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Life-cycle Cost Analysis of Using Rainwater Harvesting Systems in Hong Kong Residential Buildings

홍콩 주거건물에서 우수활용시스템의 생애주기비용분석

가오싱* Gao, Xing
김영철** Kim, Youngchul
이현우*** Lee, Hyun Woo

Abstract

This paper investigates whether the use of Rainwater Harvesting Systems (RWHSs) to provide water for washing machines in Hong Kong residential buildings would be financially attractive. In such systems, rainwater is accumulated and reused for doing laundry, garden irrigation, flushing toilets, and even drinking. Thus, the analysis of RWHSs' financial feasibility is essential for construction projects. RainCycle is used to validate financial feasibility, considering particular circumstances and data relevant to the Hong Kong context. A range of different scenarios by adjusting three factors are evaluated: catchment area, water demand, and discount rate. It is suggested that 2,000 m^2 would be a suitable catchment area in a typical Hong Kong residential building and it is demonstrated how water demand and discount rate influence the financial performance of RWHSs. In particular, the financial performance of RWHSs is sensitive to discount rates. The results suggest that the RWH system would be worthwhile for buildings with a lower number of floors, but would barely achieve financial validation in Hong Kong's super high-rise residential buildings.

Keywords : Rainwater Harvesting System, Financial Analysis, Washing Machine, Residential Building, Hong Kong
주 요 어 : 우수활용시스템, 생애주기비용분석, 세탁기, 주거건물, 홍콩

I. INTRODUCTION

Rainwater Harvesting is the accumulation and deposition of rainwater for reuse before it reaches the aquifer. This harvested water can then be used for doing laundry, irrigating gardens, flushing toilets and even drinking. Because Rainwater Harvesting Systems (RWHSs) can be installed on both residential and commercial buildings, the act of recycling rainwater is gaining popularity in many countries such as Austria (Zhang et al., 2009), India (Srinivasan et al., 2010), and Brazil (Ghisi et al., 2006). However, there is insufficient evidence to evaluate the feasibility, especially the financial feasibility, of RWHSs in high-rise residential buildings such as those common in Hong Kong.

The Annual Report of the Hong Kong Water Supplies Department (Water Supplies Department, 2012) stated that Hong Kong has a network of catchments covering some 300 square kilometers. Rainwater collected from these catchments, together with the water pumped from the Dongjiang, can be stored in 17 impounding reservoirs across the territory. However, only a few RWHS installations in residential and office buildings have been reported in Hong Kong.

With the increase in water demand from a growing population, and with the climate change rendering natural supplies more unpredictable, it is becoming increasingly necessary to diversify water sources. Hong Kong imports significant amounts of potable water from the Guang Dong Province in Mainland China, but this water source is likely to become unstable. A shortage of potable water has emerged, in part due to the economic development and urbanization of Mainland China. The 2012 Annual Report (Water Supplies Department, 2012) also pointed

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*정회원 (주저자), MSc, Engineer, Evergrande Group (Guangzhou) China
**정회원 (교신저자), PhD, Assistant Professor, Department of Civil and Architectural Engineering, City University of Hong Kong
***정회원, PhD, Assistant Professor, School of Civil and Construction Engineering, Oregon State University

Corresponding Author: Youngchul Kim, PhD, Department of Civil and Architectural Engineering, City University of Hong Kong, Tat Chee Ave Kowloon, Hong Kong
E-mail: youngkim@cityu.edu.hk

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out that the average ammoniac nitrogen and manganese levels in Dongjiang water had increased since 2009.

RWHSs are sets of equipment and methods for rainwater reuse that involve the collection of rainfall from various surfaces including roofs, roads, parking lots and other designated catchment areas. Because RWHSs prevent treated potable water from being wasted by irrigating gardens, flushing toilets and washing laundry, they are an effective method of saving water in urban areas. Previous studies show that RWHSs can contribute to saving potable water in residential buildings and local regions (Ward et al., 2012; Rahman et al., 2012; Morales-Pinzón et al., 2012; Farreny et al., 2011; Ward et al., 2010; Mbilinyi et al., 2005).

RWHSs have emerged over the last few decades in Western countries such as the UK, Austria, and the USA. Developers have used the RWHSs for water conservation and the reduction of water consumption costs. Thus, researchers are being encouraged to analyze the economic and financial performance of RWHSs in terms of cost benefit analysis. Many hydraulic and financial models (e.g. RainCycle) have been developed to enable feasibility analyses to be conducted before the actual implementation of RWHSs.

In this paper, the research objective is to determine whether RWHSs are financially attractive to developers when used in Hong Kong residential buildings by using a financial and hydraulic model. Additionally, it is also analyzed which factor contributes the most to the financial performance of RWHSs, out of catchment surface areas, water demands, and discount rates. This paper aims to depict the most typical location-specific parameters to achieve valuable and reasonable financial validation in Hong Kong. In the literature review, usages, financial analysis and modeling of RWHSs are investigated.

II. LITERATURE REVIEW

Due to the improvement of technology and water filtration systems (e.g. Gladney, 2004), harvested rainwater can be reused for various purposes. In the UK, domestic RWHSs are used predominantly for non-potable applications such as toilet flushing, garden irrigation, and doing laundry (Leggett et al., 2001; 2001a). In Hong Kong, 80% of the water used for toilet flushing comes from treated seawater, which is much more economical than fresh water (Water Supplies Department, 2013). Villarreal and Dixon (2005) found that at least one fifth of the water used for laundering clothes could be saved on an annual basis. Thus, in Hong Kong, rainwater can be more appropriately substituted in residential washing machines than in toilets.

RWHSs are a recognized technique for reducing reliance on potable water supplies that have the economic benefit of water cost reduction (Roebuck & Ashley, 2006). However, it is still debatable whether RWHSs are financially attractive. The financial validation of RWHSs should be illustrated by the life-cycle cost analysis (LCCA) that takes into account local conditions such as annual rainfall levels, configuration of buildings, typical water demands of a building, and local water prices. Gabe et al. (2012) stated that the annual cost of RWHSs in New Zealand's urban areas was lower than that of the traditional water supply system and the only cost to the sole-supply owner residents was due to the electricity used to pump the water. However, the economic analysis conducted by Farreny et al. (2011) demonstrated that the cost-efficiency of existing rainwater harvesting strategies may not be worthwhile in dry areas in Spain or areas where the water price is still low. Rahman et al. (2012) explained that the benefit cost ratios for rainwater tanks were less than 1, without government rebate. In terms of other relevant factors, Morales-Pinzón et al. (2012) found that the materials used to construct the water tank did not significantly affect financial performance while a group of apartment buildings were the most efficient in terms of lowest net present value cost. <Table 1> summarizes the previous studies addressing the financial performance of RWHSs.

The financial analyses of RWHSs can vary widely between cities due to differences in factors such as rainfall and building configurations. Thus, to financially validate the viability of RWHSs in Hong Kong, local contextual data are needed.

Financial performance models of RWHSs provide an opportunity to analyze the impacts of different input parameters (e.g. the size of the water tank) on different outputs (e.g. benefit cost ratio and net present value cost). Different discount rates (e.g. 3, 5, or 8%) also result in different life-cycle costs. Roebuck et al. (2011) found that the whole life-cycle model produced more realistic predictions of RWHSs' performance than other models because it included these highly influential parameters. Ward et al. (2012) developed a model that also considered energy cost and building occupancy. Roebuck and Ashley (2006) developed a Microsoft Excel-based software, RainCycle, that performs both hydraulic and financial analyses. RainCycle can estimate

Table 1. *Previous Studies of RWHSs' Financial Performance*

Author	Region	Type of Buildings	Positive NPV Financial Performance
Ward et al. (2012)	UK	Office & Residential	✓
Rahman et al. (2012)	Greater Sydney, Australia	Residential	Tank size 2kL ✗ 3kL ✗ 5kL ✓
Morales-Pinzón et al. (2012)	Spain	Residential	Housing type 2SH ✗ 8SH ✗ GH ✓ AH, AB ✗ GAB ✓
Farreny et al. (2011)	Granollers, Catalonia, Spain	Residential	Water price HWP ✓ LWP ✗
Ward et al. (2010)	UK	Residential	Good Design ✓ Poor Design ✗

Note. NPV: Net Present Value; 2SH: Two single houses; 8SH: Eight single houses; GH: Group of houses; AH: Apartment houses; AB: Apartment buildings; GAB: Group of apartment buildings; HWP: High water price; LWP: Low water price; ✓: Positive financial performance; ✗ : Negative financial performance

Table 2. *Different Models for RWHS Analysis*

Reference	Input	Output	Hydraulic Model Optimizing Tank Size
Ward et al. (2012)	a) Average rainfall data b) Catchment area c) Tank volume d) Roof catchment characteristics e) Water demand (No. Of WC) f) Building occupancy/ type	a) Water saving efficiency b) Energy cost c) Financial cost savings d) Basic payback period	No
Rahman et al. (2012)	a) Average rainfall data b) Catchment area c) Water tank size d) Rebate from government e) Daily water demand f) 3% Discount rate	a) Reliability of rainwater use b) Benefit cost ratio	Yes
Morales-Pinzón et al. (2012)	a) Rainfall data b) Water demand-supply ratio c) Tap water price d) Water hardness e) Days with rain >1 mm	a) Net present value b) Internal rate of return c) Energy use	Yes
Farreny et al. (2011)	a) Detailed capital cost b) Harvesting cost c) Storage cost d) Distribution cost	Net present value	Yes
Ward et al. (2010)	a) Average rainfall data b) Catchment area c) Tank volume d) Occupancy e) Filter/runoff coefficient f) Days requires storage	a) Demand net b) RWH system cost c) Mains water cost d) Total savings e) Recommended tank size	Yes

the optimum rainwater tank size as a function of rainfall, filter coefficient, and other variables. Hydraulic model and financial model components are required as inputs to RainCycle. <Table 2> summarizes the financial analysis models of RWHSs developed in the previous studies.

III. METHODOLOGY

1. Research Objectives and Questions

The research objective is to ascertain whether RWHSs are financially suitable for use with washing machines in Hong Kong residential buildings. Accordingly, the following research questions are investigated. 1) *Are RWHSs financially attractive in residential buildings in Hong Kong?* 2) *What is the optimum catchment surface area for rainwater collection?* 3) *Which factor plays the most important role in the financial performance of RWHSs, or which factor has the dominant effect on the Net Present Value (NPV) calculation?*

2. Research Method

The Microsoft Excel-based software, RainCycle, is used to analyze financial suitability. This software comprises two main processes: storage tank size and cost saving optimization. The factoring in of water tank size means that RainCycle's analysis is more reliable than that of other models. RainCycle also generates data on payback periods and NPVs of costs and savings from RWHSs. Thus, the research method consists of two steps: optimizing water tank size <Figure 1> and optimizing cost efficiency <Figure 2>. The main process follows four steps: 1) Determine the optimum tank size; 2) Examine a scenario using the selected parameters and assess its financial performance; 3) Adjust parameters such as

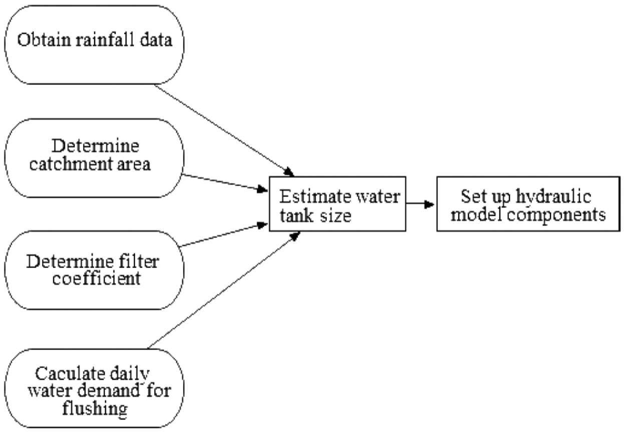


Figure 1. *Hydraulic Analysis Process*

catchment surface area, water demands, and discount rates, then repeat step 2; and 4) Draw conclusions and make suggestions.

The optimization of cost efficiency involves a large amount of input data such as capital cost, maintenance cost, operating cost, and discount rate. <Figure 2> shows the process of this financial simulation.

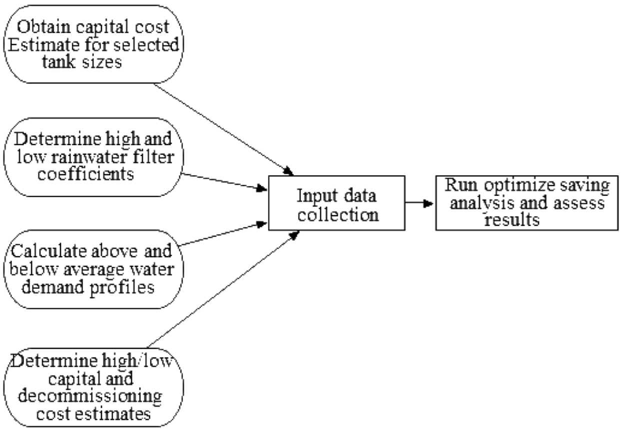


Figure 2. *Financial Simulation Process*

To investigate which factor has the most significant influence on financial performance, a control variable method is used in this paper, which demonstrates the relationship between variables and their results. The control variables tested are catchment surface area, water demand, and discount rates. RainCycle also generates payback periods, NPVs of costs and savings, and ratios of water demands met. If the financial performance indicated a negative NPV value for cost saving, the financial simulation process was repeated with different parameters.

IV. DATA COLLECTION FOR HONG KONG's CONTEXT

To evaluate the financial performance of RWHSs in Hong Kong, two categories of data are required: hydraulic and financial data. The hydraulic data include rainfall, catchment areas, and water demand. The financial data include total capital, maintenance, decommission, electrical and main water costs, and discount rate.

1. Hydraulic Data

1) Rainfall

The monthly mean levels of rainfall in Hong Kong are available in the report from the Hong Kong Observatory <Table 3>.

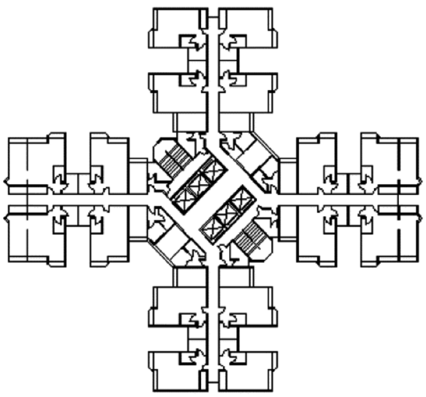
Table 3. *Monthly Mean Rainfall In Hong Kong between 1981-2010*

Month	Total (mm)	Duration (hours)	No. of Days with		
			0.1 mm or more	25 mm or more	50 mm or more
January	24.7	46	5.37	0.23	0.00
February	54.4	89	9.07	0.53	0.10
March	82.2	101	10.90	0.87	0.37
April	174.7	99	12.00	2.23	1.10
May	304.7	106	14.67	3.97	1.73
June	456.1	111	19.07	5.27	2.60
July	376.5	85	17.60	4.60	2.27
August	432.2	97	16.93	5.37	2.47
September	327.6	78	14.67	3.80	2.00
October	100.9	46	7.43	1.20	0.70
November	37.6	38	5.47	0.43	0.13
December	26.8	40	4.47	0.20	0.07
Year	2398.5	935	137.63	28.70	13.53

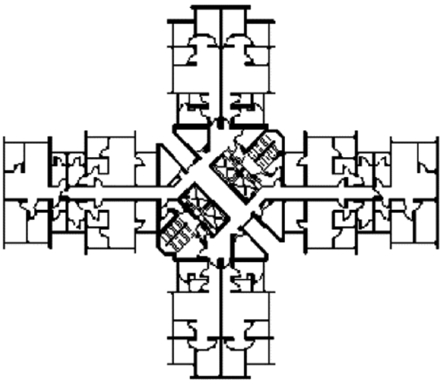
Note. Retrieved May 6, 2013, from http://www.weather.gov.hk/cis/normal/1981_2010/normals_e.htm

2) Catchment Area

A catchment area is a surface, frequently a roof, that will collect and channel rainwater to the storage tank.



a) *A Floor Plan of Harmony Block*



b) *A Floor Plan of New Cruciform Block*

Figure 3. *Typical Residential Buildings in Hong Kong*

Note. the floor plans are excerpted from Chen et al. (2001, 332) Figs. 5 and 6.

In this paper, the catchment areas of typical residential buildings in Hong Kong are calculated. <Figure 3> shows the selection of typical residential buildings that Chen et al. (2001) used to analyze embodied energy use. Although the two residential buildings shown are not representative of all residential buildings in Hong Kong, they can be considered as the exemplary cases of Hong Kong housing over the past 20 years (Chen et al., 2001). The usable floor area of each block is used to calculate catchment areas. In Hong Kong, a residential block means a single building where each floor consists of apartment housing units (or flats). The Building Ordinance in Hong Kong defines that a usable floor area includes any floor space other than staircases, staircase halls, lift landings, the space used in providing water closet fitments, urinals and lavatory basins, and the space occupied by machinery for any lift, air-conditioning system or similar service. Thus, the catchment surface area can be calculated by using Equation (1).

$$A_r=(A_u \div n)\times c \qquad (1)$$

A_r: catchment surface area
A_u: usable floor area
n: number of stories
c: area adjustment coefficient (i.e. 1.25)

The Harmony Block is a 40-story building with a usable floor area of 39,040 m^2, which comprises 16 apartment units per floor and a central core of stairs and lifts. The New Cruciform Block is a 40-story building with a usable floor area of 26,600 m^2. The estimated roof area of Harmony Block is 1,220 m^2. The estimated roof area of New Cruciform Block is 821 m^2. The average of the two estimated roof areas is used for analysis. Thus, the average roof area used is 1,020 m^2, which is reasonable and close to the value in the *Best Practice Guidance of Rainwater and Greywater Use in Buildings* by the Construction Industry Research and Information Association (CIRIA) in the UK (Leggett et al., 2001a).

However, because high-rise residential buildings demand relatively large quantities of water, it is also worth considering strategies by which available catchment areas for rainwater collection could be increased. For example, ground areas around each block could be used as an additional catchment area, along with building sides and projecting bay windows capable of catching rainwater.

Regarding the catchment area, catchment surface runoff coefficient is required. Some rain water is lost before it can be collected, due to runoff processes such as surface wetting, evaporation, and types of roof surface materials. The user manual for RainCycle indicates the typical runoff coefficients for different types of roofs, so the coefficient value of 0.9 is adopted for conventional estimations.

3) Water Demand

Data from the Hong Kong Water Supplies Department and Hong Kong Housing Authority are used to estimate the water demand for washing machines in Hong Kong. The Hong Kong Water Supplies Department (2013) finds that the average daily water demand per washing machine for Hong Kong's population was individually 13.0 liters in its 2011 survey of residential water consumption. The Hong Kong Housing Authority (2013) also shows that the average household size in 2012 was 2.9. Accordingly, Equation (2) calculates the total water demand per day of a whole building and the results are presented in <Table 4>.

$$D_{total}=D_i \times n_p \times n_f \times n_a \qquad (2)$$

D_{total}: total water demand of one block per day
D_i: average daily water demand per population in Hong Kong (=13 liters)
n_p: number of people in each apartment unit (=2.9)
n_f: number of floors in one block
n_a: number of apartments unit per floor (=16 in Figure 3)

Table 4. *Total Water Demands of 30-, 35-, and 40-storey Residential Buildings*

n_f	D_{total} (m^3)
30	18.1
35	21.1
40	24.1

Additionally, some rainwater harvesting systems incorporate a "first-flush device" that captures the initial portion of runoff from a catchment surface and diverts it away from the storage tank. This first flush effectively diverts pollutants such as leaves and dust away from entering RWHSs. This paper allows for a first-flush volume of 5 liters.

In the hydraulic analysis, a rainwater filter coefficient is required. Rainwater filter coefficients are normally obtained from manufacturers or suppliers of rainwater harvesting components. However, due to the absence of specific data, a coefficient of 0.90 is used as per the suggestion by the user manual of RainCycle, The value of 0.90 is a common value for a rainwater filter coefficient. Both Ward et al. (2010) and Roebuck and Ashley (2006) used 0.90 as the coefficient in their models of RWHSs. It is reasonable to adopt this number in the hydraulic analysis.

2. Financial Data

1) Total Initial Cost

The total initial cost varies depending on the type of RWHSs. Tank size, pump, and a catchment surface area all influence the cost of components and installation. The user manual of RainCycle characterizes the typical costs of commercial RWHSs <Table 5>. Using the calculated catchment area of 1,020 m^2 and assumed the system will contain pumps, 10 m^3 is calculated as a suitable size for the Hong Kong residential buildings analyzed. Because RainCycle's currency is British Pound (GBP), an exchange rate of 1 HKD=11.8 GBP is used (Retrieved June 8, 2013, from http://cn.investing.com/currencies/gbp-hkd). Thus, the total initial cost is 62,080 HKD for a tank size of 10 m^3.

Table 5. *Typical Cost of an RWHS*

Description	Components (HKD)	Installation (HKD)	Total cost (HKD)
10 m^3 tank; no pump (gravity driven); ≤1000 m^2 catchment surface area.	38,940	35,400	74,340
10 m^3 tank; with pump; ≤1000m^2 catchment surface area.	47,200	47,200	94,400
20 m^3 tank; no pump; ≤3000 m^2 catchment surface area.	70,800	70,800	141,600
20 m^3 tank; with pump; ≤3000 m^2 catchment surface area.	76,700	70,800	147,500
30 m^3 tank; no pump; ≤10000 m^2 catchment surface area.	118,000	118,000	236,000
30 m^3 tank; with pump; ≤10000 m^2 catchment surface area.	129,800	118,000	247,800

2) Maintenance/Operation Schedules and Cost

The maintenance and operation schedules of RWHSs vary according to labor prices in different countries. Roebuck et al. (2011) depicted the schedules and costs by using data from Leggett et al. (2001a) and Shaffer et al. (2004) and estimated the annual maintenance and operation cost at 250 GBP (2947 HKD), which is the same as that suggested in the user manual. The operation cost also considers the fee for catchment-surface cleaning every two or three years. The present study is based on the cost estimate of 1,179 HKD.

3) Discount Rates and Period

The future costs of RWHSs depend on the discount rate given, however because this is difficult to accurately predict, discount rates of 3.5, 5, 8, and 10% are used by adapting the previous studies, with a discount period of 50 years. Morales-Pinzón et al. (2012) factored in a discount rate of 5% in their financial feasibility and environmental analysis. Roebuck et al. (2011) used 3.5, 5, and 10% in their whole-life cycle model comparison. Khastagir and Jayasuriya (2010) used 5 and 10% for the investment evaluation of rainwater tanks. Hajkowicz and Young (2002) used 8% when doing an economic analysis of cases in South Australia. Following these previous investigations, costs are calculated for a range of discount rates. The discount period chosen was 50 years because the rainwater harvesting system needs a long payback period and Morales-Pinzón et al. (2012) and Roebuck et al. (2011) adopted 50 years for their analyses.

4) Electricity Costs

The latest (2013) electricity price in Hong Kong is 94 HK cent/kWhr (Retrieved June 8, 2013, from http://www.hkelectric.com/web/DomesticServices/BillingPaymentAndElectricityTariff/TariffTable/Index_en.htm), which is lower than the UK and Australia, and higher than mainland China and the United States.

5) Mains Water Costs

In Hong Kong, consumers' water charges are billed in four-monthly intervals. The bill is calculated from a tariff structure consisting of four tiers with progressively increasing prices, aimed at discouraging excessive and unnecessary use of water. The first tier of 12 m^3 is free of charge; the second tier of 31 m^3 is charged at 4.16 HKD per m^3; the third tier of 19 m^3 is charged at 6.45 HKD per m^3; and the fourth tier for any consumption above the level of 62 m^3 is charged at 9.05 HKD per m^3 (Retrieved June 8, 2013, from http://www.wsd.gov.hk/en/customer_services_and_water_bills/water_and_sewage_tariff/water_and_sewage_tariff/index.html). To simplify the estimation of mains water costs, the mean of the third and fourth tiers' water prices is used, working out at 7.8 HKD per m^3.

V. EVALUATING THE FINANCIAL PERFORMANCE OF RWHSs IN HONG KONG

To calculate which factors contribute the most to the financial performance of RWHSs in Hong Kong residential buildings, a control variable method is used to check the results in each case. The factors assessed are water catchment area, demands in the whole block, and discount rate. <Table 6> shows the parameters of the variables used to analyze RWHSs' financial performance. Ideal financial performance was calculated by adjusting the variables of catchment area, water demand, and discount rate.

Table 6. *Parameters for RWHSs' Financial Performance*

Parameters	Value		Parameters	Values	
Rainfall profile	2,398	mm/yr	Capital cost	16,5200	HKD
Runoff coefficient	0.90	-	Decommissioning cost	0	HKD
Filter coefficient	0.90	-	Catchment area	**1,020** **1,320** **2,040**	m^2
Additional inputs	0.0	m^3/yr	First-flush volume	5	liters
Discount rate	**3.5** **5.0** **8.0** **10.0**	%	Storage tank volume	15.000	m^3
Electricity cost	94	HK cent/ kWhr	Pump power rating	1.6	kW
Mains water cost	7.5	HKD/m^3	Pump capacity	60	l/min
Disposal cost	0.00	HKD/m^3	UV unit power rating	90	W
Water demand	**6,607** **7,702** **8,796**	m^3/yr	UV operating time	24	hrs

1. Catchment Area Adjustment

1) Existing Roof Area

An existing roof area refers to the catchment area that includes only the building roof without any other additional catchment areas. In <Table 7>, the scenario A uses the calculated roof area of 1,020 m^2.

Table 7. *Parameters of Catchment Area Adjustment*

Catchment area (m^2)	Water Demands (m^3/yr)	Discount Rate (%)
1,020	7,702	5.0
1,320		
2,040		

2) Enlarged Roof Area

The results of scenario A indicates that only 25.7% of the water demand is met <Table 8> when using this size of catchment area, indicating a need to enlarge the catchment area. Two approaches are used: scenario B and scenario C. Scenario B uses the top areas of projecting bay windows. While this approach does increase the catchment area, bay windows are not as efficient at rainwater collection as roofs. Thus, the top area of the bay window is multiplied by a conservative coefficient of 0.5. Equation (3) calculates the effective area of scenario B for a typical residential building with 25 stories, totaling 1,320 m^2.

$$A_{eB}=A_o+A_w\times n_a\times n_f\times c_e \tag{3}$$

A_{eB}: effective catchment area of scenario
A_o: original roof area
A_w: top area of each convex window (1.5 m^2)
n_f: number of floors per block
n_a: number of apartments unit per floor
c_e: coefficient of effectiveness (0.5)

Scenario C, meanwhile, uses a ground area around the blocks to increase the catchment area. Because this paper is based on the assumption that the used ground area is as efficient as the existing roof area, the catchment area becomes 2,040 m^2 in scenario C. Accordingly, <Table 8> depicts the outcome of the three scenarios.

Table 8. *Effect of Catchment Areas*

Catchment area	Payback period (year)	Water Demand Met (%)	RWHS Savings Over 50 years (HKD)
1,020	17	25.7	59,599
1,320	9	32.8	145,937
2,040	6	40.5	240,493

To find a suitable area for water collection, it is investigated the relationship between catchment area and life cycle cost savings of RWHSs. <Figure 4> and <Table 9> explain the relationship between the catchment surface area and the savings made over 50 years. RWHSs become financially attractive when the catchment area is over 900 m^2. When the catchment area is larger than 2,000 m^2, the curve becomes linear. Thus 2,000 m^2 is proposed as the optimum size of catchment area for

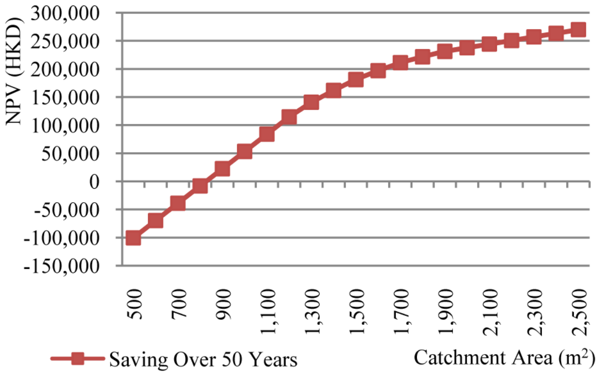


Figure 4. *RWHS Savings Over 50 years By Catchment Area*

diminishing marginal utility in financial savings. However, because larger catchment areas continue to achieve positive NPVs, they would still increase in terms of environmental benefits.

Table 9. *Changes in RWHS Savings Over 50 years*

Catchment area (m^2)	RWHS Savings Over 50 years (HKD)	Increase of Saving (HKD)	Change in Increase (HKD)
500	-8504.21	-	-
600	-5897.47	30759.54	-
700	-3290.73	30759.54	0.00
800	-683.99	30759.54	0.00
900	1922.75	30759.54	0.00
1,000	4529.50	30759.54	0.00
1,100	7136.24	30759.54	0.00
1,200	9742.98	30759.54	0.00
1,300	11945.32	25987.63	4771.91
1,400	13721.22	20955.62	5032.02
1,500	15362.50	19367.07	1588.55
1,600	16697.78	15756.35	3610.72
1,700	17916.83	14384.83	1371.52
1,800	18792.85	10336.97	4047.86
1,900	19617.96	9736.28	600.69
2,000	20162.80	6429.19	3307.10
2,100	20707.65	6429.19	0.00
2,200	21252.49	6429.19	0.00
2,300	21797.34	6429.19	0.00
2,400	22342.19	6429.19	0.00
2,500	22887.03	6429.19	0.00

2. Water Demand Variations

The typical number of stories in Hong Kong residential buildings varies from 20 to 40. As a result, buildings with 30, 35 and 40 stories are analyzed. The daily water demands per building are 18.1, 21.1, and 24.1 m^3 as shown in <Table 4>, making the yearly water demands per building 6607, 7702, and 8796 m^3 respectively.

Table 10. *Parameters of Water Demand Adjustment*

Catchment area (m^2)	Water Demands (m^3/yr)	Discount Rate (%)
2,000	6,607	5.0
	7,702	
	8,796	

<Table 11> indicates pronounced changes in amounts of capital saving and water demand met as a function of stories. The ratios of water demand met are less 50%. This suggests that a RHWS barely supplies sufficient water for washing clothes in a typical high-rise residential building.

Table 11. *Effect of Water Demands*

No. Of stories	Water Demand per day (m^3)	Payback period (year)	Water Demand Met (%)	RWHS Saving Over 50 years (HKD)
30	18.1	6	47.0	246,727
35	21.1	6	40.3	237,921
40	24.1	6	35.3	229,115

3. Discount Rate Adjustment

Discount rates of 3.5, 5, 8, and 10% are adopted to find how the discount rate influences RWHS financial performance <Table 12>.

Table 12. *Parameters of Discount Rate Variation*

Catchment area (m^2)	Water Demands (m^3/yr)	Discount Rate (%)
2,000	7,702	3.5
		5.0
		8.0
		10.0

<Table 13> shows that discount rates do not prominently effect payback periods. Rather, the cost savings vary significantly by discount rates.

Table 13. *Effect of Discount Rate Variation*

Discount Rate (%)	Payback Period (year)	RWHS Savings over 50 years (HKD)
3.5	6	326,305
5	6	237,921
8	7	134,845
10	7	94,939

VI. DISCUSSION

First, the results show that existing roof areas cannot meet the huge water demands of high-rise buildings in Hong Kong. RWHSs can only supply 25.7% of the water required for washing machines in each building. Increasing the catchment area can increase the financial performance of RWHS, but this requires almost doubling the surface area used. However RWHSs remain financially valuable if the catchment area is larger than 900 m^2.

Second, a building with fewer stories is more suitable for RWHS than one with a higher number of stories. While the payback period of RWHSs is six years regardless of the story number, the water demand met increased in buildings with fewer stories. A lower building also saved more money than a higher building. Buildings with 30 stories were estimated to save 246,727 HKD over 50 years, while buildings with 40 stories were estimated to save about 229,115 HKD. In addition, residents should not rely entirely on the treated rainwater for washing machine operation. The conventional water supply system should remain on stand by as a backup system for when rainfall is infrequent in winter. The height of residential buildings in Hong Kong means water demands are very high, even just for washing machines.

Third, the financial performance of RWHSs is sensitive to discount rates. The discount rate is critical to estimating the future value of RWHSs. The NPVs of cost savings obviously vary depending on discount rates, yet, because the discount is so hard to predict, RWHSs carry a high financial risk.

VII. CONCLUSION

In this paper, RWHSs in Hong Kong's residential buildings were explored and two methods were identified to enlarge the catchment area of these systems. Importantly, the objective was to determine whether RWHSs have financial feasibility for washing machine use in Hong Kong's residential buildings. In addition, a control variable method was used to analyze the financial performance of RHWSs with the variation of catchment surface areas, water demands, and discount rates, aiming to find which factor contributes the most to the financial performance of RWHS.

In conclusion, the use of RWHSs in Hong Kong is financially feasible only when the catchment area is larger than 900 m^2, which would make investing in RWHs in Hong Kong generally unattractive. Because of the high water demands in the super high-rise residential building, additional catchment areas and the conventional water supply system would be necessary with RWHSs. A suitable catchment area would be 2,000 m^2 in a typical Hong Kong residential building. Additionally, it is suggested that a feasibility analysis should be done before implementing RWHSs in unstable economic environments. Among the variables in RWHSs, the discount rate is the most critical variable to affect the financial performance of RWHSs. Thus, the government can play an important role in promoting RWHS by providing developers with subsidies for installing RWHSs for environmental purposes, even when the financial benefit is not high.

In order to improve the findings and discussions in this paper, more practical and empirical approaches are called for. Because this simulation was based on a typical plan of housing, results would vary in another type of housing. Empirical data would substantiate the financial costs, benefits, and NPVs estimated from this simulation. Additionally, while a coefficient of effectiveness was used to estimate the relevant costs incurred from enlarging the catchment roof area, more research into the precise coefficients involved would be valuable. In further studies, researchers are encouraged to investigate various types and circumstances of residential buildings for substantiating the financial performance of RHWSs.

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