Assessing Rainwater Harvesting Potential in Urban Areas

Subjects: Construction & Building Technology

Submitted by: Muhammad Jamaluddin Thaheem

(This entry belongs to Entry Collection "Environmental Sciences")

Definition

Water scarcity has become a major problem for many countries, resulting in declining water supply and creating a need to find alternative solutions. One potential solution is rainwater harvesting (RwH), which allows rainwater to be stored for human needs.

1. Introduction

The global population is increasing exponentially, presenting many challenges and managerial issues such as water scarcity and pertinent water management. Water scarcity is a real problem that is caused by the rapid depletion of groundwater resources and population growth. Approximately 4430 km^3 of freshwater is utilized globally, from which 70% is used in agriculture, 25% is used in industry, and 5% is used in households [1]. Furthermore, the world population will likely increase from 7 billion to 10 billion by 2050 [2], exacerbating the water demand and supply situation. Accordingly, it is predicted that around 20% of the global population will live under a severe water shortage due to a 2 °C increase in the global temperature [3]. Increasing the global demand for natural resources has resulted in the creation of the Factories of the Future approach [4]. Furthermore, recent years have shown that groundwater use has increased, leading to its depletion and contamination [5]. This increase presents serious water management problems, outbreaks of waterborne diseases, and water scarcity issues to city planners, health, and governance teams. Hence, to prevent such outbreaks and to obtain health benefits, the supply of domestic-purpose water needs to be sustained [6][7].

RwH is a new concept in green infrastructure initiatives that is gaining importance in dealing with the global water issues caused by [8]. Rainwater harvesting technologies and strategies (RwHTS) have many benefits. These include reduced environmental and health effects, less rainwater runoff, and economic viability [9]. A study of rainwater management reports that rainwater runoff can be controlled using sustainable design structures [10]. Additionally, it also facilitates the soil to absorb moisture. Thus, it can assist in the recharging of the local groundwater aquifer [11].

Thus, RwHTS can be leveraged to develop a self-sufficient and sustainable built environment. However, built environment projects are generally criticized for their under-performance in quality, product delivery, and customer satisfaction due to manual, conventional planning, designing, estimating, and managing that are needed [12][13][14][15][16][17][18]. BIM was introduced as a panacea for the issues faced by the architecture, engineering, and construction (AEC) industry. BIM can support achieving sustainable building design (reduced costs) [19][20], daylighting analysis, water harvesting, energy-saving designs [21][22], the use of sustainable materials [23], and lower lifecycle costs [24]. Siddiqui, Pearce [25] presented detailed implications of BIM tools in achieving sustainability, where the authors discussed the use of BIM for the simulation and analysis of sustainable structures. In the same spirit, RwH structures can be built using BIM [23]. The further development of BIM uses integrated BIM technologies [26]. Langar and Pearce [27] conducted a survey-based study of BIM and RwH to identify BIM implementation in the United States and the type of RwH structures constructed by the design firms.

2. RwH Technique Adoption and Discussion

With increased water demand due to population growth, water usage and demand has increased, leading to the depletion of the groundwater aquifers. Water management is essential for water scarcity counting and requires proper governance and appropriate engineering solutions. Proper governance includes democratic legitimacy regarding this matter. Sophisticated frameworks of building structures and strategies such as green infrastructures should be adopted and implemented to achieve the holistic goals of smart and sustainable cities. Furthermore, stakeholders should be persuaded to collaborate on these developments through incentives from the government and regulatory bodies. Some measures in this context include subsidized developments that consider green strategies. Furthermore, proper sustainable drainage systems (SuDs) should be implemented to maximize the RwH potential globally. Once such strategies are implemented, RwH engineering solutions can be implemented, including small dams, pit holes, porous roads, and building structures with RwH and green infrastructures to move towards smart and sustainable cities and eventually to a smart planet, as per the United Nations' sustainable development goals (SDGs).

Governing principles and engineering solutions are difficult to implement and adopt. They require active collaboration between all stakeholders. Conventional construction and projects have many loopholes in the information sharing department, creating an environment of mistrust, ultimately leading to failures and ineffectiveness, both of which are evident in developing countries like Pakistan. BIM allows all stakeholders, including designers, owners, building specialists, and contractors, to collaborate closely [28].

Moreover, sustainability in RwH can only be achieved through a proper process such as BIM. Researchers have studied BIM technology for increasing water efficiency since it improves working efficiency, examines sustainability performance, and increases collaboration between multiple working groups [12]. It has been established that BIM increases time efficiency and enhances the coordination of construction projects [29]. BIM combines visibility, harmonization, modeling, and optimization, which are the key ingredients for enhancing model efficiency [30]. These findings are complemented by the outcomes of this research, where the benefits of BIM are acknowledged.

The current research investigates the RwH potential in Islamabad, the capital of Pakistan and detailed methodology flow chart is given in **Figure 1**. RwH is an excellent source of water storage in areas that have higher water stress and demand. It can be applied anywhere in the world for RwH modeling and potential identification. This study presents BIM as an effective method to identify RwH potential accurately without any complex functions. The associated models were developed based on local knowledge. The sites were visited on ground, and the common house structure (108 m^2) was replicated using these tools. The rooftop slope can vary in different conditions. For estimating the rooftop area, satellite data can also be used, which is more accurate. Furthermore, if the rainwater harvesting techniques are considered for the whole city, then the satellite data are definitely recommended for appropriate, reliable and accurate results. Satellite data cover a large area, which is why it is recommended when the whole city is considered. However, due to the same nature and construction style at all of the sites considered here, a generic model was prepared after the survey of the specified area. Since the model was only developed and utilized to estimate the RwH potential of the structures, the evaporation factor was not induced in it. However, this should be included in future studies, which should define an evaporation constant while determining the RwH potential. As in most semi-arid regions, some fractions of the precipitation value fall into the evaporation counter, so it must be included and catered for in future research. According to building codes, for every 12 inches, there should be a step down of ¼ inch, approximately 1.19°. However, in this study, to make the rainwater flow off the roof quickly, we used 5° slopes. The amendments in the bylaws regarding these techniques have been discussed with the local development authority (CDA). The results can be even more supportive on a large scale and for buildings with larger areas. Larger buildings will have a larger roof area, contributing to more rainwater being collected and harvested.

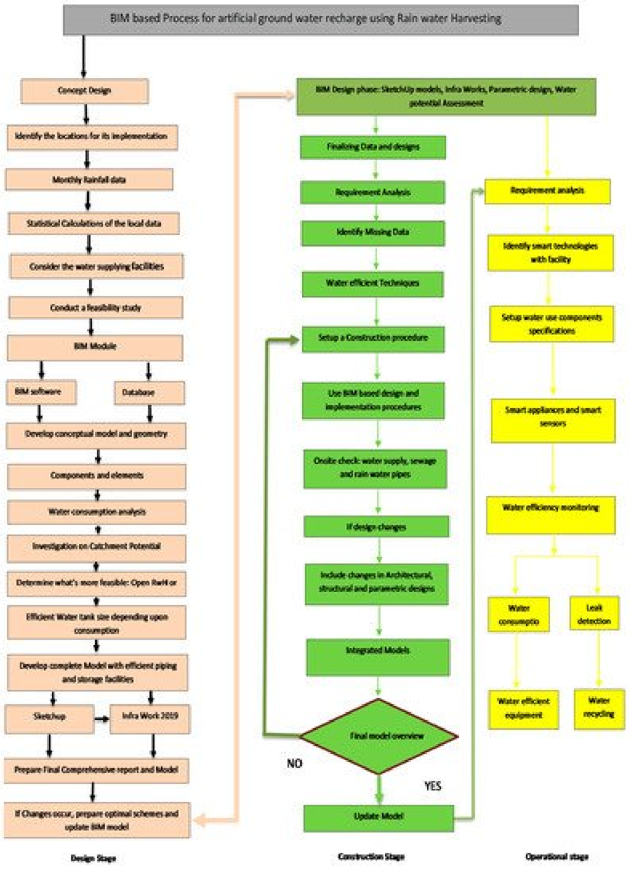

Figure 1. Stepwise automation process of RWH in BIM.

Moreover, water from multiple structures can be saved or allowed to move under gravitational flow. After natural purification, it will eventually be a source to recharge the groundwater table through soil layers. A study by Amos and Rahman [31] that was based on the economic analysis of RwH showed that more benefits can be achieved from such RwH, which ultimately reduces the cost of water from the municipal supply. This is evident in countries such as Australia, where the benefit–cost ratio (BCR) is just over one, and for that reason, subsidiaries and the hedonic price were increased, which is ultimately advantageous for the user. However, the tank size, maintenance cost, and other factors are still in the research loop, and the considerations may not be exhaustive. A study by Stec [32] showed the cost and benefit analysis of RwH based on Equation (3). In Equation (3), LCC is the life cycle cost, INV is the investment of the project, OMC is the operating cost, and DMC is the cost of liquidation and economic use.

$$\mathrm{LCC} = \mathrm{INV} + \mathrm{OMC} + \mathrm{DMC} \tag{3}$$

Islamabad is prone to rainfall and has massive RwH potential. Water that can be saved using RwH structures can be utilized for bathing, washing, and gardening purposes. The following purposes save a great deal of water and are indeed very beneficial for the city. Since it is not being used for drinking purposes, there is no need to conduct a water quality check. The study showed that if the rainwater is utilized for domestic purposes, including bathing and gardening, then it can be a viable solution to solving household water demands and concerns. However, in the case of drinking, turbidity, acidity, biochemical oxygen demand, and a few other chemical and physical properties should be checked. The study by Rodríguez-Sinobas, Zubelzu [11] showed that a tank size of 7 m^3 is beneficial for a household with more than two family members in Prague. Moreover, for low life cycle costs, OMC and INV should be less to adopt them easily. Accordingly, it will be beneficial when more people adopt this water saving methodology, and the long-term benefits of keeping water resources intact can be achieved.

Furthermore, this study also showed that water purification could be uneconomical when used for domestic purposes. In this way, time and financial resources can also be saved. Though this study concluded that BIM is a good technique to model the RwH potential, some contributing factors such as cost, legal requirements, etc., also need to be addressed for more reliable results and to propose holistic implementable solutions. Islamabad, which is located in a semi-arid climate, receives moderate rainfall over the entire year, except for during the monsoon season, when it rains excessively. Due to an increase in the population, water demand has increased drastically in this city.

Further, with continuous water pumping from groundwater and low water recharge, groundwater is depleting rapidly in this area. As such to overcome this problem, unconventional ways of storing water are mandatory for the study area. Thus, the RwH for household usage is an important method that was explored in this study. The process was visualized and complimented using BIM [33][34][35].

BIM provided a building modeling for all three sites. In the BIM environment, houses were modeled for all three sites, and calculations were performed. A simple methodology was followed in this research, where the water requirements per person per day were calculated, and the potential available water was calculated from simple statistical relationships. Afterward, the cumulative RwH was calculated and drawn against the demand line to identify the demand and availability of the water over the entire year. The results revealed that all three study sites have strong potential for rainwater storage. In terms of the monthly potential for RwH, it was found that August and September provide enough water for storage that can be used during the dry winters (October to December), when the area receives lesser rainfall [36]. On the other hand, if the three sites are compared, then Site 1 has the maximum potential for rainwater storage, as it receives maximum rainfall. However, the other two sites also receive a fair amount of rainfall for water storage, which is enough to deal with the water requirements of local households.

The results confirm that the methodology adopted in the current study gives reliable results for the study area. However, it is important to mention that small storage units can be expensive, need larger financial expenditure, and provide relatively lower potential outcomes than larger structures [37]. This is why larger rainwater storage tanks or areas are recommended to achieve the maximum output from the harvested rainwater. According to the current CDA building code, the rainwater drainage of houses must be linked with the main CDA drainage system, the water in which will ultimately become waste. Furthermore, there is no reservoir in the buildings to conserve the harvested rainwater. According to a recent study, RwH was implemented in Faisal Mosque Islamabad, and it was determined that after three days of rain, the nearing groundwater level raised up to 4250 mm. The technique included rooftop harvesting, directing the water into the ground by pit holes, and allowing it to flow using the action of gravity. A new CDA building code amendment was introduced to save water, which included conditions that roof RwH must be adopted in houses with an area of more than 38 m^2. Thus, the topic under investigation is critical to the local authorities and is welcomed by them. The same approach can be adopted and investigated for other countries.

RwH is also common in agriculture practices, including small dams and pit holes, as large amounts of water are required for crops. Asadi and Bannayan [38] showed that low crop yields are obtained with low precipitation. To counter this water issue, RwH is promoted and contributes to domestic and agricultural purposes. Moreover, RwH shows great potential in semi-arid regions and can help sustain the agriculture sector. In Ethiopia, another study by Tolossa et al. [32] showed a significant impact of the RwH techniques and strategies that helped improve soil moisture, low runoff, increased groundwater recharge, and crop yield.

Openly harvested rainwater can be used for bathing, washing, and other domestic purposes. If any design plan changes, then the structure can be improved or amended using the same tools. The second stage is the construction stage, which includes the on-ground development of the structure. Finalized data and design need to be handed over to the implementers and constructors. A complete requirement sheet that shows the demand of all of the materials involved in the process, i.e., from excavation to the finishing stage of the buildings, can be created. More advanced and efficient techniques can be used to increase the efficiency of this structure. A detailed construction procedure can be set up using BIM processes, on-site sewerage, and rainwater structures linked with the built-up area. If some changes need to be induced, then they must be included in the architectural, structural, and parametric design to smoothen the project and to avoid confusion between different stakeholders. After this, the model can be updated and moved into the next stage. The third stage is related to the maintenance of the facility. Again, a requirement list can be formed, showing all of the equipment and material to be used for maintenance. Smart technologies and smart sensors can be utilized to check the facility and the associated water flow. The sensors can help in determining the quantity of water utilized and detecting any potential leakages. Furthermore, recycling rainwater can also be achieved using smart technologies for filtration. Hence, it can be said that this process is quite easy to adopt in all kinds of residential buildings.

References

1. Raghav, S.; Painuli, R.; Kumar, D. Threats to water: Issues and challenges related to ground water and drinking water. In A New Generation Material Graphene: Applications in Water Technology; Naushad, M., Ed.; Springer International Publishing: New York City, NY, USA, 2019; pp. 1–19.
2. Samir, K.; Lutz, W. The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. Glob. Environ. Chang. 2017, 42, 181–192.
3. Hao, T.; Du, P.; Gao, Y. Water environment security indicator system for urban water management. Front. Environ. Sci. Eng. 2012, 6, 678–691.
4. Herrmann, C.; Schmidt, C.; Kurle, D.; Blume, S.; Thiede, S. Sustainability in manufacturing and factories of the future. Int. J. Precis. Eng. Manuf. Technol. 2014, 1, 283–292.
5. Pérez, A.; Hurtado-Patiño, J.; Herrera, H.; Carvajal, A.; Pérez, M.; Gonzalez-Rojas, E.; Pérez-García, J. Assessing sub-regional water scarcity using the groundwater footprint. Ecol. Indic. 2019, 96, 32–39.
6. Adnan, S.; Ullah, K.; Gao, S.; Khosa, A.H.; Wang, Z. Shifting of agro-climatic zones, their drought vulnerability, and precipitation and temperature trends in Pakistan. Int. J. Clim. 2017, 37, 529–543.
7. Tiwari, K.; Goyal, R.; Sarkar, A. GIS-based methodology for identification of suitable locations for rainwater harvesting structures. Water Resour. Manag. 2018, 32, 1811–1825.
8. Aslam, B.; Maqsoom, A.; Khalid, N.; Ullah, F.; Sepasgozar, S. Urban overheating assessment through prediction of surface temperatures: A case study of Karachi, Pakistan. ISPRS Int. J. Geo-Inf. 2021, 10, 539.
9. Wang, R.; Zimmerman, J. Economic and environmental assessment of office building rainwater harvesting systems in various U.S. cities. Environ. Sci. Technol. 2015, 49, 1768–1778.
10. Rice, J.; Martin, N. Smart infrastructure technologies: Crowdsourcing future development and benefits for Australian communities. Technol. Forecast. Soc. Chang. 2020, 153, 119256.
11. Rodríguez-Sinobas, L.; Zubelzu, S.; Perales-Momparler, S.; Canogar, S. Techniques and criteria for sustainable urban stormwater management: The case study of Valdebebas (Madrid, Spain). J. Clean. Prod. 2018, 172, 402–416.
12. Lupia, F.; Baiocchi, V.; Lelo, K.; Pulighe, G. Exploring rooftop rainwater harvesting potential for food production in urban areas. Agriculture 2017, 7, 46.
13. Ali, B.; Zahoor, H.; Nasir, A.R.; Maqsoom, A.; Khan, R.W.A.; Mazher, K.M. BIM-based claims management system: A centralized information repository for extension of time claims. Autom. Constr. 2020, 110, 102937.
14. Ullah, F.; Qayyum, S.; Thaheem, M.J.; Al-Turjman, F.; Sepasgozar, S.M. Risk management in sustainable smart cities governance: A TOE framework. Technol. Forecast. Soc. Chang. 2021, 167, 120743.
15. Ullah, F.; Sepasgozar, S.M.; Thaheem, M.J.; Al-Turjman, F. Barriers to the digitalisation and innovation of Australian Smart Real Estate: A managerial perspective on the technology non-adoption. Environ. Technol. Innov. 2021, 22, 101527.
16. Ullah, F.; Sepasgozar, S.M.; Shirowzhan, S.; Davis, S. Modelling users’ perception of the online real estate platforms in a digitally disruptive environment: An integrated KANO-SISQual approach. Telematics Informatics 2021, 63, 101660.
17. Ullah, F.; Sepasgozar, S.M.; Thaheem, M.J.; Wang, C.C.; Imran, M. It’s all about perceptions: A DEMATEL approach to exploring user perceptions of real estate online platforms. Ain Shams Eng. J. 2021.
18. Ullah, F.; Thaheem, M.J.; Sepasgozar, S.M.E.; Forcada, N. System dynamics model to determine concession period of PPP Infrastructure Projects: Overarching effects of critical success factors. J. Leg. Aff. Disput. Resolut. Eng. Constr. 2018, 10, 04518022.
19. Hamidavi, T.; Abrishami, S.; Hosseini, M. Towards intelligent structural design of buildings: A BIM-based solution. J. Build. Eng. 2020, 32, 101685.
20. Maqsoom, A.; Khan, M.U.; Khan, S.; Naeemullah; Ullah, F. Factors influencing the construction time and cost overrun in projects: Empirical evidence from Pakistani construction industry. In Proceedings of the Proceedings of the 21st International Symposium on Advancement of Construction Management and Real Estate; Chau, K., Chan, I., Lu, W., Webster, C., Eds.; Springer: Singapore, Singapore, 2018; pp. 769–778.
21. Lotfi, N.; Behnam, B.; Peyman, F. A BIM-based framework for evacuation assessment of high-rise buildings under post-

earthquake fires. J. Build. Eng. 2021, 43, 102559.
22. Ali, Q.; Thaheem, M.J.; Ullah, F.; Sepasgozar, S.M.E. The performance gap in energy-efficient office buildings: how the occupants can help? Energies 2020, 13, 1480.
23. Trindade, A.D.; Coelho, G.B.; Henriques, F.M. Influence of the climatic conditions on the hydrothermal performance of autoclaved aerated concrete masonry walls. J. Build. Eng. 2021, 33, 101578.
24. Panteli, C.; Kylili, A.; Stasiuliene, L.; Seduikyte, L.; Fokaides, P.A. A framework for building overhang design using Building Information Modeling and Life Cycle Assessment. J. Build. Eng. 2018, 20, 248–255.
25. Siddiqui, M.Z.; Pearce, A.R.; Ku, K.; Langar, S.; Ahn, Y.H.; Jacocks, K. Green BIM approaches to architectural design for increased sustainability. Available online: https://www.researchgate.net/publication/236878118_Green_BIM_Approaches_to_Architectural_Design_for_Increased_Sustainability (accessed on 6 July 2021).
26. Badenkoa, V.; Bolshakov, N.; Tishchenkob, E.; Celanic, A.; Fedotova, A.; Yadykina, V. Integration of digital twin and BIM technologies within factories of the future. Mag. Civ. Engineering. 2021, 101, 10114.
27. Langar, S.; Pearce, A.R. Implementation trends for rainwater-harvesting technologies and strategies and their relationship with Building Information Modeling. J. Arch. Eng. 2017, 23, 04016016.
28. Langar, S. The role of building information modeling (BIM) in the implementation of rainwater harvesting technologies and strategies (RwHTS). Ph.D. Thesis, Virginia Polytechnic Institute and State University, Blacksburg, VA, USA, June 2013.
29. Rehman, M.S.U.; Thaheem, M.J.; Nasir, A.R.; Khan, K.I.A. Project schedule risk management through building information modelling. Int. J. Constr. Manag. 2020, 1–11.
30. Lee, C.-Y.; Chong, H.-Y.; Wang, X. Streamlining digital modeling and Building Information Modelling (BIM) uses for the oil and gas projects. Arch. Comput. Methods Eng. 2018, 25, 349–396.
31. Amos, C.; Rahman, A.; Gathenya, J.M. Economic analysis of rainwater harvesting systems comparing developing and developed countries: A case study of Australia and Kenya. J. Clean. Prod. 2018, 172, 196–207.
32. Stec, A. Sustainable Water Management in Buildings; Springer: Berlin Germany, 2020; p. 90.
33. Ullah, F.; Sepasgozar, S.M.E.; Wang, C. A systematic review of smart real estate technology: Drivers of, and barriers to, the use of digital disruptive technologies and online platforms. Sustainability 2018, 10, 3142.
34. Ullah, F. A beginner's guide to developing review-based conceptual frameworks in the built environment. Architecture 2021, 1, 5–24.
35. Malik, Q.; Nasir, A.R.; Muhammad, R.; Thaheem, M.J.; Ullah, F.; Khan, K.I.A.; Hassan, M.U. BIMp-Chart—A Global Decision Support System for Measuring BIM Implementation Level in Construction Organizations. Sustainability 2021, 13, 9270.
36. Dahutia, P.; Pathak, B.; Bhuyan, P.K. Aerosols characteristics, trends and their climatic implications over Northeast India and adjoining South Asia. Int. J. Clim. 2018, 38, 1234–1256.
37. Lasage, R.; Verburg, P.H. Evaluation of small scale water harvesting techniques for semi-arid environments. J. Arid. Environ. 2015, 118, 48–57.
38. Asadi, S.; Bannayan, M.; Monti, A. The association of crop production and precipitation; a comparison of two methodologies. Arid. Land Res. Manag. 2018, 33, 155–176.

Keywords

rainwater harvesting (RwH);water demand;building information modeling (BIM);hydrological investigation;sustainable drainage systems (SuDs);residential buildings