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Simulation-based Spatial System for Rainwater Harvesting Systems In the Sustainable Campus Project

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Abstract

Rainwater harvesting systems (RWHSs) are promoted by many governments to ease urban water shortages. Such systems have also been adopted by the Sustainable Campus Project in Taiwan. However, spatial-temporal variances in precipitation significantly influence the hydraulic and economic performance of RWHSs, and a decision supporting system is essential for large scale application. This study proposes a simulation-based spatial system (SBSS) incorporating economic analysis to support the decision making of RWHSs. A case study is presented, which adapts the SBSS to the rooftop RWHSs of seven universities in the Taipei Area applied as part of the Sustainable Campus Project. Compared with the traditional generalized method, the SBSS enhances the information value. Also, the results of the case study show that SBSS provides more holistic and comprehensive support for the decision making of both end-users and policy makers. Therefore, the SBSS is a useful tool for promoting RWHSs on a large scale.

Keywords: rainwater harvesting system; spatial variance; simulation

1. Introduction

Rainwater harvesting systems (RWHSs) utilize on-site water resources, reduce urban runoff and save money for potable water (Villarreal *et al.*, 2005; Chanan *et al.*, 2006; Chisi *et al.*, 2007). Such systems have been promoted by many governments to address water-shortage problems. For example, the Education Ministry in Taiwan has included RWHSs in the Sustainable Campus Project (SCP) to demonstrate sustainable solutions to the general public (EM, 2005). Despite the efforts to promote rainwater harvesting, RWHSs have major limitations in that the efficiency of such systems is significantly influenced by spatial and temporal variations in precipitation, which subsequently influence their economic performance (RELMA, 2006).

Some researchers have also indicated that the wider application of RWHSs has been slow because no system addressing spatial information related to precipitation has been adequately developed; the current methods of assessment tend to be simplistic, using only generalized methods, and the Life-Cycle Costs (LCC) of RWHSs are often overlooked (RELMA, 2006; Roebuck, 2007).

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Traditionally, researchers often address temporal variations of rainfall using simulation methods based on historical rainfall data. The mass balance equation has generally been adopted to design storage volume, and to predict the hydraulic performance (Chisi *et al.*, 2007; Liaw *et al.*, 2004; Fewekes, 1999). However, most studies have only focused on single-site systems, contributing little to large scale applications, such as the case of SCP.

Due to the importance of spatial variance in planning RWHSs, Geographic Information System (GIS) technologies have often been applied to process and analyze the complicated spatial data and visualize results in site selection and potential assessment (Roebuck *et al.*, 2007; Shandas *et al.*, 2003; Mbilinyi *et al.*, 2007). However, the hydraulic performance of RWHSs based on spatial distribution has not been well quantified. Moreover, economic evaluation has not been properly integrated. Thus, the spatial-temporal complexity of precipitation should be incorporated with economic analysis in RWHS design. Only by providing all such needed information can planners have a comprehensive understanding of RWHSs and make sound decisions when selecting options.

This study proposes a simulation-based spatial system (SBSS) incorporating hydraulic simulation and Life-Cycle Cost Analysis (LCCA) to quantify the hydraulic and economic performance of RWHSs. The case study includes the RWHSs applied as part of the SCP in seven universities. The study had two aims: (1) to support end-users in individual RWHS design by providing more information than the traditional

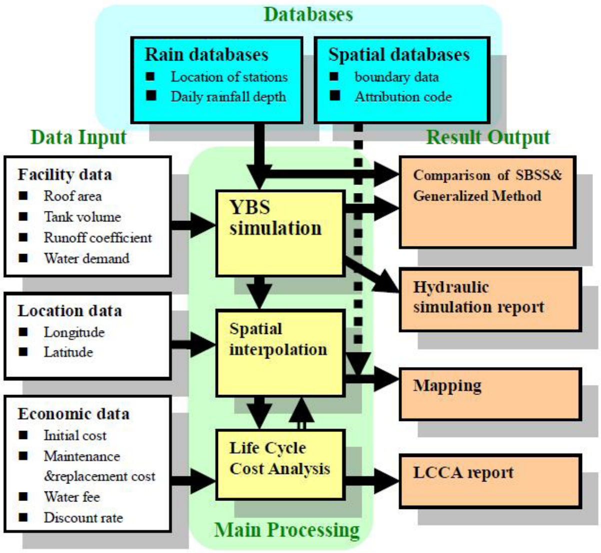

Fig.1. Framework of the SBSS

generalized method; (2) to explore a comprehensive approach that considers the spatial and temporal variations in rainfall to facilitate policy makers when dealing with large scale projects.

2. Methodology

Despite Taiwan's high average annual precipitation (approximately 2,500 mm/yr), only 20% of the total rainfall is utilized (WRB, 2000). This discrepancy has arisen because of the uneven spatial and temporal distribution of the rainfall, and also because of Taiwan's precipitous landforms that result in short river channels and difficulties in storing rainwater. Therefore, how to increase the utilization of rainwater is a vital issue for sustainable water policy in Taiwan. Based on GIS technology, this study used SBSS and focused on the hydraulic and economic performance of the rooftop RWHSs in the case study. The details of SBSS are described as follows:

Fig.1. illustrates the conceptual framework, which consists of four main components: (1) data input, (2) main processing, (3) databases, and (4) output of the results. First, the data of the major parameters (e.g., facilities, location, and economic) have to be input into the SBSS. Based on the input data and databases from the rain stations, the hydraulic performances of the rain stations were obtained using the Yield-Before-Spillage (YBS) simulation model. The annual rainwater supply of the RWHSs was therefore determined, and used for economic analysis. The Inverse Distance Weighting (IWD, p = 2) method was used to interpolate the spatial information.

2.1 Rainfall Databases

Daily rainfall data from 31 rain stations (15 within Taipei City and 16 in Taipei County) were adopted in the databases of the SBSS. The data covered 22 years (from Jan. 1, 1988 to Dec. 31, 2009). Fig.2. demonstrates the interpolated average annual

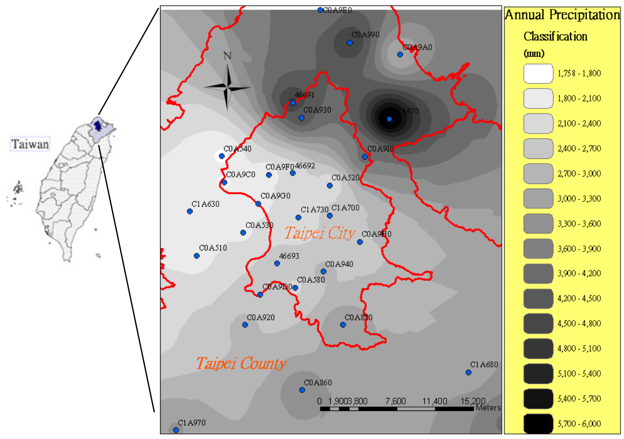

Fig.2. Location of 31 Rainfall Stations and Spatial Distribution of Average Annual Precipitation

precipitation and the locations of the rain stations. The average annual precipitation of these rain stations was 2,983mm/yr, while the highest precipitation was 6,305 mm/yr at Dapin station (No. 31, C0A860), and the lowest precipitation was 1,678 mm/yr at Kungdu station (No. 1, C1A970). Despite a difference in annual precipitation of nearly 3.5 times, the distance between these two stations is only 17.2 km. This clearly shows how significantly the spatial factors influence the rainwater supply, and also the importance of applying spatial technology in the large-scaled application of RWHSs.

2.2 Simulation Model

The performance of the rainwater supply of most RWHSs depends on four major parameters: rainfall depth, tank volume, rooftop area, and water demand. The YBS model considers the demand withdrawn before the spillage is determined. The operational algorithm of the YBS model can be written mathematically as:

$$Y_t = Min(D_t, S_{t-1}) \tag{1}$$

$$S_t = Min(S_{t-1} + Q_t - Y_t, V) \tag{2}$$

$$Q_t = C \cdot I_t \cdot A \tag{3}$$

Where Y_t is the yield of rainwater (m^3) during the tth time period; D_t denotes water demand (m^3) at time t; S_{t-1} is storage volume (m^3) of rainwater in the tank at the t-1th time period; V is tank volume (m^3); Q_t denotes the rooftop rainwater runoff (m^3); I_t is rainfall depth (m) during the time interval t; A is rooftop area (m^2); and C is the runoff coefficient. C was set as 0.82 based on the findings of Liaw *et al.*(2004).

The hydraulic performance of the RWHSs is estimated using the annual rainwater supply W (m^3), and water-saving efficiency E which is defined as the total rainwater supply over total demand. They can be described mathematically as:

$$W = \frac{365 \cdot \sum_{t=1}^{n} Y_t}{n} \tag{4}$$

$$E = \frac{\sum_{t=1}^{n} Y_t}{\sum_{t=1}^{n} D_t} \tag{5}$$

where n denotes the total number of daily rainfall data. Both W and E are applied in LCCA to predict the economic performance of RWHSs.

2.3 LCCA

LCCA aims to systematically determine the costs attributable to each of the alternative actions over a period of time. It involves the investigation of initial cost, maintenance and operating costs, and the residual cost (Kirk *et al.*, 1995). This study uses Payback-Period (PP) and Saving to Investment Ratio (SIR) measures in the LCCA. The higher the SIR, the greater the saving per dollar spent.

Apart from being well-known for saving potable water, RWHSs have also been reported to be effective in reducing urban storm runoff (Chanan *et al.*, 2006; Liaw *et al.*, 2005). Such systems can also serve as an emergency water supply in the aftermath of major disasters (Chiu, 2007). However, the economic benefits (or negative cost) of runoff reduction and emergency water supply are difficult to quantify. This study focuses on the economic benefits of saving potable water and assumes that the opportunity cost resulting from the space occupied by rainwater tanks is negligible.

2.4 Comparison with the Traditional Generalized Method

The traditional generalized method has been applied for evaluating RWHSs on a large scale (Wung *et al.*, 2006; ABRI, 2007). However, it depends solely on the average annual or monthly precipitation and applies a constant utilization rate to predict the hydraulic performance. In other words, the effect of the temporal distribution of rainfall is often overlooked in the generalized method.

Fig.3. shows the predicted annual rainwater supply of 31 rain stations using both the SBSS (based on Equation (4)) and generalized methods (setting utilization rates as 50% and 60%, respectively, and using the hydraulic parameters of one building in Jinwin University of Science and Technology as a test). The sequence numbers of rainfall stations are arranged according to the amount of average annual precipitation. With the generalized method, the annual rainwater supply increases as the sequence number of the station increases; meanwhile, greater variation occurs in the case of the SBSS, especially for rainfall stations with higher annual precipitation (e.g. Nos. 18–26).

The variation occurs because of the difference in rainfall types. For example, despite similar average annual precipitation, RWHSs in areas with an even temporal distribution of rainfall tend to perform better than those with concentrated distribution. This is because excess rainwater in a single torrential

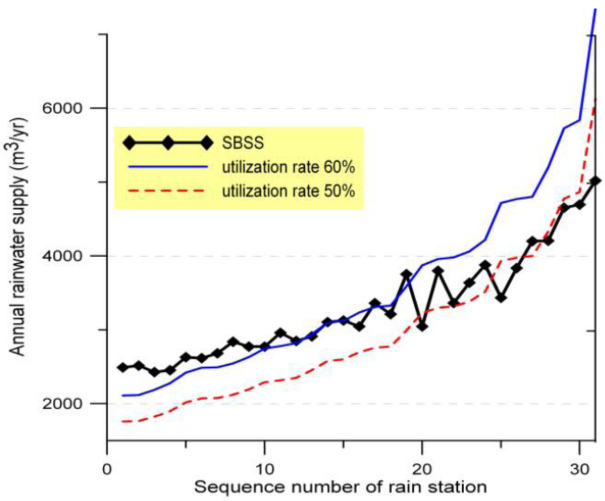

Fig.3. Comparison of the Annual Rainwater Supply Obtained by SBSS and the Generalized Method

rainfall event often overflows without being utilized. Therefore, the rainfall types should not be overlooked in the large-scaled evaluation of RWHSs. Also, it is important to note that the generalized method tends to underestimate performance in areas with lower precipitation, while it over estimates performance in areas with higher precipitation. Therefore, the SBSS using hydraulic simulation to address rainfall type enhances the information value of the evaluation of RWHSs in large scale applications.

3. Background of Case Studies

This study investigated buildings in seven universities in the Taipei Area and chose one building from each university to install a RWHS and apply subsidies from the SCP. These universities include: Fu Jen Catholic University (FJU), National Yang Ming University (NYMU), National Taiwan University (NTU), Shih Hsin University (SHU), Chinese Culture University (CCU), Jinwin University of Science and Technology (JUST), and National Chengchi University (NCCU).

The rooftop RWHSs are mostly composed of several sub-systems: the catchment area, connecting pipelines, filters, storage tanks, pumps, distribution tanks, control devices, and dual-supply-pipeline system. In 2007, the Water Resources Agency (WRA) in Taiwan established a recommended contaminant level for rainwater harvested from rooftops and used to flush toilets. Accordingly, it is necessary to install UV disinfection or a chlorinator to meet the new standard for coli forms. Both RWHS design and results of LCCA must be presented for applying the financial support from SCP.

4. Results and Discussion

4.1 Individual System Design

The SBSS supports the optimum design by providing an understanding of the relationship between tank volume and water-saving efficiency. For example, Fig.4 shows the relationship between E and the tank volumes of 5 different types of buildings in JUST, showing that building type D has the highest water saving efficiency. However, end-users of SBSS should also consider other factors, e.g., available space for tanks, tank materials, feasibility for pipe connections, and aesthetics, when designing RWHSs. After the discussion among members of general affairs in JUST, building type D, with a 60 m^3 tank volume design, was chosen for the RWHS installations applied as part of the SCP. The design will certainly affect the life cycle costs and, consequently, the decision for acceptance in SCP.

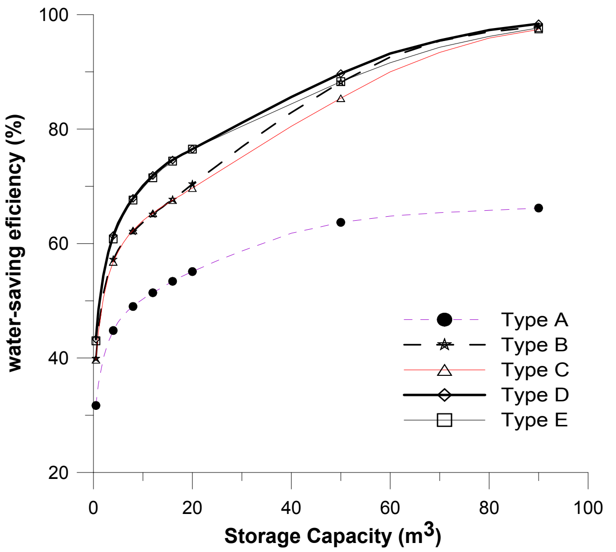

Fig.4. Relation between V and E for 5 Types of Buildings in JUST

4.2 Investigation of Life Cycle Costs

Maintenance and replacement are necessary to ensure the continued adequate functioning of RWHSs throughout their service life.

Under normal conditions, maintenance should be limited to the programmed cleaning of filters and replenishing of sodium hypochlorite if necessary. RWHSs use energy for pumping, system control, and chlorinators. As the systems also save energy for pumping potable water to portable distribution tanks on roofs, the overall energy consumption is mainly for the controlling devices and the chlorinator or UV disinfection. Table 1. lists the major costs of the RWHS in JUST for the SCP as an example.

4.3 LCCA Results and Evaluation of SCP

Table 2. summarizes the results of LCCA (the discount rate is set as 3% as commonly suggested by governmental projects) from seven universities for SCP. The payback periods for the universities were calculated to be the lowest (21 years) for NCCU and the highest (32 years) for NYMU. Table 1. also shows that only the SIR of NCCU is higher than 1, denoting that it is cost-effective.

Due to political reasons in Taiwan, current water fees are much lower than the actual costs, resulting in the poor economic performance of RWHSs in general. However, for promoting wider installation of RWHSs, policy makers should select and encourage RWHSs with better hydraulic and economic performance. In the case of the SCP, universities with higher SIR, (e.g. NCCU and JUST) should be encouraged to install RWHSs, so that less or no subsidies are needed. Conversely, for universities with lower SIR, other alternative water saving approaches (e.g. gray water reuse) should be taken into account.

Table 2. Results of LCCA for SCP

	FJU	NYMU	NTU	SHU	CCU	JUST	NCCU
PP (yr)	31	32	28	25	26	24	21
SIR	0.72	0.71	0.80	0.90	0.86	0.95	1.05

5. Conclusion

RWHSs have been regarded as an important solution to urban water shortages. However, the problem of

Table 1. Detailed Facility Parameters and Life Cycle Costs for the Rooftop RWHS in JUST

Roof top area (m^2)		**Tank volume (m^3)**		**Runoff coefficient**
2000		60		0.82
	Material	**Unit ($NT*)**	**Quantity**	**Total ($NT)**
Initial Costs	Water pump	28,000	2	56,000
	Tank (stainless steel, 10 m^3)	52,500	6	315,000
	Filter	30,000	1	30,000
	Dual-supply-pipeline-system	395,000	--	395,000
	Chlorinator	22,200	1	22,200
	Control device	26,000	1	26,000
	Labor	--	--	152,800
	Construction insurance	1.1% of all costs	--	10,527
	Design and management	8% of all costs	--	76,560
	Item	**Cost (NT$)**		**Frequency**
Maintenance	Labor	2,000		Every year
	NaOCl	1,000		Every year
	Electricity	1,259		Every year
Replacement	Pump parts and PVC pipe lines	23,000		Every 7 years

* 1$US equals about 30$NT

spatial and temporal variations in precipitation may limit the large-scaled application of RWHSs, unless spatial-temporal complexity and economic analysis are integrated into the evaluation process. Based on GIS and simulation methods, the SBSS in this study addresses temporal and spatial variations in precipitation for large scale application, so that the information value can thereby be enhanced.

In the case study, SBSS quantified the hydraulic and economic performance of the RWHSs in seven university campuses involved in the Sustainable Campus Project. This study provides a straightforward and holistic approach to understanding RWHSs and supports decision making by both end-users and policy makers. With the appropriate use of this system in suitable cases, the quality of decisions can therefore be enhanced. The SBSS proposed by this study has been identified to be a useful tool for promoting RWHSs on a large scale for easing urban water shortage problems. However, other types of RWHSs need to be included and the Web-SBSS should be further developed in the future enhancement of SBSS for wider applications.

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References

1) ABRI, Architecture and Building Research Institute (2007) Evaluation Manual for Green Building in Taiwan. Taipei: Ministry of the Interior, Taiwan. (in Chinese)
2) Chanan, A. and Woods, P. (2006) Introducing Total Water Cycle Management in Sydney, Kogarah Council. Desalination, 187 (1-3), pp.11-16.
3) Chisi, E., and Ferreira, D.F. (2007) Potential for Potable Water Saving by Using Rainwater and Greywater in a Multi-storey Residential Building in Southern Brazil. Building and Environment, 42, pp.2512-2522.
4) Chiu, Y.R., Liaw, C.H., and Lee, Y.S. (2007) Planning Decentralized Water Supply System in the Aftermath of Major Disasters. Proceedings of 2nd International Conference on Urban Disaster (CD-ROM); Taipei, Taiwan, Nov 27-29.
5) EM, Education Ministry (2005) Guidelines for Sustainable Campus Project. Taipei:
6) Fewekes, A. (1999) Modeling the Performance of Rainwater Collection Systems: toward Generalized Approach. Urban Water, 1, pp.323-333.
7) Kirk, S. and Dell'isola, A.J. (1995) Life Cycle Costing for Design Professionals, 2nd Edition, New York, McGraw-Hill Inc.
8) Liaw, C.H. and Tsai, Y.L. (2004) Optimum Storage Volume of Rooftop Rain Water Harvesting Systems for Domestic Use. Journal of the American Water Resources Association (JAWRA), 40(4), pp.901-912.
9) Liaw, C.H., Tsai, Y.L., and Cheng, M.S. (2005) Hydrologic Analysis of Distributed Small-scale Storm Water Control Systems. Journal of Hydroscience and Hydraulic Engineering, 23(1), pp.1-12.
10) Mbilinyi, B.P., Tumbo, S.D., Mahoo, H.F. and Mkiramwinyi, F.O. (2007) GIS-based Decision Support System for Identifying Potential Sites for Rainwater Harvesting. Physics and Chemistry of the Earth, 32, pp.1072-1081.
11) RELMA in ICRAF & UNEP (2006) Rainwater Harvesting Potential in Africa: Spatial Perspectives Volume One. www.unep.org/pdf/RWH_in_Africa-final.pdf. Accessed August 2009.
12) Roebuck, R. and Ashley, R. (2007)Predicting the Hydraulic and Life-cycle Cost Performance of Rainwater Harvesting Systems Using a Computer Based Modeling Tool. Water Practice & Technology http://www.iwaponline.com/wpt/002/02/default.htm. Accessed October 2009.
13) Shandas, V., Alberti, M., Gibson, J., Moddemeyer, S., and Irons, J.M. (2003) A GIS-based Water Demand Analysis for Municipal Application. Proceedings of 2003 Map India Conference; New Delhi, India, January 28-31.
14) Villarreal, E.L. and Dixon, A. (2005) Analysis of a Rainwater Collection System for Domestic Water Supply in Ringdansen, Norrkoping, Sweden. Building and Environment, 40(9), pp. 1174-1184.
15) WRB, Water Resources Bureau (2000) Water Resources Sustainable Development Taiwan. Water Resources Bureau, Taipei, Ministry of Economic Affairs.
16) Wung, T.C., Lin, S.H., and Hung, S.M. (2006) Rainwater Reuse Supply and Demand Response in Urban Elementary School of Different Districts in Taipei. Resources Conservation & Recycling, 46, pp.149-167.