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Rural community water management through directional tunnelling: visual modelling of rainwater harvesting system

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Abstract

Rainwater, a prominent source of water, needs to be properly harvested for better utilisation during water unavailable circumstances. Creating rainwater storage structures is an important aspect in the planning of water resources as it serves for future water usage and consumption. Advancements in rainwater storage structures are not happening on a large scale. Most of the structures are limited to individual household rainwater collection. Innovations and advanced technology applications must address rainwater storage functioning for a community. This research work proposes an innovative method called directional tunnelling for the activity of rainwater harvesting and its management for a small community in a rural area. Initially, rainwater is harvested in multiple individual household tanks, and later the excess of water from the corresponding tanks is subsequently collected in a community tank named as directional tunnel. All the details related to rural community water management have been discussed as well as highlighted by visual modelling using Building Information Modelling (BIM) tools. The current research work is intended on the rural aspect; therefore, the directional tunnel's practical execution and results are portrayed in a better manner through a case study at a village in Rajasthan, India.

Key words: Building Information Modelling (BIM), directional tunnelling, rainwater harvesting, rural community water management

Highlights

- Water scarcity is a global issue, and the rainwater harvesting method is one of the prominent techniques in water saving methods.
- Current research work proposes a creative approach called the directional tunnelling method for rainwater harvesting among small communities in a locality.
- Rainwater is harvested in multiple individual household tanks of a community, and the surplus of water from the same tanks is diverted to a community tank, known as a directional tunnel.
- The directional tunnel is placed in an angular position below the ground level to hold a large capacity of rainwater with minimum space occupancy.
- By the usage of Building Information Modelling (BIM) tools, a visual model is created for clear awareness and practical implementation of the innovative method, i.e., directional tunnel.

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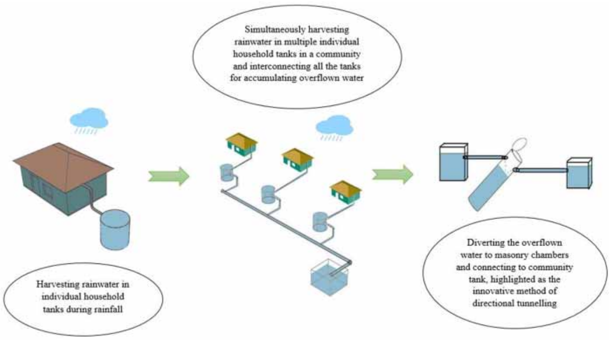
Graphical Abstract



INTRODUCTION

Rainwater is the primary source for various utilities such as drinking, domestic usage, daily life activities, agriculture, livestock and its management, reservoir storage, groundwater recharge and many more (Pathak & Heijnen 2007). Since rainwater behaves as the main source for different water-related activities, any community planning to harvest rainwater must understand the total requirement of water quantity in a particular location. Data collection with respect to rainwater catchments and rate of consumption from the households in villages helps in planning and implementation of rural community water supply (Ishaku *et al.* 2012). Depending on the demand and consumption limits, the method of rainwater harvesting can be adopted and followed by people for future need. For instance, in any urban area, rainwater can be stored by planning a proper rooftop rainwater harvesting system. The collected rainwater is stored in huge containers or man-made structures of ample size since space becomes a constraint in congested locations. Besides, it can also be inferred that rainwater storage in commercial buildings of Portugal was preferred for gaining economic benefits (Matos *et al.* 2015).

Meanwhile, in any rural area, rainwater harvesting can be followed by means of proper rooftop rainwater harvesting system, improving the groundwater levels by surface excavation and recharging the subsurface aquifers, since space is not a constraint in most of the countryside locations. In comparison with both the rural and urban areas, per capita water demand is always more in rural areas because of the driving factors such as the number of people in the family, variance in the day-to-day life activities, agricultural work, livestock maintenance etc. Apparently, proper planning of the rainwater harvesting system or tanks is highly reliant on water demand in the location (Londra *et al.* 2015).

Effective planning of water storage should constitute a trouble-free method in the long run. Most of the noteworthy challenges in man-made water storage structures are bound to store runoff water, reduce evaporation loss, and store infiltrating water. In India, rainwater harvesting in urban areas is adopted through recharge pits, recharge trenches, tube wells, and recharge wells whereas in rural areas through gully plugs, contour bunds, gabion structures, percolation tanks, check dams, recharge shafts, dug-well recharge, and groundwater dams (Freshwater 2003). The current research work is focused on rural rainwater harvesting; hence a thorough literature study was done concerning different types of traditional rainwater harvesting structures in rural areas of India from ancient times. The most prominent methods of rainwater collection system have been discussed (Table 1).

After the evolution of brick, cement and steel, people started constructing masonry structures as well as reinforced concrete structures to store rainwater as it would last longer with less maintenance. All the traditional rainwater harvesting structures (Table 1) or village ponds constructed as a part of a

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Table 1 | Different types of rainwater collection system in rural areas of India

S. no.	Name of the method	Working system	Major remarks
1.	Paar system (Percolation system)	Rainwater flows from the catchments and percolates into the sandy soil.	Traditional masonry technique.
2.	Kuis/Beris (Narrow opened well)	10–12 m deep pits were dug near tanks to collect the seepage, and the pit gets wider as it gets deeper into the ground and creates a large surface area for water to seep.	Prevents the collected water from evaporating.
3.	Saza Kuva (Open well)	Well pit with a huge circular foundation and an elevated platform sloping away from the well.	Source for irrigation in hilly regions of Western Rajasthan.
4.	Johad (Earthen check dam)	Small earthen check dams that capture and conserve rainwater, improve percolation and groundwater recharge.	Built by brick/stone masonry.
5.	Cheruvu (village pond)	Reservoirs to store runoff.	Supplemented with sluices, canals, and flood weirs to supply water.
6.	Baoli/Bavadi (stepped well system)	Stone blocks lined on the walls of the trenches without mortar and created with stairs leading down to the water.	Constructed to serve water across seasonal fluctuations.

Source: Rainwater Harvesting (2001).

rainwater harvesting system in rural areas were located at a distant place from the living area. Most of the women and children in rural areas invest more time in fetching water from remote locations (Baguma *et al.* 2010). Plan of action intended towards community water management in rural areas must satisfy the purpose of the nearest location of a water source to all the people living in a community (Onyenechere 2004). Even though many rainwater harvesting measures are being followed in India from ancient times, the progressive speed is less because of investment in capital and time. Taking permission from government authorities is also a time consuming and lengthy process. Another fundamental challenge lies in individuals, where people do not show interest and come forward in the installation of a rainwater harvesting system at personal residence (Rumi Aijaz 2020). Community water management measures have to be encouraged for overcoming the challenges in the perspective of rainwater harvesting. By the construction of a community tank, the people living in smaller communities can save time by fetching water from a near location.

Previously different types of efforts were made for storing rainwater by constructing overhead and underground structures as community tanks. Some of the attempts made in underground water storage structures were a vertical underground tank with one surface open to atmosphere, a vertical tank with a manhole, a vertical underground tank having inlet through pipe (Takai 2002), ground tank etc. The main point pertaining to open vertical tanks was that the water surface exposed to the atmosphere gets evaporated and the next layer comes to sun exposure, by which the rate of evaporation remains the same. Simultaneously, the energy required for drawing water from a vertical tank makes the users invest more money. Space remains a major constraint for a large-sized community tank because of huge land occupancy. In order to overcome the issues, problems, constraints faced in vertical underground tanks, this research work proposes an innovative method called directional tunnel for underground rainwater storage.

Construction of creative structures mainly lies in the hands of Civil Engineers, but new technologies and systems must be well understood before practical execution. Building Information Modelling (BIM) gives the scope of defining a new concept or technology in a comprehensible way before the initiation of construction. BIM can be defined in many ways as per different standards followed worldwide. In general, BIM is a visual platform for sharing and understanding a newly created structure or a system in which all the owners, architects, engineers, contractors, stakeholders are involved (Azhar *et al.* 2012). BIM is the process of utilising advanced technology for acquiring the data regarding

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the project from its formation to a functioning stage (Li *et al.* 2017). The concept of application of BIM makes the project owners plan and design a project/structure in multiple dimensions. Since the inception of BIM, evolution over the years has helped to transform or develop a structure from two-dimensional (2D) way to eight-dimensional (8D) way. 2D is the creation of a plan for the whole model. 3D is the creation of visualisations of the planned model with a realistic atmosphere. Including time as a fourth dimension to the project extends the scope of tracking various phases of project duration. Incorporating cost as the fifth dimension gives the advantage of cost management in the project. 6D of BIM is facility management in which complete parameters, usage of the structure in the project can be managed. Whereas 7D is the sustainability perspective in which the carbon cycle process can be evaluated for the particular project prior to inception (Hardin & McCool 2015). Finally, 8D is Prevention through Design (PtD) as it can be achieved through proper design of optimised safety principles by the identification of on-site risks in construction (Kamardeen 2010).

BIM tools give the flexibility to multiple stakeholders for working in collaboration by analysing demonstration of sequential construction phases in an urban project through 4D BIM (Ciribini *et al.* 2016). Before the initiation of a project, benefits, limitations and possible solutions for practical problems in the construction work of urban projects can be performed by the execution of BIM (Migilinskas *et al.* 2013). The practice of BIM tools requires skill, expertise, and in-depth knowledge regarding the adoption of suitable software for the expected outcome (Kalfa 2018). For instance, in order to create a photorealistic 3D model and cost estimation (4D) for the planned project, the areas of application have to be identified and well understood by referring data from previous projects (Hartmann *et al.* 2008). Over the years, the concept of BIM has been well interpreted and employed in many countries for urban case studies, whereas literature pertaining to the implementation of BIM in the rural aspect are fewer in number. 2D mapping and 3D visualisations were executed for rural projects in accordance with landscape projects in Norway (Hassan *et al.* 2016), whereas total life cycle planning, design, construction, and operation management were performed for Yangyou Village River Ecological Landscape Reconstruction Design Project in China through software like Rhino, Autodesk Revit, and Lumion (Wei *et al.* 2020).

Literature study infers that BIM is underutilised in the rural scenario for technical applications in Civil Engineering and a focus in BIM on the rural aspect can lead to its enhancement. In the current research work, rainwater harvesting and the innovative method of directional tunnelling have been explored using BIM. By the implementation of BIM for a rural level project, the activity of planning all the different phases and levels of construction can be performed. The advantage of modelling and visualising the complete surrounding environment can be achieved. For a rural level project, space is not a constraint; therefore, conceptualising the neighbouring conditions of the infrastructure area gives a better scenario for Civil Engineers during the execution of on-site work. Any inputs or changes received from clients/users in a rural project can be updated in a BIM model even at the mid-stage and can be reviewed. Execution of Civil Engineering projects by the intervention of advanced technology is minimal at remote locations. Factors like inadequate resources, transportation of equipment to site location, machinery charges, budget etc. might behave as negative agents for the implementation of advanced technology and it must be habitual to rural areas and related projects. With the help of rural BIM, planning the technological parameters for rural projects has to be formulated. The important features' comparison between rural BIM and urban BIM has been emphasised (Figure 1).

Visual modelling of the rural rainwater harvesting system indicating the method of construction and the surrounding environment would make on-site construction easy. Any innovation requires practical execution to analyse the benefits, drawbacks, and limitations of its study. The acquired knowledge based on the case study sets standards for future adoption and development. As a part of the case study, Ramnathpura, a rural area in Rajasthan, India, was selected for the implementation of the rainwater harvesting plan. Its geographic coordinates are 28°18′38.628″ N, and 75°39′43.38″

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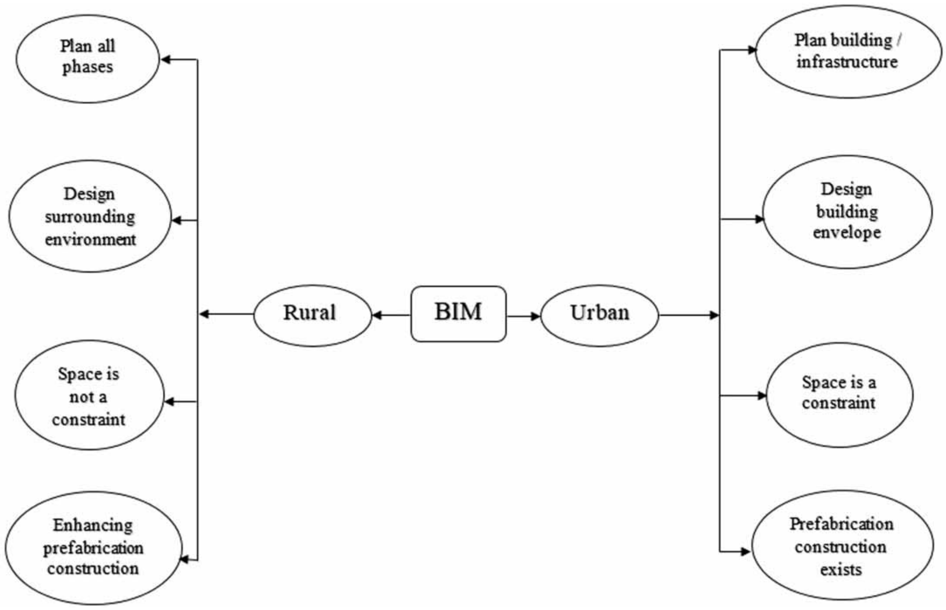

Figure 1 | Comparison of features between rural BIM and urban BIM.

E. Twenty-five houses were selected for the individual household tanks and a vacant land was chosen for the directional tunnel, which was accessible to all the users. The material chosen for all types of rainwater harvesting tanks in the case study was Glass Reinforced Plastic (GRP), and the tanks can be called GRP tanks (Weston 1980). Since the method of rainwater harvesting system is innovative, the type of material opted for is unique and followed a procedure that has future scope. The impact created by visual modelling of the rainwater harvesting system is also discussed through the case study.

METHOD

The innovative method of rainwater harvesting in the current research work is towards rural water management for a community. Initially, individual household water tanks would be constructed to store rainwater collected from rooftop harvesting systems. Gutters and downspouts would be connected to the roof of an individual house, and the corresponding connections make the rainwater flow and reach the individual household tank. The upper portion of an individual household tank would be connected with a pipe and water exceeding the storage limit would be conveyed to the community tank (Figure 2).

Directional tunnel, as the community tank in the setup of the rural community water management, is an innovative method of construction. It is highlighted as the solution for water shortages among community water storage methods. The concept of directional tunnelling assures that a large capacity of rainwater can be held with minimum space occupancy. The objectives of the directional tunnel for rainwater harvesting are: to reduce the rate and amount of water evaporation in the stored structure; to store a large volume of water using less ground space without interfering with surrounding structures; to consume less energy for drawing water from the stored facility.

The community tank is placed at an angular position below the ground level, and thus gets the name of directional tunnel. Since the community tank is in an angular position, the energy required for drawing water from the directional tunnel's storage is less. The method of the directional tunnel involves the practice of storing both the overflowed rainwater from the individual household tanks

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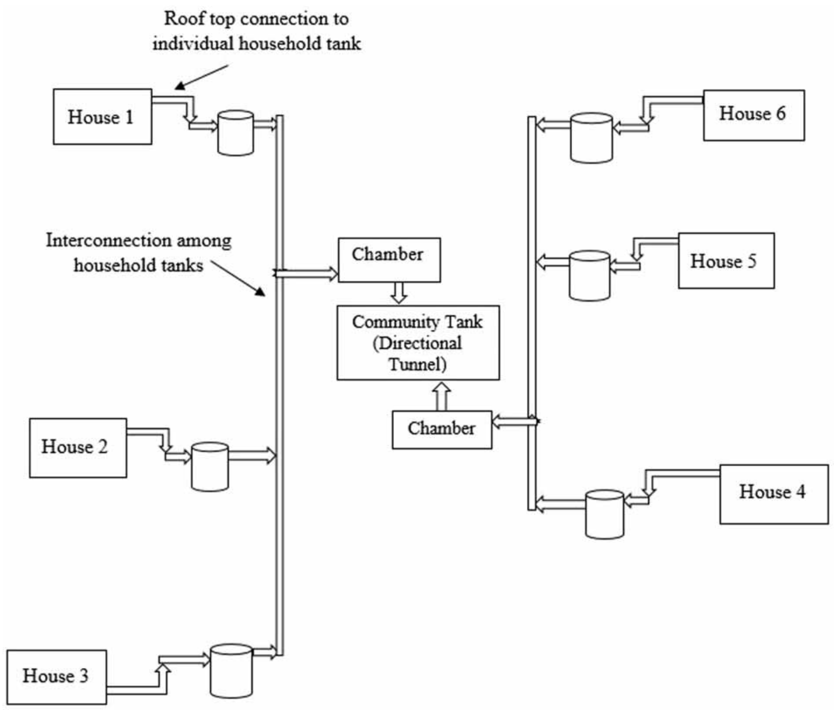

Figure 2 | Setup for rural community water management.

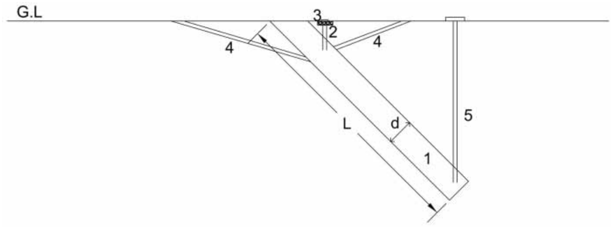

Figure 3 | Rainwater harvesting in directional tunnel. 1 – Water storing directional tunnel 2 – Inlet pipe from runoff 3 – Water filter at runoff inlet 4 – Multiple inlets from individual household tanks 5 – Outlet pipe. L – Length of the directional tunnel, d – diameter of the directional tunnel.

and runoff water near the location of the community tank. A filter is placed at the inlet pipe used for accumulating clean water (Figure 3).

MATERIALS AND METHODOLOGY

In order to obtain and understand the benefits as well as practical challenges of the directional tunnelling method, the current research work carried out a case study with the application of BIM in a rural scenario. The physical struggle by the water carriers in a family can be reduced by the proposed water management plan in any rural area by focusing on a selected community. Before the on-site construction, the concept of BIM was taken into effect, and the whole rural water management setup was modelled. Adoption of compatible software for modelling rural environment is a crucial factor in a case study. Autodesk Infraworks, a BIM tool supported by Autodesk, was undertaken for the visual modelling of infrastructure, site location and roads for the creation of Worcester Polytechnic Institute 3D campus (Ozcan-Deniz 2016). Likewise, Autodesk Infraworks was selected for the

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scope of visual modelling incorporating the surrounding environment, boundaries and limitations of a structure's occupancy in the current research work. The entire visual modelling of rural community water management, including the directional tunnel, was performed using AutoCAD 3D and Autodesk Infraworks software.

Determination of the size of rainwater tanks takes the initial step in modelling. The tank, after its size determination, must serve for regular water supply so that the structure behaves like a resource across seasons (Jung *et al.* 2014). Rainwater tanks in individual houses are dependent on the efficiency of collection, type of catchment, connected devices, and amount of rainfall (Mukheibir *et al.* 2014). The capacity of individual household tanks was determined based on these dependent factors. The size of the tank was determined by considering the rainwater harvesting guidelines. Equation (1) (India Water Portal 2006) used in determination of the volume of the tank (V) is

$$V = \text{Roof area} \times \text{total annual rainfall} \times \text{Runoff coefficient} \tag{1}$$

Considered data: As per the selected twenty-five individual houses in the community, the dimensions of all the roofs were calculated. The average roof area determined was 54 m^2. The nearest rainfall data station – Surajgarh – was taken in to effect for total annual rainfall as 0.452 m (Water Resources Department – Rajasthan 2019). Runoff coefficient was taken as 0.8 for roof type of tile/corrugated metal (Central Pollution Control Board – ENVIS 2016). A calculation of volume for an individual household tank was performed (Table 2).

Table 2 | Volume calculation for individual household tank

Roof area (m^2)	54
Total annual rainfall (m)	0.452
Runoff coefficient	0.8
Volume of an individual household tank (V) (m^3)	19.526

The volume of the individual household tank was finalised to accommodate 20 m^3 of stored rainwater. The shape of the tank was fixed to be cylindrical with a diameter of 3.05 m and height of 3.05 m. Equation (2) (Central Pollution Control Board – ENVIS 2016) was used in the determination of the volume of the directional tunnel (V_1)

$$V_1 = \text{Dry season} \times \text{No. of people using tank} \times \text{Per capita per day consumption} \tag{2}$$

Considered data: A minimum number of the dry season or water-scarce days for the people in the community was taken as 30. A total number of 100 people was considered for using the directional tunnel as a water source and minimum per capita water consumption of 0.05 m^3 on an insufficient water day for drinking, cooking and limited activities. A calculation of the volume for the directional tunnel was performed (Table 3).

Table 3 | Volume calculation for directional tunnel

Dry season (Number of days)	30
No. of people using tank	100
Per capita per day consumption (m^3)	0.05
Volume of directional tunnel (V_1) (m^3)	150

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The directional tunnel model was planned to hold a volume of 150 m^3 as it could provide water to the selected community in the village, which comprised approximately 90–100 people. Hence, dimensions were finalised as 3.05 m diameter, 21.34 m length and with an angular value of 45°. Individual household tank (Figure 4) and directional tunnel (Figure 5) 3D models were created in AutoCAD 3D modelling.

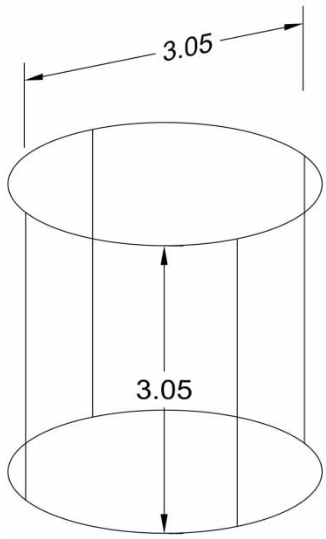

Figure 4 | Individual household tank (all dimensions are in metres).

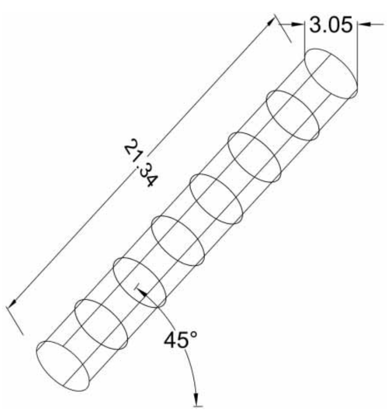

Figure 5 | Directional tunnel (community tank). All dimensions are in metres.

Autodesk Infraworks: The primary idea behind using Autodesk Infraworks was for the establishment of a real-world atmosphere of the whole rural community water management. Visualisation and creation of the selected village, Ramnathpura, were performed in Autodesk Infraworks. The models developed in AutoCAD were used in the formation of visualisation of the rainwater harvesting system in Autodesk Infraworks. The visualisations involved the development of the whole community's scenario in the village, integrating features like roads, vegetation and boundary limits. Later, modelling with respect to the connections between individual household tanks and the directional tunnel was carried out.

With the completion of visual modelling for the entire rainwater harvesting system of the community, on-site construction of the proposed plan commenced. Since glass fibre was selected as the primary material for individual household tanks and the directional tunnel, the raw materials used for GRP water tanks were glass fibre sheets, epoxy resin and hardener. The first step involved was

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the preparation of a wooden dye. After the preparation of the dye, glass fibre sheets were stacked in 3 layers and coated with an epoxy resin and hardener mixture in the hand lay-up process in a mix ratio of 10:1 respectively. Simultaneously, the base and roof of the tank were also prepared of the same material composition. After all the parts were prefabricated separately, the GRP panels were assembled altogether at the site area (Figure 6). The final GRP water tank had a thickness of 0.495 m (Figure 7). Later, water was filled in the tanks to test for any leakages or defects. Once the GRP water tank was identified as in a perfect condition, installation of tanks below the ground level followed. The tank was placed 2.45 m below the ground level (Figure 8).

With the help of gutters and downspouts, rooftop connections were made for the free flow of rain-water to the individual household tank. First flush connection was integrated into the individual household tanks, since it has the advantages of collecting settleable solids, debris and improving

Figure 6 | Assembling GRP panels.

Figure 7 | Final GRP water tank.

Figure 8 | Complete tank after placing.

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the water quality through rooftop rainwater connections (Stump *et al.* 2012). After the construction and installation of 25 GRP water tanks at individual houses, the installation of the directional tunnel was carried out. The material and method adopted for the directional tunnel were similar to those of individual household tanks. Therefore all the GRP panels were prefabricated and assembled at the worksite. The joints between the panels were covered with glass fibre sheets, and a total of seven individual GRP water tanks were connected in series to form a directional tunnel structure to hold a volume of 150 m^3 of harvested rainwater (Figure 9). The final directional tunnel had parameters of 3.05 m diameter and 21.34 m length (Figure 10). Subsequently, the interconnection of pipes among the individual GRP water tanks was done. Excavation for pipelines was done to a depth of 0.6 m. Finally, all the pipeline connections were joined to individual masonry chambers, and three inlets were connected to the directional tunnel for the excess rainwater in individual GRP water tanks to flow and reach the directional tunnel.

Figure 9 | Assembling GRP panels of the directional tunnel.

Figure 10 | Final directional tunnel.

RESULTS AND DISCUSSION

Simple methods or techniques can be implemented with minimum efforts. But the application of new technology requires a better understanding for its practical execution. The current research work applied BIM tools for better understanding of the unique method; that is, directional tunnelling's enforcement in the practical world. As a part of the feasibility study, multiple field visits were conducted to identify suitable locations in the village. Consequently, all the probable places for individual household tanks and directional tunnel were identified, and distances were measured. Since the directional tunnelling method for rainwater harvesting was a creative technique, modelling and visualisations were performed for the villagers and stakeholders to be involved in the execution. Individual consent from the selected house participants was very much required. After modelling the whole rainwater harvesting

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system of the community, a flythrough model video was rendered. The video was communicated to all the users regarding rainwater harvesting, highlighting interconnection among individual household tanks (Figure 11(a)) and directional tunnel connection (Figure 11(b)). Representation of the rainwater harvesting system made the users perceive the working system and resulted in their clearance. The environment surrounding the selected community in the village, the interconnection of individual household tanks and directional tunnel were the main constraints considered, whereas any users' houses and any temporary structures were not considered, during modelling. In the visual modelling of the rainwater harvesting system, to maintain water level balance in the masonry chambers, it is assumed that the surface level for all masonry chambers near the directional tunnel is the same.

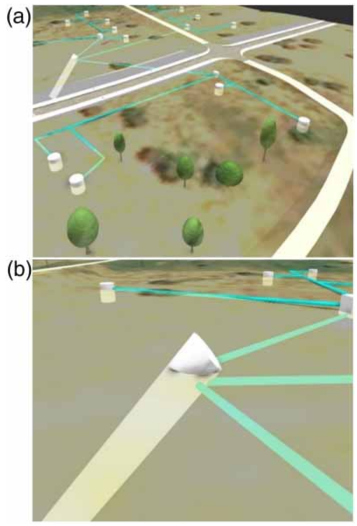

Figure 11 | (a) Flythrough model – interconnection among individual household tanks. (b) Flythrough model – directional tunnel connection.

The construction of GRP water tanks was followed with the principle of prefabrication. The selected village was situated at a distant location from the fabrication workshop. Ambiguity over the process of assembling the GRP panels existed among the labour. The erection of GRP panels (Figure 12) was performed to form a cylindrical shape for rainwater harvesting tanks and shared with the mason. It produced the successful outcome of preparing GRP water tanks at the construction site. With the experience of GRP water tanks, installation of the directional tunnel was done. Significant time-saving in the construction was observed.

The selection of the type of raw material for the concept of rural community water management is open to any kind of material. The selection of glass fibre in the current case study was highly

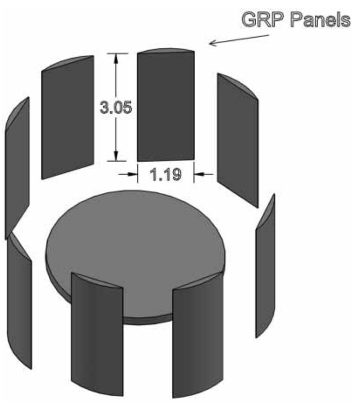

Figure 12 | Erection of GRP panels (dimensions are in metres).

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dependent on factors like availability and cost efficiency from the vendors. Of equal potential, another alternative to glass fibre sheets is carbon fibre sheets, but they are quite expensive.

The practical challenge was the implementation of the whole research work on site. The inner joints of the directional tunnel and individual GRP water tanks were covered with layers of glass fibre sheets; as a result, water leakages were controlled. The outer vertical joints between the panels were also firmly sealed. Minor leakages from the walls of the GRP water tanks were resolved by the external and internal application of epoxy resin – hardener mixture coats. Since twenty-five families were involved as a part of the case study, difference of opinion arose during directional tunnel installation and utilisation. Flooding in the low-lying areas was avoided because of the whole facilitated system. No regular maintenance was required as filters were part of the rainwater harvesting system. Reliance on groundwater, and external water sources, was prevented since the groundwater table is depleted and the people in the community drew water from individual household tanks and directional tunnel depending on the requirement in case of water inadequacy. The aim to store a large capacity of rainwater with minimum space occupancy was achieved. A significant limitation observed in the directional tunnel was the increment of water storage beyond its fixed size since the demand for water might increase in a community depending on the increase in population as well as the number of water-deficient days.

CONCLUSION

Availability of water is becoming limited with the rise in population across countries. Consequently, water-saving methods have gained importance. Rainwater harvesting is one of the most viable water-saving techniques. Numerous rainwater harvesting techniques have been followed in India. The novel approach of directional tunnelling for community water management discussed through current research is in use at the community in Ramnathpura, India, and it has not been implemented anywhere else. The directional tunnel is intended to save rainwater for multipurpose water-related activities besides drinking purposes, with a total storage capacity up to $150\,m^3$. Coordination among users was highlighted to the villagers. Even though the method of directional tunnelling in the current research work is discussed via a case study of a rural aspect, the authors recommend its future scope in urban areas if the primary condition, like space for the structure's occupancy, is met. Rainwater harvesting through a directional tunnel in urban communities requires a collaborative effort from all participants. Moreover, cities are prone to severe air pollution and may further cause water pollution. Considering these valid constraints, the process of directional tunnelling can be adopted in urban communities.

The advent of new technologies in rural areas is limited, and the current research work portrayed BIM as the solution as the visualisation tool for rural community water management before its on-site execution. The process of prefabrication, assembling of GRP panels, and rendering of flythrough videos turned out to be successful outcomes in making users accept the implementation of the method and labour in the faster execution of work. Future scope of research work can be focused on the different types of rainwater harvesting structures resulting in rural community water management from the current research findings.

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results, discussions and conclusions conveyed through this research are those of the writers and do not implicate the opinions of the Department of Science and Technology, India.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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