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Innovative Strategy for Rainwater Harvesting in Saline-affected Urban Areas: A Case Study of a Sports Complex in Delhi

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Abstract: Water scarcity remains a critical global challenge, requiring immediate, sustainable management strategies, particularly in areas with an increasing disparity between water supply and demand. In India, and especially in Delhi, this issue is acute. In response to growing environmental concerns and the urgent need for sustainable water resource management, rainwater harvesting has emerged as a practical and effective solution for water conservation. This study investigates the application of rainwater harvesting to sustainably support water needs for a sports complex located in a salinity affected region. The land, originally intended for agriculture, has been converted into a complex featuring hydro-landscape facilities, including swimming pools, water polo areas, diving pools, toddler pools, and leisure pools. These facilities require an initial water input of 6,754.5 m³ and an annual replenishment of 7,957.28 m³ due to evaporation and seepage. By calculating the total rainwater harvesting potential based on the runoff coefficient, annual rainfall intensity, and the complex's catchment area, the study reveals that 29,693.8 m³ of rainwater can be harvested annually, providing a surplus of 14,981.7 m³ of potable water. This analysis demonstrates the viability of designing sports complexes in saline areas using efficient land use and rainwater harvesting, and presenting a scalable model for sustainable water management in similar regions worldwide.

Keywords: Rainwater harvesting, management techniques, sports complex, water management, saline region.

Introduction

Water is essential for human health, regulating body temperature and supporting crucial physiological functions, yet only 2.5% of the Earth's water is freshwater, with most locked away in glaciers and ice caps, leaving limited amounts accessible for human use (Semertzidis, 2019). Groundwater, which comprises nearly 90% of the world usable freshwater, is a critical resource, however, overexploitation is an escalating global issue (Shiklomanov & Rodda, 2003). Northern India, particularly Delhi, is at the centre of this crisis (NGRI, 2019). The challenges in groundwater management are especially pronounced in Delhi’s Rohini sub-city, where rapid urbanization, industrial growth, and limited natural recharge contribute to declining groundwater tables and increasing salinity (Mallick et al., 2015). These issues are further compounded by extensive construction activities that strain local water resources, resulting in severe water scarcity, particularly during the summer when demand peaks, and public supplies become insufficient. Reports from the New Delhi Municipal Council and the Delhi Jal Board highlight the acute shortages faced by residents of Begumpur in Rohini, underscoring the urgent need for innovative water management solutions (Ghosh, 2021). Rainwater harvesting (RWH) has thus emerged as a sustainable approach that addresses water scarcity, reduces dependency on traditional sources, and mitigates the flood risks (Waseem & Leta, 2023). RWH offers benefits that extend beyond immediate water availability. It captures storm water that would otherwise contribute to runoff, reducing urban flooding and conserving essential water resources (Walia et al., 2024). Techniques like rooftop collection systems, which capture rainwater from buildings for filtration and storage are widely used, as are surface runoff harvesting enhanced by contour farming and bunds that facilitate water capture on land surfaces. Infiltration pits also allow rainwater to percolate into the ground, which recharges aquifers and improves groundwater quality, a particular advantage in regions affected by high salinity (Mane, 2014). In urban areas such as Rohini, where reliance on municipal water supplies is significant, RWH has the potential to reduce demand by up to 60% (Zdeb et al., 2018). Additionally, RWH contributes to groundwater quality improvement through aquifer recharge, which is especially crucial in saline-affected areas like Rohini (Bhattacharya & Rane, 2009). This approach conserves the energy required for water treatment, reducing the need for extensive processing, and also promotes ecological stability by mitigating runoff and enhancing natural water reserves (Garcia et al., 2015). The relevance of RWH to mitigate groundwater salinity issues in urbanized areas like Delhi is particularly significant due to factors like urban sprawl, waste disposal, and agricultural runoff, which have resulted in contamination. In locations such as Okhla and

Bhalswa, landfill leachate has caused high levels of chloride and sulfate in groundwater, posing a major threat to water quality (Angmo et al., 2021).

Excessive groundwater extraction further exacerbates this issue by drawing saline water from deeper aquifers into freshwater zones, leading to a progressive decline in water quality. Traditional water management practices have proven inadequate in combating these issues, creating an urgent need for solutions like RWH, which reduce salinity intrusion, while providing potable water that meets drinking standards (Mosti et al., 2004; Bocanegra et al., 2014; Taffere et al., 2016). Numerous studies have demonstrated the feasibility of RWH across various contexts, from agriculture to urban settings, establishing it as an effective and sustainable solution for water-stressed regions like Delhi (Bhatt, 2016). Despite India's relatively high annual rainfall, urban areas like Rohini still experience chronic water shortages due to unpredictable monsoon timing and waterlogging from heavy rains, complicating water management (Bhatt, 2016).

A well-organized RWH strategy could alleviate these issues by storing water during times of abundance and distributing it during periods of scarcity, positioning RWH as a key approach to address both water scarcity and salinity in the region. RWH can significantly contribute to water security by providing a local, renewable water source that lessens reliance on distant reservoirs and complex infrastructure. This local source stabilizes groundwater levels, benefiting both communities and ecosystems that depend on these resources. Nonetheless, the broader adoption of RWH is not without challenges. High initial costs for setup, ongoing maintenance, and limited public awareness of the benefits are key barriers that must be overcome to fully realize the potential of RWH systems (Rekha, 2002; Mane, 2014). Although rooftop RWH systems can offer a reliable water source, installation requires skilled labour, materials, and financial investment, which can deter widespread adoption, particularly in economically strained communities.

Moreover, limited awareness of RWH's long-term benefits often results in underutilization, even in water-scarce regions. Public engagement and incentives could therefore play a critical role in fostering greater acceptance of RWH in densely populated areas like Rohini. Unlike traditional water management systems, which often exacerbate water scarcity and flooding due to reliance on centralized, large-scale infrastructure, RWH offers a decentralized, community-based approach essential for achieving water security amid climate change and urban expansion (Waseem & Leta, 2023). Conventional systems have historically failed to provide reliable solutions in rapidly urbanizing areas, as they lack the flexibility to address the specific and localized needs of diverse communities. In contrast, RWH can be tailored to meet the requirements of households, neighbourhoods, or even entire urban district, offering an adaptability that large-scale systems often lack. As climate change drives more extreme weather patterns, with intense rainfall events followed by dry periods, RWH's dual role in flood mitigation and drought relief becomes increasingly critical. By capturing rainwater at its source, RWH reduces runoff during heavy rains, helping to prevent flash flooding, creates reserves for dry periods, and enhances resilience to climate variability.

The implementation of RWH could also support broader environmental goals, such as reducing the urban heat island effect. Retaining more water within urban landscapes can cool local temperatures, a particularly relevant factor in cities like Delhi, where rapid urban expansion has led to significant changes in land use and surface characteristics, exacerbating heat waves and reducing green spaces. RWH systems, by encouraging the natural infiltration of rainwater into the soil, help to restore ecological balance lost to urban development. In nutshell, RWH presents a substantial potential to address water scarcity and salinity challenges in Delhi’s Rohini region and similar urbanized areas. By alleviating pressure on municipal water supplies, enhancing groundwater quality, reducing flood risks, and promoting ecological stability, RWH represents a forward-looking approach to urban water management. Overcoming barriers such as high initial costs, maintenance requirements, and limited public awareness will be essential to maximize the benefits of RWH systems (Martínez et al., 2014). Addressing these challenges requires coordinated efforts from government agencies, local authorities, and communities to create a comprehensive RWH strategy that is economically viable and sustainable over the long term. By integrating RWH into the broader water management framework, Delhi can take meaningful steps toward securing a stable water future, enhancing resilience to climate impacts, and fostering ecological sustainability in rapidly urbanizing regions like Rohini.

Area of Study

The area of study is a sports complex Rohini that lies in northwest district of Delhi. The sports complex is located at latitude of 28.72831^{o} N and longitude 77.07521^{o} E (Fig. 1). Groundwater level in Rohini has significantly lowered in recent times due to excessive private and government groundwater extraction. The resulting depletion of the freshwater layer, coupled with an inadequate public water supply system has led to increasing salinity in most areas, rendering the groundwater unsuitable for domestic use. This poses concerns about water quality and future water supply. In response, exploring alternative sources, such as rainwater harvesting is crucial to address the pressing water scarcity issues in Rohini sub-city.

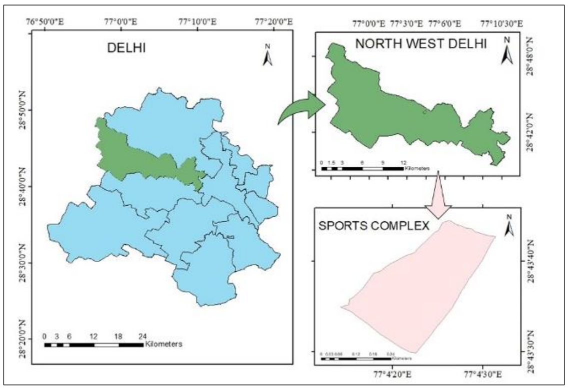

Fig. 1 Study area map.

The sports complex Centre of excellence was proposed by Delhi Development Authority to meet the demand of sports fans and prospective athletes. This Centre, which covers an area of 82000 m^2, will offer a full range of sports facilities (DDA, 2022). Various water bodies have been suggested for the sports complex including swimming pools, toddler pools, leisure pools and diving pools etc. The sports complex has got the land use pattern which consists of green lawn, lawn tennis courts, jogging track, volley ball court, cricket ground, cricket practice pitch, hockey cum football ground, skating rink, basketball courts, aquatic complex, open air theatre, solid waste management plant and golf cart parking shed etc. Rohini sports complex comprises of swimming pool complex (toddler pools, leisure pools and diving pools etc.), cricket ground, practice pitches, hockey cum football ground, lawn tennis courts, basketball courts, net ball courts, volley ball courts, skating rink, open air theatre, nursery, golf cart parking, jogging track parking, pavilions with maintenance offices, toilets, and SWM unit (Fig. 2).

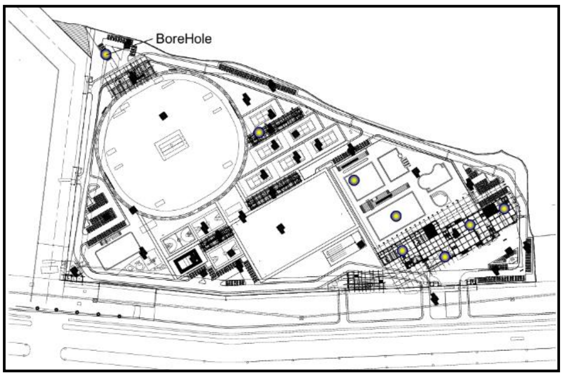

Fig. 2 Landuse plan of the sports complex.

The average rainfall in the study area is about 800-900 mm per year (Rajput et al., 2023) with the humidity varying from 40% to 80% (Das, 2015) and temperature variation from 5ºC to 45ºC (Rajput et al., 2023), evaporation recorded as 1.5 m and specific yield varies in the study area from 10% to 20% (Das, 2015). Ground water occurs in alluvial sand, silt and gravel comprising potential aquifer zones. Only in small patches around the study area, water table is deeper having range of 10m to 20m. Water table elevations range from 180 to 190 m and the general ground water flow is from northwest to southeast. In general, the water table has declined all over the district over the past decade, as the study area has recorded a fall in water table of about <1m to 7m, with 2 to 4m decline in most parts of the study area (IMD, 2015; CGWB, 2021-2022).

The area of the proposed sports complex is a low-lying area which was filled with water during the field work. The difference in road level is about 3m. Some portion of the area was filled for construction of road. Since it was not possible to make bore holes on flooded water, it was taken where the filling was done. Eight bore holes, each 15m deep were marked, and the samples taken verified that the filled-up strata existed up to 3.5m depth (Fig.3).

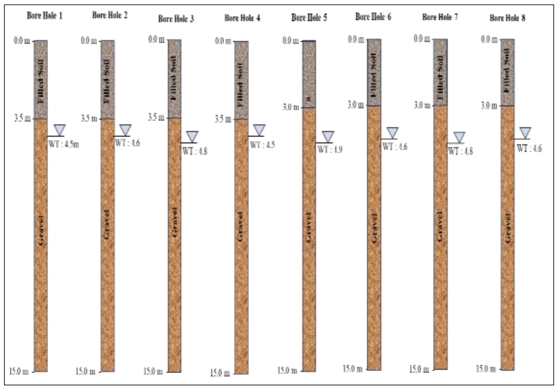

Fig. 3 Soil profile of boreholes in study area.

Below 3.5m depth, silt sand with gravel has been found till the depth of exploration. Water table was encountered in the bore hole at 4.5m to 4.9m depth (Fig.3).

Materials and Methods

In this study, the rainwater assessment and utilization methodology were implemented through a series of specific steps tailored to the study area. Initially, a detailed survey was conducted to accurately measure the surface areas of distinct features, including rooftops, roads, water bodies, pathways, horticultural areas, flooring, and lawns within the designated region. This meticulous measurement was crucial for obtaining precise data on the available surfaces for potential rainwater harvesting. Subsequent to surface area determination, runoff coefficients were specifically assigned to each type of surface. These coefficients were selected based on the permeability and other relevant characteristics of the surfaces (Donahue, 2013), reflecting the fraction of rainfall expected to transform into runoff (Table 1).

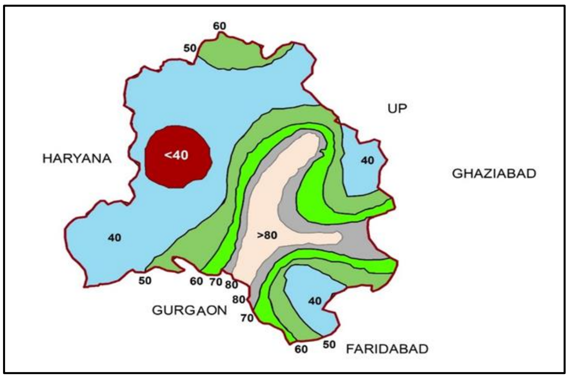

Fig. 4 Isohytal map showing annual average rainfall of Delhi (cm).

Subsequently, the design incorporated monthly rainfall intensity data, drawing insights from existing literature and IMD reports to gain a specific insight into anticipated precipitation levels. The Isohytal map, Figure 4 was plotted by ArcGIS 10.8.1 delineating the lines of equal rainfall, providing crucial spatial information for understanding precipitation patterns across the areas in the capital city Delhi. It was concluded that Delhi receives an approximate annual precipitation of 794 mm, with 81% concentrated in the monsoon months spanning from June to September (Taffere et al., 2016). The monthly rainfall values utilized for design considerations are illustrated in Figure 5.

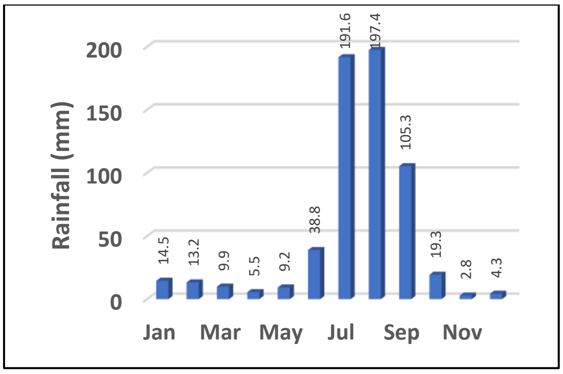

Fig. 5 Monthly rainfall intensity of Delhi (Mandal et al., 2010).

The heart of the methodology involved the application of the formula "Q = C * I * A" (Burra & Reddy, 2021) to calculate the monthly and annual rainwater harvest for each specific surface. In this formula, 'Q' represented the harvested rainwater, 'C' denoted the runoff coefficient, 'I' stood for monthly rainfall intensity, and 'A' represented the surface area. This quantitative calculation provided a detailed breakdown of the potential rainwater harvest from each surface throughout the study period. The rational method was selected as it best suited the monthly rainfall data provided by the Indian Meteorological Department (IMD). It assumes that rainfall is uniformly distributed across the catchment, incorporates all rainfall abstractions into a runoff coefficient, and presumes that the rainfall event duration meets or exceeds the catchment's time of concentration (Chin, 2019). Following this, evaporation losses in various water bodies were calculated, considering local environmental conditions affecting water evaporation rates. To mitigate these losses, the harvested rainwater was strategically utilized, acting as a compensatory mechanism to maintain water levels in the identified bodies. Additionally, surplus rainwater was directed to purpose-designed storage tanks, ensuring the efficient capture and storage of excess rainfall. This storage approach served as a proactive measure to guarantee a reserve of water for future use, particularly during periods of diminished rainfall when water demand could surpass natural supply.

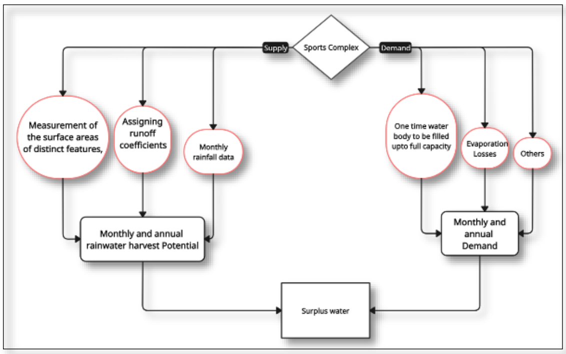

Fig. 6 Flow chart of the method adopted for design.

The final stage involved calculating drinking water availability, considering factors such as the quality of harvested rainwater, the storage capacity of tanks, and the localized demand for potable water. This site-specific methodology not only assessed and harvested rainwater but also aimed to ensure the sustainability and optimized utilization of water resources in the unique context of the study area.

Results and Discussion

Assessing the feasibility and designing a rainwater harvesting system for the sports complex involved evaluating the water requirements of the complex, and calculating the water potential that can be effectively collected from various surfaces available. This mainly considered potential benefits and site-specific factors. Design phase involved factors such as rainwater harvesting structure, evaluating total surplus volume in peak months and storage tanks for the sports complex (Fig. 6).

Table 1. Runoff coefficients used for various types of surfaces ((Donahue, 2013).

Type of surface	Roof top area	Roads	Water body	Pathways	Horticulture part	Synthetic flooring	Concrete flooring	Tile paving	Lawn Area
Runoff coefficient	0.9	0.8	1	0.7	0.3	0.95	0.9	0.7	0.3

Table 2. Monthly rainwater harvest potential of various surfaces.

Type of surface	**Area (m^2)**	**Runoff coefficient**	**Monthly Harvest (m^3)**												**Annual Harvest (m^3)**
			Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	
Roof top area	7830	0.9	102.2	93.0	69.8	38.8	64.8	273.4	1350.2	1391.1	742.0	136.0	19.7	30.3	4311.4
Roads	12133	0.8	140.7	128.1	96.1	53.4	89.3	376.6	1859.7	1916.0	1022.1	187.3	27.2	41.7	5938.4
Water body	3066	1	44.5	40.5	30.4	16.9	28.2	118.9	587.4	605.2	322.8	59.2	8.6	13.2	1875.6
Pathways	8793	0.7	89.2	81.2	60.9	33.9	56.6	238.8	1179.3	1215.0	648.1	118.8	17.2	26.5	3765.7
Horticulture	12597	0.3	54.8	49.9	37.4	20.8	34.8	146.6	724.1	746.0	397.9	72.9	10.6	16.3	2312.1
Synthetic flooring	7814	0.95	107.6	98.0	73.5	40.8	68.3	288.0	1422.3	1465.4	781.7	143.3	20.8	31.9	4541.6
Concrete flooring	879	0.9	11.5	10.4	7.8	4.4	7.3	30.7	151.6	156.2	83.3	15.3	2.2	3.4	484.0
Tile paving	4824	0.7	49.0	44.6	33.4	18.6	31.1	131.0	647.0	666.6	355.6	65.2	9.5	14.5	2065.9
Lawn Area	23969	0.3	104.3	94.9	71.2	39.5	66.2	279.0	1377.7	1419.4	757.2	138.8	20.1	30.9	4399.3
Total			703.8	640.7	480.5	266.9	446.5	1883.2	9299.3	9580.8	5110.8	936.7	135.9	208.7	29693.8

Table 3. Monthly evaporation losses of various surfaces.

Type of surface	**Area (m^2)**	**Depth (m)**	**Free Board (m)**	**Volume (m^3)**	**Monthly Loss (m^3)**												**Annual Loss (m^3)**
					Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	
Water polo	750	2	0.3	1275	53.3	82.5	132.8	225.0	300.0	249.8	174.8	99.8	110.3	111.8	76.5	58.5	1674.8
Diving pool	750	5	0.3	3525	53.3	82.5	132.8	225.0	300.0	249.8	174.8	99.8	110.3	111.8	76.5	58.5	1674.8
Leisure pool	466	1.2	0.3	419.4	33.1	559.2	82.5	139.8	186.4	155.2	108.6	62.0	68.5	69.4	47.5	36.3	1548.5
Swimming pool	1249	1.5	0.3	1498.8	88.7	137.4	221.1	374.7	499.6	415.9	291.0	166.1	183.6	186.1	127.4	97.4	2789.0
Toddlers pool	121	0.6	0.3	36.3	8.6	13.3	21.4	36.3	48.4	40.3	28.2	16.1	17.8	18.0	12.3	9.4	270.2
Total				6754.5	236.9	874.9	590.5	1000.8	1334.4	1110.9	777.3	443.7	490.4	497.1	340.3	260.2	7957.2

Table 4. Monthly fluctuation of water level in water bodies and makeup tank.

Month	Evaporation losses (m^3)	Monthly Rain water (m^3)	Water in Water bodies (m^3)	Water in makeup tank (m^3)	Height of water (m)
January	236.9	703.8	6517.6	14408.2	5.8
February	874.9	640.7	5879.6	14174.0	5.7
March	590.5	480.5	6164.0	14064.0	5.6
April	1000.8	266.9	5753.7	13330.1	5.3
May	1334.4	446.5	5420.1	12442.3	5.0
June	1110.9	1883.2	5643.6	13214.6	5.3
July	777.3	9299.3	5977.2	14982.1	6.0
August	443.7	9580.8	6310.8	9137.2	3.7
September	490.4	5110.8	6264.1	13757.5	5.5
October	497.1	936.7	6257.4	14197.2	5.7
Nov	340.3	135.9	6414.2	13992.8	5.6
Dec	260.2	208.7	6494.3	13941.3	5.6

The study utilized a basic rational method formula to calculate rainfall potential, where the monthly rainwater potential of a surface is determined by multiplying the runoff coefficient of that surface, monthly rainfall intensity, and the area of the specific region. The calculated potentials for different surfaces within the sports complex are presented in Table 2. Additionally, the study encompassed the examination of the evaporation losses to enhance the system's efficiency (Bhimala et al., 2023). Apart from the initial water bodies' single filling, the focus of the study was on addressing losses as the primary requirement, which could be offset by the monthly rainfall potential gathered from diverse surfaces within the sports complex.

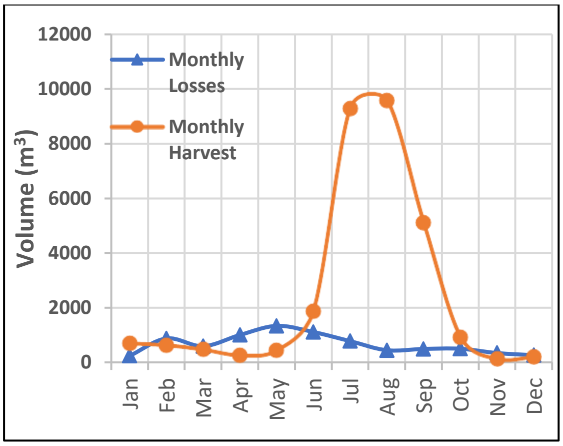

Fig. 7 Monthly rainwater harvest and evaporation losses.

Table 3 outlines the evaporation losses taken into account for various surfaces in the complex. Seepage losses in water bodies with liners are minimal and can be disregarded. The fluctuations in water levels within these bodies are mainly attributable to evaporative losses. To counteract these fluctuations, rainwater can be effectively employed. Systems for harvesting rainwater can gather and store rainfall, offering a solution to replenish pool water. By channelling rainwater runoff from rooftops or designated catchment areas, it can be directed to the water bodies to refill and maintain the preferred water level. The system has an annual harvest potential of 29,693.4 m^3 and experiences annual losses of 7,957.2 m^3 from the water bodies (Fig. 7). Additionally, the water bodies need to be filled once a year to their full capacity, which is 6,754.5 m^3. Once filled, the only ongoing demand is to compensate for the losses in the water bodies. Therefore, a makeup tank designed to compensate for losses or adjustments in a system is suggested. The volume of water to be adjusted in the makeup tank will be 14981.7 m^3.

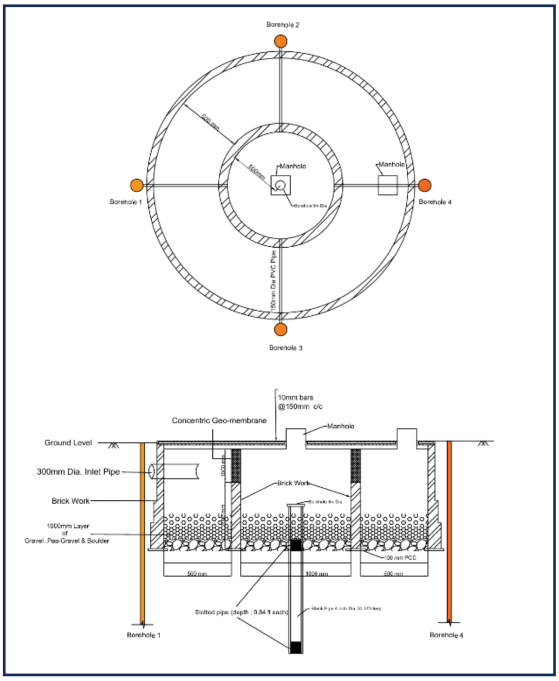

Fig. 8 Suggested rainwater harvesting structure.

For design purpose, considering a single makeup tank with an effective depth of 6 m and a cross-sectional area of 2497 m^2 was considered. Since the area of make tank seems to be very large, therefore practically instead of giving a single majestic tank, several small makeup tanks with 6m depth each and a total effective area of 2497 m^2 were suggested (Fig.8). Commencing the design phase in August, the variations in water levels within the water bodies and the makeup tank were determined (Table 4). July marks the final month of the process, during which each water body is emptied and undergoes cleansing, and refilling, including the makeup tank.

Conclusion

This investigation has identified significant challenges within a sports complex in a semi-arid region, where rapid urbanization, excessive groundwater extraction, and limited natural recharge have caused a steep decline in the water table. This reduction in groundwater has led to low soil moisture levels, creating a dry, nutrient-deficient environment that hinders vegetation growth. Compounding these issues is the absence of a rainwater harvesting system, which has restricted effective groundwater recharge, leaving the soil critically low in both macro-nutrients, such as organic carbon, phosphate, and nitrogen, and micro-nutrients like boron, zinc, cadmium, and copper. To address these challenges, this study proposes a comprehensive approach designed to optimize rainwater harvesting and improve overall water management within the complex.

By implementing this strategy, the complex is expected to generate a surplus water supply sufficient for diverse on-site needs, significantly enhancing its sustainability and functionality. This approach not only offers an effective solution for this sports complex, but also presents a replicable model for sustainable water management in similar high-demand areas across India. Future research could build on this approach by using advanced simulations and exploring alternative system designs to further enhance rainwater collection and sustainable water use.

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