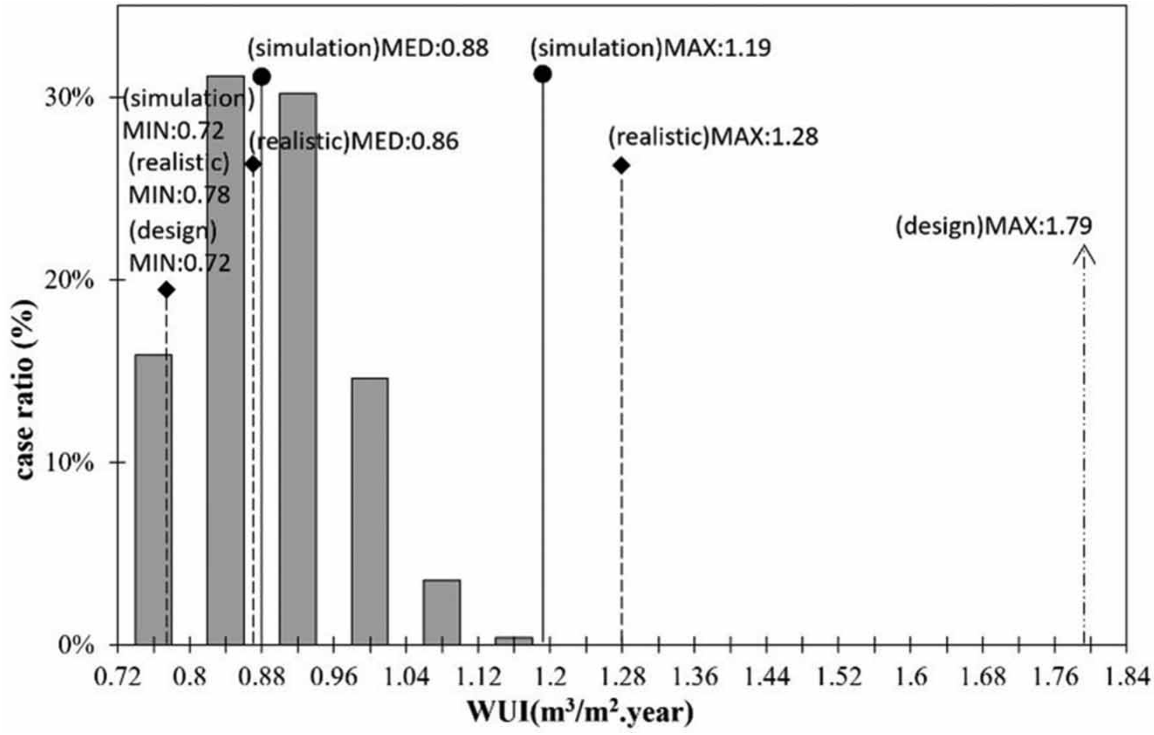

Fig. 5 | Distribution of basic equipment's water consumption.

median simulated water consumption was 0.88 (m^3/ m^2·year). This indicates a close alignment with the designed minimum water consumption. There was a high adoption rate of water-saving equipment in green office buildings, often resulting in water consumption closely approaching the designed minimum with minimal effort. However, if the water consumption of the equipment exceeds the median despite the use of water-saving equipment, a reevaluation of the design would be necessary, as shown in Figure 5.

Allocating additional water consumption involves nuanced considerations for non-essential water usage, with complexities arising from factors such as irrigation choices, landscape pool inclusion, and cooling water tower design. Serving as the reference point, designs exceeding 0.5 (m^3/m^2·year) should incorporate water-saving irrigation systems or water-saving cooling towers. Research from the existing literature highlights the efficacy of implementing humidity control in cooling water towers, resulting in an average water saving of 62.6%. Additionally, adopting smart water-saving irrigation systems demonstrates the potential to conserve approximately 50% of irrigation water. This contributes significantly to an overall reduction in additional water consumption. However, aligning with the overarching goal of achieving near-zero water consumption in buildings, it is imperative to fundamentally minimize designs that contribute to other water consumption. Strategic measures include reducing designed areas dedicated to water-consuming turf, eliminating pool installations, and substituting water-cooled air conditioners with air-cooled and inverter-type air conditioners. These proactive strategies aim to drive water consumption in building designs toward zero, effectively realizing the aspiration of near-zero water consumption, as shown in Figure 6.

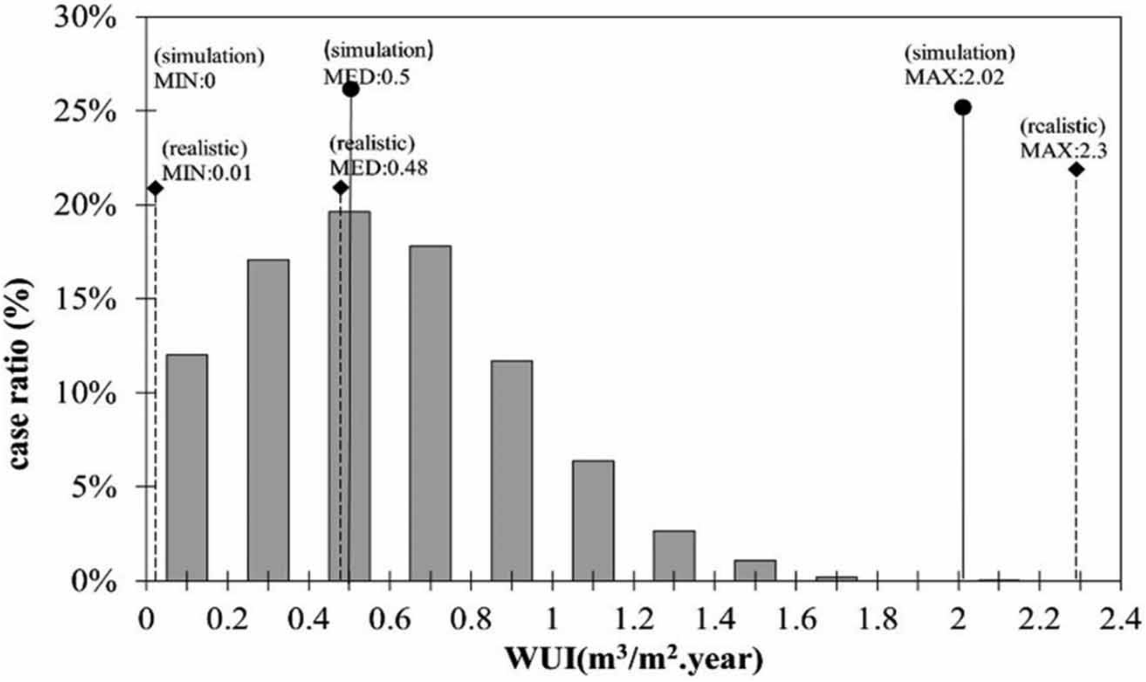

Fig. 6 | Distribution of additional water consumption.

4.2. Compensatory water design

This study examined 73 instances of green office buildings, with 15 cases (22%) not using compensatory water. The remaining 58 cases have implemented rainwater collection and utilization to acquire compensatory water. Among these, the 53-case majority (72%) were specifically designed for irrigation water compensation. Two cases were designed to recycle flushed water, demonstrating a commitment to near-zero water consumption. Only two cases used compensatory water design for both irrigation and flushing. In compensatory water design, the expected water usage was determined by the designed compensatory needs. However, the designed compensatory water source may not always be sufficient to meet additional water needs. Among the 57 cases designed to use compensatory water, the scatter plot of the original design/estimated actual compensatory water volume shows that in seven cases, the designed compensatory water volume exceeded the actual compensatory water volume. This indicates a need for incorporating more compensatory water sources in the design to meet water requirements, as shown in Figure 7.

This study analyzed 73 green office-type buildings and found that 58 cases had a designated provision for makeup water. It is essential to evaluate and measure any differences between the initially designed makeup water usage and the estimated actual makeup water utilization due to potential variations. Therefore, this study conducted separate calculations for the three components of additional makeup water (see Figure 8). Figure 8 illustrates the significant untapped potential for using makeup water in most cases. The average available makeup water was calculated at 1.32 (m^3/m^2·year), the original design makeup water at 0.32 (m^3/m^2·year), and the estimated actual makeup water at 0.28 (m^3/m^2·year). Consequently, the available makeup water was approximately five times the actual makeup water. To optimize rainwater recovery for makeup water, we recommend enhancing roof rainwater collection, potentially leading to a threefold increase in collection efficiency.

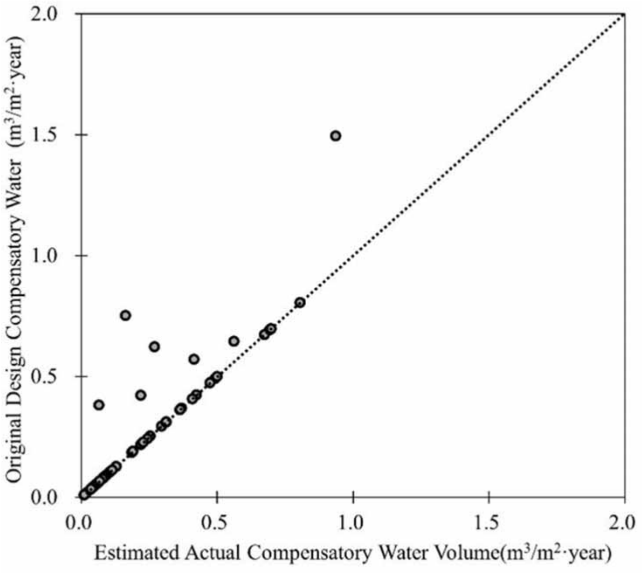

Fig. 7 | Original design/estimation of makeup water distribution chart.

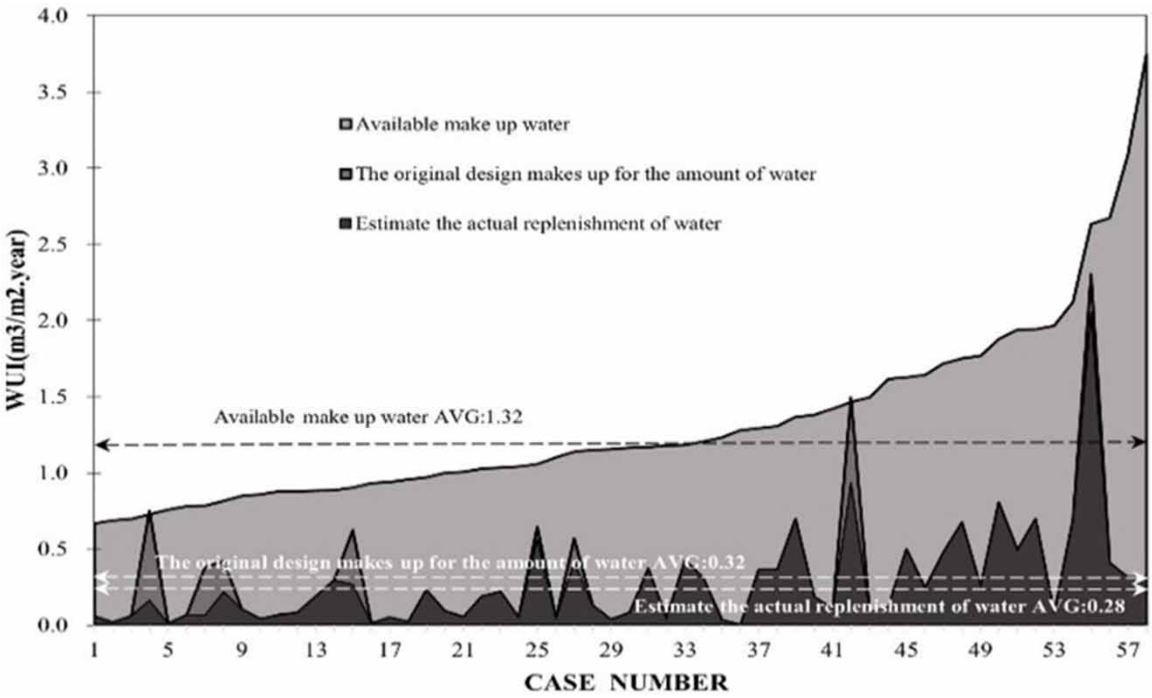

Fig. 8 | Distribution of water-saving. Available/Original Design/Estimated Actual Water Compensation Volume Area map.

This study employed a systematic approach to calculate equipment water consumption, additional water consumption, and compensatory water consumption for each case. We then examined the distribution of the water usage proportions and calculated the water-saving rates based on the collected data. The analysis focused on the existing patterns in the design of water-saving rates for green office buildings. The water-saving rate distribution is presented in Figure 9, revealing a range between 26 and 76%. The median water-saving rate was 53%, averaging 52%. After subjecting the data to a Monte Carlo simulation with 10,000 iterations, the water-saving rate varied between 18 and 88%, and the median remained 52%. These findings indicate that efforts to promote water-saving initiatives in green buildings have yielded significant results in recent years. In most cases, approximately half of the water consumption can be saved. However, the objective of achieving 'nearly zero consumption' still indicates a notable disparity, with water-saving rates ranging from 90 to 100% for water buildings.

4.3. Feasibility of a zero water consumption building

Without additional water usage and using only basic water-based facilities such as toilets, urinals, faucets, and water dispensers, the estimated water consumption was approximately 0.72 cubic meters per square meter per year (m^3/m^2·year). However, due to the limitations set by Taiwanese regulations, recycled and reclaimed water cannot replace water that comes into direct contact with human bodies. This research has established the criteria for determining whether 'recycled and reclaimed water can be used as a substitute (compensatory water)' and presents the corresponding data in Table 3. By using minimal equipment, water consumption of 0.24 (m^3/m^2·year) can be replaced with recycled and reclaimed water. With a median value of 1.23 (m^3/m^2·year) for available additional water, it is feasible to fully supplement water usage and have a substantial surplus of compensatory water for other purposes. However, the remaining 0.48 (m^3/m^2·year) cannot be replaced due to the current regulatory restrictions, as shown in Table 3.

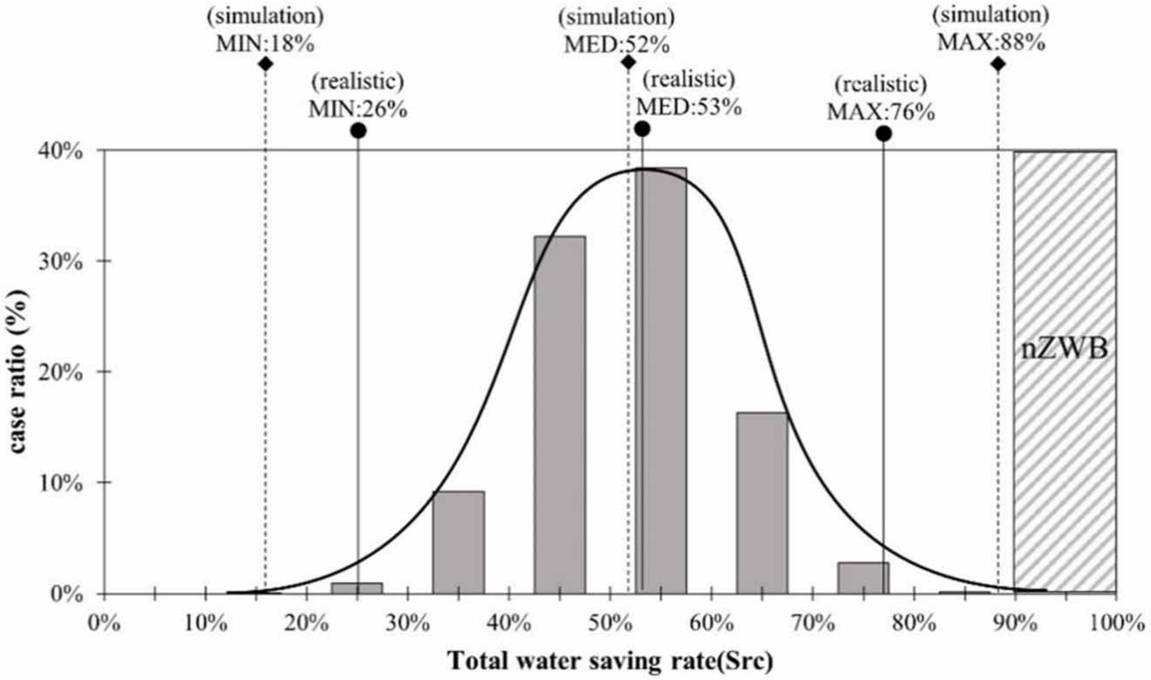

Fig. 9 | Distribution map of water-saving rates.

Table 3 | Summary of water use in green office buildings.

	Minimum	Median	Maximum
Equipment water use (simulation)	0.72	0.88	1.19
Equipment water (design)	0.72	0.86	1.79
Additional water usage (simulation)	0	0.5	2.02
Additional water (total of each category)	0.14	0.8	3.87
compensatory water usage	0.01	0.19	2.06
Available compensatory for water (total for each category)	0.52	1.23	4.42

Note. Unit: annual water consumption per unit area of building m^3/m^2·year.

Currently, the water conservation rates in green office-type buildings range from 26 to 76%, with a median of 53%. This finding indicates a substantial deviation from the ideal 100% conservation rate, which signifies zero water consumption. The annual water consumption benchmark for office buildings is 2.63 (m^3/m^2·year). The present study developed a refined water usage to calculate the water consumption of various water-use items in office-type green building cases. Recent trends demonstrate that green office-type buildings, through strategic design and water-saving equipment, exhibit a median value of 0.88 (m^3/m^2·year) for basic equipment water consumption. When considering all additional water consumption items, the median value for compensatory water usage is 0.8 (m^3/m^2·year), indicating significant water savings compared to the baseline. Further analysis suggests that, with advancements in water-saving technologies, the water consumption of basic equipment in office buildings could be reduced to 0.72 (m^3/m^2·year). However, due to Taiwan's regulations restricting the use of reclaimed water for human contact, the remaining water used by equipment and any additional water can be offset by increasing the reusable water compensatory rate, effectively achieving nearly zero water consumption. The potential inclusion of a recycled drinking water filtration system could enable buildings in the same area to collectively utilize a shared water purification plant in the future. Designing for equipment water usage combined with the median additional water used by current office buildings appears to be sufficient for compensation in current designs. The water consumption of office buildings can be considered as the median of the water consumption of equipment plus the additional water used by office buildings. However, there is a need to increase the rainwater collection area, adopt non-water-cooled central air conditioners or water-saving air conditioners, and implement measures such as smart watering to reduce additional water consumption or augment available water for compensatory purposes.

The study analyzed equipment water usage, additional water usage, and supplementary water usage, laying the groundwork for potentially transforming office buildings into zero water consumption structures. Generally, building water conservation has primarily focused on the water usage of building equipment. However, office-type buildings involve additional elements such as irrigation and cooling tower water. Mitigating the usage of these components is crucial for achieving the zero water consumption goal. This study redefined and integrated the water estimation method for office-type buildings, considering maximum, minimum, and design water consumption. This enables a more precise assessment of water conservation rates.

5. CONCLUSION

This study systematically explored methods for calculating water efficiency and zero water consumption approach in office buildings, drawing from existing literature on water conservation. The research aims to develop a refined water usage to calculate the water consumption of various water-use items in office-type green building cases. The water conservation rates in green office-type buildings range from 26 to 76%, with a median of 53%. This finding indicates a substantial deviation from the ideal 100% conservation rate, which signifies zero water consumption. The annual water consumption benchmark for office buildings is 2.63 (m^3/m^2·year). Despite their classification as office-type buildings, their baseline water usage can fluctuate due to additional water consumption. Using water conservation rates enables a meticulous determination of a building's water efficiency and the extent of its water-saving capabilities. The feasibility of zero water buildings was validated and determined the crucial operation for the zero water consumption goal. Consequently, design engineers can employ this methodology to compute water conservation rates for their designs, aiming for the construction of a zero water consumption building.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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