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Evaluation of Water Efficiency in Green Building in Taiwan

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Abstract: Low carbon policies, including those aimed at increasing water efficiency, have been adopted as a crucial strategy for combating global warming and climate change. The green building evaluation system used in Taiwan was first applied in 1999 and initially utilized a building's water efficiency as the threshold index for determining the building's environmental impact. Since 1999, more than a thousand buildings have been certified as green buildings using this evaluation system. The quantitative effects of water conservation efforts should be provided to policy makers as a form of positive feedback. To that end, the present study offers a calculation process for estimating the quantitative volume of water saved by practical green buildings. The baseline water usage for all kinds of buildings was determined to serve as the criterion for determining the water-saving efficiency of individual buildings. An investigation of the average water-saving rate from 2000 to 2013 for 1320 buildings certified as green buildings was also conducted to validate the estimation results and found that these green buildings saved an average of approximately 37.6% compared to the baseline water usage rate for all buildings. Water savings will inevitably follow from the use of water-saving appliances or water-saving designs for buildings. The proposed calculation process can be used to clarify the relationships between specific water-saving concepts and the real water usage efficiency of green buildings.

Keywords: green building; low carbon society; water resource; saving water

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1. Introduction

The mitigation of global greenhouse gas emissions and other goals of sustainable development have become important issues for many countries around the world [1–3]. Amongst the various environmental issues, water conservation is one of the most critical global problems and one which is only increasing in importance with continuing population growth and the effects of global warming [4]. Taiwan is located in the Asian monsoon area and has an abundant supply of rainwater, with annual precipitation averaging around 2500 mm. However, water shortages have recently become a critical problem during the dry season. The crucial, central factors causing these shortages are the uneven distribution of torrential rain, steep hillsides and short rivers. Furthermore, the heavy demand for domestic water use in municipal areas, as well as the difficulties associated with building new reservoirs, are also critical factors [5]. Given such challenges, various government agencies in countries around the world are endeavoring to spread the concept of water conservation among their populaces. Consistent with this global trend, the Architecture and Building Research Institute (ABRI) of Taiwan's Ministry of Interior proposed the green building concept and introduced an evaluation system for evaluating green buildings in Taiwan [6,7]. In order to save water resources through building equipment designs, this system prioritizes water conservation as one of its critical categories [8,9]. With the institutionalization of green building and the proactive promotion of certification systems, the use of water-saving designs and facilities in construction have seen rapid progress in recent years. Thus far, the planning and implementation of water conservation efforts, including the utilization of rain water, the recycling of reclaimed water, and the use of water-saving sanitary appliances in buildings, have had a significant influence on the use of water resources, as well as positive benefits on energy-saving and carbon-reduction policies [10]. The green building evaluation system used in Taiwan was first applied in 1999 and initially utilized a building's water efficiency as the threshold index for determining the building's environmental impact. Since 1999, more than a thousand buildings have been certified as green buildings using this evaluation system. The quantitative effects of water conservation efforts should be provided to policy makers as a form of positive feedback. Theoretically, water-saving designs and the adoption of water-saving facilities should benefit buildings in terms of their water usage efficiency [11–14]. However, actual real-world water usage is complex, being affected by a wide range of human behaviors and other factors [15,16].

Regarding the issue of the effective use of water resources, the actual water consumption of a building with a green building certification should be different from those of buildings without water-saving designs. Relatedly, the question of whether substantial water-saving effects are achieved by such designs, as well as questions regarding their energy-saving and carbon-reduction benefits, are widely discussed, with various investigations having been undertaken to answer them [17,18]. To date, however, there are still no solid means of verifying or providing clear evidence to determine the quantitative effects of various water conservation strategies. As such, this study establishes a model for estimating water-saving benefits in order to clarify the effective use of water resources. To that end, an empirical investigation of buildings with green building certification was conducted to verify the values estimated by the model after statistical analysis. More specifically, quantified values of reasonable water-saving benefits for Taiwan for every year from 2000 to 2013 (*i.e.*, since the launch of the green building certification system) were derived to examine the effects of water conservation and to validate the proposed model.

2. Materials and Methods

2.1. Water Indexes in the Green Building Evaluation System

This study focused on the water conservation measures for green buildings in Taiwan with the aim of providing a quantitative procedure for proving water-saving efficiency [7]. The water conservation index is a ranking system for the adoption of water-conserving items, including water closets, urinals, faucets and baths, and for the reuse of rainwater and grey water. The framework of the ranking and evaluation system is shown below in Equations (1)–(6)

$$\boldsymbol{WI} = \mathrm{a} + \mathrm{b} + \mathrm{c} + \mathrm{d} + \mathrm{e}\,(\boldsymbol{WI} \leqslant 9) \tag{1}$$

$$a = \sum_{-2}^{3} a_i \times r;\ watercloset, a_i = -2.0, 1.0, 2.0, 3.0 \tag{2}$$

$$b = \sum_{-1}^{1} b_i \times r;\ urinals, b_i = -1.0, 0.5, 1.0 \tag{3}$$

$$c = \sum_{-1}^{1} c_i \times r;\ faucets, c_i = -1.0, 0.5, 1.0 \tag{4}$$

$$d = \sum_{-2}^{1} d_i \times r;\ bathing, d_i = -2.0, -1.5, -1.0, 0.0, 1.0 \tag{5}$$

$$e = \sum_{-2}^{4} e_i \times r;\ reuse, e_i = -2.0, 0.0, 3.0, 4.0 \quad (6)$$

WI: Water index of a green building's water resource indicator system ($0.0 \leqslant \boldsymbol{WI} \leqslant 9.0$).

a, *b*, *c*, *d*, *e*: Parameters of water closets, urinals, faucets, baths and of the reuse of rainwater and grey water with the ranking value.

r: Adoption rate of parameters (%).

As a practical process of the assessment of the ***WI*** value, the applied building should submit the proof documents about the saving water design items; then, the referee committee would confirm and determine the final rating value of the ***WI*** index. This rating system focuses on the saving water design and the adoption of water efficiency facilities for green buildings. The evaluation consideration engages the design and facility, not including usage patterns or behavior styles. Therefore, the rating value of saving water is a conceptual assessment for the water efficiency parameter without real water saving volume.

A study of household tap-water consumption revealed that the proportion of the water used in flushing toilets and in bathing amounts to approximately 50% of the total household water consumption [8]. Many house designers have used luxurious water facilities in the housing they design, causing high volumes of water to be consumed as a result. The use of water-saving equipment to replace such facilities therefore has a great potential to save a large amount of water. For example, the amounts of water used in taking a shower and having a bath are quite different. A single shower uses around 70 L of water, whereas a single bath uses around 150 L. Indeed, the water consumption in showering depends not only on the flow rate of the tap, but also the duration of the shower. This evaluation system is designed for the common options for water efficiency in the built phase; the factors of behavior or usage style are not involved. Furthermore, current house designs in Taiwan tend to include at least two sets of bathtubs and toilets, and quite a few families have their own massage bathtubs. Such designs can only be improved upon by removing the tubs and replacing them with shower nozzles, so that more water can potentially be saved. The commonly-used water-saving devices in Taiwan now include new-style water taps, water-saving toilets, dual-flush water closets, water-saving shower nozzles and auto-sensor flushing device systems, among others. Such water-saving devices can be used not only in housing, but also in other kinds of buildings. Public buildings, in particular, should take the lead in using water-saving devices.

2.2. Process and Calculation

The study selected a sample of buildings that have received green building certification in Taiwan and developed a quantitative water-saving efficiency estimation model; furthermore, an empirical investigation was conducted through the classification and selection of multiple factors. The selected cases had to meet the representation and reliability assessment requirements in statistics. The water index ranking system for green building certification in Taiwan was first implemented in 2005, so it is necessary to estimate the water-saving efficiency of buildings before the implementation of the ranking system. In order to evaluate the overall water efficiency from the performance of the green building certification system, the estimation for water-saving efficiency will use the empirical data and average value from practical cases.

The parameter ***WI*** of the water resource index ranking system for each year was calculated according to the type of building. This study used the average value of parameter ***WI*** of the water resource index ranking system of each building type in the year to expand the investigation of the cases. According to the calculation results, the annual average values of ***WI*** for each building type were typically between five and six and had a normal distribution pattern. In order to estimate the water saving amount of cases before 2005, this study calculated the average according to the building type and set it as the ***WI*** value of all types of cases from 1999 to 2006, thus bringing it into the formula and estimating the water saving amount. As no buildings was certified in the first year, 1999, this study determined the annual savings benefit in Taiwan since 2000, when the green building certification system was first implemented.

3. Baseline and Evaluation Model

3.1. Building Category and Water Usage Baseline

The water demand and the actual water consumption of buildings are actually quite complex, not only because of the difference in building types, but also because even among buildings of the same type, individual buildings may differ substantially due to factors, such as building age, occupancy, density, *etc*. Moreover, a building's usage and demand patterns will change after the actual construction is completed. All of these factors cause considerable difficulty in accurately estimating water consumption. Therefore, in order to more accurately estimate the actual consumption of green buildings to serve as the basis for assessing water-saving efficiency, the operating time factor was added to the factor of building types as one of the water consumption estimation criteria. Herein, the water unit intensity (***WUI***) formula is defined by the parameters of occupancy density, yearly water usage and occupancy rate, shown as Equations (7)–(10).

$$WUI = P_{di} \times Q_{wi} \times F_{ri} \tag{7}$$

$$P_{di} = \prod_{i=1}^{12} P_{di};\ 0.03 \leqslant P_{di} \leqslant 1.2 \tag{8}$$

$$Q_{wi} = \prod_{i=1}^{8} Q_{wi};\ 1 \leqslant Q_{wi} \leqslant 130 \tag{9}$$

$$F_{ri} = \prod_{i=1}^{5} F_{ri};\ 0.4 \leqslant F_{ri} \leqslant 0.8 \tag{10}$$

WUI: Water consumption density per unit area of the building ($m^3/m^2 \cdot$ year).
P_{di}: Person density ($person/m^2$).
Q_{wi}: Yearly water usage (m^3/person/year).
F_{ri}: Occupancy rate (%).

This study proposes ***WUI*** as the definition of building water usage density and to serve as the baseline of building water usage to evaluate the water efficiency of building water consumption. Regarding the setting of the ranges for each of the individual parameters, they were determined on the basis of empirical data and real case studies in previous reports. The parameters were calculated using integer standardization based on the clustering rule and a reasonable situational model. The ranges for the individual parameters are shown in Table 1.

Table 1. Standardized water usage baseline parameter ranges.

Person Density P_{di} ($person/m^2$)	Yearly Water Usage Q_{wi} (m^3/person/year)	Occupancy Rate F_{ri} (%)
0.03	1	40
0.05	5	50
0.1	10	60
0.15	25	70
0.2	40	80
0.25	60	-
0.3	100	-
0.35	130	-
0.4	-	-
0.5	-	-
0.8	-	-
1.2	-	-

Due to the various categories of buildings, this study, in accordance with existing literature and relevant research and investigations, divided the buildings according to 52 different types of water utilization based on the building's utilization time characteristics in order to estimate the baseline for water consumption more precisely. After estimating the parameter levels for the standardized building water consumption and water consumption parameters, the baseline for each type of water consumption was estimated. Table 2 shows the ***WUI*** values for the different space categorizations of the 52 types of baseline water consumption.

Table 2. ***WUI*** for space categorizations of the 52 types of baseline water usage.

Building Type	Groups	Category	P_{di}	Q_{wi}	F_{ri}	*WUI*
Type A (Public meetings)	A-1 assembly hall	A11	0.25	10	0.5	1.25
		A12	0.80	10	0.5	4.00
		A13	0.80	10	0.5	4.00
		A14	1.20	10	0.4	4.80
	A-2 transportation	A21	0.35	10	0.4	1.40
Type B (Business)	B-1 entertainment	B11	0.80	5	0.5	1.50
		B12	0.40	5	0.5	1.00
	B-2 department store	B21	0.25	5	0.5	0.63
		B22	0.25	5	0.5	0.63
		B23	0.35	5	0.5	0.88
	B-3 catering building	B31	0.35	10	0.5	1.75
		B32	0.35	5	0.5	0.88
		B33	0.40	25	0.7	7.00
	B-4 hotel	B41	0.05	100	0.7	3.50
Type C (Industry, warehousing)	C-1 special warehouse	C11	0.03	10	0.5	0.15
		C12	0.03	10	0.5	0.15
		C13	0.03	1	0.4	0.01
		C14	0.03	1	0.4	0.01
		C15	-	-	-	-
	C-2 general warehouse	C21	0.10	25	0.7	1.75
		C22	0.10	25	0.7	1.75
		C23	0.10	40	0.7	2.80
		C24	0.10	40	0.7	2.80
Type D (Leisure, culture and education)	D-1 convenience store	D11	0.25	5	0.5	0.63
		D12	0.25	60	0.5	7.50
		D13	0.15	130	0.5	9.75
	D-2 cultural and educational facility	D21	0.15	25	0.7	2.63
		D22	0.40	10	0.6	2.40
	D-3 elementary school building	D31	0.40	10	0.6	2.40
	D-4 school building	D41	0.40	10	0.6	2.40
		D42	0.20	25	0.7	3.50
	D-5 tutoring center and childcare	D51	0.40	10	0.6	2.40
Type E (Religion, funeral and interment)	E religion, funeral and interment	E11	0.80	10	0.5	4.00

Table 2. *Cont.*

Building Type	Groups	Category	P_{di}	Q_{wi}	F_{ri}	WUI
Type F (Health, welfare, rehabilitation)	F-1 healthcare	F11	0.10	100	0.7	7.00
		F12	0.10	10	0.5	0.50
		F13	0.10	10	0.5	0.50
		F14	0.30	5	0.5	0.75
		F15	0.30	5	0.5	0.75
		F16	0.15	25	0.7	2.63
	F-2 social welfare	F21	0.05	100	0.5	2.50
	F-3 child welfare	F31	0.05	100	0.5	2.50
	F-4 prison	F41	0.05	100	0.5	2.50
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
	G-3 shop and clinics	G31	0.25	5	0.5	0.63
Type H (Residence)	H-1 lodge and care house	H11	0.05	100	0.7	3.50
	H-2 house	H21	0.04	100	0.8	3.20
		H22	0.03	100	0.8	2.40
		H23	0.02	100	0.8	1.60
Type I (Dangerous goods)	I dangerous factory or warehouse	I11	0.03	1	0.4	0.01
		I12	0.03	1	0.4	0.01

With regard to the building category, spatial contrasts were computed by referring to 52 types of space according to building categories A–I under the building code of Taiwan. Type C15 represents a special factory/warehouse, featuring high water consumption units, such as central kitchens, central laundry facilities, *etc.*, in which the quantity of water consumed should be estimated based on the scale of the operating facilities and the given building's production demands. There is no standardized parameter for defining the different categories of buildings so far. Residential buildings are divided into three categories: apartments (H21), bungalow (H22) and detached houses (H23), with the major parameter variance being the occupant density per unit construction floor area P_{di} (person/m^2).

Overall, other than accommodation or medical buildings, which involve everyday-life water demands, the per-capita water demand per unit of buildings in general is mainly determined by the use of toilets and for cleaning activities. The water demands of accommodation buildings, on the other hand, include the water needed for cleaning and bathing, toilet flushing, cooking and other purposes. Based on the unity and efficiency principle of the estimation formula and for the sake of consistency in our assessments, water consumption was translated into average per-capita water consumption per unit for all building types. A building's total water consumption is mainly influenced by the two factors of per-capita consumption per unit and user density, and basically, these two factors are independent variables.

3.2. Water Efficiency Evaluation

To more precisely estimate the quantity of water actually consumed by a given green building, the factor of operating time was added to the building categories when estimating the baseline for the quantity of water consumed. After the water consumption per unit of the floor area of a building with green building certification was acquired, this study used statistical quantitative methods and an empirical investigation for comparison and analysis, determining the actual gross water consumption as a basis for estimating the quantity of a building's annual water conservation. Accordingly, the baseline for annual water consumption for each category of building W_{ty} (m^3/year) was established, and the formula for the estimated quantity of annual water conservation W_{st} (m^3/year) is provided below.

$$W_{ty} = A_f \times WUI \tag{11}$$

$\boldsymbol{W_{ty}}$: Annual water consumption for each category of building (m^3/year).
$\boldsymbol{A_f}$: The floor area of a building (m^2).
$\boldsymbol{WUI}$: Water consumption density per unit area of a building ($m^3/m^2 \cdot$ year).

$$\boldsymbol{W_{st}} = \boldsymbol{W_{ty}} \times (\boldsymbol{WI} \div 9) \quad (12)$$

$\boldsymbol{W_{st}}$: The estimated quantity of a building's annual water conservation (m^3/year).
$\boldsymbol{W_{ty}}$: Annual water consumption of each category of building (m^3/year).
$\boldsymbol{WI}$: Water index of a green building's water resource indicator system ($0.0 \leqslant \boldsymbol{WI} \leqslant 9.0$).

The score for the water resource indicator system for a green building's rating assessment system, ***WI***, is the key parameter for estimation. This study used the real cases with green building certification, and each case has a certified rating value of the ***WI*** index. The average values of the water resource indicator rating scores for 2007–2013 (***WI***) were, for the most part, normally distributed between 3.0 and 5.0. Table 3 shows the average values of the ***WI*** scores for the green buildings for each year. The missing data (-) means there is no certification case for that building type of the year in Table 3.

Table 3. The annual average values of ***WI*** for the different building types.

Building Type	2007	2008	2009	2010	2011	2012	2013	Average
Office	4.74	5.4	4.85	4.49	4.9	4.74	5.28	4.91
Department store	-	-	-	-	5.33	5.46	6	5.6
Hostel	-	-	-	-	-	-	5.64	5.64
Hospital	-	-	-	5.20	5.25	5.25	5.03	5.18
School	4.44	4.94	4.95	4.26	5.11	5.07	5.01	4.82
Residence	4.86	4.81	4.34	5.91	4.78	5.79	5.76	5.18
Others	5.32	5.19	5.14	5.14	4.88	5.15	5.11	5.14

According to the guideline of Taiwan green building in the water index, the evaluation adopted the ***WI*** ranking system as a quantitative assessment for certification from 2005. This alterative rating method clarified the certification process, but no change for the design motivation and option of water efficiency to the previous evaluation system. Including the average values of ***WI***, the water resource indicator rating score helps to streamline the estimation of water-saving benefits for the year's water resource indicator.

Based on our determinations of the average values for ***WI***, this study further used a regression formula to estimate the reasonably-predictable parameters for buildings certified as green buildings prior to the implementation of the green building rating system in 2005. Therefore, this study was able to determine the gross water-saving benefits of buildings with green building certification from 2000, the year when the green building labeling was first applied, through 2013. The estimation formula for the gross water-saving benefit of a given building is provided as follows.

$$W_{gst} = \sum_{n=2000}^{2013} W_{stn} \quad (13)$$

$\boldsymbol{W_{gst}}$: The estimated quantity of water saving with green building certification, (m^3).
$\boldsymbol{W_{stn}}$: The estimated water saving of the year (n, 2000–2013), (m^3/year).

4. Results and Discussion

This study was designed to compare the actual quantities of water consumed by buildings with green building certification in Taiwan with the standard quantity of water consumed by buildings in general in order to verify the accuracy of the proposed estimation model. To that end, a total sample of 105 actual water consumption quantities was obtained. The average quantity of water consumption per person will vary with the category of the building and will also be categorized for the type of building based on the use time. To enhance the accuracy and reliability of the estimation by using the standard water consumption quantity established, this study compared the actual quantities of water consumed, data that were provided by Taipei Water Company, with the standard water consumption quantity in order to review and verify the reliability of the proposed model. There are 13 cases where a negative water savings was found, as shown as Figure 1, which fail the saving water expectation in general. The reasons for the failure of the model in these cases were subsequently clarified on a case-by-case basis through a field survey. For some of the cases, the buildings had changed their primary building function, whereas others were found to have management and operation problems. However, there were 45 cases for which the water-saving rate was over 60%, and the overall average water-saving rate for the buildings investigated was 49.05%. These findings reveal that, overall, green buildings exhibit real water usage efficiency and water-saving performance.

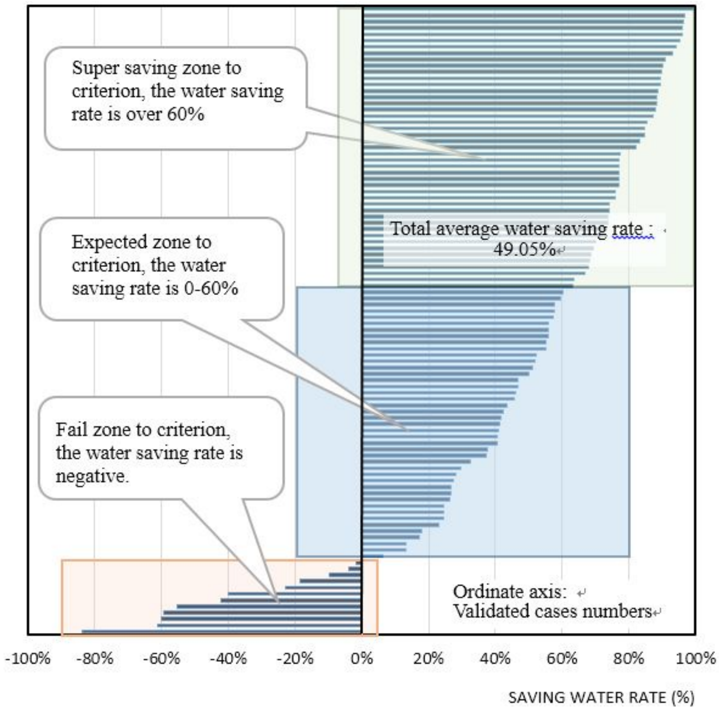

Figure 1. Distribution of water-saving rates for validated cases.

This study, based on the estimating model for quantifying water demanded and the quantity of water saved by buildings, proceeded with theoretically reasonable calculations of water-saving benefits, with major estimation factors, including the baseline for the annual water consumption of a building (W_{ty}) and the score of the water index (WI) used to estimate the quantity (W_{st}) of annual water savings for a building with green building certification accordingly.

Figure 2 demonstrates the standard quantity of water consumption, the estimated quantity of water consumption and the gross water-saving benefit for each category of building for every year since the implementation of the green building labeling system in Taiwan. Table 4 shows the quantities of gross water savings for each category of building and the estimated results of the gross water savings year by year.

Regarding the estimation of water-saving benefits for the water resource indicators, the average quantity of water savings for buildings with green building certification was estimated to reach 37.6%, which is close to the initial estimation for the water-saving results of a green building in general. A comparison of the estimated and actual water-saving values is shown in Table 5, which indicate that most of the estimation values are verified.

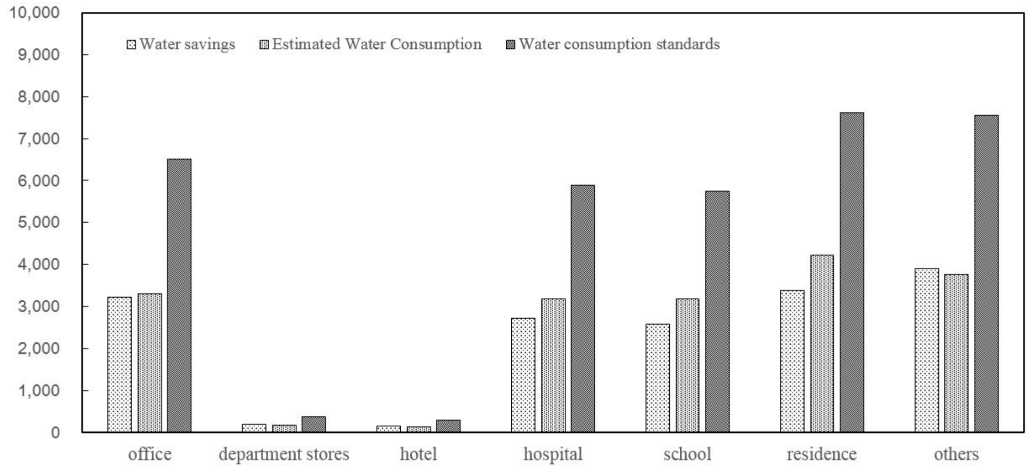

Figure 2. The comparison of the quantity of water consumption and water savings for each category of building (2000–2013) (unit: $\times 10^3$ m^3).

Table 4. The quantities of gross water saving for each category of building (unit: $\times 10^3$ m^3).

	Office	Department Stores	Hostel	Hospital	School	Residence	Others	Total
2001	-	-	-	-	-	61.38	-	61.38
2002	-	-	-	-	-	46.98	-	46.98
2003	11.82	-	30.57	-	-	23.84	0.92	67.15
2004	21.46	-	-	-	17.51	111.05	73.86	223.88
2005	98.33	-	-	-	66.88	96.51	43.95	305.66
2006	172.71	1.39	-	12.52	153.16	120.18	145.65	605.62
2007	220.10	11.20	-	26.09	216.97	182.26	308.03	964.66
2008	434.45	-	-	251.35	229.80	260.93	101.57	1278.10
2009	264.00	103.61	-	509.50	323.39	541.06	304.10	2045.66
2010	371.44	-	-	81.17	226.73	301.35	217.75	1198.43
2011	329.65	6.38	-	108.07	369.00	524.66	414.94	1752.70
2012	499.92	52.93	34.29	77.60	536.97	500.56	1082.88	2785.15
2013	839.53	13.07	95.95	1727.98	505.33	708.33	1228.58	5118.79

Table 5. Comparison of estimated values for the water-saving effects of buildings.

Year	The Estimated Quantity of Water Savings (W_{stn1}) in This Study ($\times 10^3$ m^3)	Water-Saving Percentage %
2001	61.4	32.2%
2002	47.0	32.1%
2003	67.1	25.2%
2004	223.9	46.3%
2005	305.7	25.7%
2006	605.6	10.7%
2007	964.7	20.7%
2008	1278.1	36.8%
2009	2045.7	32.4%
2010	1198.4	48.7%
2011	1752.7	31.9%
2012	2785.2	32.2%
2013	5118.8	46.9%
Total	16,485.8	37.6%

5. Conclusions

In terms of the effective use of water resources, the findings of this study, as determined by investigating the current status of water savings using empirical methods, verify the quantified water saving effects for buildings with green building certification in Taiwan. At first, the building water usage baseline ***WUI*** was summarized and was then used, in conjunction with the quantification estimation model for water-saving efficiency, as a criterion basis for the quantification of building water-saving rates. A quantitative estimation model for water savings was thus established in order to evaluate the water efficiency performance of the green building certification system in Taiwan. According to the data provided by the Taipei Water Company and a field survey, the actual quantities of water consumed by green buildings and their water-saving rate were validated.

This paper details the calculation process used to estimate the quantitative volumes of water saved by practical green buildings in Taiwan. The baseline of water usage for all kinds of buildings was confirmed and used as the criterion base for water-saving performance. According to the results, the average water-saving rate for 1320 cases with green building certification during 2000–2013 in Taiwan was approximately 37.6%. The proposed calculation process clarified the relationships between water-saving concepts and the real water efficiency of green buildings. Thus, efforts to save water could be consolidated to achieve synergy in sustainable development.

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