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Original Article

Suitability model development for rooftop rainwater harvesting (RRWH) system in an urban area using geographical information systems

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Abstract

A Rooftop Rainwater Harvesting (RRWH) system may improve water security as it allows water collection to be done directly at home, especially in an urban area. Geographical Information System (GIS) approach has been utilized in this study as a platform for urban environmental analysis, in which the suitability of the rooftop as a catchment area for RRWH system in terms of quality and quantity were evaluated. The GIS model was developed to simulate and predict the suitability of rooftop based on its estimated volume of collected rainwater and Water Index Quality (WQI). Furthermore, weightages for several criteria such as roof material (RM), roof condition (RC), roof area (RA) and runoff coefficient (RuCO) have been determined using an Analytical Hierarchy Process (AHP). Then, Weighted Linear Combination (WLC) was applied to aggregate all these criteria according to their significance. The final map produced from the developed suitability model for RRWH system was quantized into three categories: highly suitable, moderately suitable, and not suitable. The results demonstrate that asbestos is not suitable with a total of 53, concrete is moderately suitable with the total of 178, and metal is highly suitable with the total of 150; for use in rooftop rainwater harvesting. Overall, this study showed that the study area is moderately suitable for RRWH system adoption.

Keywords: analytical hierarchy process (AHP), geographical information system (GIS), rooftop rainwater harvesting (RRWH), water quality index (WQI), weighted linear combination (WLC)

1. Introduction

Rainwater harvesting is a technique used to collect and store the harvested rainwater from land use/ land cover, water catchment, road surface, and building (Ojwang, Dietrich, Anebagilu, Beyer, & Rottensteiner, 2017). It has frequently been practised in different parts of the world. The climate change with rapid development at urban areas has affected the availability of water resources and thus, leads to rainwater harvesting as the chosen approach for the collection of harvested rainwater that partially meets the household water demand (Notaro, Liu, & Freni, 2016). Besides, the advantages from this approach can help save water in non-potable use, being inexpensive and highly decentralized, empowering individuals and communities to manage their water, mitigating flooding in urban areas, and reducing nutrient loads to waterways (Lani, Syafiuddin, Yusop, Adam, & Amin, 2018). It also environmentally safe and can be reasonably utilized. It provides a reliable renewable resource with special management and little investment. The harvested

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water can be transported with little energy. The potential of rainwater harvesting was divided based on the spatial scales; small scale (indicates large geographic areas such as cultivation area) and large scale (indicates greater detail such as building roof) (Nthuni, Lübker & Schaab, 2014). For large scale, geodata obtained from remote sensing (building footprint and roofing area) with ancillary data (roof material (RM), roof condition (RC), runoff coefficient (RuCO) and rainfall) were applied mainly to generate a map that reveals the potential areas for implementing rainwater harvesting (Hari, Reddy, Vikas, Srinivas, & Vikas, 2018). In an urban area, the roof is the first candidate for rainwater harvesting as it represents approximately half of the total sealed surface in cities (Farreny *et al*., 2011). However, Zhang *et al*. (2014) raised the issue of harvested rainwater quality from this resource as the rainwater might carry nutrient pollution (Vijayaraghavan, Joshi, & Balasubramaniam, 2012), microbial pathogens (Simmons, Hope, Lewis, Whitmore, & Gao, 2001), heavy metals (Lee, Bak, & Han, 2012), and pesticides (Zobrist *et al*., 2000).

The application of Geographical Information System (GIS) for rainwater harvesting showed good performance in both scales; small and large. As an example, Radwan, Alazba, and Mossad (2018), Siddha and Sahu (2018) and Yousif and Bubenzer (2015) have assessed the potential of rainwater harvesting at a large area, while Adugna, Jensen, Lemma, and Gebrie (2018), Lani, Yusuf, and Syafiuddin (2018) and Sambhaji and Gaikwad (2016) have successfully evaluated the performance of rainwater harvesting at a small scale. The quantity and quality of rooftop harvested rainwater depend on the RMs, and the formula used for volume estimation (VE) for harvested rainwater by Gould (2008) has been enhanced by Prayogo and Susilo (2019). The type of RM used for the catchment area can affect the quality of harvested rainwater (Jones & Hunt, 2010). Based on previous studies, the findings have shown that asbestos is not suitable for rooftop rainwater harvesting as the material is easily mixed with other minerals that may affect the quality of rooftop harvested rainwater (Campopiano *et al*., 2009; Roy 2013). For quality assessment of the rooftop harvested rainwater, the "first flush" method was applied. This method must first be applied to remove the contaminating elements such as dirt, bird droppings and insect bodies before the quality assessment can be done. Furthermore, many studies have successfully developed suitability models for rainwater harvesting using an Analytical Hierarchy Process (AHP) (Aydi, Abichou, Nasr, Louati, & Zairi, 2016; Gumusay, Koseoglu, & Bakirman, 2016; Özkan, Dengiz, & Turan, 2019) with different methods of model validation. These studies showed that the AHP technique can assist the suitability model development by assigning weights to the criteria involved.

Although prior research has established the potential of rainwater harvesting to improve water security, there is a need to investigate how effectively urban environmental analysis can be used to assess the potential of rooftop rainwater harvesting (RRWH) adoption in an urban area. Therefore, the aim of this research was to assess the potential of RRWH involving various RMs (metal, concrete, and asbestos) through VE, Water Quality Index (WQI) and suitability model using AHP in a GIS environment. This research integrated quantity and quality data of rooftop harvested rainwater for VE and WQI and combined RM, RC, RA and RuCO as the criteria to develop the suitability model for rooftop rainwater harvesting.

2. Materials and Methods

Figure 1 illustrates the flow of the methodology in this study. The methodology was categorized into three phases, (i) database development (ii) volume estimation and WQI assessment, and (iii) GIS model development.

3. Study Area

The study area for this research is in Taman Sri Serdang, Seri Kembangan. It lies between latitudes 332600N – 333000N and longitudes 412600E – 413200E, covering an area of 0.2 km². According to the 2012 census, this area was occupied by 14,360 people (Lim, Shaharuddin, & Sam, 2013) and the area consists of commercial, residential, mosque, police station, and school buildings. Meanwhile, the annual rainfall at this area was estimated to be around 2,600 mm per year.

3.1 Data development

This study utilised a building footprint that was extracted from the previous work that was carried out by Norman, Shafri, Idrees, Mansor, and Yusuf (2019) and Norman, Shafri, Mansor, Yusuf, and Radzali (2020) specifically for RRWH system application in a heterogeneous urban area. It has three types of RMs: asbestos, concrete, and metal, and each with its RC that indicates the degradation level of the roof that is either new or old. All this information has been demonstrated as confounding criteria determining the quality of RRWH (Gwenzi, Dunjana, Pisa, Tauro, & Nyamadzawo, 2015). Geodatabase of the obtained building footprint was developed using ArcGIS v10.8 software. Attributes for the geodatabase are RM, RC, RA, rainfall, RuCO and XY coordinates. The total number of roofs involved in this study is 762.

3.2 Volume estimation

The estimated volume for the RRWH system for each roof is dependent upon the size of the catchment area or RA, monthly rainfall received and RuCO. Subsequently, to calculate how much rainwater can be harvested, the value of RA (m^2) will be multiplied with monthly rainfall (mm) and RuCO (Ghisi & Ferreira, 2007). The value of each parameter has been substituted into the following equation:

$$VE = RA\ (m^2) \times (R\ (mm) / 1000) \times RuCO \quad (1)$$

where,
- VE volume estimate of RRWH
- RA roof area
- R rainfall monthly
- RuCO runoff coefficient

3.3 WQI assessment

The quality of harvested rainwater plays an important role in defining the suitability of the roof as a catchment area for RRWH system in an urban area. The quality of harvested rainwater is determined by measuring its

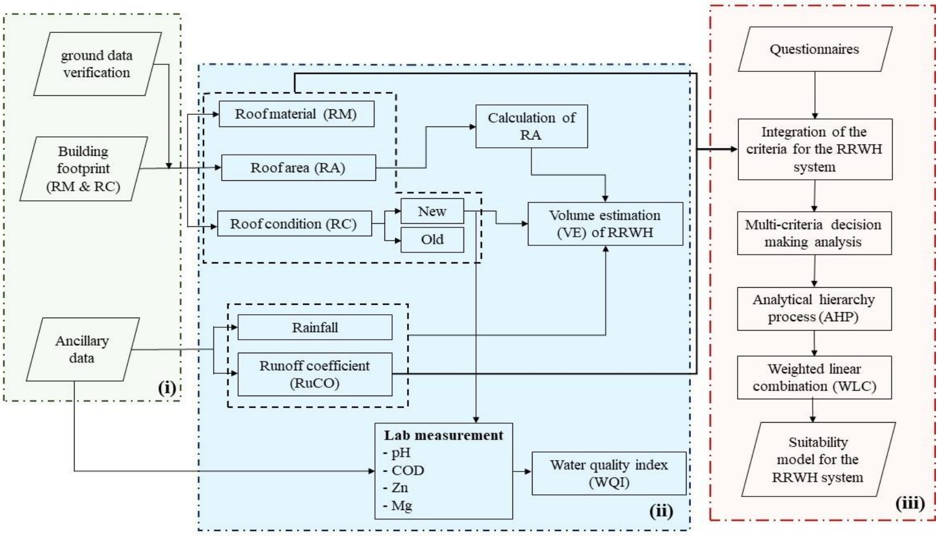

Figure 1. Flowchart of methodology

physical and chemical parameters. The quality of harvested rainwater based on three different rooftop materials is checked before and after treatment of rainwater. The qualities of harvested rainwater based on different rooftop materials before and after treatment are compared with the Natural Drinking Quality Water Standard (NDWQS) as guidelines and references. The harvested rainwater is treated using coagulation and acid-based titration to remove colloidal impurities (Radzali, Shafri, Norman, & Saufi, 2018). Hence, water quality index (WQI) of RRWH system in Taman Sri Serdang was assessed based on the observation of any changes in the chemical of substances. In this assessment, the chemical parameters, for instance pH (the potential activity of hydrogen ions (H+) in moles per liter in the rainwater samples), heavy metals focusing on Zinc (Zn) and Manganese (Mg), and Chemical Oxygen Demand (COD, the estimate of the capacity of water to consume oxygen during decomposition), were evaluated and compared to the values in the Drinking Water Quality Standard from the Ministry of Health Malaysia (Talha, 2019). The guidelines from the Ministry of Health Malaysia used to assess the quality of water for domestic use are related to safety of humans on contact, and to the health of ecosystems. The laboratory procedures are conducted according to the standard operation of Standard Tests for Water and Wastewater. The laboratory experiment is done for before and after treatment of rainwater and repeated for three cycles on different rain pattern.

3.4 GIS development

Several confounding criteria have been determined before the GIS model for rooftop suitability as a catchment area for the RRWH system can be developed in Taman Sri Serdang. A total of 4 criteria were identified: RM, RC, RA and RuCO. The determination was done based on literature reviews and via a set of questionnaires responded to by 30 experts. Furthermore, these criteria were based on the generality in the references and the availability of the data within the study area. Then, all the selected criteria were adopted into multi-criteria decision analysis (MCDA) and the analytical hierarchy process (AHP) for further analysis.

Previous studies have shown that AHP is the best method to be included in the GIS analysis to identify a suitable site for rainwater harvesting (Hari *et al*., 2018; Wu *et al*., 2018). This method can organize the complex decisions and perform the analysis based on mathematical knowledge and experts. The main code in AHP is symbolizing the components of any problem hierarchically in displaying the relationships between each level. Following this approach, the main goal should be on the uppermost level for resolving a problem, while the lower level consists of more detailed criteria that influence the main objective. The matrix of pairwise comparisons was applied to determine the weights for each criterion. The suitability assessment which involves two criteria was determined by their relative importances with the help of pairwise comparisons.

Finally, the suitability index was calculated using the WLC method, whereby the product of each weight with its matching criterion was summed to a standard score using Equation 1:

$$S = \sum_{i=1}^{n} WiXi \qquad (1)$$

where S indicates the suitability, *Wi* is the weight for each factor and *Xi* is the rate or score for classes in the criteria.

4. Results and Discussion

4.1 Database of the building footprints

Example of attributes for building footprint in the study, such as RM, RC, RuCO, slope length and size of roof area, can be seen in Figure 2. All the information was then used and applied for further analysis.

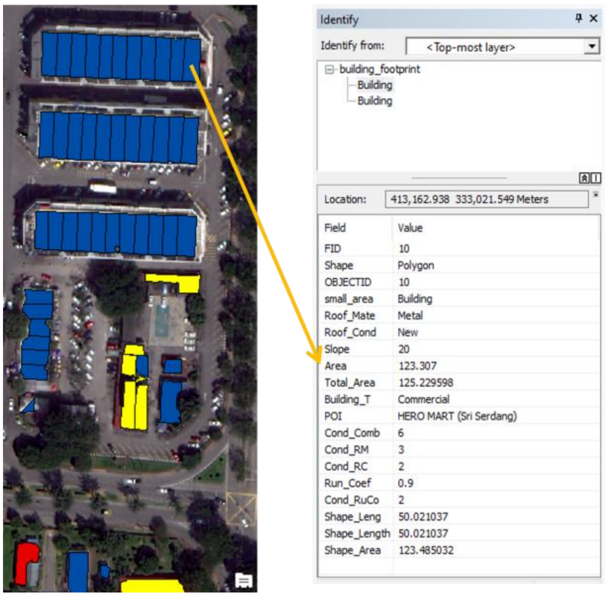

Figure 2. Attributes of the building footprint

4.2 Volume estimation

Table 1 showed most of the roofs in the study area as new concrete (179), having the minimum and maximum values of the calculated VE were 6.409 m^3 and 3,623.065 m^3 respectively. Meanwhile, the total VE of the potential harvested rainwater for the whole concrete (new) rooftop was predicted to be 62,316 m^3. On the other hand, the minority rooftop (new asbestos) can potentially harvest approximately 1,686 m^3 of rainwater in a total of the minimum and minimum VE of 33.248 m^3 and 251.121 m^3 respectively. As for metal (87) rooftop, the potential volume of rooftop rainwater to be harvested was 19,005 m^3 in which the minimum and maximum values of the VE obtained were 0.149 m^3 and 722 m^3 respectively. Thus, from 276 new roofs in the study area can potentially provide 83,006 m^3 of harvested rainwater in a year.

4.3 WQI assessment

The level of quality for rooftop harvested rainwater was based on the calculated index value (IV). In this study, two categories of WQI were determined (good water and poor water) and the result was used to evaluate the suitability of the roof to be exploited for RRWH system. The ranking of the best rooftop for rainwater harvesting for standard roofing materials from the best to the worst quality was metal, concrete, and asbestos roofs. The ranking of rooftop harvested rainwater was identified according to the quality of rainwater samples. For the quality of the rainwater storage, the metal roof was recommended roofing material in urban or rainwater harvesting area implement.

Table 2 shows the results on the chemical content for each type of roof. The pH for concrete runoff was found to be higher than for metal, due to the presence of alkaline substances and metals (Zhang *et al*. 2014). Then, asbestos had the highest COD of 37.33 while concrete and metal had 21.33 and 26.67 for COD, respectively. The results indicate that asbestos is highly contaminating and could cause harmful effects (Smartt 2004).

Moving on to the WQI, the results in Table 3 illustrate that concrete roofs have good quality harvested rainwater with an IV of 77.56. On the other hand, asbestos and metal roofs were categorized as poor quality due to the IVs 176.26 and 187.31, respectively.

Table 3. WQI of new RM

Roofing material	Number of roofs	Index value (IV)	Category
New asbestos	10	176.26	Poor Water
New concrete	179	77.56	Good Water
New metal	87	187.31	Poor Water

Table 1. VE of new roofs for RRWH system

Roof material (RM)	Number of roofs	Min VE (m^3)	Max VE (m^3)	Total VE (m^3)
New asbestos	10	33.248	251.121	1,685.858
New concrete	179	6.409	3,623.065	62,315.64
New metal	87	0.149	721.808	19,004.529

Table 2. Results of chemical testing

Roofing material	Chemical parameter (mg/L)								
	pH	QS	Heavy metal				COD	QS
			Zn	QS	Mg	QS		
Asbestos	7.5	5.5-9.0	0.18	0.20	0.0005	3	37.33	10
Concrete	7.45	5.5-9.0	0.24	0.20	0.0005	3	21.33	10
Metal	6.93	5.5-9.0	1.37	0.20	0.010	3	26.67	10

Note: QS (Quality Standard) value for pH, Zn, Mg, and COD above showed the permissible limit of the Drinking Water Quality Standard from the Ministry of Health Malaysia (2016).

4.4 GIS model for RRWH system suitability

4.4.1 AHP weightage for the criteria

The criteria shown in Table 4 have been used as inputs in the AHP method. The calculation of the matrix of pairwise comparisons was carried out by defining the importance levels between one criterion and another. Each attribute or class was given a score in which high score indicates that the criterion with that class is more favourable to be used for the RRWH and vice versa. Finally, the weightage obtained via the AHP was used in the formula as in Equation 2.

$$\text{Suitability Index} = [(0.40 \times RM) + (0.43 \times RuCO) + (0.12 \times RC) + (0.05 \times RA)] \quad (2)$$

The final map of the suitability of RRWH system as shown in Figure 3 was produced by aggregating the criteria (RMs, RC (old and new), RA (old and new) and RuCO) and the classes using Weighted Overlay tool in ArcGIS software. The results of the suitability map were grouped into three categories: highly suitable (recommended to be used for non-potable usage), moderately suitable (can be used for non-potable usage), and not suitable (cannot be used either for drinking or non-potable usage) in which each category indicates the suitability of the rooftop for implementing RRWH.

Table 5 shows the total of identified roofs (including new and old) based on the suitability of the roof for RRWH system. The results demonstrate that asbestos roof is not suitable to be used for rainwater harvesting with a total of 53 out of 53 (100%) roofs having been identified as not suitable. This finding shows that asbestos is highly contaminating and not safe due to the chemical compounds from this material that leach into the runoff (Norman *et al*., 2020) and consequently, they affect the quality of the harvested rainwater. Thus, the harvested rainwater from this material cannot be used either for drinking or non-potable uses. On the other hand, the metal roofs were for 100% highly suitable for RRWH in the study area.

Then, from 559 concrete roofs, 31.84% were categorised as moderately suitable to be used for harvesting the rainwater, while the remaining 68.16% were classified as not suitable. This is because metal and concrete roofs have smooth surfaces, thus these materials have a low degree of bacteria, and are highly recommended for rainwater harvesting purposes (Mendez *et al*. 2011).

5. Conclusions

The suitability of the GIS model for RRWH system in this study has considered both significant elements in environmental monitoring: quality and quantity of collected rainwater. The criteria RM, RC, RA, rainfall and RuCO have played an important role in determining the success of the proposed model. After the old type of roofs were excluded due to their high potential for contamination, the results of quantity assessment (VE) presented concrete as the best material to be used as the catchment area for RRWH. This is because the concrete roofs covered most of the study area, for

Table 4. Weightage and the score for each criterion

Criterion	Class		Score	Weightage
RM	Asbestos		1	0.40
	Concrete		2	
	Metal		3	
RuCO	Asbestos (0.85)		1	0.43
	Concrete (0.95)		3	
	Metal (0.90)		2	
RC	Asbestos	New	2	0.12
		Old	1	
	Concrete	New	4	
		Old	3	
	Metal	New	6	
		Old	5	
RA (m^2)	<130		3	0.05
	< 480 – 130		2	
	> 480		1	

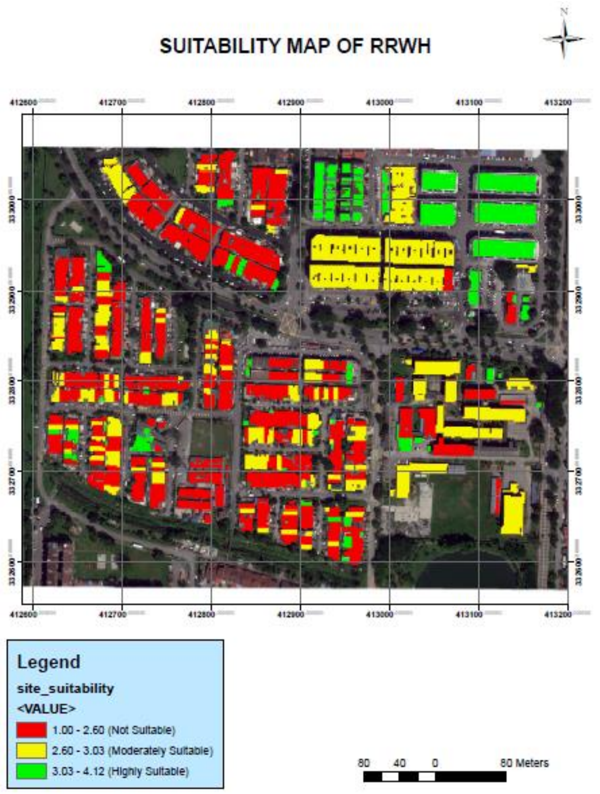

Figure 3. Map of suitability for RRWH system

Table 5. Roof material selection for RRWH system suitability map

	Not suitable	Moderately suitable	Highly suitable	Total
Asbestos	53	0	0	53
Concrete	381	178	0	559
Metal	0	0	150	150
Total	434	178	150	762

64.86% (179 out of 276) of the total new roofs, with the highest total VE of 62,315.64 m^3. The quality of harvested rainwater should ensure clean and safe water sources, even though limited to non-potable uses such as toilet flushing, landscape irrigation and car washing. The WQI values produced were compared to the Drinking Water Quality Standard and the results indicated that new concrete roofs are the most suitable rooftops for providing good water from rainwater harvesting. Besides VE and WQI, other criteria (RuCO, RMs, RC, RA (including old and new)) were considered to further analyse the overall quality and quantity of the potential rooftops in the study area for RRWH system. The result indicate that metal roofs are highly suitable for RRWH system. Less contamination with lower pH and high RuCO for metal roofs have made this material the best rooftop alternative to be used for RRWH system.

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