A Strategic Design Approach for Implementing Rainwater Management System Using an Integration of GIS and BIM Tool

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Abstract

An increase in urbanization and uncontrolled development has resulted in a water stress situation, which necessitates the exploration of alternate water sources. Rainwater has proven to be a prominent alternate water source after being efficiently harvested. On-ground implementation of the Rainwater Harvesting System (RWHs) at a community level in urban areas has always been challenging and requires technological advancement. To facilitate the implementation of RWHs, the proposed study provides a comprehensive methodology by integrating the Geographical Information System (GIS) and the Building Information Modeling (BIM) tools. Initially, the hydro-spatial analysis was performed with a GIS tool to obtain an optimized rainstorm collection network and to aid in establishing the geometrical properties of RWHs. Further, an outcome from the analysis was utilized to develop a visualization model using the BIM tool. The proposed methodology is implemented as a case study in the municipality of Jaipur (India). The developed multidimensional BIM contributes to the sustainability of the project in terms of resources, economy, and efficiency over the life cycle. As an outcome, the proposed study provides a comprehensive methodology for effectively utilizing rainwater to cope with the growing water demand and contribute to flood mitigation in urban regions.

Keywords: Water; Sustainability; Rainwater Harvesting; Geographical Information System; Building Information Modeling

1 Introduction

With the increase in population and urbanisation, meeting water demand has become a primary concern in most urban areas (Sitzenfrei et al., 2017). Over half of the world's population would face extreme water scarcity by 2050 (Marzouk & Othman, 2020). To address water-related challenges, various initiatives have been enforced to build sustainable water management practices which aids in conserving and utilizing water resources (Słyś & Stec, 2020). In most regions Rainwater Harvesting (RWH) has been implemented to alleviate water scarcity by serving as an alternate water source (Gwenzi & Nyamadzawo, 2014). Rainwater serve as the primary source for numerous utilities, including drinking, residential use, everyday life activities, agriculture, animal management, reservoir storage, groundwater recharge after being effectively collected and stored (Kimbonguila et al., 2019).

Along with traditional RWH practices, modern RWH practices such as bio-swales, rain gardens, pervious pavements, and green roofs are often designed and implemented in developed regions by simulating natural hydrological responses and to percolate urban rainstorms through soil infiltration, stormwater retention, storage, purification, groundwater recharge to reduce the risk of the flood (Everett et al. 2016). On the other hand, the design and implementation of the RWHs in urban areas have a substantial impact on society's environmental and economic consequences while serving as an alternate water source (Amos, Rahman & Gathenya, 2016). Strategic planning, identification of RWH sites, and design considerations play an important role to create efficient RWHs (Raya & Gupta, 2020; Patil et al., 2022). While designing and planning for the centralized RWHs numerous statical methods, water balance methods, non-dimensional design methods, and detailed design approaches were applied (Patil & Gupta, 2022; Semaan et al., 2020). Along with these approaches, modern tools such as STORM and SWMM have been applied to analyse and manage the urban drainage network (Wang, Pan & Luo, 2019a).

However in numerous instances, designing the centralized RWHs in urban areas are critical, due to the presence of on-ground components such as power and communication lines, potable water networks, gas pipes, and ground gradients (Li & Matthew, 1990). In such a case, computer models and mapping tools, such as Geographical Information System (GIS), have proved extremely useful in incorporating multiple parameters at a single point by digitizing the maps and performing the spatial analysis (Mustajoki & Marttunen, 2017). In addition to GIS tool, to assess and improve the drainage network management, interface method or multiple developed tools aid in enhancing optimal placement of model element or system controllers have been used (Leitão et al., 2018).

Very few studies focused on GIS-based management applications that accommodate varied data resources, such as BIM data, CAD data, and simulation results, to promote data fusion and increased decision-making on GIS-based platforms (Zhang et al., 2020). Moreover, the visualization of the analysed data from the GIS could be employed using a proven effective tool, i.e., BIM, since it focuses on the implementation of digital modelling and informatics management throughout the entire construction project life cycle (Eastman et al., 2011). Representation of the 3D model for stakeholder involvement, environmental impact studies, collision testing with existing infrastructure, energy consumption behaviour monitoring at both the building and community levels, heritage preservation, urban emergency response, and updating the topographic information system after completing the structure is performed by integrating the GIS and BIM tool (Amirebrahimi et al., 2015; Wang, Pan & Luo, 2019b).

Although the previously used approaches provide the visualization of simulations by allowing multiple mathematical analyses, which consumes a significant amount of precise data and needs technological improvement, which restricts its application in developing countries. The applied household approaches necessitate a significant capital investment and area, which is not realistically possible for low and middle-income groups. To facilitate the implementation of RWHs and to cover this significant knowledge gap, the current study provides an alternate way to develop the rainstorm collection network and estimates the geometrical properties of the centralised RWHs over the region using the integration of ArcGIS and BIM tools. The municipality area of Jaipur (India) is considered as a case study to validate the proposed methodology.

2 Methodology

The proposed study's methodology is categorized into three components: hydro-spatial analysis, design, and visualization, as illustrated in figure 1. To begin, a hydro-spatial analysis of the developed digital elevation model (DEM) and the acquired satellite data is required to establish a relationship between the topography and hydrological parameters of the region. Later, at the design stage, the results obtained from the hydro-spatial analysis assist to determine the geometrical characteristics of the RWH components in accordance with Indian standard codes and design guidelines. Finally, the visualization of the RWHs is created using the BIM tool, enhancing information sharing among stakeholders across different project phases.

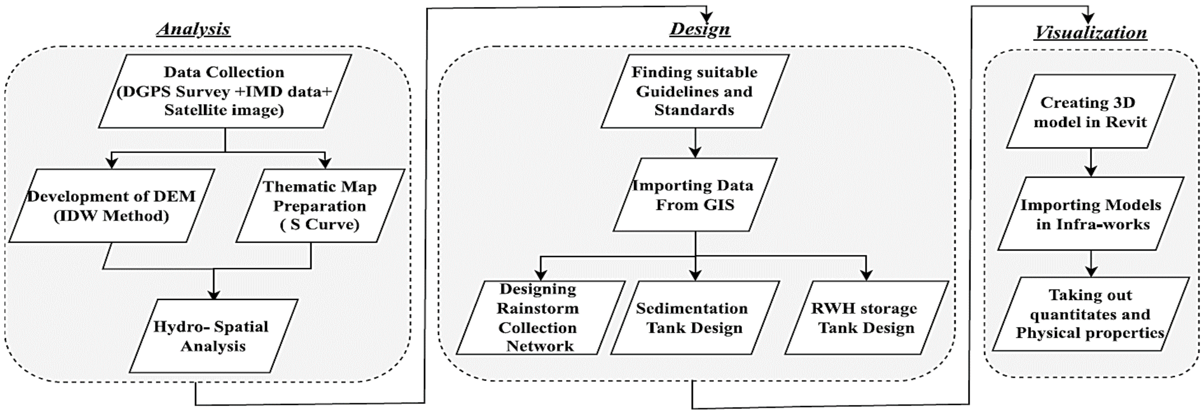

Fig. 1: Proposed Methodology

2.1 Hydro-spatial Analysis

A DEM is required to perform the hydro-spatial analysis over the study region. The data from the Differential Global Positioning System (DGPS) survey must be collected in the WGS-84 coordinate system for creating the DEM. The z-coordinate values from the data were incorporated for creating a DEM using an inverse distance weighted (IDW) interpolation method in the ArcGIS environment. The generated (DEM) was processed for creating the flow accumulation map in identifying RWH locations and establishing the drainage network. The flow accumulation raster is generated by pre-processing the DEM (Fill DEM) and developing the Flow direction raster, which was consecutively consumed as raw data. Finally, the stream order tool provides a stream order with threshold values for the flow accumulation map. The generated flow accumulation map provides the flow path and locations where the maximum flow would occur.

Further, multiple spatially referenced thematic maps are required to be generated from the acquired raw data for determining the hydrological characteristics of the region. Eventually, for estimating the amount of runoff, the SCS-CN (Soil Conservation Service-Curve Number) approach (SCS Engineering Division, 1986) was used. Raster maps for land use/land cover and soil hydrologic group were utilized to create the CN (Curve number) raster, which was then used to create the first soil abstraction raster. Finally, the runoff raster was created by combining the rainfall and initial soil abstraction rasters. The conditional tool (Con) and Raster Calculator tools have been used in the ArcGIS environment to create the runoff raster.

2.2 Design

The geometrical characteristics of RWHs components were determined using the outcomes hydro-spatial analysis. The runoff values from the stream order were used to determine the size of the rainstorm collection network. After collecting rainstorm water, a provision of a sedimentation tank near the RWH storage tank is necessary to remove silt before storing the water in a tank. Henceforth, the design of the sedimentation tank is performed using the guidelines stated in IS 10261(1982). After the primary treatment, water must be stored in a tank for future use. A 10-day design period is considered while determining the underground tank size.

2.3 Visualization

After determining the geometrical characteristics, the multidimensional visualization model is required to share the data among the stakeholders. The three main parts of the 3D model are the surface model, existing building, and pipe system modeling. To create the 3D model, all the data was organized into layers and imported into multiple BIM tools. The determined drain path in Shapefile (.*SHP format) was directly imported as a pipeline in the InfraWorks tool. Whereas in the case of the sedimentation tank and storage tank, a 3D model is required to prepare in the Autodesk Revit tool that could be imported into the InfraWorks tool with georeferencing.

3 Implementation

The municipal region of Jaipur (India) is considered as a case study to validate the practical applicability of the proposed methodology. The municipality boundaries of Jaipur spread from 26° 46’ to 27° 01’ north and 75° 37’ to 76° 57’ east. The administration of the city is overseen by the Jaipur Municipal Corporation (JMC), which encompasses the 467 square kilometers and is divided into two municipal corporations: the Greater Jaipur Municipal Corporation and the Jaipur Heritage Municipal Corporation, with 150 and 100 wards, respectively. To conduct the proposed study, ward number 06 of Greater Jaipur Municipal Corporation falls under the Jamna Puri area, is considered. The ward is located on the Northwest side of the city at latitude 26°59’09.88 "N to 26°59’53.37 "N and Longitude 75°45’11.54"E to 75°44’11.02"E and having an area of about 1.6462 sq. km.

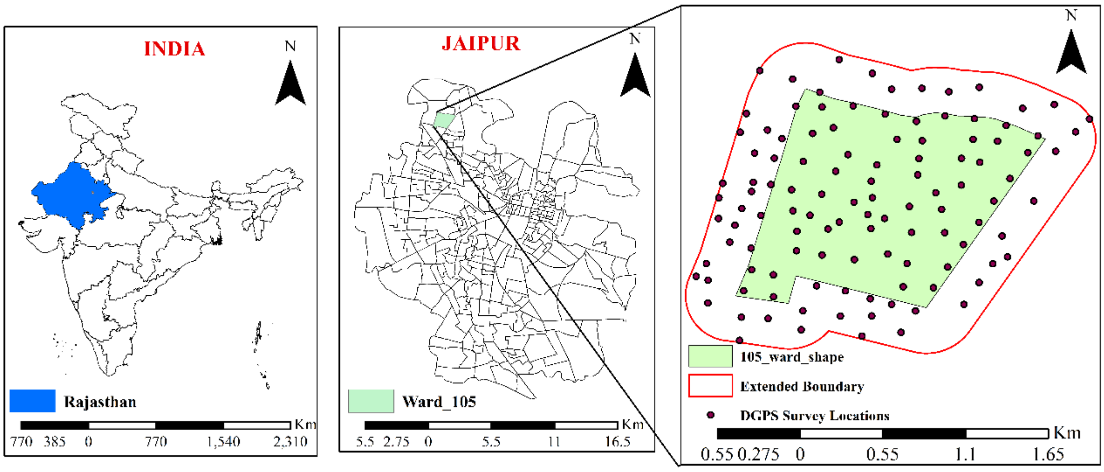

Fig. 2: Study area map

3.1 Data Collection and Preparation

A Differential Global Positioning System (DGPS) survey was conducted over the study area to collect three-dimensional coordinates in the WGS-84 coordinate system. The raw data was pre-processed with GNSS software (Trimble Survey Division, 2013) for removing inaccuracies and calibrating the readings to centimeter precision. The processed data ground data were imported into the ArcGIS environment and plotted as a shape file. Over the study area total of 115 three-dimensional coordinates were collected by considering a 500 m buffer area. The satellite images of IRS (Indian Remote Sensing) Resourcesat LISS-4 with the scene specifications 95-52-D, captured on 9/10/2019, having a spatial resolution of 5 m, have been procured from National Remote Sensing Centre, India. Daily rainfall data for Jaipur from the year 2011 to the year 2021 has been acquired from the Climate Data Service Portal of IMD (Indian Meteorological Department), Pune. The single rainfall raster was created for 2011 to 2021 and clipped within the study area. The study compromises two soil types, C and D, which were downloaded from the United Nations FAO (Food and Agricultural Organization) soil map (FAO, soil map) (Neitsch et al., 2011; FAO Map Catalog, n.d.).

3.2 Hydro-spatial Analysis

Importing the DGPS survey data in the ArcGIS tool led to the preparation of DEM raster by using the IDW interpolation method. The created DEM was used further to create a flow accumulation raster by performing hydro-spatial analysis. The created accumulation raster for the region was multiplied by the per-hr. rainfall value of 0.1693 mm/hr. (i.e., average rainfall value for the rainy season) to create the runoff raster. The created runoff raster provides the volume of water along the drainage path in the form of the cell value. The maximum and minimum values of the runoff raster were used in determining the drain size. The maximum peak runoff values at the end of the ward were used for estimating the geometrical properties of the RWH tank by considering 10 days of average rainfall. Figure 3. shows the maps created while performing hydro spatial analysis.

3.3 Drainage Mapping

The generated runoff raster was required to classify using the peak runoff value to design the economic drainage network over the area. By understanding the maximum and minimum runoff values, the standard drain size of depths 0.5m, 1.5m, 2m, and 2.75m was considered for classifying the runoff raster. Based on the calculated peak runoff values, the runoff raster was classified as 1.702m^3/hr., 31.86 m^3/hr., 68.68m^3/hr., and 148.74 m^3/hr., and the new runoff raster was created. The created runoff raster was converted to polyline features for quantifying the geometric characteristics of flow lines. The acquired LISS-4 image was used as a base map for aligning the drainage network, and digitization was performed. Depending on the size, the created shapefile files were classified as lateral, sub-mains, main, and outfall drains. The runoff values generated by considering 10 days of average rainfall were used to determine the geometrical characteristics of the storage tank.

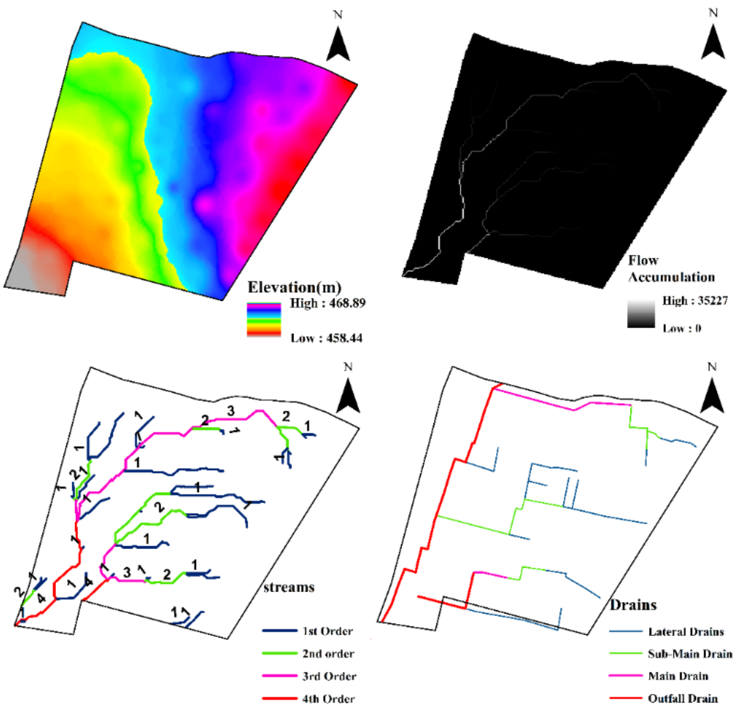

Fig. 3: Hydro Spatial Analysis

3.4 Visualization

A 3D model for the storage tank and sedimentation tank was created in the Autodesk Revit tool directly imported into InfraWorks. The created georeferenced shapefiles for the drainage network were imported directly in InfraWorks as the pipelines. The visualizations involved the development of the real-time scenario in the study region, integrating features like roads, vegetation, and boundary limits. The model builder feature in the Infraworks help in incorporating the on-ground objects.

4 Results and Discussion

The selection of suitable sites and their technological design are key factors in the success of RWHs (Al-Adamat et al., 2012). Numerous design techniques and modern tools were implemented to increase the sustainability and efficiency of the RWHs. Most researchers integrated the multicriteria analysis (MCA) and GIS to provide a rational, objective, and unbiased technique for identifying potential regions for RWH creation by utilizing the ground survey data (Alwan, Aziz & Hamoodi, 2020). Multiple simulations and mathematical models were implemented along with the MCA to perform the micro-level planning (Patil & Gupta, 2022).

Considering past research, the proposed methodology provides a strategic approach for creating community RWHs. The performed hydro-spatial analysis over the study area comes out with designing a rainstorm collection network and establishing the geometrical characteristics of RWHs components. The detailed characteristics of the classified drains are mentioned in Table 1.

Table 1: Drain Characteristics

Drain Name	Drain Depth (m)	Drain Width (m)	Perimeter (m)	Area (m^2)	Total Length (m)	Peak Runoff (m3/hr)
Lateral Drain	0.5	1	2	0.5	3114.767	1.702
Sub Main Drain	1.5	3	6	4.5	1535.113	31.86
Main Drain	2	4	8	8	975.5422	68.68
Outfall Drain	2.72	5.44	10.88	14.8	3681.807	148.74

After designing the collection network, the sedimentation tank and storage tank design were performed using the obtained runoff values. The visual model is prepared using Autodesk Revit and integrating with the InfraWorks tool by incorporating multiple information layers of buildings, roads, and topography. The properties of the designed model were extracted and mentioned in Table 2.

Table 2: RWHs components Characteristics

RWH Component	Area (m^2)	Volume(m^3)	Dimensions
Sedimentation Tank	195	1072.5	30*6.5*5.5
Storage Tank	1912	17121.1	40*47.80*37.80*10

The identified location of the starting and ending node of the drain during execution for placing the drainage network without any clashes and misalignment issues. BIM helps to visualize the present drainage network by incorporating multiple information layers of buildings, roads, topography, and drainage network characteristics. The Figure 4 a, b, c) represents the different information layers for the RWH system and collection network which integrated in Infraworks model, respectively. The created visual model for the entire RWHs increases the information sharing among the stakeholders and aids the planner in estimating the resource at the initial planning phase. The study uses the rectangular open-drain section, which could be modified with alternate materials and shapes based on requirements and present locations.

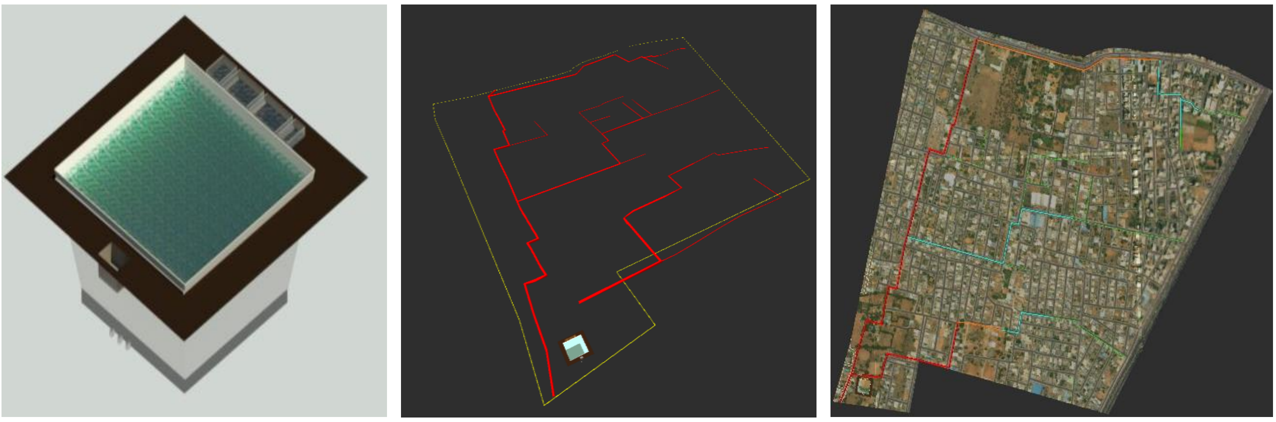

Fig. 4: a) RWH tank visualization **b)** Drainage Network visualization **c)** InfraWorks Visualization

5 Conclusion

Exploration of alternate water sources is essential to meet the global water demand rise. Strategic planning, advancement in technology, and design considerations are required for enhancing the efficiency of rainwater harvesting system (RWHs). The suggested methodology in the study integrates Geographical Information System (GIS) and Building Information Modelling (BIM) tools to provide a strategic approach for creating a community RWHs over a region. The methodology was applied to a municipality ward of Jaipur city, India, as a case study. The performed hydro-spatial analysis aids in determining the geometrical characteristics of RWHs components such as drain size, sedimentation tank size, and storage tank design spread over the wards. In addition, created visualization using the determined geometrical characteristics enhance the information sharing among the stakeholders by incorporating topographic information such as the location of roads, buildings, and important structures, conflict's resolution during the execution. Further detailed design of the RWH structure over the distributed locations would increase the study's feasibility by creating a continuous chain of RWHs along the periphery of the municipality, which could be incorporated in a future study.

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