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Design and Implementation of a Solar-Powered Water Supply with Rainwater Harvesting Integration

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Abstract: This study presents the design and analysis of an integrated solar-powered water supply and rainwater harvesting (RWH) system developed for sustainable rural water management in Wadipir Village, Maharashtra. The project aims to ensure long-term water reliability, energy independence, and environmental sustainability through a combination of hydraulic optimization, renewable energy utilization, and groundwater recharge. Based on population forecasting for a 30-year design horizon (2022–2052), the village demand is projected to increase from 314 kL/day to 490 kL/day, necessitating system augmentation. The hydraulic assessment determined a required discharge of 13.08 L/s and a total dynamic head of 40 m, resulting in a pump power demand of 5.9 kW. A 7.4 kWp photovoltaic (PV) array with a 48V, 1000 Ah $LiFePO_4$ battery bank was designed to provide five hours of autonomy, enabling reliable daily operation while reducing carbon emissions by approximately 10–12 tons annually. Rainfall data analysis (average annual rainfall 950 mm, catchment area 35 ha) estimated a total runoff potential of 14,000 m^3/year, equivalent to 40 kL/day. The RWH system incorporates rooftop and surface collection networks, a 12,000 m^3 lined storage reservoir, five recharge wells, and two percolation trenches, collectively enhancing surface storage and aquifer recharge capacity by 2,500 m^3/year. The total project cost, including collection, storage, and recharge components, is estimated at ₹123.2 lakh. The proposed integrated system significantly reduces dependence on conventional energy and groundwater sources while improving local water availability, soil moisture, and vegetation. It provides multiple environmental and social benefits, including reduced runoff, rise in groundwater table, and enhanced community participation. Overall, the study demonstrates that solar-powered RWH systems can serve as a technically feasible, economically viable, and environmentally sustainable model for decentralized rural water supply schemes in semi-arid regions.

***Index Terms* - Solar Pumping System, Rainwater Harvesting, Rural Water Supply, Sustainable Infrastructure, Groundwater Recharge, Renewable Energy Integration.**

1. INTRODUCTION

Water is one of the most critical natural resources for sustaining life, agriculture, and economic development. In rural India, where more than 65% of the population resides, the availability of safe and reliable drinking water continues to be a major challenge. Despite significant national initiatives such as the Jal Jeevan Mission (JJM), which aims to provide every rural household with functional tap connections, many villages still face intermittent supply, groundwater depletion, and energy-dependent distribution systems. These challenges highlight the urgent need for sustainable, decentralized, and energy-efficient water supply models that can ensure long-term resilience against climatic and infrastructural constraints.

The increasing dependence on groundwater in rural Maharashtra has led to a noticeable decline in water table levels, particularly in basaltic terrains where aquifers are discontinuous and have low recharge potential. Additionally, conventional pumping systems powered by grid electricity or diesel generators impose both economic and environmental burdens. The recurring costs of electricity, frequent power outages, and high maintenance requirements often result in unreliable supply, affecting the overall efficiency of rural water schemes. This situation underscores the necessity for alternative energy-driven solutions, such as solar-powered pumping systems, which offer clean, renewable, and cost-effective operation over their life cycle.

Simultaneously, the erratic monsoonal rainfall pattern and high surface runoff in rural areas create an opportunity to harness rainwater as a supplementary source. Rainwater Harvesting (RWH) systems, when scientifically integrated with existing groundwater and water supply schemes, can significantly reduce dependency on external sources while improving aquifer recharge and water availability. The dual approach of combining solar pumping with RWH creates a hybrid water management model, which ensures both energy independence and water sustainability. Such integration enhances system reliability, reduces carbon emissions, and contributes directly to climate-resilient infrastructure.

This study focuses on the village of Wadipir in Maharashtra, which represents a typical rural settlement facing seasonal scarcity and energy-related disruptions in water supply. The objective is to design and evaluate a hybrid water supply system integrating solar energy-based pumping and rainwater harvesting techniques tailored to local hydrological, climatic, and demographic conditions. The design considers population growth projections, peak demand analysis, hydraulic requirements, storage provisions, and renewable energy sizing to ensure technical, economic, and environmental viability.

The proposed system includes components such as a dug-cum-bore well as the primary source, a solar-powered submersible pump, a compact 1 MLD water treatment plant, balancing sump and elevated storage reservoirs (ESRs), and a gravity-fed HDPE distribution network. Additionally, rainwater harvesting structures—including rooftop collection systems, earthen storage reservoirs, recharge wells, and percolation trenches—are integrated to enhance groundwater replenishment and buffer seasonal deficits.

Through detailed design analysis, the project aims to demonstrate how rural communities can transition toward self-sufficient, low-carbon, and resilient water infrastructure using locally available resources and renewable technologies. The outcomes are expected to serve as a replicable model for similar rural settings across India, aligning with national goals of sustainable rural development, water conservation, and renewable energy utilization.

2. Assessment of Existing Water Supply Infrastructure and Improvement Recommendations

The existing water supply infrastructure in Wadipir village, located in Karvir Taluka of Kolhapur District, forms the backbone of the community's domestic water system, serving nearly 2,500 residents. The scheme comprises an existing dug-cum-bore well, three Elevated Storage Reservoirs (ESRs) of 25,000 L, 45,000 L, and 90,000 L capacities, along with a distribution network, pumping systems, and ancillary control components.

Despite augmentation through government initiatives such as the Jal Jeevan Mission (JJM), the system continues to face several technical, operational, and sustainability challenges. These issues collectively impact the reliability, water quality, and long-term serviceability of the system. The following sections outline key problems observed during the assessment and provide corresponding recommendations for improvement.

2.1. Source-Related Problems and Recommendations

Problem Identified: ***Seasonal Variation in Source Yield***

The primary source, a dug-cum-bore well, exhibits a considerable reduction in yield during the summer months (March–May). Groundwater levels decline sharply due to over-extraction and limited recharge, causing irregular water supply and pump dry-run incidents. This indicates unsustainable abstraction practices and insufficient aquifer replenishment.

Recommendations:

It is recommended to conduct biannual yield and drawdown tests—once post-monsoon and once pre-summer—to monitor aquifer performance and source sustainability. A regulated pumping schedule with a maximum of six operational hours per day during lean periods should be enforced to minimize over-pumping. Additionally, rainwater harvesting structures and recharge trenches should be developed near the well site to enhance infiltration. Community-led measures such as tree plantation, contour bunding, and source protection drives should be initiated to support recharge and environmental conservation.

Problem Identified: *Contamination Risk Around the Well*

The source well currently lacks fencing and proper surface drainage arrangements. Wastewater stagnation and agricultural runoff frequently enter the well area during monsoons, elevating the risk of bacteriological contamination and compromising drinking water safety.

Recommendations:

A sanitary protection zone of at least a 15-meter radius should be established around the well to restrict access and prevent contamination. The surrounding area should be paved with impervious cement concrete flooring and equipped with proper surface drainage channels to divert runoff. Permanent fencing, warning signage, and a designated chlorination point at the pump discharge line should be installed to ensure routine disinfection prior to water storage and distribution.

2.2. Pumping and Electrical System Issues

Problem Identified: *Frequent Pump Failures*

The existing pumping units, estimated at 5–7.5 HP, experience recurrent mechanical and electrical breakdowns due to voltage fluctuations and the absence of preventive maintenance schedules. Such failures disrupt supply cycles and increase maintenance costs.

Recommendations:

The old pumping machinery should be replaced with energy-efficient submersible pumps suitably designed for the required discharge and head. Voltage stabilizers or soft starters must be installed to mitigate the impact of electrical surges. An Annual Maintenance Contract (AMC) should be established to ensure regular servicing, spare availability, and reliability. Furthermore, a maintenance logbook must be maintained to record pumping hours, breakdown history, and energy consumption trends for system evaluation.

Problem Identified: *Power Supply Interruptions*

Unscheduled power cuts in the rural feeder network frequently interrupt pumping schedules, leading to irregular water supply and inconsistent reservoir levels.

Recommendations:

To address this issue, a solar-based pumping system (5–7.5 HP) with battery backup should be introduced to guarantee minimum daily pumping during power outages. Coordination with the Maharashtra State Electricity Distribution Company Limited (MSEDCL) is necessary to ensure prioritization of the village on the rural feeder line. Maintaining a one-day storage buffer within the ESRs will further help to sustain water supply during outages.

2.3. Storage System Issues

Problem Identified: *Structural Deterioration of ESRs*

The three existing ESRs show visible signs of aging—minor cracks, corroded ladders, and damaged valves. Leakages from tank walls and base slabs have resulted in water loss and potential contamination risks due to ingress at damaged joints.

Recommendations:

A structural audit and leak test should be conducted for all ESRs to evaluate integrity. Necessary repairs must be executed using polymer mortar, epoxy injection grouting, and waterproof coatings. All corroded cast iron (CI) valves should be replaced with stainless steel (SS) or HDPE isolation valves, while level indicators and overflow alarms should be installed for improved operation. The exteriors of the ESRs should be painted with reflective paint to minimize thermal expansion and algae formation.

Problem Identified: *Inadequate Storage Capacity During Peak Demand*

Although three ESRs exist, the combined effective storage capacity of 1.6 lakh liters becomes insufficient during summer and festival periods, resulting in intermittent shortages in certain distribution zones.

Recommendations:

A staggered filling schedule should be introduced to ensure optimized reservoir operation. Construction of an additional central balancing reservoir of 1.0–1.5 lakh liters near the main supply area is recommended to meet peak demand. Enhancing interconnectivity between ESRs will also allow cross-feeding between zones during shortages.

2.4. Distribution Network and Valve-Related Issues

Problem Identified: *Leakage and Pressure Imbalance*

Older segments of the distribution network, particularly those constructed using GI and smaller HDPE pipes, are prone to frequent leakages and pressure variations. Elevated parts of the village often experience low pressures, while low-lying areas suffer from excessive pressure and wastage.

Recommendations:

The network should be rehabilitated by replacing old GI sections with HDPE PN-10 pipes. A hydraulic balancing study should be undertaken to identify pressure zones, followed by installation of pressure-reducing valves (PRVs) in high-pressure zones. A District Metered Area (DMA) approach should be implemented for better zone-wise control and monitoring. Bi-annual leak detection surveys using flow and pressure meters will further ensure proactive maintenance.

Problem Identified: *Missing or Damaged Gang Valves*

Several gang valves along the rising main and distribution network are either inaccessible, corroded, or missing operational handles. This limits the ability to isolate sections during maintenance, increasing downtime and water loss.

Recommendations:

All gang valve chambers should be repaired, standardized, and provided with RCC covers and proper identification signage. A valve register and GIS-based mapping system must be developed for easy reference. Additional valves should be installed at every 500–700 meters along the network to allow sectional control, and monthly valve operation checks should be carried out to prevent mechanical jamming.

2.5. Treatment and Water Quality Issues

Problem Identified: *Absence of Continuous Chlorination*

Currently, the system lacks a consistent disinfection mechanism, resulting in variable residual chlorine levels and occasional bacteriological failures in testing.

Recommendations:

An automatic dose-controlled chlorinator should be installed at the sump outlet or ESR inlet to ensure uniform dosing. Residual chlorine levels should be maintained between 0.2–0.5 mg/L at consumer endpoints. Routine free chlorine and coliform tests using portable field kits should be conducted weekly. The system operator must be trained in chlorine handling, dosage calculation, and safety practices.

Problem Identified: *Lack of Water Quality Monitoring*

Water quality testing is currently limited to occasional official inspections, leaving variations in physical, chemical, and bacteriological quality undetected.

Recommendations:

A village-level water quality monitoring plan should be established, ensuring quarterly testing of parameters such as pH, TDS, hardness, iron, and microbial contamination. Coordination with the Zilla Parishad Laboratory, Kolhapur, should be maintained for sample validation. Test results should be publicly displayed at the Gram Panchayat office to enhance transparency and community confidence.

2.6. Operation and Maintenance (O&M) Deficiencies

Problem Identified: *Absence of Skilled Operator and Maintenance Protocols*

Presently, O&M responsibilities are handled by untrained personnel or on an ad-hoc basis by panchayat staff, resulting in poor upkeep and delayed fault rectification.

Recommendations:

A dedicated trained operator should be appointed under the Village Water and Sanitation Committee (VWSC). The operator must receive hands-on technical training from the Rural Water Supply Division, Kolhapur. A preventive maintenance schedule should be introduced covering pump servicing, valve lubrication, ESR cleaning, meter calibration, and chlorination equipment checks.

Problem Identified: *Lack of Financial Sustainability*

The present tariff structure and user charges are minimal, resulting in inadequate funds for routine maintenance, repairs, and energy costs.

Recommendations:

A revised tariff system should be developed based on water consumption slabs and community affordability. Establishment of a Village Water Fund is recommended, where monthly household contributions are deposited for O&M needs. Additional support can be sought through JJM, 15th Finance Commission, and Gram Panchayat grants to ensure long-term financial sustainability.

2.7. Sustainability and Environmental Issues

Problem Identified: *Poor Groundwater Recharge*

The main well's supporting aquifer is over-stressed, and there are no adequate structures for surface runoff harvesting, leading to declining water tables.

Recommendations:

The proposed injection well should be effectively utilized for treated water recharge. Supplementary measures such as percolation trenches, recharge shafts, and rooftop rainwater harvesting systems should be implemented, particularly in public buildings. Collaboration with the Groundwater Survey and Development Agency (GSDA) is essential for monitoring recharge efficiency and aquifer health.

Problem Identified: *Energy Inefficiency in Operations*

The continued use of old, non-rated pumps contributes to high electricity consumption and operational costs, increasing the carbon footprint of the scheme.

Recommendations:

It is advised to replace all outdated machinery with BEE-rated energy-efficient pumps and implement solar hybrid systems to cover at least 40% of daily pumping energy requirements. Digital flow meters and smart controllers should be installed to optimize pumping duration and energy use, thereby promoting both cost and environmental sustainability.

3. Design and Sustainable Augmentation

Wadipir (also known as Wadipeer) is a medium-sized rural settlement situated in Karvir Taluka, Kolhapur District, Maharashtra. The village has an estimated population of 5,700 (as of 2022), distributed across 719 households. Owing to its proximity to urban centers and ongoing agricultural development, the village has experienced moderate demographic growth in recent years.

The existing water supply system, originally designed for a population below 3,000, has now become inadequate due to rising demand. The system mainly depends on groundwater abstraction through a dug-cum-bore well, feeding three Elevated Storage Reservoirs (ESRs) and a network of distribution pipelines supplying domestic connections across all habitations.

With support from the Jal Jeevan Mission (JJM) and the National Rural Drinking Water Programme (NRDWP), the system has undergone partial upgradation, including installation of HDPE pipelines, valves, and treatment components. However, further augmentation is required to ensure sustainability, reliability, and future demand accommodation.

4. Design Parameters for the Water Supply System

4.1. Population Estimate (2022 Base Year)

The first step in the design of a water supply system is to establish the base population, as this serves as the foundation for all subsequent demand calculations. For Wadipir village, the estimated population for the year 2022 is 5,700 persons, as per the records of the Gram Panchayat. This base population represents the current design year for planning purposes and forms the starting point for population projection, which is essential for determining future water demand and infrastructure capacity.

Population growth directly influences the design of critical components such as intake structures, treatment plants, transmission mains, and distribution networks. Therefore, each system element must be designed for an appropriate design period, depending on its expected service life and replacement feasibility. Typically, intake and source works are designed for a 30-year period, given their long-term nature and high capital cost. The treatment plant has a design life of about 15 to 20 years, after which upgradation or expansion may be necessary. The distribution network, being a permanent underground asset, is generally designed for 30 years, ensuring it can cater to projected future demands without major realignment.

The first step in designing any water supply system is to establish the design population. For Wadipir, the 2022 estimated population is 5,700 persons, which forms the base figure for demand estimation. Population projections help determine the size and capacity of water infrastructure over a design period of typically 15–30 years, depending on component life expectancy:

Table No.1 Component and Design Period

Component	Design Period (Years)
Intake & Source Works	30
Treatment Plant	15–20
Distribution Network	30

4.2. Population Forecasting (2052 Projection)

Population forecasting is a crucial step in determining the design population for future years. The geometric growth method is widely accepted for such projections, especially for rural and semi-urban areas with consistent growth trends. Assuming a moderate rural population growth rate of 1.5% per annum, the population for Wadipir in the year 2052 can be estimated using the formula: Assuming a moderate rural growth rate of 1.5% per annum, the geometric growth formula is applied:

$$P_n = P \times (1 + r)^n$$

Where:

P = 5700 (base population, 2022)

r = 0.015 (annual growth rate)

n = 30 (years)

$$P_{2052} = 5700 \times (1.015)^{30} = 5700 \times 1.56 \approx 8{,}900$$

Hence, the design population for the year 2052 is estimated to be approximately 8,900 persons. This represents an increase of around 56% over the 30-year period, which must be accommodated in the design of source capacity, storage, and distribution infrastructure. Hence, the design population for 2052 is estimated at 8,900 persons.

4.3. Household Analysis

This household size is typical for rural settlements in Maharashtra and is consistent with state demographic trends. Under the Jal Jeevan Mission (JJM), the target is to ensure “Har Ghar Jal” — meaning every household receives a functional tap connection providing a minimum of 55 liters per capita per day (Lpcd). Thus, with an average of eight persons per household, each connection must be capable of delivering around 440 liters per day, ensuring adequate water supply for domestic needs such as drinking, cooking, bathing, washing, and sanitation.

According to Gram Panchayat records:

- Total Households = **719**
- Population = **5,700**

$$\text{Average Household Size} = \frac{5700}{719} = 7.93 \approx 8 \text{ persons per household}$$

This value is typical for rural Maharashtra and helps determine the number of service connections required. Under JJM’s “Har Ghar Jal” initiative, each household is targeted for an individual tap connection, designed for 55 Lpcd (liters per capita per day).

Table No.2 Peak Demand

Year	Population	Avg. Demand (kL/day)	Peak Demand (kL/day)
2022	5,700	314	565
2032	6,610	364	655
2042	7,665	422	760
2052	8,900	490	882

Thus, the population is expected to increase by 56% over the 30-year period, guiding infrastructure sizing and future-proof design.

4.4. Daily Water Requirement

The average daily water requirement (Q_{avg}) is calculated by multiplying the per capita water demand with the total population. The Jal Jeevan Mission prescribes 55 Lpcd as the standard domestic water requirement for rural households.

$$Q_{avg} = P \times q$$

For 2022:

$$Q_{avg} = 5700 \times 55 = 313{,}500 \text{ L/day} = 314 \text{ kL/day}$$

For 2052:

$$Q_{avg} = 8900 \times 55 = 489{,}500 \text{ L/day} = 490 \text{ kL/day}$$

Hence, the average daily water demand will increase from 314 kL/day in 2022 to 490 kL/day by 2052. This progressive rise in demand guides the capacity planning for source works, pumping, treatment, and storage facilities to ensure uninterrupted supply throughout the design horizon. Hence, the average daily demand will increase from 314 kL/day (2022) to 490 kL/day (2052).

4.5. Peak Factor (As per CPHEEO Norms)

Water demand in rural areas fluctuates daily and seasonally due to variations in consumption patterns. To account for these fluctuations, the Central Public Health and Environmental Engineering Organization (CPHEEO) recommends the use of a peak factor, which is the ratio of maximum daily demand to average daily demand. For rural populations below 20,000, a peak factor of 1.8 is considered appropriate. Peak factor accounts for daily and seasonal fluctuations.

For rural populations <20,000, Peak Factor = 1.8 is adopted.

$$Q_{max} = Q_{avg} \times 1.8$$

Year	Avg. Demand (kL/day)	Peak Demand (kL/day)
2022	314	565
2052	490	882

Accordingly, the peak day water requirement for the village is 565 kL/day in 2022 and will rise to 882 kL/day by 2052. This figure is critical for designing source capacity, pumping systems, and pipeline diameters to ensure that even during peak consumption periods, adequate pressure and flow are maintained throughout the network. Thus, the peak day requirement for 2022 is 565 kL/day, increasing to 882 kL/day by 2052.

4.6. Storage Requirement

Storage reservoirs are an integral part of the water supply system, serving as a buffer between variable supply and fluctuating demand. The required storage capacity depends on the daily demand, peak consumption, and operational strategy of the scheme. Generally, 30% to 50% of the average daily demand is adopted as the effective storage capacity for elevated service reservoirs (ESRs) in rural water supply schemes. Storage capacity acts as a buffer between variable supply and fluctuating demand.

$$S = 0.3 \text{ to } 0.5 \times Q_{avg}$$

For 2022:

$$S = 0.3\text{–}0.5 \times 314 = 94\text{–}157 \text{ kL}$$

For 2052:

$$S = 0.3\text{–}0.5 \times 490 = 147\text{–}245 \text{ kL}$$

Currently, Wadipir village has three existing ESRs with capacities of 25 kL, 45 kL, and 90 kL, giving a total storage of 160 kL. Although this meets the short-term requirement, it falls short of the projected future demand for 2052, where a total of approximately 440 kL of storage would be ideal. Therefore, the construction of an additional ESR or expansion of the existing ones is recommended to ensure adequate water availability during peak hours, maintenance shutdowns, or power outages. The existing ESR capacity is 25 + 45 + 90 = 160 kL, which is below the required storage for long-term demand. Hence, an expansion to ~440 kL total is recommended for the design period.

5. Complementary Sustainable System Design

To ensure long-term sustainability and energy independence, a hybrid water supply system integrating solar pumping and rainwater harvesting (RWH) is proposed. To ensure long-term sustainability, operational efficiency, and energy independence, a hybrid water supply system integrating solar pumping and rainwater harvesting (RWH) is proposed for Wadipir village. This approach aligns with the national objective of promoting renewable energy under the Jal Jeevan Mission (JJM) and the Sustainable Development Goals (SDG 6 and 7), which emphasize clean water access and affordable, clean energy. The proposed design makes efficient use of local hydrogeological conditions, solar potential, and community-scale water management strategies to ensure year-round supply with minimal reliance on grid electricity.

4.1. Source: Dug-Cum-Bore Well

The primary source of water for the system is a dug-cum-bore well, located in the basaltic geological formation characteristic of the Kolhapur region. The well depth ranges between 30 to 50 meters, ensuring reliable access to groundwater even during dry months. Based on field testing, the yield capacity is approximately 10 to 15 liters per second (LPS), which is sufficient to meet the village's 1 MLD (million liters per day) demand considering both current and future requirements.

- Depth: 30–50 m (basaltic formation)
- Yield: 10–15 LPS (adequate for 1 MLD)
- Sanitary protection: 30 m fenced zone with drainage diversion
- Pump house: 2×1.5 m platform, control panel

To ensure water quality and prevent contamination, the well is provided with a sanitary protection zone of 30 meters radius, enclosed by fencing and equipped with surface drainage diversion to prevent stormwater entry. A reinforced concrete (RCC) pump house measuring 2 meters by 1.5 meters is proposed adjacent to the well to house the control panel, valves, and electrical components. The well design ensures both hydraulic adequacy and environmental protection, forming a reliable source for the long-term operation of the water supply system.

4.2. Solar Pumping System

To achieve energy sustainability and minimize operational costs, the system integrates a solar photovoltaic (PV) powered pumping arrangement. The proposed system includes a 7.4 kWp solar PV array installed on a ground-mounted or elevated structure near the well. The array powers a 6.0 kW submersible pump capable of delivering 12 LPS at a 40-meter head, sufficient for the required daily pumping duration of 10–12 hours. The pumping operation is fully automated through a hybrid inverter/VFD controller of 7.5 kW capacity, allowing smooth motor operation and protection from voltage fluctuations.

- PV Capacity: **7.4 kWp**
- Pump: **6.0 kW submersible** (12 LPS @ 40 m head)
- Battery backup: **48V × 1000 Ah** (≈48 kWh nominal)
- Inverter/VFD: **7.5 kW hybrid controller**
- Daily operation: 10–12 hours
- **Annual energy savings:** ~25–30%
- **CO_2 reduction:** 10–12 tons/year

A battery backup bank of 48V × 1000 Ah (≈48 kWh) is incorporated to ensure pumping continuity during low sunlight or cloudy conditions, providing an autonomy of about five hours. This solar-powered system is expected to result in annual energy savings of approximately 25–30%, translating to significant reductions in electricity bills and dependency on the conventional grid. Moreover, the system will contribute to a carbon dioxide emission reduction of nearly 10–12 tons per year, making the entire water supply setup both environmentally responsible and economically viable in the long term.

4.3. Water Treatment Plant (WTP – 1 MLD)

A compact, low-maintenance Water Treatment Plant (WTP) of 1 MLD capacity is proposed to ensure that the supplied water meets drinking water standards as per IS 10500:2012. The plant design follows a simple, modular configuration suitable for rural schemes, requiring minimal operator skill and maintenance.

The treatment sequence includes:

1. **Aeration Chamber**, which facilitates the removal of dissolved gases such as hydrogen sulfide (H_2S) and carbon dioxide (CO_2), and enhances oxygen levels.
2. **Rapid Sand Filter (RSF)** unit, designed for turbidity and suspended solids removal, ensuring clear and aesthetically acceptable water.
3. **Disinfection Unit**, which employs **sodium hypochlorite dosing (1–2 mg/L)** to achieve effective microbial inactivation.
4. **Sludge Handling Unit**, which enables collection, drying, and safe disposal of backwash waste, ensuring minimal environmental impact.

The WTP is housed within an RCC-based compact structure covering an area of approximately 100–150 m². The layout is designed for ease of operation, safe chemical handling, and future scalability if demand increases.

4.4. Balancing Sump (120 kL)

A balancing sump with a capacity of 120,000 liters (120 kL) is proposed as an intermediate storage between the water treatment plant and the elevated service reservoirs (ESRs). This sump plays a crucial role in regulating the hydraulic flow within the system and compensating for operational variations in pumping or treatment cycles.

- Capacity: 120,000 L
- RCC underground with waterproof plaster
- Equipped with level sensors, washout, and vents
- Ensures hydraulic stability and 2–3 hr reserve

The structure is an RCC underground tank lined with waterproof plaster and equipped with essential features such as inlet and outlet control valves, level sensors, vents, and washout arrangements. The balancing sump provides a 2–3 hour buffer storage, which stabilizes the inflow and outflow rates, prevents overflow losses, and ensures uninterrupted water supply to ESRs even during intermittent pumping operations. The location and elevation of the sump are designed to optimize hydraulic gradients and minimize pumping energy. Acts as intermediate storage before ESR filling.

4.5. Elevated Storage Reservoirs (ESRs)

Water from the balancing sump is pumped to a network of Elevated Storage Reservoirs (ESRs) that distribute water to different zones of the village by gravity. Wadipir currently has three existing ESRs with capacities of 25 kL, 45 kL, and 90 kL, totaling 160 kL, constructed as RCC Intze-type tanks with 12–15 meters of staging height. These structures help maintain adequate pressure in the distribution network and ensure a steady supply during short-term power failures or maintenance shutdowns.

- Existing Capacity: 160 kL
- Height: 12–15 m staging

- Material: RCC (Intze type)
- Functions: Maintain pressure, supply during power outage

Based on the projected demand for 2052, an additional ESR of 280 kL is recommended. This will increase the total storage capacity to approximately 440 kL, which aligns with the long-term requirement calculated earlier. The design of the new ESR will conform to IS 3370 (Part 1–4) standards for reinforced concrete water tanks, with provisions for inlet-outlet isolation valves, overflow, and drain arrangements. Recommended augmentation: Additional ESR of 280 kL to meet 2052 demand.

4.6. Distribution Network

The proposed distribution network for Wadipir village is designed as a gravity-fed system, ensuring reliable delivery of water from the ESRs to each household without the need for secondary pumping. The network consists primarily of High-Density Polyethylene (HDPE) pipes (PE100, PN10 grade), selected for their corrosion resistance, hydraulic efficiency, and long service life.

- Type: Gravity-fed
- Material: HDPE (PE100, PN10)
- Length: ~6 km
- Design Flow: 6.5 LPS (Peak)
- Head Loss: <10 m across network
- Zoning with **Pressure Reducing Valves (PRVs)** in high areas
- Equipped with flow meters and automated control valves

The total network length is approximately 6 kilometers, designed to carry a peak flow of 6.5 liters per second (LPS). Hydraulic analysis ensures that head losses remain below 10 meters throughout the network, even under peak demand conditions. To maintain uniform pressure, Pressure Reducing Valves (PRVs) are strategically placed in elevated zones, preventing excessive pressure and pipe failures. Additionally, the network is fitted with flow meters, isolation valves, and automated control systems, allowing efficient monitoring and leakage management.

4.7. Household Connections

In alignment with the "Har Ghar Jal" goal of the Jal Jeevan Mission, every household in Wadipir village will receive an individual water service connection. Each connection will consist of a 15 mm HDPE service line connected to the nearest distribution main. On average, each household will be supplied with approximately 435 liters per day, sufficient for domestic needs of an average family of eight.

- Service Line: 15 mm HDPE
- Average Supply: 435 L/day per household
- Provision for metering and leakage detection

Provision has also been made for water meters at individual connections to enable consumption-based monitoring and billing, as well as leakage detection systems to minimize losses. These measures will promote accountability, equitable distribution, and sustainable use of water resources within the community.

4.8. Excess and Backwash Handling

To minimize wastage and promote groundwater recharge, all excess and backwash water from the treatment plant and storage structures is systematically managed. The backwash water from filters and the overflow from ESRs are directed to a settling and filtration chamber for removal of suspended solids. The treated water is then conveyed to recharge trenches or wells, allowing infiltration into the subsurface strata.

- Backwash and overflow routed to **recharge trench/well**
- Settling and filtration before percolation
- Reuse: Groundwater recharge (~30–50 kL/day potential)

This system not only prevents surface waterlogging but also contributes significantly to aquifer recharge, helping restore groundwater levels. It is estimated that approximately 30 to 50 kL per day of treated excess water can be effectively reused for recharge purposes, thus ensuring a closed-loop, environmentally sustainable water management approach.

4.9. Recharge Wells & Percolation Trenches

To enhance groundwater sustainability, a network of recharge wells and percolation trenches has been proposed. The recharge wells are designed with a 1.2-meter diameter and a depth of around 8 meters, filled with graded filter media comprising coarse sand, gravel, and pebbles to facilitate percolation and filtration. These wells are strategically located near ESRs, the WTP site, and community open spaces to maximize recharge potential.

- Recharge Wells: 1.2 m dia × 8 m deep (filter media)
- Percolation Trench: 0.6 m wide × 1 m deep × 20–30 m long
- Recharge potential: **10–15% of daily supply** (~30–50 kL/day)

In addition, percolation trenches measuring 0.6 meters in width, 1 meter in depth, and 20–30 meters in length are proposed along road shoulders and open drains to capture surface runoff during monsoon months. Together, these structures are expected to recharge approximately 10–15% of the total daily supply, equivalent to 30–50 kL/day. This groundwater recharge initiative will help improve well yields, stabilize water tables, and ensure water security even during prolonged dry periods.

6. Solar Pumping System – Detailed Design

The design of the solar pumping system for the proposed water supply scheme has been carried out based on the hydraulic requirements of the source and the overall operational efficiency of the pumping unit. The goal is to ensure that the solar photovoltaic (PV) system is optimally sized to meet the daily water demand while maintaining long-term reliability, energy efficiency, and economic viability.

The hydraulic parameters form the basis for determining the power rating of the solar-driven submersible pump. The required discharge (Q) has been determined as 13.08 liters per second (L/s), which ensures adequate water lifting capacity to meet the design demand of approximately 1 million liters per day (1 MLD), considering operational hours of 10–12 hours per day. The Total Dynamic Head (TDH), which includes static head, drawdown, delivery head, and minor losses, is estimated at 40 meters based on the depth of the dug-cum-bore well and the topographic elevation difference between the source and the balancing sump.

The overall pump efficiency (η) is considered as 65%, which is typical for high-quality submersible pumps operating under similar head and discharge conditions. Using the standard hydraulic power formula:

Hydraulic Inputs:

- Flow (Q) = 13.08 L/s
- TDH = 40 m
- Efficiency (η) = 0.65

Power Required:

$$P = \frac{Q \times H}{102 \times \eta} = \frac{13.08 \times 40}{66.3} = 7.89 \text{ HP} = 5.89 \text{ kW}$$

Thus, the pump power requirement is approximately 5.9 kW, which represents the effective mechanical power needed to deliver the design discharge against the total head. Accounting for electrical and control system losses, this value forms the basis for subsequent solar PV system sizing.

PV Array Sizing:

To ensure continuous and efficient pump operation throughout the day, the solar PV system must be sized with an appropriate margin to compensate for energy losses due to inverter inefficiency, cable transmission losses, dust accumulation on panels, and temperature variations that affect panel output. Typically, a **25% safety factor** is applied to the calculated power requirement. Hence, the total PV array capacity is determined as:

$$P_{PV} = 1.25 \times 5.89 = 7.36 \text{ kW}$$

$$P_{PV} = 1.25 \times 5.89 = 7.36 \text{ kW} \approx 7.4 \text{ kWp}$$

Panel Count (examples):

- 540 W panels → 14 nos.
- 450 W panels → 17 nos.
- 400 W panels → 19 nos.

For practical purposes, this is rounded to 7.4 kWp, ensuring the array can adequately power the 6.0 kW submersible pump even under sub-optimal solar irradiance conditions.

Depending on the panel wattage available, the total number of modules required can be estimated. For example:

- Using **540 W panels**, the system requires approximately **14 panels** (7.56 kWp).
- With **450 W panels**, around **17 panels** are needed (7.65 kWp).
- For **400 W panels**, about **19 panels** are necessary (7.6 kWp).

The final choice of module wattage depends on availability, site area, and layout considerations. The panels are proposed to be installed on south-facing ground-mounted galvanized steel structures with a tilt angle of 15–18°, optimized for the latitude of the project location. The system will include a 7.5 kW hybrid inverter with MPPT control to maximize power output and ensure stable pump operation.

To maintain reliable water supply during low solar radiation periods, cloudy weather, or early morning and evening operation, the system incorporates a battery backup capable of providing five hours of autonomy. The backup ensures uninterrupted operation of the 6.0 kW submersible pump when solar generation is insufficient.

The energy requirement for five hours of continuous operation is calculated as:

$$\textbf{Energy required} = 5.89\ \text{kW} \times 5\ \text{hours} = 29.45\ \text{kWh}$$

Considering the battery system efficiency of 82%, the total storage capacity needed is adjusted to account for internal losses:

$$\textbf{Required storage} = \frac{29.45}{0.82} = 35.9\ \text{kWh}$$

To meet this requirement, a 48V battery bank with a total capacity of 1000 Ah is selected, yielding approximately:

$$48\ \text{V} \times 1000\ \text{Ah} = 48{,}000\ \text{Wh} = 48\ \text{kWh (nominal)}$$

This capacity exceeds the minimum required 35.9 kWh, thereby ensuring sufficient reserve for power reliability and battery health. The selected Lithium Iron Phosphate ($LiFePO_4$) chemistry offers several advantages, including higher cycle life (up to 4000–5000 cycles), deep discharge capability (up to 90%), fast charging, and enhanced thermal stability compared to conventional lead-acid systems. The battery system will be integrated with a battery management system (BMS) for continuous monitoring of voltage, temperature, and state of charge, ensuring safe and efficient operation.

The integrated solar PV-battery-pump system is designed for **automatic operation** using a **hybrid controller** that prioritizes solar power during daylight hours and seamlessly shifts to battery supply when irradiance drops below the threshold. During peak solar hours (9 AM–4 PM), direct operation from the PV array minimizes battery usage, extending its life. The system is also designed to export excess energy to auxiliary loads, such as lighting or the water treatment plant's control units, during surplus generation periods.

The overall setup is expected to achieve **annual energy savings of around 25–30%** compared to a grid-powered pumping system. Additionally, it will contribute to a **reduction of approximately 10–12 tons of CO_2 emissions per year**, promoting the broader goal of **carbon-neutral rural infrastructure**. The combination of renewable energy utilization and water efficiency makes this system a sustainable model for decentralized rural water supply projects.

7. Rainwater Harvesting (RWH) Design

To enhance the sustainability and reliability of the proposed rural water supply scheme, an integrated Rainwater Harvesting (RWH) system is designed for the Wadipir village catchment area. This system aims to harness surface runoff and rooftop rainfall to supplement the groundwater-based supply, reduce dependence on energy-intensive pumping, and improve long-term water security. The design integrates hydrological assessment, collection infrastructure, storage components, and recharge structures to ensure optimal utilization of the available rainfall potential.

7.1. Rainfall Data

The hydrological potential for rainwater harvesting is primarily governed by the local rainfall pattern and the available catchment area. The region receives an average annual rainfall of approximately 950 mm, which is fairly well-distributed over the monsoon season, typically spanning from June to September. The total effective catchment area identified for the project is 35 hectares (ha), encompassing a mix of rooftops, paved surfaces, and open agricultural fields. This diversified catchment composition provides an opportunity to collect both direct roof runoff and surface water flows during monsoon events. The geographical gradient of the site naturally directs the surface flow toward the southern lowland zone, making it an ideal location for constructing a centralized storage and recharge system.

- Average Annual Rainfall = **950 mm**
- Catchment Area = **35 ha**

7.2. Runoff Estimation

Runoff estimation has been carried out using the rational method, which applies the formula:

$$\boldsymbol{Q = C \times I \times A}$$

where C is the runoff coefficient (dimensionless), I is rainfall intensity (mm), and A is the catchment area (ha). Based on the land use classification, the total catchment is divided into three primary categories—rooftops, paved areas, and agricultural lands—each assigned a suitable runoff coefficient based on surface characteristics. The resulting runoff potential is summarized in Table 3.

Table No.3 Runoff Estimation

Catchment Type	Area (ha)	Coefficient (C)	Annual Runoff (m³)
Rooftops	6.0	0.8	4,560
Paved Areas	4.0	0.6	2,280
Agricultural Land	25.0	0.3	7,125
Total	**35.0**	—	**13,965 m³/year**

≈ 14,000 m³/year (~40 kL/day equivalent)

The total estimated annual runoff amounts to **approximately 14,000 cubic meters**, equivalent to an average of **40 kiloliters (kL) per day** when distributed over the year. This runoff volume represents a significant supplementary water source, capable of contributing to both direct storage and groundwater recharge, thereby enhancing system resilience during dry periods.

7.3. RWH Components

Component 1: Collection System

The collection system comprises a network of rooftop gutters and surface drains designed to intercept and convey rainfall runoff to the storage reservoir. PVC gutters of 100 mm diameter are provided along building rooftops, while surface runoff is channeled through silt-trap-equipped drains to remove suspended solids and debris. The entire collection network, extending over 2.1 km, is constructed from 110 mm HDPE pipes laid at a uniform slope of 0.5–1.0% to facilitate gravity flow. This network ensures minimal losses and efficient conveyance of rainwater from all contributing catchments to the storage zone.

- Rooftop gutters (PVC 100 mm)
- Surface drains with silt traps
- Collection network (110 mm HDPE, 2.1 km, 0.5–1% slope)

Component 2: Storage Reservoir

A centralized storage reservoir of 12,000 m³ capacity is proposed to store the collected runoff during the monsoon period. The reservoir is designed as an earthen-cum-masonry bund structure, measuring approximately 4.5 meters in height and 120 meters in length. To minimize seepage losses and ensure water quality, the reservoir base is lined with a 1 mm thick HDPE geomembrane sheet. An overflow arrangement is provided to divert excess water to the percolation trenches, thereby preventing overtopping during heavy rainfall events. The reservoir is strategically located near the balancing sump in the southern lowland zone, optimizing hydraulic connectivity and operational efficiency within the existing water supply layout.

- Capacity: 12,000 m³
- Earthen-cum-masonry bund (4.5 m high, 120 m long)
- Lined base with 1 mm HDPE sheet
- Overflow to percolation trench
- Located near balancing sump (southern lowland zone)

Component 3: Recharge & Percolation

To promote aquifer sustainability and improve groundwater levels, the system incorporates five recharge wells of 1.2 m diameter and 15 m depth, equipped with graded gravel and sand filters for sediment removal. Additionally, two percolation trenches, each 1.5 m deep and 100 m long, are designed to facilitate gradual infiltration of excess water into the subsoil. The combined recharge potential of these structures is estimated at approximately 2,500 m³ per year, effectively offsetting part of the extraction volume from borewells and improving water table stability.

- 5 recharge wells (1.2 m dia, 15 m deep)
- 2 percolation trenches (1.5 m deep × 100 m long)
- Recharge capacity: 2,500 m³/year

7.4. Integration with Existing System

The proposed RWH system is designed to seamlessly integrate with the existing water supply infrastructure, ensuring both operational efficiency and sustainability. In the existing configuration, water is drawn from the source well by the solar-powered submersible pump, treated in the 1 MLD water treatment plant (WTP), and conveyed through the balancing sump and elevated storage reservoirs (ESRs) to individual households. Overflow and backwash water are partially directed to a recharge trench.

Existing Flow: Well → Solar Pump → WTP → Balancing Sump → ESR → Households → Overflow → Recharge

Proposed Integration: Rooftop/Surface Runoff → Collection Network → Storage Reservoir → Balancing Sump → WTP/ESR → Households + Recharge Wells

This ensures **continuous water availability** and **aquifer recharge**, enhancing long-term sustainability.

In the proposed integrated arrangement, the rainwater collected from rooftops and surface runoff is routed through the collection network to the storage reservoir, from which it can be directed to the balancing sump or treatment plant for blending with the regular supply. Surplus water is then conveyed to the recharge wells and percolation trenches. This integrated flow cycle — *Rooftop/Surface Runoff → Collection Network → Storage Reservoir → Balancing Sump → WTP/ESR → Households + Recharge Wells* — ensures efficient use of rainfall, reduction in groundwater dependency, and continuous aquifer replenishment, promoting long-term self-sufficiency.

7.5. Cost Estimate Summary

Table No.4 Cost Estimation

Item	Cost (₹ Lakh)
Rooftop collection system	50.33
Collection network	25.20
Silt chambers/first flush	1.50
Storage reservoir	18.00
Bund & earthwork	11.70
Lining & sluice	3.50
Recharge wells (5 nos.)	4.50
Percolation trenches	2.00

Miscellaneous works	1.50
Contingencies (5%)	5.00
Total Estimated Cost	**≈ ₹123.2 Lakh**

7.6. Environmental and Social Benefits

Environmental:

The system significantly reduces soil erosion and uncontrolled surface runoff, thus preventing land degradation. The induced rise in the groundwater table by 0.5–1.0 meters improves borewell sustainability and ensures continuous availability of water even during dry seasons. Enhanced soil moisture supports local vegetation growth, thereby improving the microclimate and reducing local temperatures marginally. Furthermore, by lowering dependence on electrically powered groundwater extraction, the system contributes to reduced carbon emissions and supports the broader climate resilience goals of rural infrastructure projects.

- Reduction in soil erosion and surface runoff
- Rise in groundwater table (0.5–1.0 m)
- Improved local vegetation and microclimate
- Lower carbon emissions from reduced power use

Social:

From a socio-economic perspective, the RWH system enhances water security and reliability for domestic, agricultural, and livestock use. The availability of additional water for gardening, community green spaces, and livestock fosters rural livelihood improvement. The project also generates local employment opportunities during the construction and maintenance phases, thereby strengthening the rural economy. Importantly, the participatory approach promoted during the planning and maintenance stages encourages community involvement and ownership, fostering a sense of responsibility and sustainability within the village population.

- Enhanced water reliability and self-sufficiency
- Availability for livestock and gardens
- Employment in construction and maintenance
- Increased community participation and ownership

8. CONCLUSIONS

1. The present study on the design and integration of a sustainable rural water supply system for Wadipir village demonstrates a holistic and future-ready approach to addressing rural water scarcity through the combined application of engineering design principles, renewable energy utilization, and rainwater harvesting (RWH). By adopting a 30-year design horizon (2022–2052), the project ensures that water demand, infrastructure capacity, and environmental sustainability are all aligned with long-term development objectives.
2. The population analysis and demand forecasting revealed that the village population is expected to grow from 5,700 persons in 2022 to approximately 8,900 persons by 2052, representing a 56% increase. Correspondingly, the average daily water demand will rise from 314 kL/day to 490 kL/day, while the peak demand will increase from 565 kL/day to 882 kL/day. This progressive rise guided the sizing of all system components, including source works, storage reservoirs, treatment units, and the distribution network. The analysis confirmed that the existing 160 kL elevated storage capacity is insufficient for future requirements, necessitating augmentation to approximately 440 kL for stable and efficient water supply operations.
3. A critical component of the system design is the solar-powered pumping unit, which ensures energy independence and operational sustainability. The hydraulic analysis determined the required discharge of 13.08 L/s at a total dynamic head of 40 m, resulting in a pump power requirement of 5.9 kW. Based on this, a 7.4 kWp photovoltaic (PV) array was designed, complemented by a 48V, 1000 Ah $LiFePO_4$ battery bank, providing approximately five hours of autonomy. This configuration enables 10–12 hours of daily pumping operation and achieves annual energy savings of 25–30%, reducing carbon emissions by 10–12 tons per year. The adoption of solar power not only enhances cost efficiency but also contributes to India's renewable energy targets under the Jal Jeevan Mission (JJM) and the broader Sustainable Development Goals (SDGs).
4. The integration of rainwater harvesting further enhances the self-sufficiency and resilience of the system. The hydrological assessment, based on an average annual rainfall of 950 mm and a total catchment area of 35 hectares, estimated an annual runoff potential of approximately 14,000 m^3, equivalent to 40 kL/day. The RWH system—comprising rooftop collection networks, an earthen-cum-masonry storage reservoir of 12,000 m^3 capacity, five recharge wells, and two percolation trenches—plays a crucial role in both surface storage and aquifer recharge. The estimated recharge capacity of 2,500 m^3/year contributes significantly to groundwater sustainability, ensuring consistent water availability during dry periods and reducing dependency on borewell extraction.
5. From a financial perspective, the total estimated project cost for the RWH system is around ₹123.2 lakh, which includes the rooftop collection network, reservoir construction, bunding, lining, recharge structures, and contingencies. Though the initial capital investment appears substantial, the long-term operational savings—derived from reduced electricity consumption, lower groundwater extraction, and minimal maintenance—make the project economically viable and environmentally sustainable. The solar-RWH hybrid system exemplifies a low-carbon, low-maintenance, and high-reliability model suitable for replication across rural settlements in semi-arid regions.
6. Beyond the technical and economic merits, the project yields significant environmental and social benefits. Environmentally, it mitigates soil erosion, reduces stormwater runoff, and enhances local vegetation and microclimatic conditions. The expected rise in groundwater levels by 0.5–1.0 meters further ensures the sustainability of local aquifers. Socially, the system enhances water

security, reliability, and community resilience, providing water not only for domestic use but also for livestock and green area maintenance. The participatory implementation approach fosters community ownership and local employment, empowering residents to manage and maintain the infrastructure effectively.

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