Asian Journal of Water, Environment and Pollution, Vol. 18, No. 4 (2021), pp. 29–35.
DOI 10.3233/AJW210040

Application of GIS in Rainwater Harvesting Research: A Scoping Review

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Received February 12, 2021; revised and accepted June 23, 2021

Abstract: The spatial and temporal variability of quantity and quality of water are important aspects of water resources management. Water demand has been increasing across the globe, but the fresh water supply is limited. Rainwater harvesting (RWH) systems are increasingly being embraced as an alternative freshwater source. This study reviews the dynamics of global research on RWH that utilises geographic information systems (GIS). It is found that the interest and use of RWH utilising GIS have increased over the recent years. However, the full potential of GIS in large scale RWH is yet to be untapped. We make recommendations for future research on RWH based on GIS. This includes new software and model development that links RWH with GIS to plan and design large scale RWH and automated building footprint extraction for estimating RWH potential. GIS can play a bigger role in achieving Sustainable Development Goals (SDGs) by incorporating GIS with RWH since GIS can handle large spatial data efficiently, which can help in locating areas that are suitable for rainwater harvesting.

Key words: Rainwater harvesting, GIS, water, SDGs.

Introduction

Freshwater is one of the most important natural resources that sustains life on earth. Only 1% of the world's 2.5% fresh water is available for human consumption. Water shortage is a critical issue worldwide due to several factors such as population growth, excessive water demand, urbanisation, water pollution and unsustainable water resource utilisation in many regions under a changing climate (Ahmad et al., 2014). To enhance water security, alternative water sources are receiving increasing attention, such as rainwater harvesting (RWH), grey water reuse and wastewater recycling. Among these, RWH is considered to be an attractive option in reducing potable water demand, especially for non-potable purposes (Domínguez et al., 2017; Preeti et al., 2019). RWH system is a component of water sensitive urban design, which aims to reduce the demand for mains water and restore the natural water cycle in an urban environment (Farswan et al., 2019; Rahman et al., 2020).

Geographic Information System (GIS) is a computer-based information system that is used to store and process large volumes of spatial information for solving important scientific and non-scientific problems. The main advantage of GIS is that the digital database that is developed at any stage can also be used in the future, and any related information can conveniently and effectively be retrieved. GIS can generate efficient maps and figures, which are not only comprehensive but also easy to interpret by the general public, decision-makers and stakeholders (Moody et al., 2012). GIS can assist in large scale RWH as it can identify large areas of rainwater collection and storage (Balkhair et

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al., 2019). For example, it can find all the roof areas in a suburb/city and estimate how much rainwater can be harvested at a suburban scale. In this regard, United Nations' Sustainable Development Goals (SDGs), linked with water, can be better achieved as rainwater is a renewable source of water. Amos et al. (2020) noted that the harvested rainwater can meet household water demand, and also boost household agriculture, which has the potential to increase crop yields and supplement household nutrition. They noted that the integrated use of harvested rainwater and household agriculture can contribute to at least 8 of the 17 SDGs, particularly goals 2 to 6 on an individual level and goals 11, 12, and 15 more on a global level. Gain et al. (2016) proposed the 'Global Water Security Index' to assess water security as one (goal 6) of the SDGs at the global level. Brovelli et al. (2019) developed a SIMILE system, where geospatial data and techniques play a vital role. The objective of this system was to strengthen the management of the water resources of the subalpine lakes and to achieve SDGs (goal 6). All these researches show how GIS can assist in better achieving the SDGs by better water conservation, reuse and management.

RWH can play a greater role if integrated with GIS, which can enhance the volume of harvested rainwater and its reuse potential. The application of GIS in RWH research is relatively new. In this regard, this scoping review aims to evaluate the current state of GIS application to RWH, gaps in the current knowledge and needs for further research. It is expected that this scoping review will enhance the application of GIS in RWH.

Review Methodology

Figure 1 shows the adopted methodology for this review. All previous relevant studies were identified via electronic databases, focussing on peer-reviewed publications, supported by citation tracking and hand searching. The selected databases included Google Scholar, SCOPUS, Web of Science and ScienceDirect.The search strategy was implemented using a combination of keywords that were used in the title, keyword and abstract search fields in the selected databases. The study period covered the years ranging from 2004 to 2019 because the greatest development in the selected field of study took place during these years. Total publications related to the topic identified via the selected keywords "rainwater harvesting and GIS" were 165. The search was refined to eliminate duplications and irrelevant information. The final selected sample contained 140 journal articles, which were investigated with respect to the name of the journal, year of publication, country of origin and disciplines as per Scopus classification. SciMAT and Excel were used in this analysis.

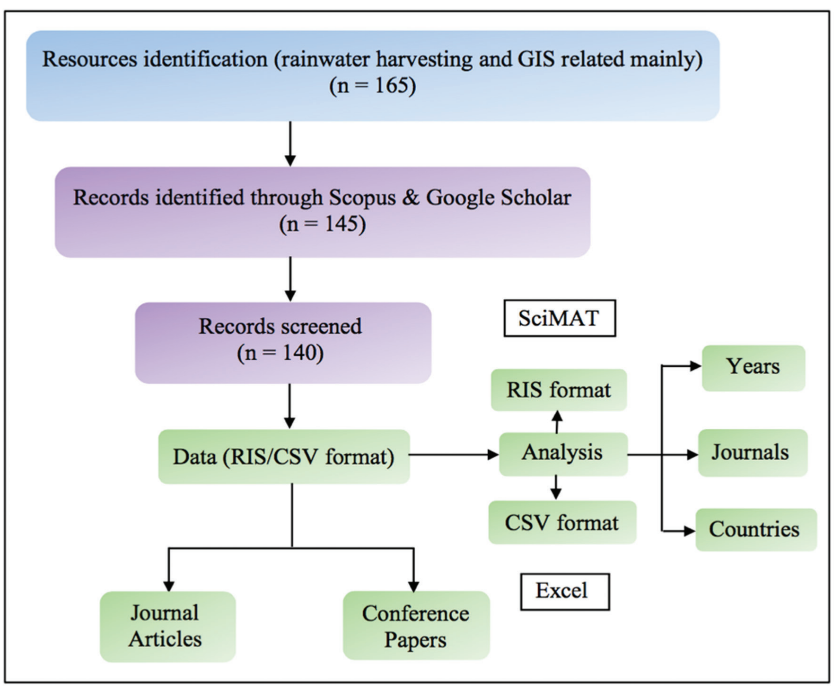

Figure 1: Flow diagram showing the adopted scoping review method.

Results and Discussion

GIS has been used in RWH studies by a number of researchers. For example, Jasrotia et al. (2009) used GIS and remote sensing techniques to study the water balance in the Devak-Rui watershed, Jammu Himalaya, India. GIS software was used for the generation of various thematic maps like slope, drainage and soil, which were further utilised for the RWH site suitability analysis. Kim et al. (2012) conducted a year-long study on RWH and utilisation for non-potable water use in six different building types where GIS played a key role in identifying building types and calculating roof areas. Fonseca et al. (2017) developed a decision support system for estimating the optimal tank size of RWH systems for nine case studies in the State of Mexico. Adham et al. (2018) identified potentially suitable sites for the dam to harvest rainwater in the western desert of Iraq using GIS-based suitability model created in ArcGIS 10.2. Results showed RWH potential maps, which may help planners and decision-makers to identify suitable areas to harvest rainwater. High resolution data and cost factors should also be considered for further analysis. In their study, ArcGIS was found to be a flexible, time-saving and cost-effective tool to map large areas. However, more research needs to be undertaken on automated rooftop digitization using GIS, spatiotemporal modelling, new software and tools to promote RWH. Figure 2 shows the locations of the selected 140 articles used in this scoping review. Table 1 summarises the application of GIS in RWH in a number of countries where RWH has been popular.

Over the past two decades, the number of studies on GIS based RWH research has increased significantly as shown in Figure 3a. The number of articles increased from one in 2004 to 23 in 2018, and 16 in the first half of 2019. It is clear from Figure 3 that nearly 49% of the articles were published in the period between 2016 and June 2019. Figure 3b shows the distribution of the countries with respect to a number of articles published on GIS-based RWH research. India secures the leading position with a total of 48 articles. This is followed by Saudi Arabia with 17 articles, the USA with 16 articles, Egypt with 12 articles, China with 11 articles, Iraq with 9 articles and Malaysia with 7 articles. The rest of the countries published less than 5% of the selected 140 articles.

Table 1: Examples of GIS use in RWH research

Country	*Use of GIS*	*Reference*
India	Identify RWH potential and suitable sites for RWH using GIS-based MCDA.	Singh et al. (2017)
Iraq	Identify and select suitable sites for potential dam site using ArcMap 10.4.1.	Ibrahim et al. (2019)
Australia	Evaluate rooftop rainwater harvesting potential using GIS.	Baby et al. (2019)
USA	GIS surface maps are analysed in combination with local utility consumption data to determine potential reduction in potable water consumption for households.	Grant et al. (2018)
South Africa	GIS-based RWH decision support system (RHADESS) which indicates suitable areas of different types of RWH and quantifies their hydrological impact in terms of change in runoff.	Kahinda et al. (2009)
India	Assess rainwater harvesting potential and identify suitable sites/zones for different RWH structures using remote sensing, GIS and MCDA techniques.	Jha et al. (2014)
Sri Lanka	Remote sensing and GIS techniques to develop a methodology to determine the main reason for the abundance of abandoned tanks in the Hambantota District and select the suitable areas for locating tanks.	Senanayake et al. (2012)
Iraq	Remote sensing approach was integrated with GIS to estimate the physical variables of a reservoir system.	Sayl et al. (2016)
Malaysia	Remote sensing and GIS are used in an urban environment to analyse, map and model the effect of various factors on rainwater quality.	Norman et al. (2019)
Palestine	Develop domestic water poverty and map of domestic RWH suitability for the West Bank. The map identifies the spatial distribution of water needs (water-poor areas) and the potential of RWH techniques for domestic water use.	Shadeed et al. (2019)

Figure 2: Locations of the selected 140 articles on GIS based RWH research.

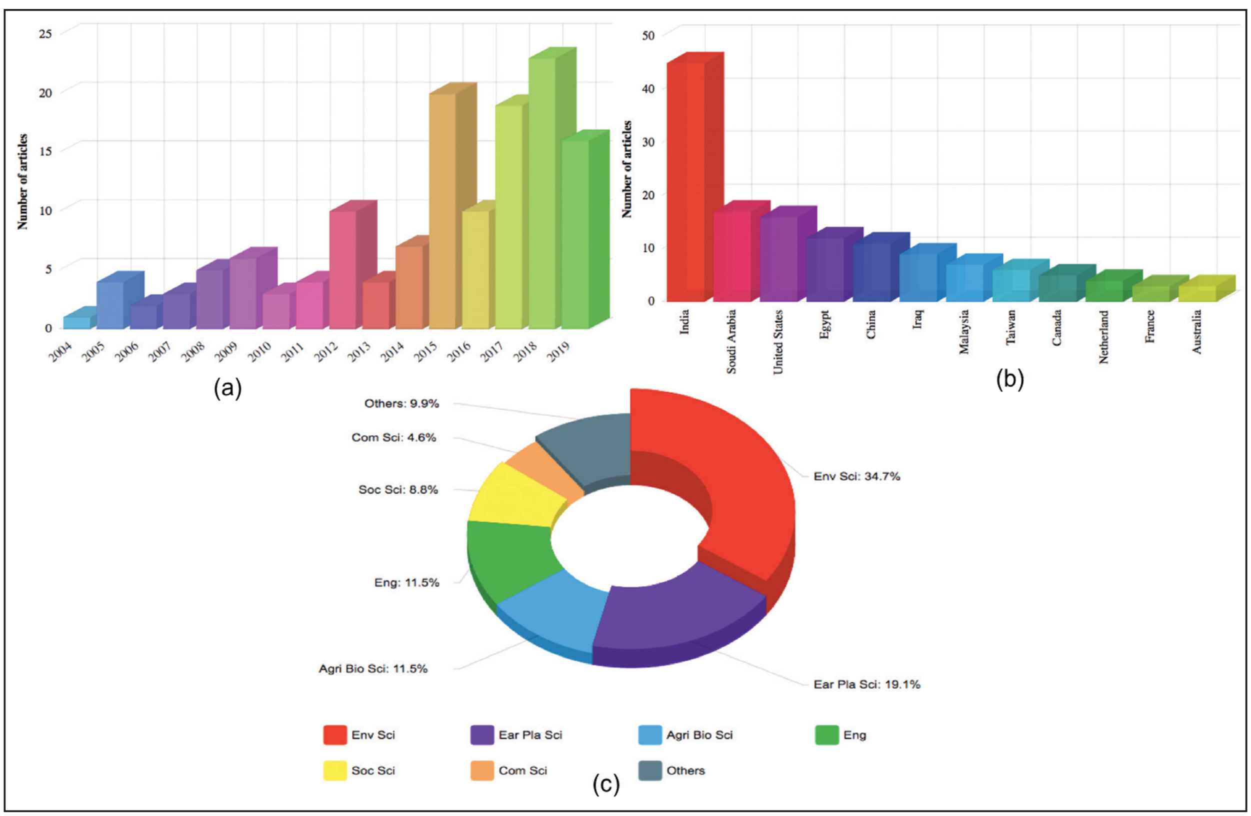

Figure 3: (a) Publications on GIS based RWH in the period 2004 to mid-2019, (b) distributions of GIS based articles across different countries, (c) comparative trends of different disciplines involved in RWH using GIS.

The comparative trends of different disciplines involved in GIS-based RWH research is shown in Figure 3c. *Environmental Sciences* claim the highest number of articles, with 59.1% of the total sample. This is followed by *Earth and Planetary Sciences*, with 19.1%, *Engineering and Agricultural and Biological Sciences* with 11.5%, *Social Sciences* with 8.8%, *Computer Science* with 4.6% and others with 9.9%. *Environmental and Earth and Planetary Sciences* are the leading categories and the primary drivers of the GIS-based RWH research.

The collaborative relationships between the most active countries involved in GIS-based RWH research are shown in Figure 4a. The size of the circle defines the number of articles for a country; the lines represent the links established between countries, where the line thickness depends on the number of collaborations and the different colours of clusters identify the main collaborating groups. Four clusters (red, green, blue and yellow) are formed where the red cluster is led by India in terms of a number of articles. It includes Iraq, Malaysia, Taiwan, South Africa and some of their partner countries such as the Netherlands and Pakistan. The blue cluster is led by Saudi Arabia and includes countries such as Egypt, China, Canada, UK, Germany and Czech Republic. The green cluster is led by the United States and includes countries such as France, Chile and Australia. Finally, the yellow cluster is led by Jordan and includes countries such as Cyprus and Japan.

Figure 4b shows the relationships between the journals publishing the most articles on GIS-based RWH research. The size of the circle defines the number of articles for each journal and the lines represent the links established among them. As shown in Figure 4, the light green cluster is led by the *Arabian Journal of Geosciences* in terms of the number of articles and it includes *Environmental Earth Sciences*, *Journal of the Geological Society of India* and *Environmental Monitoring and Assessment*. The red cluster is led by *Water Resources Management* and includes *Agricultural Water Management, Journal of Cleaner Production* and so on. Green cluster is led by *Water* and finally blue cluster is led by *Environment, Development and Sustainability*.

Further Research Opportunities on GIS-based RWH

There has been an increasing interest in RWH in recent years. Most of the previous RWH applications have been found to concentrate on the household level, either at detached houses or multi-unit buildings. This did not require the use of GIS as the roof area of small buildings can be calculated from the building drawings; however, for large-scale application of RWH, the roof area of all the buildings in a locality/city needs to be estimated, where GIS could be very useful. Manual digitisation is tedious, costly and time consuming. Hence, automated building footprint extraction needs to be considered with the help of GIS and remote sensing for a more efficient model building that can estimate the RWH potential for large-scale water harvesting projects. In this regard, the following areas of further research are identified:

- It has been found that only a few countries are proactive in adopting GIS in RWH research. It

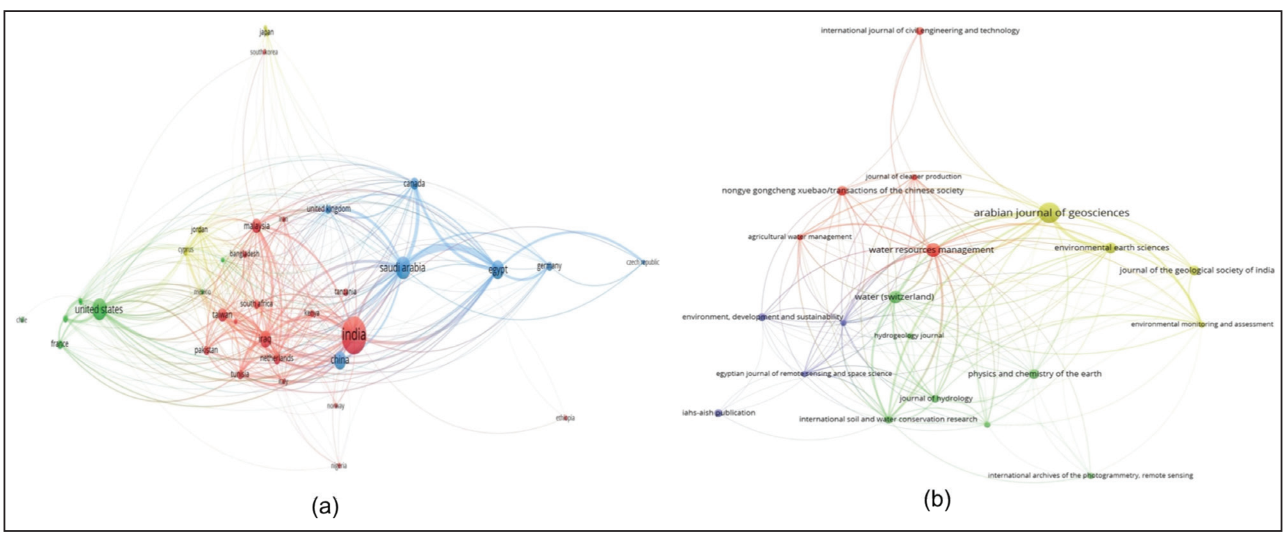

Figure 4: (a) The relationships between countries involved in GIS based RWH research, (b) most active journals publishing on GIS based RWH research.

is suggested that more collaborations are needed between different countries to promote the application of GIS in RWH and a global research group should be established.

- High resolution GIS data is not readily available for RWH research, which needs further support from government and international agencies to make GIS data free/affordable.
- New software and models that link RWH with GIS need to be developed so that these can be used to plan and design large scale RWH projects.
- More research should be carried out on how GIS-based large scale RWH can be used to meet the freshwater demand of isolated/rural communities, which will help to achieve water-related SDGs.
- Further research is warranted to meet the water crisis under extreme drought conditions (due to climate change) where innovative ways of GIS-based rainwater collection and storage systems can help to boost critical agriculture, mitigate heat island effect and bushfire risk.

Conclusion

It has been found that the application of GIS in RWH is quite new, however, it has been increasing with time. It has been shown that 49% of the selected 140 articles on GIS-based RWH were published from 2016 to 2019. It has also been found that only a few countries are active in GIS-based RWH research. India has been identified to be at the forefront of GIS-based RWH research with the highest number of published articles (48), followed by Saudi Arabia (17) and the USA (16). GIS-based RWH has drawn the attention of researchers from diverse disciplines of knowledge. *Environmental Sciences* claims the highest number of studies (59.1%), followed by *Earth and Planetary Sciences* (19.1%) and *Engineering* (11.5%). The journal with the highest number of articles published on GIS-based RWH is the *Arabian Journal of Geosciences* (14), followed by *Water Resources Management* (7), *Water* (6) and *Environmental Earth Sciences* (5). In relation to GIS-based RWH, it has been found that ArcGIS is a useful tool for integrating various types of information to find suitable sites for rainwater harvesting. ArcGIS is a flexible, time-saving and cost-effective tool for screening large areas for their suitability of RWH intervention. Areas of further research have been identified to promote GIS-based RWH which can help to initiate large scale RWH projects. This can assist in critical water supply in rural areas where fresh water supply is limited. This in essence will contribute towards meeting the water-related SDGs.

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