

A design plan for rooftop rainwater harvesting in a large defence establishment in central India



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ABSTRACT

Water scarcity in India is impending with the gap between population rise and water demand widening at an alarming rate. Prompt action is imperative to mitigate the malady and make the country liveable. Rooftop rainwater harvesting is an option that can arrest India's declining trend of groundwater levels if implemented in mega-scale countrywide. There are innumerable feasible structures with large roof areas that could be used to harness rainwater. Large building complexes, such as those of ordnance factories, industrial buildings, military barracks, etc., are the ideal sites where huge bulk of water can be injected underground through rooftop rainwater harvesting. An attempt has been made in this contribution to propose a design plan for rooftop rainwater harvesting at the Gun Carriage Factory, Jabalpur, India, that has a large network of connected buildings. About half of these buildings numbering about 16 with a roof area of 60,062 m² were examined from feasibility perspective. These buildings together can harness about 59,671 m³ of rainwater at a rate of about one m³ of water for one m² of roof area. Calculations with design plans were made for each of these buildings. It was advisable for some of the buildings to have combined harvesting systems due to their locational proximity. Similar approach could be adopted in the innumerable *pucca* buildings across India in massive scale to at least partially eradicate the impending water crisis the country is likely to face in the years to come.

1. Introduction

India is fast approaching to become a water-scarce country by 2050 [1]. From per capita annual water availability of 5177 m³ in 1951, the availability has now reduced to less than 1700 m³ per person per year making it a water-deficient country. By 2050, this availability may further reduce to around 1140 m³ per person annually compelling India to experience an emergency due to severe water scarcity. Falkenmark water stress indicator points out that a country faces water crisis when its per capita availability falls below 1000 m³ per year [2]. Therefore, with a crisis-like situation lurching ahead in two decades from now, it is time that every citizen of India tries to conserve as much water as possible to augment the natural storage of water.

India receives 4000 billion cubic metres (BCM) of rainwater on annual basis. Out of this, 1869 BCM (47%) flows as surface runoff and 1121 BCM is utilizable resources of which 685 BCM is surface water and

436 BCM is groundwater [3]. To make the water resources sustainable, the Federal and all State Governments have been trying hard to harness as much surplus surface runoff as possible to augment the natural groundwater recharge through several sponsored schemes.

Central Ground Water Board [1] estimates that about 717 BCM of rainwater is required to bring the groundwater levels to 3 to 5 m below the ground from abysmally low levels found in many pockets of the country at present, especially in north-western India. It is envisaged that India shall be making 14.18 million structures in the coming few years with a budgetary provision of about 1335.3 billion Indian rupees (i.e., US \$16.10 billion) [1]. Of these structures, about 10.61 million structures are meant for rooftop rainwater harvesting, especially in urban areas.

In fact, India is fast getting urbanized with about 495 million people (35%) living in urban agglomerates in 2021 [4]. The urban population is projected to grow to about 600 million people (40%) by 2031 and

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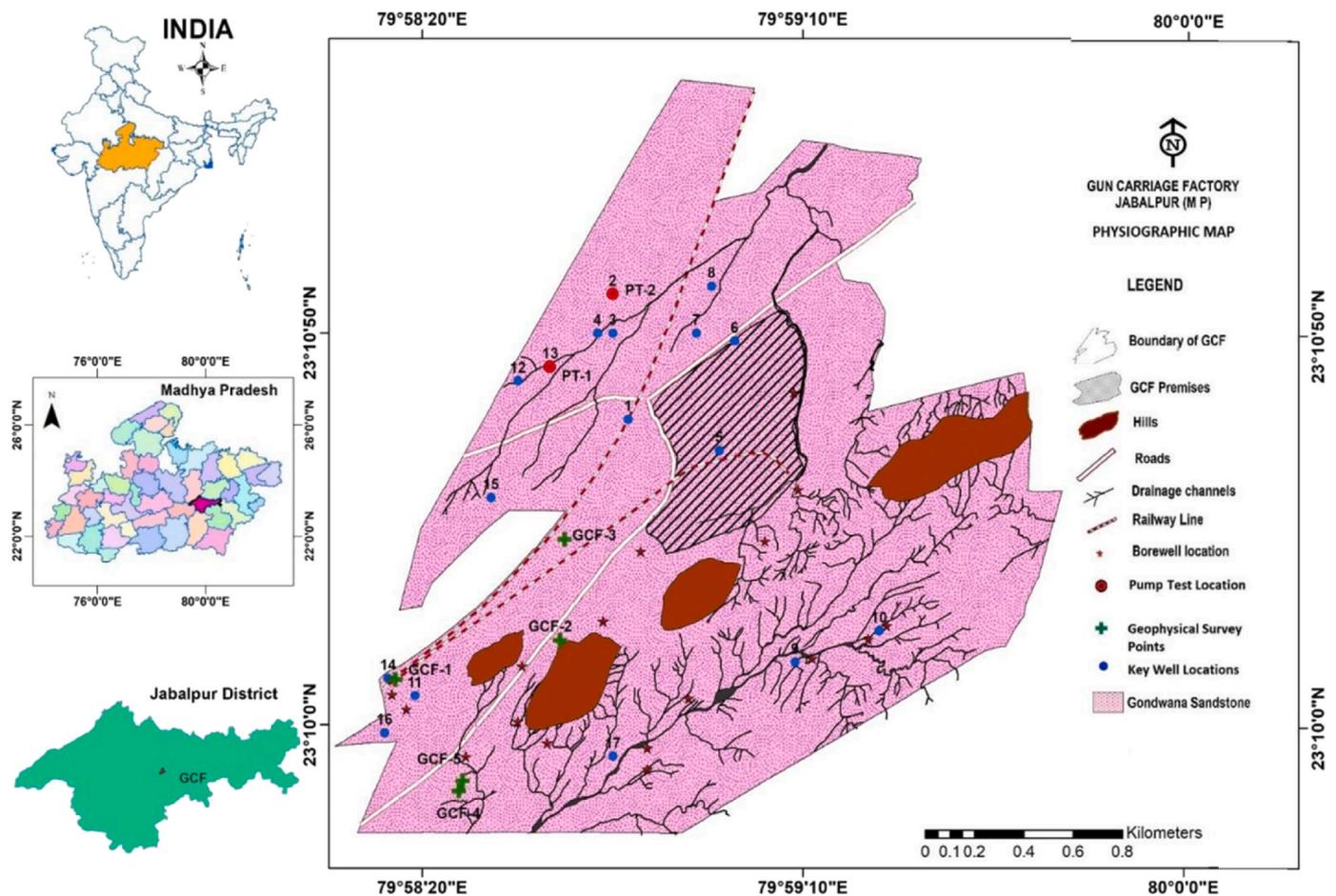


Fig. 1. Physiography at the Gun Carriage Factory estate, Jabalpur, India.

850 million people (50%) by 2051 [5]. Hence, roof areas are most likely to rise with time.

The Central and State Governments have been promoting rooftop rainwater harvesting (RWH) by giving various incentives to the house owners. Many municipalities have even made it mandatory to install rooftop rainwater harvesting systems in every new structure with a roof area of > 100 m² [6]. The campaign is on to install such systems in older structures as well, including the larger factory premises, office buildings, military barracks, and other defence installations. Many of these establishments are not aware of the technical know-how as to how to plan for rooftop rainwater harvesting in their premises.

In fact, many building complexes are reluctant to implement this scheme because it does not become economical for them to carry out all detailed field investigations including drilling of test boreholes for evaluation of aquifer parameters. To encourage these entities, which are often located away from human habitations, this contribution tries to convey that many of the field parameters could be assumed based on prescribed norms recommended by various Government Departments from time to time in their technical reports/brochures. These reports/brochures are based on several field studies carried out by responsible officers in different parts of the country in various field terrains. Assistance from some local geologist or geophysicist may be necessary, if need be, to decipher the underground features.

Therefore, in order to increase larger stake-holder participation in this national campaign, the primary objective of this contribution is to demystify the science behind RWH and prepare a design plan for it in a large defence establishment (ordnance factory) in central India, so that the steps followed, and the plans thus made, would be helpful in

preparing similar designs for many such larger establishments across the country and also the world.

Rajiv Gandhi National Groundwater Training and Research Institute, Raipur, India received a request from the Gun Carriage Factory (GCF), Jabalpur (Fig. 1) to conduct a feasibility study and prepare a rooftop RWH scheme for its premises. The authors of this paper were deputed to carry out the investigation in 2016. The material presented in this contribution summarizes their field investigations and findings.

With gradual strengthening of the military bases in terms of human resources by number or otherwise, there is a greater demand for water in these bases now than before in India [7–9]. Situation is not different even in countries like the United States of America [10]. This work, therefore, would work as a guideline for carrying out similar studies elsewhere across the globe in large defence establishments and industrial units.

In fact, there are many instances of rooftop RWH in the literature. But most of these examples pertain to only one building or at best 2–3 buildings at a time. Limited literature is available on investigations involving more than 10 buildings taken together. The present contribution outlines a design plan for 16 buildings in a factory complex. Generally, one borewell is conventionally used for recharge purposes in a building, and the filtration process of the harvested water is avoided in most cases. But this paper tries to focus on the design components, especially the chain of three chambers in a row and drilling of multiple wells inside a recharge chamber, not commonly practiced in India. This work, therefore, is unique since similar plans for defence establishments and industrial units can be designed at one go with one-time investigation saving time and money for multiple surveys.

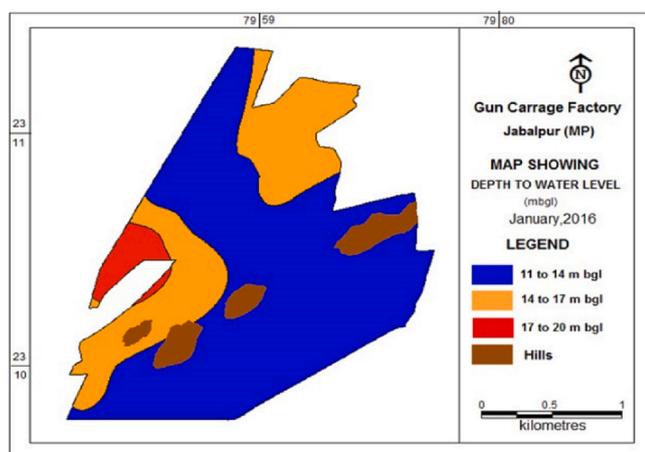


Fig. 2. Depth to water level map of the Gun Carriage Factory estate, Jabalpur, India.

2. Methods

2.1. Study area

Gun Carriage Factory (GCF), Jabalpur is a unit of Ordnance Factory Board under the Department of Defence Production, Ministry of Defence, Government of India. It was established at Jabalpur in 1904 as the first Ordnance Factory of central India. With its mission being "Production of State-of-the-Art Battlefield Equipment", GCF has been providing the Indian Armed Forces with the latest armaments and weapons for the past 100 years. It is located at the outskirts of Jabalpur, a tier-2 city in the State of Madhya Pradesh, India. The entire GCF estate spreads over an area of 1723.56 acres (6.975 km²), out of which the main GCF factory premises cover an area of 157.005 acres (0.635 km²) (Fig. 1).

Data collected from the observatory of the India Meteorological Department (IMD) at Jabalpur (August 17, 2016) reveals that the climate around the city is characterized by a hot summer and general dryness except during the rainy season. December has the minimum temperature of 9.7 °C, while the maximum temperature of 42 °C is felt in the month of May. The provisionally collected average annual rainfall is about 1461 mm of which 90% (1315 mm) falls during the southwest monsoon period, i.e., June to September. Maximum mean monthly rainfall is about 467.50 mm in the month of July and minimum mean is about 4 mm in December. Historically, the maximum rainfall received in a period of 24 h is about 233.4 mm. Therefore, surplus rainfall is available for harvesting during the monsoon period.

The observatory of Central Water Commission (CWC) at village Pariat close to the present study area too reports an annual normal rainfall of 1462 mm [11]. But despite being a high rainfall zone with annual precipitation varying between 1400–1500 mm [12,13], its long-term plot at Jabalpur shows a declining trend [14]. This is also reflected in the long-term trend of groundwater levels around Jabalpur,

Table 1

Estimation of subsurface storage space at the Gun Carriage Factory estate, Jabalpur, India.

Catchment area (m ²)	Category/ Priority	Water level contour Interval (mbgl)	Area identified for recharge (m ²)	Postmonsoon depth to water level below 3 mbgl	Volume of unsaturated zone (m ³)	Average specific yield	Total subsurface potential as volume of water (m ³)
6,975,000	I	11 - 14	4,473,337.5	9.6	6 = (4 × 5) 42,944,040	0.02	8 = (6 × 7) 858,880.8
	II	14 - 17	2,203,853.2	12.5	27,548,165	0.02	550,963.3
	III	17 - 20	297,809.4	14.8	4,407,579.12	0.02	88,151.58
TOTAL			6,975,000.10		74,899,784.12		1,497,996

especially during the premonsoon season [15], indicating increased demand and developmental activities [16].

2.2. Modus operandi

Prior to field investigations, technical meetings were held with GCF to understand their requirements, with Geological Survey of India to understand the geological set-up and finally with India Meteorological Department for collection of historical rainfall data. Several field traverses were then made for a brief appraisal of geology and physiography. Detailed well inventory was done in 17 wells to gather hydrogeological information. Two pumping tests were conducted to estimate the hydraulic parameters of aquifers. Geophysical surveys were carried out at five locations to understand the subsurface geophysics, lithological variations with depth, weathering depth and fracture pattern. Five water samples (one from rainwater and four from borewells) were collected randomly for analysis of chemical parameters. Detailed surveys were then conducted in individual buildings for the design of rooftop RWH structures. Rooftop areas and volume of rainwater that could be harnessed were estimated and finally designs were made for different buildings depending on land availability.

3. Results and discussion

3.1. Local hydrogeology

Upper Gondwana sandstones form the primary water bearing horizon around the GCF estate. They are overlain by Lameta beds of about 10 m thick and underlain by porphyritic granite and granite gneiss of Mahakausal Group of Precambrian Age. The sandstones are characterized by fine to medium grain-size and poor to moderate sorting of sediments giving rise to high degree of porosity and permeability. They form good aquifers and are suitable for groundwater storage and recovery. Naik et al. [17] give a detailed account of hydrogeology of the GCF estate.

The 17 borewells inventoried in January 2016 show depth to water levels (DTW) of 11.20 - 18.60 mbgl (metre below ground level) with deeper water levels (> 17 mbgl) toward the south-west (Fig. 2). Out of 30 wells inside the estate, 18 are production wells. Two of the wells evaluated show an average transmissivity of 106 m²/day and a specific capacity of 244 lpm/m. Since there was no any authentic litholog available to understand the subsurface conditions, five vertical electrical soundings were conducted to decipher fracture depths to effect favourable recharge. These studies indicate shallow fractures within a depth of 15–35 m [17].

3.2. Estimation of subsurface storage space

Estimation of subsurface storage space for groundwater recharge in GCF estate is based on the thickness of available space in unsaturated zone below 3 mbgl in postmonsoon period and the specific yield of the phreatic aquifer, which is taken as 2% for this area. Groundwater level contours at an interval of 3 m were drawn to assess the thickness of the

Table 2
Rainwater available in different buildings of Gun Carriage Factory, Jabalpur, India, for rooftop rainwater harvesting and dimensions of the settling, filter, and recharge chambers.

Sl. No.	Location	Bldg. No.	Length	Breadth	Roof Area (m ²)	Total water collected from roof in a year (m ³)*	Max. water collected from roof in 15 min (m ³)**	Capacity of settling chamber (m ³)**	Settling/Filter Chamber Dimensions (Length x Breadth x Height = Volume)	Recharge Chamber Dimensions (m ³) (for 1 borewell)	No. of borewells suggested#
1	Main building	24	64	14.93	955.5	949.3	19.5	24.4	4 × 3 × 3.5 = 42	1.5 × 1.5 × 3.5	1
2a	Tool Room-I	61	70	15	1050.0	1043.2	21.4	26.8			
2b	Tool Room-II	61	50.2	7.1	356.4	354.1	7.3	9.1			
2c	Tool Room-III	61	35	7.1	248.5	246.9	5.1	6.3			
	Tool Room	61						42.2	4 × 3 × 3.5 = 42	1.5 × 1.5 × 3.5	1
	Total										
3a	GMS-I	23	21.95	15.24	334.5	332.3	6.8	8.5			
3b	GMS-II	23	83.53	77.13	6442.7	6400.7	131.4	164.3			
3c	GMS-III	23	37.19	16.15	600.6	596.7	12.3	15.3			
	GMS Total	23						188.1	9 × 6 × 3.5 = 189	1.5 × 1.5 × 3.5	2
4	GFS-I	P-8	70	75	5250.0	5215.8	107.1	133.9	8 × 5 × 3.5 = 140	1.5 × 1.5 × 3.5	2
5a	Canteen-I	138	59.45	31.4	1866.7	1854.6	38.1	47.6			
5b	Canteen-II	138	3.9	21.34	83.2	82.7	1.7	2.1	4 × 4 × 3.5 = 56	1.5 × 1.5 × 3.5	1
	Canteen							49.7			
	Total							161.1	8 × 6 × 3.5 = 168	1.5 × 1.5 × 3.5	2
6	155MM Complex	112	121.95	51.82	6319.4	6278.2	128.9	161.1	4 × 4 × 3.5 = 56	1.5 × 1.5 × 3.5	1
7	ADGS	311	72	30.5	2196.0	2181.7	44.8	56.0			
8a	MM-I	57, 63	26.52	10.03	266.0	264.3	5.4	6.8			
8b	MM-II	57, 63	33.37	9.8	327.0	324.9	6.7	8.3			
	MM total	57, 63						15.1	4 × 3 × 3.5 = 42	1.5 × 1.5 × 3.5	1
9	TGS-I	367	76.2	52.9	4031.0	4004.7	82.2	102.8	6 × 5 × 3.5 = 105	1.5 × 1.5 × 3.5	1
10	T-72	411	76	54	4104.0	4077.2	83.7	104.7	6 × 5 × 3.5 = 105	1.5 × 1.5 × 3.5	1
11	FGS-I	346	137.6	91.4	12,576.6	12,494.6	256.6	320.7	10 × 9 × 3.5 = 315	1.5 × 1.5 × 3.5	4
12	FGS-II	261	52.5	42.4	2226.0	2211.5	45.4	56.8	4 × 4 × 3.5 = 56	1.5 × 1.5 × 3.5	1
13	FGS-II	345	61.65	15.93	982.1	975.7	20.0	25.0	4 × 3 × 3.5 = 42	1.5 × 1.5 × 3.5	1
	Annex.										
14	NEW	New	70	45	3150.0	3129.5	64.3	80.3	5 × 5 × 3.5 = 88	1.5 × 1.5 × 3.5	1
	155MM										
15	BHP	407	72	30.5	2196.0	2181.7	44.8	56.0	4 × 4 × 3.5 = 56	1.5 × 1.5 × 3.5	1
16	Storedhed		90	50	4500.0	4470.7	91.8	114.8	6 × 6 × 3.5 = 126	1.5 × 1.5 × 3.5	2
	New										
	TOTAL				60,062.4	59,670.8	1225.3	1531.6	1628		

Annual rainfall (m) = 1.461; Maximum rainfall in 15 min (m) = 0.03; Actual runoff coefficient = 0.8 × 0.85 = 0.68.

*Total water collected from roof in a year (m³) = Roof Area (RA) × Annual Rainfall (1.461 m) × Actual runoff coefficient (0.8 × 0.85 = 0.68)

** Maximum water collected from roof in 15 min (m³) = RA × Maximum rainfall in 15 min (0.03 m) × Actual runoff coefficient (0.68)

*** Capacity of settling chamber (m³) = RA × Maximum rainfall in 15 min (0.03 m) × runoff coefficient (0.85)

Settling/Filter Chamber Dimensions (m³) = (Length x Breadth x Height)

Recharge Chamber Dimensions (m³) (for 1 borewell) = (Length x Breadth x Height) = 1.5 × 1.5 × 3.5 m³ = 7875 m³

#Based on volume of rainwater to be collected in a day = Total water collected from roof in a year / 50 (i.e., no. of rainy days in a year)/72 m³.

subsurface aquifer (Fig. 2). Three categories were made based on this map: Category-I (DTW between 11- 14 mbgl), Category-II (DTW between 14–17 mbgl) and Category-III (DTW between 17–20 mbgl). The main GCF factory area falls in Category-I. Accordingly, the total volume of unsaturated strata below 3 mbgl is estimated at 74,899,784 m³ and the actual amount of water required to recharge this space is calculated at 1497,996 m³ with the specific yield of the aquifer, i.e., 0.02. Calculations are shown in Table 1.

3.3. Design of rooftop rainwater harvesting structures in GCF premises

The authority in GCF desired that the rooftop RWH design plan be made for 16 selected buildings only as given in Table 2. The typical plan consists of three parts: a settling/collection chamber, a filter chamber, and a recharge chamber, as shown in Fig. 3. The rooftop water first shall collect in the settling chamber where suspended particles shall settle down. Then the water will enter the filter chamber. The filtered water will then be connected to the recharge borewell in the recharge chamber and get injected into the aquifer by gravity. These three chambers together form a recharge system. The process of recharge is shown in Fig. 3, design filter in Fig. 4, and the plan views in Fig. 5.

3.4. Design parameters for settling chamber

A settling/collection chamber/tank (Fig. 3) is meant for removing silt and other floating impurities from the rainwater. It also acts like a buffer tank in the recharge system before the rainwater enters the filter chamber. The bottom of this chamber is cemented well to avoid scouring of the unpaved bottom surface and formation of a cavity due to impact of the falling water.

For designing the optimum capacity of the chamber, three factors, such as (i) size of catchment, (ii) intensity of rainfall and (iii) rate of recharge, are considered. Since the chamber acts as a buffer tank, it is designed in such a way that it retains the inflow of rainfall for a longer duration, since the rate of recharge will be much slower compared to the rate of inflow. Accordingly, the capacity of the chamber is designed to hold the runoff occurring from peak rainfall intensity for at least 15 min. For Jabalpur, 30 mm (= 0.03 m) is taken as the peak rainfall intensity for 15 min as per the local IMD observatory. With a runoff coefficient (C) of 0.85 [18] for galvanized sheets that form the roofs of the GCF, the capacity of the chamber is thus calculated as roof area (m²) x 0.030 m x 0.85.

Table 2 gives the building-wise calculations for the capacities of the settling chambers. In this table, another coefficient, i.e., 0.80 [18], meant for evaporation, spillage and first flush etc. is multiplied with the

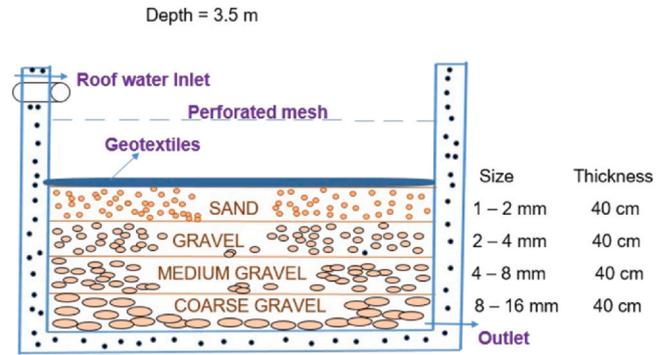


Fig. 4. Design of a filter chamber (not to scale).

runoff coefficient of 0.85 to give the actual runoff coefficient for an optimum estimation of rainwater that can be minimally harvested in a rooftop recharge system. The dimensions of the settling chamber for each building depending on the volume of rainwater expected in 15 min of peak rainfall intensity, are given in Table 2 keeping its depth at 3.5 m.

3.5. Design parameters for filter chamber

The dimensions of both settling and filter chambers have been kept the same (Table 2). The layering sequence shall be a 0.4 m thick pebble layer with the pebble size of 8–16 mm at the bottom followed upward by the same thickness of two pebble layers with their sizes being 4–8 mm and 2–4 mm, respectively, and then about the same thickness of 1–2 mm sized sand layer at the top (Fig. 4).

Operation and maintenance of the filter chamber is always a problem with natural sand filters. Therefore, at the top of the sand layer, use of geotextiles is recommended. Geotextiles are permeable fabrics typically made up of polypropylene or polyester. Use of geotextile shall save the sand filter from silt deposition. Also, silt deposited in the filter chamber could be easily cleaned periodically by removing the geotextile cover on it. The geotextile can again be placed on the top sand layer after cleaning it or, if necessary, a new piece of geotextile can be used for better performance. Geotextile selected should be such that it allows easy passage of water. A perforated mesh may be put a few centimetres above the geotextile cover and below the pipe transferring water from the settling chamber so that the filter layers are not disturbed with the impact of the inlet water.

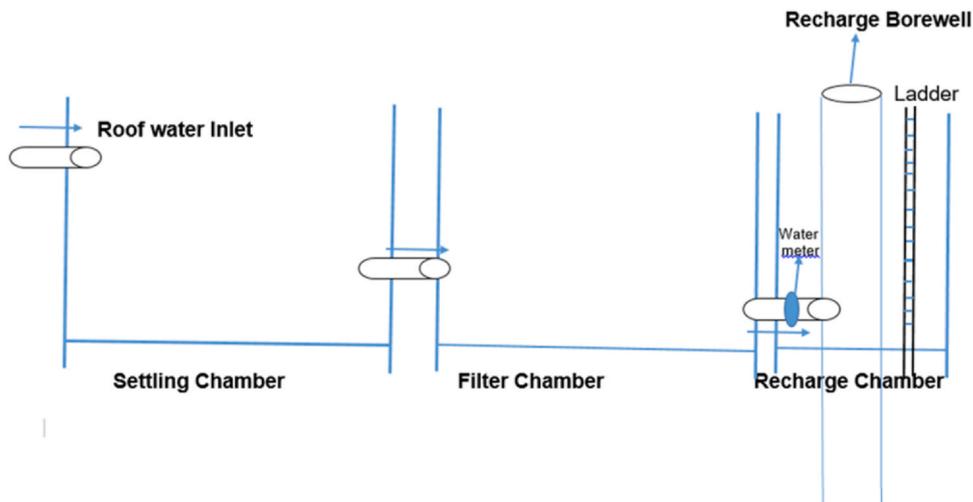


Fig. 3. A recharge system with settling, filter and recharge chambers and a recharge borewell (not to scale).

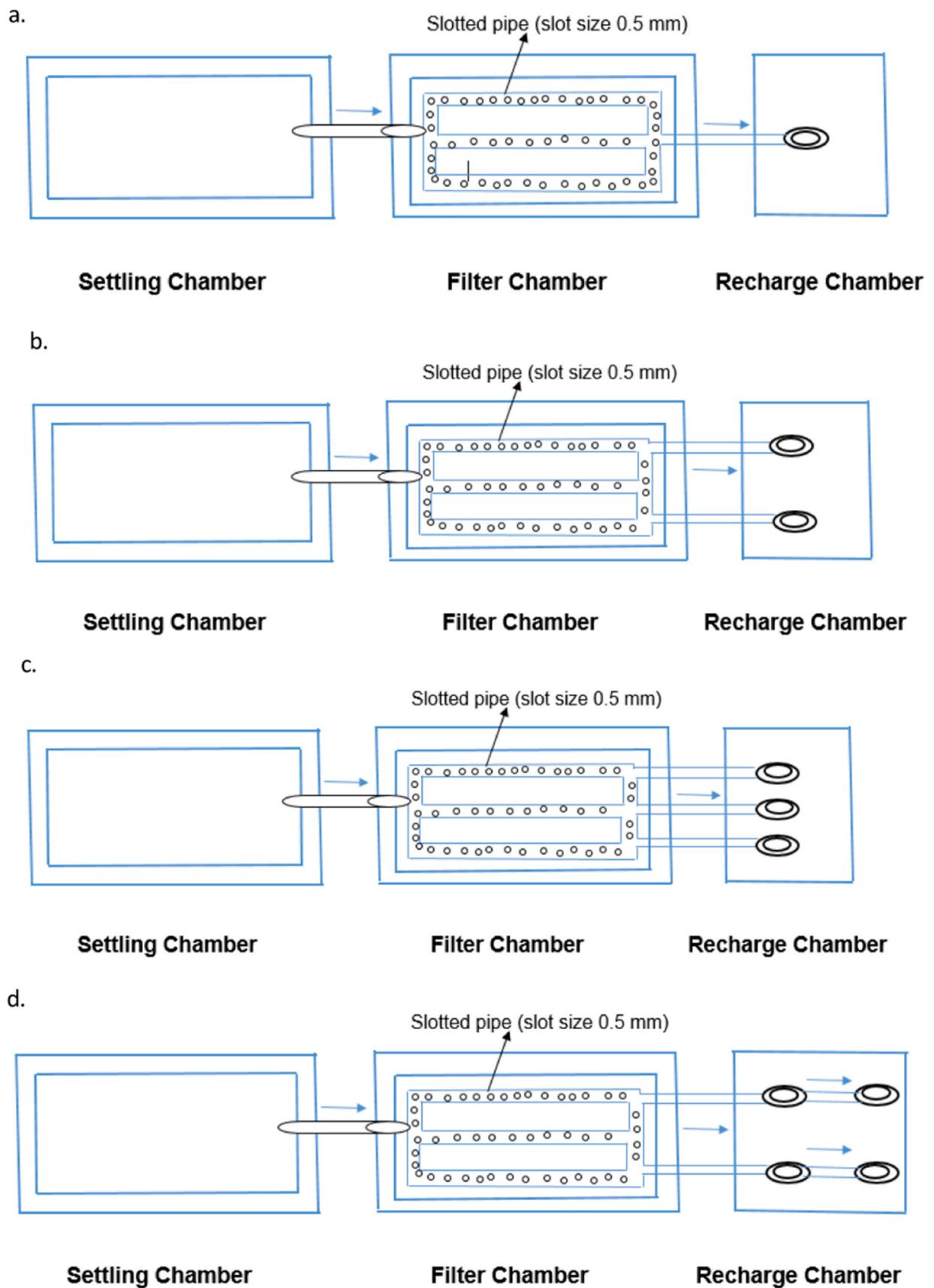


Fig. 5. Layout plan of a recharge system with (a) one, (b) two, (c) three and (d) four borewells in the recharge chamber (not to scale).

3.6. Design parameters for recharge chamber

Recharge chamber shall house the borehole(s) through which filtered rainwater shall be injected into the aquifer through gravity. Its dimensions are kept at 1.5 m x 1.5 m x 3.5 m for each injection borewell. Depending on the harvested rainwater to be injected and number of borewells required (Table 2), its dimension shall vary for each building.

There is no record of litholog available of the main GCF campus. Therefore, based on geophysical surveys [17], the depth of the recharge well(s) may be restricted to 50 m. Casing depth may be in the order of 20–25 m depending on the depth of weathering. The diameter of the main pipe may be fixed at 8" (203 mm). The casing may be of PVC with an inner diameter of 9" (229 mm). Provision for water meter(s) may be kept in each recharge chamber to estimate the volume of recharge occurring periodically. A typical recharge borewell is shown in Fig. 6.

3.7. Building-wise rooftop rainwater harvesting

The rainwater collected from each of the 16 buildings of the GCF is calculated in Table 2, which is self-explanatory. The combined rooftop area from these 16 buildings is 60,062.4 m². Total rainfall available annually from these rooftops is 59,670.8 m³. As stated earlier, the peak rainfall intensity for Jabalpur city for 15 min is taken as 30 mm. Accordingly, in 15 min, the total rainfall available from all rooftops is estimated at 1225 m³. The total capacity of settling chambers is thus calculated at 1531.6 m³ taking a runoff co-efficient (C) of 0.85 (i.e., 60,062.4 × 0.03 × 0.85 = 1531.60 m³) (Table 2).

The recharge rate of one recharge well is taken as 2 litres per second (lps) or 7.2 m³/hr, which comes to about 172.8 m³/day. Taking recharge through a borewell for 10 hrs a day, the recharge rate per day is estimated at 72 m³/day/borewell for the whole of GCF (16 buildings). This recharge rate is more conservative than a rate of 10 m³/hr./borewell, i.e., 100 m³/day/borewell for a 10-hr operation period, recommended by a recharge experiment conducted by a team of experts from the Ministry of Water Resources, River Development and Ganga Rejuvenation, Government of India at the GCF campus [19].

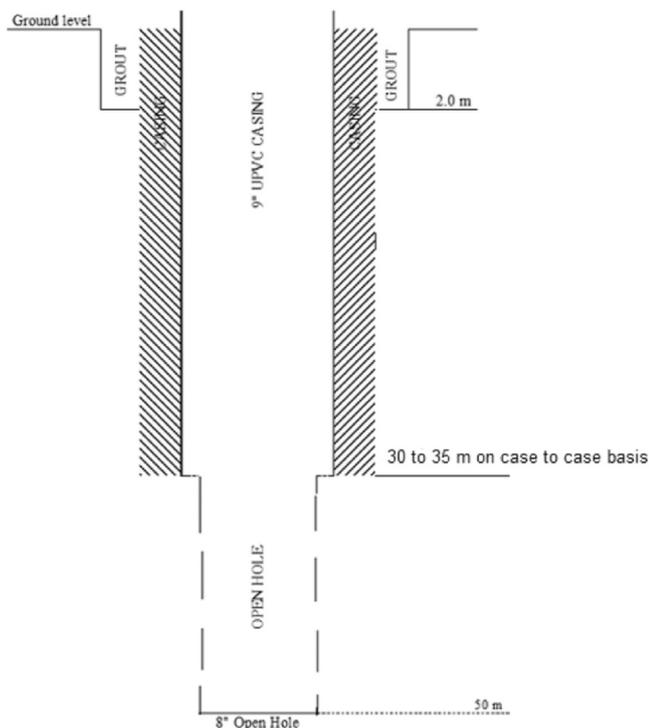


Fig. 6. A typical design of a recharge well in Gun Carriage Factory, Jabalpur, India.

Table 3
Rainwater available in selected combined buildings of Gun Carriage Factory, Jabalpur, India, for rooftop rainwater harvesting.

Sl. No.	Location	Roof area (m ²) (1)	Annual rainfall (m) (2)	Maximum 15 min of rainfall (m) (3)	Actual Runoff coefficient (0.8*0.85 = 0.68) (4)	Total water collected from roof in a year (m ³) (1 × 2 × 4)	Maximum water collected from roof in 15 min (m ³) (1 × 3 × 4)	Capacity of Settling Chamber (m ³) (1 × 3 × 0.85)	No. of borewells suggested#
1	Half of Main building (24), Tool room (61), whole of GMS (23) and Building Nos. 57 & 63.	8044.4	1.461	0.03	0.68	7991.95	164.1	205.1	3
2	FGS-II (261) and FGS-II Annex (345)	3208.1	1.461	0.03	0.68	3187.18	65.4	81.8	1
3	Canteen (138), GFS-I (Industrial building) (8) and Storeshed new	11699.9	1.461	0.03	0.68	11623.62	238.7	298.3	4

#Based on volume of rainwater to be collected in a day = Total water collected from roof in a year / 50 (i.e., no. of rainy days in a year)/72 m³.

Table 4
Dimensions of settling, filter, and recharge chambers in selected combined buildings of Gun Carriage Factory, Jabalpur, India.

Sl. No.	Location	Roof area (RA) (m ²)	Capacity of settling chamber (m ³) (RA*0.03*0.85)	Settling Chamber		Filter Chamber		Recharge Chamber			Capacity of settling/filter chambers (m ³)	
				Length (m)	Breadth (m)	Height (m)	Length (m)	Breadth (m)	Height (m)	Length (m)		Breadth (m)
1	Half of Main building (24), Tool room (61), whole of GMS (23) and Building Nos. 57 & 63.	8044.4	205.1	10	6	3.5	10	6	10	6	3.5	210
2	FGS-II (261) and FGS-II Annex (345)	3208.1	81.8	6	4	3.5	6	4	1.5	1.5	3.5	84
3	Canteen (138), GFS-I (Industrial building) (8) and Storeshed new	11,699.9	298.3	11	8	3.5	11	8	11	8	3.5	308

The number of rainy days in Jabalpur in a year is taken as 50 [20] giving a total rainfall availability of 59,670.8 m³ on annual basis. Availability of rainfall is thus calculated at 1193.4 m³ per rainy day. Taking the capacity of a borewell at 72 m³/day, a minimum of 17 no. of borewells need to be installed at the GCF estate to harness the rainwater from these 16 buildings. Table 2 gives the number of injection wells desired per building. This calculation is based on the total water collected from roofs in a year divided by 50 (rainy days) that gives the total volume of water available for injection per day.

However, since most buildings are adjacent to each other, the suggestion is to construct one common recharge structure for the adjacent buildings. There are only three cases, where combined recharge systems could be attempted at GCF, i.e., Case I: Main Building (No. 24), Tool Room (No. 61), GMS (No. 23), Building Nos. 57 and 63 (MM), Case II: FGS-II (No. 261) and FGS-II Annexure (No. 345), and Case III: Building Nos GFS-I (No. 8), Canteen (No. 138) and Storeshed. Design calculations for these combined building plans are shown in Tables 3 and 4. There shall be requirements of multiple recharge wells in these combined buildings to tap all collected rainwater. Accordingly, dimensions of recharge chambers shall vary to accommodate two to four wells in one master chamber as shown in Fig. 5 b, c, d. **Chemical Quality of Groundwater:** Chemically, concentrations of the groundwater quality parameters generally lie within the standards prescribed by the Bureau of Indian Standards [21] for drinking purposes (Table 5). However, the water sample collected at the Madras Pump House shows total hardness (TH) concentrations of 210 mg/L, while the acceptable limit is 200 mg/L. Another sample at New Colony area within the campus shows a TH value of 195 mg/L, just 5 mg/L less than the recommended limit. Clearly, few samples are in border areas for total hardness. Therefore, it is expected that there will be dilution of these concentrations due to injection of rainwater in massive scale through the rooftop RWH in the GCF estate. Dilution of the chemical constituents in host aquifers due to stormwater recharge was reported by Naik et al. [22] in the Kingdom of Bahrain.

The only rainwater sample collected is acidic in nature (pH 5.51) as is generally the case elsewhere too [23], but it automatically becomes normal once it enters the ground due to buffering effects of substances like calcium carbonate, clay, humus, and aluminum oxides present in the soil [24]. The pH value in groundwater at the GCF estate varies between 7.67 and 8.05.

4. Limitations of this study

The GCF being a restricted area militarily, very limited hydro-geological studies have been carried inside its premises. The estate does not have any exploratory well drilled inside it, and therefore recorded litholog and pumping test data are not available. Accordingly, litholog data from a nearby well in the adjacent area were used to understand the underground disposition of aquifer system better [17]. To confirm the fracture pattern inside the aquifer to release the harvested water at a specific depth, five vertical electrical soundings were subsequently conducted, which are far less expensive than drilling of a test borewell. Two pumping tests were conducted in two existing large diameter wells (dugwells) to evaluate the hydraulic parameters. Although these tests gave a transmissivity value of 106 m²/day and a specific capacity of 244 lpm/m for the shallow aquifer below, its specific yield value could not be obtained and was assumed to be in the order of 2%. The recommended specific yield value of sandstone that underlie the study area is taken as 3% by the Ground Water Estimation Committee 2015 of the Ministry of Water Resources, Government of India (2017) [25]. Therefore, the value of 2% is very conservative and represents the minimum ability at which rainwater could be released underground inside the aquifer.

Another important assumption is the recharge rate of 2 litres per second (lps) or 7.2 m³/hr or 172.8 m³/day per borewell from the recharge chamber. Thus, taking the recharge through a borewell for 10

Table 5
Chemical quality of groundwater in Gun Carriage Factory, Jabalpur, India.

S. No.	Location	Source	pH	EC μS/cm	CO ₃ ←Concentrations in mg/L→	HCO ₃	Cl	F	SO ₄	Na	K	Ca	Mg	TH
1	Rainwater- GCF	RW	5.51	11	0	12	7	0.2	2	0.2	0.2	4	2.4	20
2	GCF-Factory (E2)	BW	7.89	392	0	128	35	0.6	36	21.9	0.8	46	7.2	145
3	GCF-Factory (E5)	BW	7.83	420	0	177	35	0.4	33	23.1	1.2	46	12	165
4	GCF-Estate (Madras Pump House)	BW	7.67	656	0	171	71	0.6	40	56.6	5.2	60	14.4	210
5	GCF-Estate (New Colony)	BW	8.05	395	0	226	11	0.4	6	8	0.2	70	4.8	195

hrs a day, the recharge rate per day is estimated at 72 m³/day/borewell from the entire study area (16 buildings). This assumed rate corroborates well with a recharge rate of 10³/hr/borewell or 100 m³/day/borewell for the 10 h of operation of a borewell estimated in a field experiment conducted subsequently by a team of experts constituted by the Ministry of Water Resources, Government of India [19]. Certainty the recharge rate of 72.8 m³/day per borewell is a conservative value, but it represents the minimum amount of recharge that may be affected by a recharge well and the maximum is always better.

Other assumptions are considering 30 mm of peak rainfall intensity for 15 min duration and number of rainy days of 50 in a year in the design calculations in Tables 2 and 3. But these values are as per the recommendations of the local Indian Meteorological Department Observatory from where these data were personally collected. Guhathakurta et al. (2020) [20] too found these values while studying the observed rainfall variability and changes over Madhya Pradesh State of which the study area is an important part. The runoff coefficient of 0.86 for galvanized sheets and another coefficient of 0.80 due to evaporation losses, spillage etc. are as per the prescribed norms defined by the Central Public Works Department (2002) nationally [18] and cannot be disputed. Therefore, although there are certain assumptions in this study, the values adopted are as per the norms prescribed by the recognized national bodies in India and cannot normally be challenged unless working in a different set up than the one in which those norms were defined. Therefore, the conclusions drawn in this study are based on actual science without any obliteration.

5. Conclusions

This study is aimed at motivating the larger building complexes, military barracks, ordinance factories, industrial houses, etc. to install rooftop rainwater harvesting systems in their premises to alleviate water shortages not only of their own, if any, but also of the nation during the drier months. Often these establishments have a chain of houses in a row, and this contribution demonstrates how easy it is to practice rainwater harvesting in such complexes with the help of their own engineers who normally are trained in water management principles. At places wherever there is paucity of field data, assistance may be sought from the local geologists and geophysicists for better understanding of the underground features. Many Government Agencies have published prescribed norms based on several field studies across the country, and on a case-by-case basis, the recommended values of many field parameters can be taken from their reports/brochures to avoid expensive field experiments.

The present study examines 16 buildings of the Gun Carriage Factory (GCF), Jabalpur, India, out of a total of about 32 buildings, from feasibility perspective for rooftop rainwater harvesting. The total roof area of the 16 buildings comes to about 60,062 m² that can harvest approximately 60,000 m³ of rainwater on annual basis, giving an availability ratio of one m³ of rainwater for every m² of roof area. In 15 min of peak rainfall intensity, about 0.03 m of rainwater is expected in the area with a total yield of about 1225 m³ of water during this short period. The settling chamber in each system is designed in such a way

that it can store at least 25% more volume of water than expected in these 15 min of intense rainfall period. There is no strict rule for the dimensions of the filter and recharge chambers. In this contribution, the lengths of all chambers, i.e., settling, filter and recharge chambers, have been kept the same to maintain uniformity so that they are visually appealing. The dimensions of the recharge chamber may vary depending on the number of borewells being drilled inside them so that these wells do not collapse and there could be easy maneuverings inside the chamber. With their depths maintained at 3.5 m, a minimum area of 1.5 m x 1.5 m is assigned to each borewell in this study.

Rainwater is generally clean globally, and so is the case in this study area, but since water is harvested from the rooftop, the roof material, its age, maintenance, nearby overhanging trees etc. can significantly affect the quality of water. Although the filter chamber cleans out most of the contaminants, the harvested water quality may be examined from a regulatory perspective before its injection into the aquifer or human consumption. The first flush of the rainwater must be avoided to screen out the silt particles, dry leaves and other unwanted materials flowing into the harvesting system. In areas where harvested rainwater is to be used for direct drinking, extra care is necessary for safeguard of the people's health [26,27]. A low-cost primary treatment of the harvested water may often be necessary for pH balancing, pathogen removal etc. [28]. Of late, there has been increasing use of nature-based solutions in urban areas while harvesting rainwater to maintain cleanliness, so in case contamination is suspected, there is an option to adopt nature-based solutions [29,30].

One problem with rooftop rainwater harvesting (RWH) is the lack of maintenance of the associated structures at least at an interval of two years. Experience in the city of Raipur, India shows that out of the seven rooftop RWH structures examined, all of them collapsed in a span of just two years due to lack of regular attention, such as desilting of the collection and filter chambers, breaking apart of the connecting pipes, etc. [31]. Therefore, a budgetary provision must be kept for maintenance of these structures post their implementation.

India, with a population of 1.417 billion people [32], consists of 7935 towns and 475 urban agglomerates, 53 of which have more than a million population [33]. These urban areas have innumerable buildings of diverse types. Besides, there are 242,395 manufacturing factories [34], 41 ordinance factories [35], numerous military barracks and many other similar structures with large roof areas. If about half of the buildings in an ordinance factory with a roof area of 60,000 m² could recharge about 60,000 m³ of rainwater at the rate of one m³ per one m² of roof area, what not to expect from tens of thousands of similar structures across the country?

Finally, no Government effort becomes successful unless the public participates en masse. What lacks in India currently is a sense of awareness toward participatory groundwater management, a concept the Government of India is striving to instill among all its citizens through several of its schemes, such as the Jal Shakti Abhiyan, Atal Bhujal Yojana, Prime Minister's Krishi Sinchai Yojana, Ajadi ka Amrut Mohotsav (celebration of 75 years of India's Independence), etc. Until the time the public understands and values its own role in water management, India cannot be free of water scarcity problems.

Therefore, all efforts must be made to educate people in whatever way possible to make them aware of the dark future India shall have unless the malady is not tackled with full hearts together.

Data Availability

All data generated or analyzed during this study are included in this published article. However, if additional information is still desired, the datasets generated during and/or analyzed during the current study shall be available from the corresponding author on reasonable request.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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