Climate-Resilient Rural Water Supply Systems in India: Integration of Sustainability, Smart Infrastructure, and Water Security under Jal Jeevan Mission

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ABSTRACT

Rural water supply systems in India are undergoing a significant transformation from infrastructure-oriented schemes toward integrated climate-resilient water security frameworks under the Jal Jeevan Mission (JJM). Traditionally, rural water supply projects primarily focused on providing basic infrastructure such as hand pumps, bore wells, pipelines, and limited distribution systems. However, increasing groundwater depletion, climate variability, water quality deterioration, and rising rural water demand have necessitated the development of sustainable, technology-driven, and environmentally resilient water management systems. This paper critically reviews the evolving framework of rural water supply infrastructure in India by integrating engineering systems, groundwater recharge mechanisms, climate-resilient infrastructure planning, smart water management technologies, ESG-based development principles, and circular water economy concepts. The study adopts a qualitative analytical review methodology based on government reports, technical manuals, policy documents, and published literature related to Jal Jeevan Mission, Integrated Water Resource Management (IWRM), and sustainable rural infrastructure development. The review highlights the importance of source sustainability, decentralized governance, smart monitoring systems, and groundwater recharge structures in ensuring long-term rural water security. Case studies from Gujarat, Telangana, Rajasthan, and Maharashtra demonstrate the effectiveness of integrated water infrastructure models in improving service reliability and climate resilience. The paper further examines implementation challenges such as groundwater overexploitation, operation and maintenance deficiencies, financial sustainability constraints, and institutional fragmentation. The study concludes that future-ready rural water systems in India must integrate engineering infrastructure, environmental sustainability, digital monitoring, climate adaptation, and community participation to ensure equitable and resilient rural water security aligned with Sustainable Development Goals (SDGs).

Keywords: Rural water supply, Jal Jeevan Mission, climate resilience, groundwater recharge, water security, ESG infrastructure, smart water systems, Integrated Water Resource Management, circular water economy, sustainable rural infrastructure.

INTRODUCTION

Access to safe drinking water is a fundamental requirement for sustainable development, public health protection, and social well-being. Globally, nearly 2 billion people still do not have access to safely managed drinking water services, particularly in rural and climate-vulnerable regions. Developing countries face increasing pressure on water resources due to rapid population growth, urbanization, industrialization, groundwater depletion, and climate change.

India is among the most water-stressed countries in the world despite receiving significant annual rainfall. Rural areas continue to face severe challenges related to seasonal water scarcity, declining groundwater levels, inadequate infrastructure, poor operation and maintenance practices, and water quality contamination caused by fluoride, arsenic, iron, and bacteriological pollutants. According to NITI Aayog estimates, nearly 600 million people in India face high to extreme water stress, while groundwater contributes approximately 85% of rural drinking water supply.

Historically, rural water supply systems in India focused mainly on infrastructure development through bore wells, hand pumps, and isolated piped water supply systems. However, such approaches frequently failed due to inadequate source sustainability planning, poor governance mechanisms, limited maintenance systems, and climate-induced variability in water availability.

The launch of the Jal Jeevan Mission (JJM) in 2019 under the vision of "Har Ghar Jal" marked a paradigm shift in India's rural water supply strategy. The mission emphasizes Functional Household Tap Connections (FHTCs), source sustainability, community participation, water quality surveillance, greywater management, and decentralized operation and maintenance systems.

Modern rural water supply systems combine:

- Source sustainability
- Groundwater recharge
- Water treatment
- Smart monitoring
- Community participation
- Environmental protection
- Climate resilience
- Zero discharge and reuse concepts
- Climate-resilient infrastructure planning
- Integrated Water Resource Management (IWRM)
- ESG-based infrastructure development
- Smart monitoring systems
- Circular water economy concepts
- Sustainable groundwater management

These systems directly contribute to rural development, public health, women empowerment, sanitation, and long-term environmental sustainability.

Despite significant progress, several challenges remain concerning climate adaptation, institutional coordination, energy efficiency, long-term sustainability, groundwater depletion, and operational resilience.

This paper critically reviews the emerging framework of rural water supply systems in India and examines the integration of sustainability, smart infrastructure, climate resilience, ESG principles, and water security concepts under Jal Jeevan Mission.

Under the vision of **"Har Ghar Jal"** through the **Jal Jeevan Mission**, India is transforming rural water infrastructure from isolated water supply systems into comprehensive water security and public health programmes.

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Concept of Rural Water Supply

A rural water supply scheme is a complete chain that starts from the water source and ends at the household tap connection.

The system includes:

- Water source development
- Source sustainability measures
- Water abstraction systems
- Treatment and storage infrastructure
- Transmission and distribution networks
- Household tap connections
- Monitoring and automation systems
- Operation & maintenance frameworks
- Wastewater management and recharge systems

Thus, rural water supply is fundamentally a **water security management system**, not only a civil engineering project.

Jal Jeevan Mission and "Har Ghar Jal"

The Government of India launched the Jal Jeevan Mission to provide:

- Functional Household Tap Connections (FHTC)
- Safe drinking water to every rural household
- Sustainable and equitable water supply
- Community-managed water infrastructure

Complete Components of a Rural Water Supply Scheme

C.1 Water Source Identification and Sustainability

The first and most critical component is the identification of a sustainable water source.

Possible sources include

- Surface water reservoirs
- Rivers and canals
- Groundwater aquifers
- Springs in hilly regions
- Rainwater harvesting structures

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Key activities include

- Hydrogeological investigation
- Aquifer mapping
- Yield assessment
- Water quality analysis
- Seasonal reliability studies

Source sustainability measures include:

- Watershed development
- Catchment protection
- Recharge pits
- Percolation tanks
- Check dams
- Recharge shafts
- Rainwater harvesting

These measures help maintain long-term groundwater availability and reduce over-extraction.

C2. Groundwater Recharge and Water Conservation Systems

Groundwater recharge is essential for sustainable rural water supply.

Major Recharge Structures

Recharge Pits

Used to infiltrate rooftop and storm water runoff into shallow aquifers.

Recharge Shafts

Deep recharge structures used where top strata are impermeable.

Check Dams

Small barriers constructed across streams to increase infiltration and groundwater recharge.

Percolation Tanks

Store runoff water and promote slow infiltration into groundwater zones.

Farm Ponds and Recharge Trenches

Improve local water retention and aquifer recharge.

These systems:

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- Improve groundwater levels
- Increase drought resilience
- Reduce dependency on deep borewells
- Enhance source sustainability

C3. Water Abstraction and Intake Infrastructure

Depending on the source type, the scheme includes:

Intake Structures

- River intake wells
- Jack wells
- Infiltration galleries

Pumping Systems

- Raw water pumping stations
- Submersible pumps
- Vertical turbine pumps
- Solar-powered pumping systems

Modern systems increasingly use:

- Energy-efficient pumps
- Variable frequency drives (VFDs)
- Solar photovoltaic systems
- Smart energy management

C4. Water Treatment Infrastructure

Water treatment is critical for public health protection.

Typical Water Treatment Plant (WTP) Components

Preliminary Treatment

- Screening
- Grit removal
- Aeration

Primary Treatment

- Coagulation

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- Flocculation
- Sedimentation

Filtration

- Rapid sand filters
- Pressure filters
- Multimedia filtration

Disinfection

- Chlorination
- UV treatment
- Ozonation (limited cases)

Water treatment plants ensure:

- Removal of turbidity
- Bacterial control
- Fluoride and iron removal
- Arsenic mitigation
- Safe potable water standards

C5. Storage and Distribution Infrastructure

Storage Structures

Clear Water Reservoirs (CWR)

Elevated Storage Reservoirs (ESR)

Ground Service Reservoirs (GSR)

Distribution Network

The distribution system includes:

- Rising mains
- Transmission pipelines
- Distribution pipelines
- Valve chambers
- Air valves and scour valves
- Pressure reducing valves

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- Bulk meters
- Household service connections

Proper hydraulic design ensures:

- Adequate residual pressure
- Uniform distribution
- Reduced leakage

Minimum non-revenue water losses

LITERATURE REVIEW

Global Rural Water Supply Challenges

International studies indicate that sustainable rural water supply remains a major challenge in developing economies due to inadequate infrastructure financing, climate vulnerability, groundwater depletion, and institutional fragmentation. WHO and UNICEF Joint Monitoring Programme (JMP) reports emphasize that service sustainability depends not only on infrastructure creation but also on long-term operation, source security, and governance systems.

Several African and Asian countries continue to face high rates of rural water system failure due to poor maintenance practices, energy shortages, and inadequate community ownership.

Rural Water Supply in India

Studies on rural water supply in India highlight the historical dependence on groundwater-based systems and the limitations of isolated infrastructure-centric approaches. Earlier rural schemes often suffered from:

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- Source failure
- Seasonal unreliability
- Groundwater depletion
- Poor water quality
- Inadequate O&M systems
- Limited institutional accountability

Recent literature emphasizes the importance of:

- Multi-source water systems
- Groundwater recharge
- Smart monitoring technologies
- Decentralized governance
- Community participation
- Water quality surveillance

Climate Resilience and Water Infrastructure

Climate change is increasingly affecting hydrological cycles, groundwater recharge, rainfall patterns, and drought frequency. Research indicates that future rural water systems must adopt:

- Climate-adaptive infrastructure
- Recharge-based sustainability
- Multi-source integration
- Flood-resilient infrastructure
- Energy-efficient pumping systems

Studies also highlight the growing role of solar-powered pumping systems, smart SCADA monitoring, and IoT-based water management technologies in improving system resilience.

Research Gap

Existing studies primarily focus on either infrastructure expansion, groundwater management, or governance systems independently. Limited research comprehensively integrates:

- Engineering infrastructure
- Climate resilience
- ESG principles
- Smart monitoring systems

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- Circular water economy
- IWRM frameworks

within a unified rural water security framework for India.

This paper addresses this gap through an integrated analytical review of sustainable rural water infrastructure systems.

RESEARCH METHODOLOGY

The study adopts a qualitative analytical review methodology based on secondary data, technical reports, policy documents, and published literature.

Data Sources

The analysis is based on:

- Jal Jeevan Mission reports
- Ministry of Jal Shakti publications
- NITI Aayog reports
- Central Ground Water Board data
- WHO and UNICEF reports
- IPCC climate assessment reports
- Peer-reviewed journal articles
- Rural infrastructure technical manuals

Analytical Framework

The study evaluates rural water supply systems using the following dimensions:

- Engineering infrastructure
- Source sustainability
- Climate resilience
- Water governance
- Smart technologies
- ESG-based infrastructure development
- Circular water economy concepts

Scope of the Study

The study focuses on:

- Rural piped water supply systems

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- Groundwater recharge infrastructure
- Water treatment and storage systems
- Smart monitoring technologies
- Climate-resilient planning approaches
- Decentralized governance systems

Quantitative Data and Statistics

Rural Water Supply Coverage in India

Parameter	Estimated Value
Rural households with tap water access in 2019	~17%
Rural households with tap water access in 2026	>75%
Groundwater contribution to rural drinking water	~85%
Population facing water stress in India	~600 million
Districts affected by groundwater depletion	>250
Average NRW losses in rural systems	20–40%

Climate Vulnerability Indicators

Climate Risk	Impact on Rural Water Systems
Erratic monsoon	Reduced recharge
Heat waves	Increased demand
Drought	Source failure
Flash floods	Infrastructure damage
Groundwater depletion	Reduced sustainability

Case Studies

Gujarat Rural Water Grid

Gujarat developed an integrated rural water grid system connecting surface reservoirs, transmission pipelines, pumping systems, and village-level distribution networks. The project significantly reduced groundwater dependency and improved drought resilience in water-scarce regions.

Telangana Mission Bhagiratha

Mission Bhagiratha implemented a large-scale rural drinking water infrastructure network integrating centralized treatment plants, bulk transmission systems, ESRs, and household tap connections. The program improved rural water accessibility and service reliability.

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Rajasthan Groundwater Recharge Initiatives

Rajasthan implemented recharge structures including check dams, percolation tanks, and recharge wells in drought-prone districts. These interventions improved groundwater levels and increased long-term water availability.

Hiware Bazar Watershed Model, Maharashtra

Hiware Bazar village adopted integrated watershed management, groundwater recharge, water budgeting, and community participation, transforming a drought-prone village into a sustainable water management model.

Figures and Tables

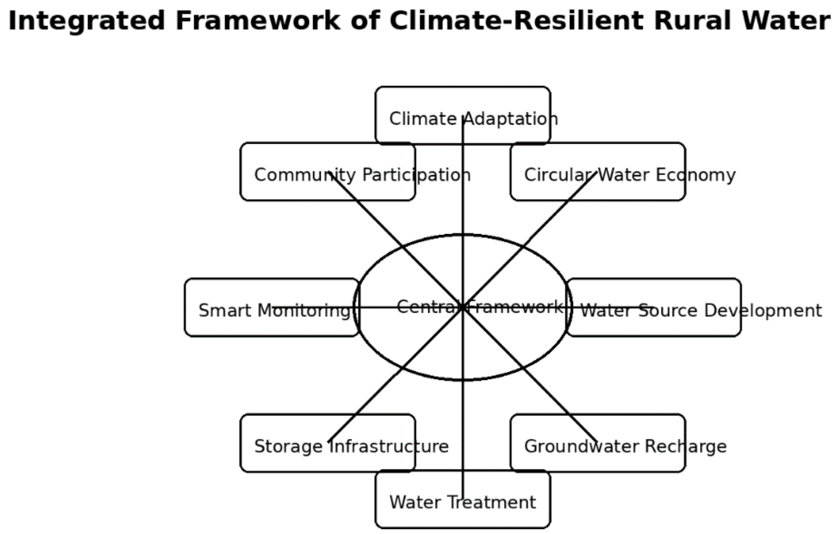

Figure 1

Integrated Framework of Climate-Resilient Rural Water Supply Systems

Figure Description

The figure should illustrate a circular integrated framework showing interconnected components:

Central Core

“Climate-Resilient Rural Water Security”

Connected Components:

- Water Source Development
- Groundwater Recharge
- Water Treatment Systems
- Storage Infrastructure

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- Smart Monitoring
- Community Participation
- ESG Governance
- Climate Adaptation
- Wastewater Reuse
- Circular Water Economy

Outer Layer:

- SDGs
- Sustainability
- Public Health
- Environmental Protection
- Rural Development

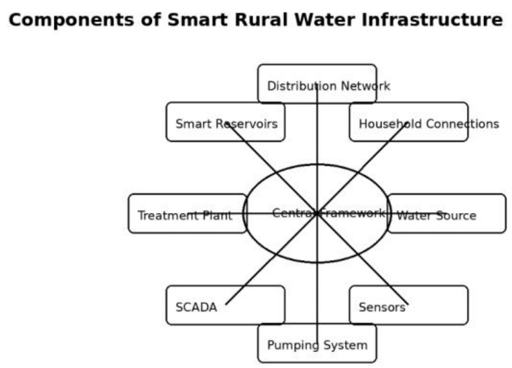

Figure 2

Components of Smart Rural Water Infrastructure

Figure Description

Create a flow-based technical schematic showing:

Water Source → Sensors → Pumping System → SCADA Control → Treatment Plant → Smart Reservoirs → Distribution Network → Household Connections

Supporting Smart Components:

- IoT Sensors
- GIS Mapping
- Digital Dashboard
- Remote Monitoring

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- Leak Detection
- Smart Metering

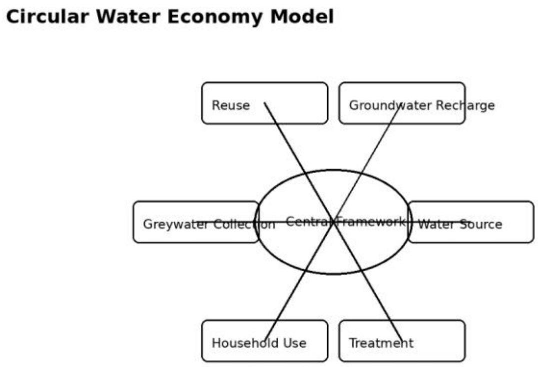

Figure 3

Circular Water Economy Model for Rural Areas

Figure Description

A circular cycle diagram including:

Water Source →

Water Treatment → Household Use → Greywater Collection → Decentralized Treatment → Reuse for Irrigation/Gardening → Groundwater Recharge → Back to Source Sustainability

Add sustainability arrows showing:

- Reduced Pollution
- Reduced Freshwater Demand
- Aquifer Recharge
- Water Reuse

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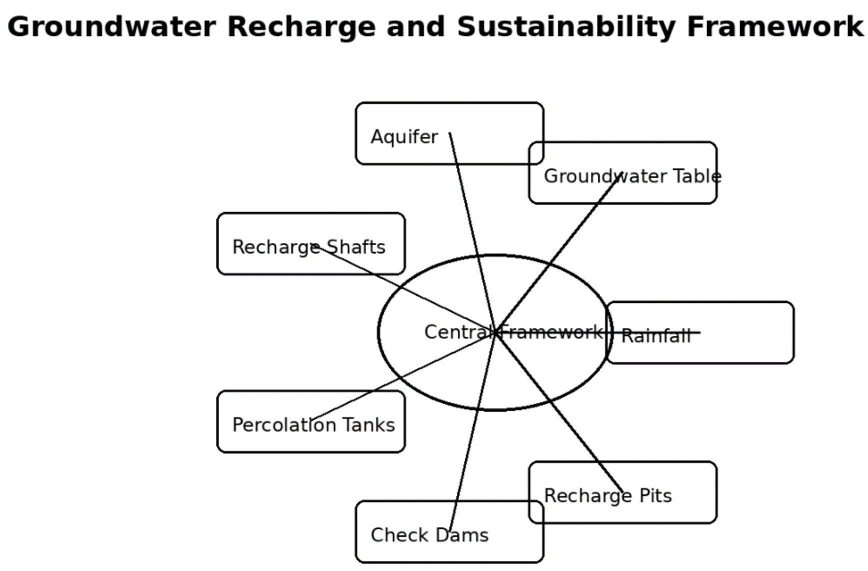

Figure 4

Groundwater Recharge and Sustainability Framework

Figure Description

Cross-sectional hydrogeological schematic showing:

- Rainfall
- Surface runoff
- Recharge pits
- Check dams
- Percolation tanks
- Recharge shafts
- Aquifer layers
- Groundwater table
- Bore wells

Show arrows indicating infiltration and groundwater recharge pathways.

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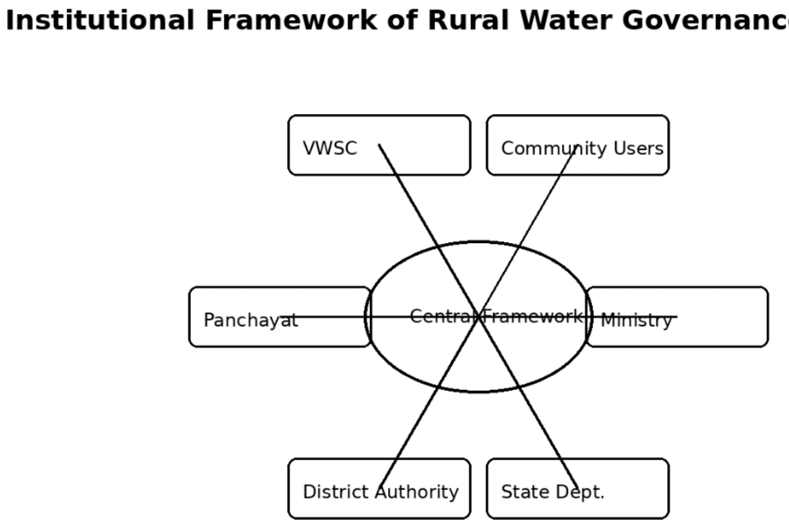

Figure 5

Institutional Framework of Rural Water Governance

Figure Description

Hierarchical governance model showing:

- Ministry of Jal Shakti
- State Water Departments
- District Water Authorities
- Panchayats
- Village Water and Sanitation Committees (VWSCs)
- Community Users

Show interaction arrows for:

- Monitoring
- Funding
- O&M
- Governance
- Water Quality Surveillance

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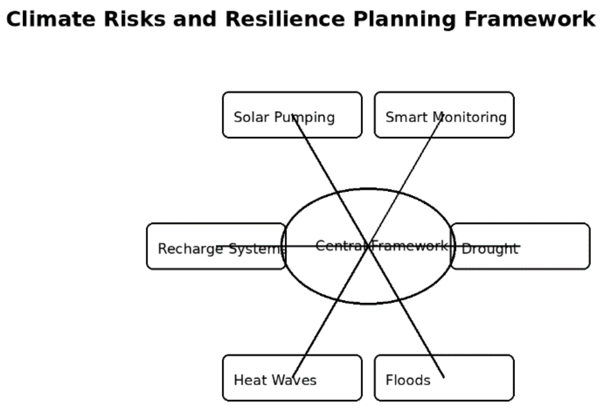

FIGURE 6

Climate Risks and Resilience Planning Framework

Figure Description

Left Side:

Climate Risks

- Drought
- Floods
- Heat Waves
- Groundwater Depletion
- Erratic Rainfall

Right Side:

Adaptation Measures

- Multi-source systems
- Recharge infrastructure
- Flood-resilient design
- Solar pumping
- Smart monitoring
- Demand management

Centre:

“Climate-Resilient Water Infrastructure”

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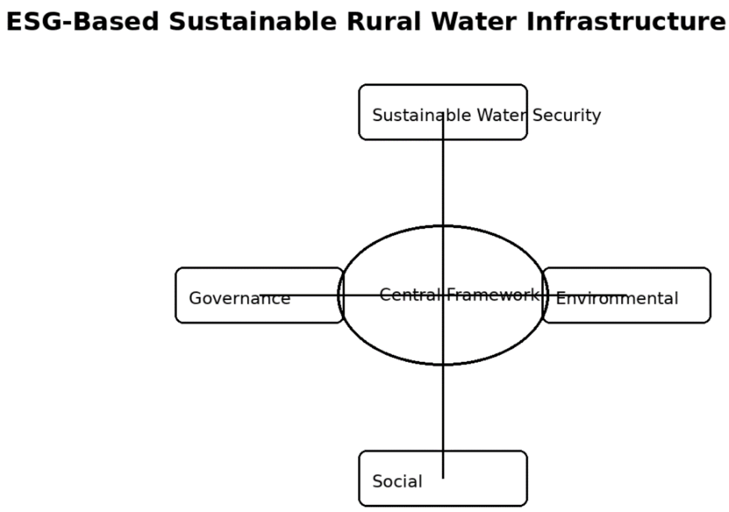

Figure 7

ESG-Based Sustainable Rural Water Infrastructure Model

Figure Description

Three intersecting circles:

- Environmental
- Social
- Governance

  Inside intersections:

- Sustainable extraction
- Public health
- Transparency
- Women participation
- Renewable energy
- Smart governance
- Community ownership

Centre:

"Sustainable Rural Water Security"

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Tables and Figures for Scopus Journal Manuscript

Table 1

Comparison Between Conventional and Modern Rural Water Supply Systems

Parameter	Conventional Rural Water Systems	Modern Climate-Resilient Rural Water Systems
Primary Objective	Basic water access	Sustainable water security
Water Source	Single groundwater source	Multi-source integrated systems
Infrastructure Focus	Pipelines and pumps	Integrated socio-technical systems
Source Sustainability	Limited consideration	Recharge-based sustainability
Water Treatment	Minimal treatment	Advanced multi-stage treatment
Monitoring	Manual inspection	IoT and SCADA-based monitoring
Energy Systems	Grid-dependent pumps	Solar and energy-efficient systems
Governance	Department-centric	Community-managed governance
Climate Resilience	Limited	Climate-adaptive infrastructure
Wastewater Management	Neglected	Circular water economy and reuse
Asset Management	Reactive maintenance	Predictive digital maintenance
Water Quality Surveillance	Periodic testing	Real-time monitoring systems
Sustainability Approach	Infrastructure-oriented	ESG and SDG aligned systems

Table 2

Major Groundwater Recharge Structures and Their Functions

Recharge Structure	Primary Function	Technical Application	Key Benefits
Recharge Pits	Storm water infiltration	Rooftop runoff recharge	Improves shallow aquifer recharge
Recharge Shafts	Deep aquifer recharge	Impermeable top strata areas	Enhances deep groundwater levels
Check Dams	Flow retardation and infiltration	Seasonal streams	Reduces runoff and increases recharge
Percolation Tanks	Surface storage and infiltration	Rural catchment areas	Sustains groundwater availability
Farm Ponds	Local water retention	Agricultural regions	Enhances drought resilience
Recharge Trenches	Linear infiltration	Roadside and open areas	Improves recharge efficiency

Rainwater Harvesting Systems	**Rainwater conservation**	**Rooftops and community buildings**	**Reduces dependency on groundwater**
Watershed Structures	**Catchment treatment**	**Hilly and drought-prone regions**	**Improves ecosystem sustainability**

Table 3

Climate Risks and Adaptation Strategies in Rural Water Infrastructure

Climate Risk	**Impact on Water Systems**	**Adaptation Strategy**
Erratic Rainfall	**Reduced recharge and unreliable supply**	**Multi-source water systems**
Drought Conditions	**Groundwater depletion**	**Recharge-based sustainability planning**
Flash Floods	**Damage to pipelines and pump houses**	**Elevated and flood-protected infrastructure**
Heat Waves	**Increased water demand**	**Demand-side management and storage optimization**
River Flow Variability	**Unstable surface water supply**	**Integrated reservoir management**
Groundwater Decline	**Reduced borewell yield**	**Aquifer recharge and watershed development**
Energy Disruptions	**Pumping interruptions**	**Solar-powered pumping systems**
Water Quality Deterioration	**Public health risks**	**Advanced treatment and surveillance systems**

Table 4

ESG Indicators in Rural Water Infrastructure Development

ESG Component	**Indicators**	**Infrastructure Implications**
Environmental	**Groundwater recharge**	**Sustainable source management**
Environmental	**Renewable energy use**	**Reduced carbon footprint**
Environmental	**Wastewater reuse**	**Circular water economy**
Environmental	**Leakage reduction**	**Lower non-revenue water losses**
Social	**Household tap connections**	**Improved public health**
Social	**Women participation**	**Gender-inclusive governance**
Social	**Community ownership**	**Improved sustainability**
Social	**Water quality surveillance**	**Reduced disease burden**
Governance	**SCADA monitoring**	**Transparency and accountability**
Governance	**Digital dashboards**	**Performance monitoring**

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Governance	**GIS asset mapping**	**Efficient infrastructure management**
Governance	**Community auditing**	**Improved institutional governance**

Table 5

Major Components of Rural Water Supply Systems

System Component	**Key Infrastructure Elements**	**Functional Role**
Source Development	**Reservoirs, aquifers, springs**	**Water availability**
Recharge Infrastructure	**Check dams, recharge pits**	**Source sustainability**
Intake Systems	**Jack wells, intake wells**	**Raw water abstraction**
Pumping Systems	**Pumps, VFDs, solar systems**	**Water conveyance**
Water Treatment Plants	**Filters, chlorination units**	**Water purification**
Storage Systems	**CWR, ESR, GSR**	**Supply balancing**
Distribution Networks	**Pipelines, valves, meters**	**Water delivery**
Smart Monitoring	**IoT sensors, SCADA**	**Real-time management**
Water Quality Systems	**Testing labs, sensors**	**Public health protection**
O&M Systems	**Maintenance frameworks**	**Long-term sustainability**
Wastewater Systems	**Reed beds, soak pits**	**Greywater reuse**

Table 6

Smart Technologies Used in Modern Rural Water Supply Systems

Technology	**Function**	**Benefits**
IoT Sensors	**Flow and pressure monitoring**	**Real-time performance tracking**
SCADA Systems	**Remote monitoring and automation**	**Improved operational efficiency**
GIS Mapping	**Asset and network mapping**	**Better maintenance planning**
GPS Surveying	**Infrastructure positioning**	**Accurate asset management**
Smart Meters	**Consumption measurement**	**Demand management**
Digital Dashboards	**Data visualization**	**Governance transparency**
AI-Based Analytics	**Predictive maintenance**	**Reduced system failures**
Solar Pumping Systems	**Renewable energy integration**	**Lower operational cost**

CRITICAL DISCUSSION

Despite substantial progress under Jal Jeevan Mission, several challenges remain.

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Groundwater Overexploitation

Many rural schemes continue to rely heavily on groundwater extraction, increasing long-term sustainability risks.

Operation and Maintenance Challenges

Rural systems frequently suffer from:

- Pump failures
- Leakage losses
- Poor maintenance
- Energy inefficiency
- Limited technical manpower

Financial Sustainability

High energy costs, inadequate tariff recovery, and dependence on government funding affect long-term sustainability.

Institutional Fragmentation

Coordination gaps between departments, local bodies, and agencies often delay implementation and maintenance activities.

Climate Risks

Climate variability is increasing uncertainty in:

- Water availability
- Groundwater recharge
- Reservoir reliability
- Infrastructure performance

Future Research and Policy Directions

Future rural water systems should focus on:

- AI-enabled predictive monitoring
- Smart metering systems
- Digital twins for water infrastructure
- Renewable-energy-powered pumping
- Decentralized wastewater reuse
- Climate-resilient infrastructure design

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- Integrated aquifer management
- Community-led governance models

CONCLUSION

Rural water supply systems in India are evolving from conventional infrastructure-oriented schemes toward integrated climate-resilient water security frameworks. The Jal Jeevan Mission has accelerated this transformation by integrating source sustainability, groundwater recharge, digital monitoring, localized governance, and ESG-driven infrastructure planning. The study demonstrates that future-ready rural water systems must combine engineering infrastructure, climate adaptation, groundwater sustainability, smart technologies, community participation, and circular water economy concepts to ensure long-term water security.

Sustainable rural water infrastructure should not merely focus on delivering water but on managing water resources intelligently, equitably, efficiently, and resiliently under increasing climate uncertainty.

Future policy and infrastructure planning must therefore prioritize:

- Recharge-based sustainability
- Climate resilience
- Smart governance
- Integrated Water Resource Management
- Community participation
- Renewable energy integration
- Long-term operational sustainability

Such integrated approaches are essential for achieving Sustainable Development Goals (SDGs) and ensuring resilient rural development in India.

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