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Digital Water Technologies for Sustainable Water Resources Management in India: A Review

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Abstract- India's water-management challenge is shaped by substantial spatial and seasonal variability, pressure on groundwater, uneven service provision, and fragmented information systems. Digital water technologies including in situ sensors, satellite remote sensing, geographic information systems (GIS), telemetry, smart meters, and data analytics can improve observation and operational decisions, but their value depends on reliable data, institutional capacity, and governance. This review synthesizes their potential roles across resource assessment, groundwater monitoring, irrigation, urban distribution, water quality, wastewater reuse, and public participation. Official assessments illustrate both the scale and heterogeneity of the task: India's 2024 national groundwater assessment estimated annual extraction at 245.64 billion cubic metres (bcm), with agriculture accounting for 87% of extraction; 751 assessment units were categorized as over-exploited. The review argues that India should prioritize interoperable, locally maintainable systems that connect monitoring to accountable decisions, rather than technology deployment alone. Key constraints include uneven monitoring coverage, inconsistent data standards, sensor calibration and maintenance, connectivity and power limitations, cybersecurity, privacy, affordability, and the risk that data-poor communities remain invisible. A phased implementation framework is proposed, linking problem definition and baseline measurement to pilot validation, institutional integration, public reporting, and outcome evaluation. Digital systems can strengthen water governance when integrated with hydrological knowledge, community participation, and demand-side measures; they cannot substitute for allocation reform, infrastructure investment, or ecological safeguards.

Keywords- digital water, water resources management, Internet of Things, remote sensing. Groundwater, irrigation, water governance

I. INTRODUCTION

Water resources management in India must respond to monsoon variability, contrasting hydrogeological settings, growing urban demand, irrigation requirements, pollution pressures, and differences in administrative capacity. NITI Aayog's 2018 Composite Water Management Index report cited an estimate that 600 million people faced high to extreme water stress; this is a dated estimate from that report, not a current population measurement [2]. More recent official groundwater accounting continues to show strong geographic variation. The 2024 assessment estimated 406.19 bcm of annual extractable groundwater resources and 245.64 bcm of annual extraction, an overall extraction stage of 60.47%; 751 of 6,746 assessment units were classified as over-exploited [1]. National averages therefore conceal local risks and cannot alone guide local allocation decisions.

Digital water technologies may help close information gaps by collecting observations at higher temporal or spatial resolution, integrating heterogeneous datasets, and supporting decisions from source to service delivery. These technologies include remote sensing and GIS, telemetry and Internet of Things (IoT) sensors, supervisory control and data acquisition, smart metering, decision-support models, and public data platforms. Their potential is not automatic: sensing does not ensure representative sampling, prediction does not ensure a legitimate allocation, and a dashboard does not ensure an agency can act. The National Water Policy emphasizes integrated and participatory management, providing a governance basis for deploying these systems as decision support [3].

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This review examines opportunities, limitations, and implementation priorities for digital water technology in India. It treats digitalization as an enabling layer within integrated water resources management (IWRM), rather than a standalone technical remedy.

II. REVIEW APPROACH

This article is a narrative review and policy synthesis, not a systematic review or meta-analysis. It draws on Indian government assessments and policy materials, peer-reviewed studies on satellite observation, geospatial methods, and sensor-based monitoring, and official water data platforms. The synthesis organizes the evidence by management function and implementation condition. Because the source text did not provide a reference list or reproducible search protocol, this review does not claim exhaustive coverage; it prioritizes sources that support the statements made here.

III. WATER-MANAGEMENT CONTEXT AND INFORMATION NEEDS

1. Heterogeneous resources and pressures

India's water challenges are spatially uneven and connected across surface water, groundwater, land use, and energy. The 2024 groundwater assessment attributed 87% of estimated groundwater extraction to agriculture (213.29 bcm), 11% to domestic use, and 2% to industry [1]. The same assessment found that extraction exceeded annual extractable resources in selected states and territories, while many assessment units were categorized as safe. This pattern supports geographically targeted monitoring and management rather than a uniform national technology package.

Satellite gravimetry has demonstrated how remote observation can reveal large-scale groundwater storage change where well records are sparse. Rodell et al. used GRACE satellite observations and land-surface models to estimate groundwater depletion in northwestern India for 2002–2008 [4]. Such products are valuable for regional assessment, but their spatial resolution and modeling assumptions mean they should be interpreted alongside observation wells, aquifer knowledge, and local abstraction records. At national scale, the Central Water Commission's 2024 water-resources assessment also used remote-sensing technology with a 38-year dataset, illustrating the growing role of geospatial observations in official resource assessment [9].

2. Data fragmentation and operational decisions

Water decisions depend on data describing rainfall, river flows, reservoirs, aquifers, water quality, withdrawals, infrastructure condition, and service reliability. These observations are collected by organizations using different formats, periods, spatial units, and quality-control procedures. NITI Aayog identified limitations in water-data coverage and detail as a barrier to data-informed decisions [2]. India-WRIS and the National Water Data Portal provide institutional platforms for data dissemination and access [5,6]; their value depends on sustained updates, discoverability, metadata, and links to operational workflows.

IV. DIGITAL TECHNOLOGIES AND APPLICATIONS

1. Remote sensing and geospatial analytics

Satellite imagery, radar, digital elevation models, and GIS support surface-water mapping, reservoir observation, flood and drought characterization, irrigation mapping, soil-moisture estimation, and crop water-demand analysis. A systematic review of Indian agricultural water-management studies describes applications spanning evapotranspiration, irrigation requirements, drought assessment, watershed runoff, waterlogging, recharge-site identification, and soil moisture [7]. Remote sensing offers broad spatial coverage, but cloud cover, revisit intervals, sensor resolution, retrieval uncertainty, and the need for ground validation limit its use as a direct substitute for field measurements.

2. Sensors, telemetry, and smart infrastructure

In situ sensors can monitor water level, flow, pressure, electrical conductivity, pH, turbidity, and selected chemical parameters. Telemetry can transmit observations from wells, treatment facilities,

reservoirs, and distribution networks to operators. In urban systems, networked pressure and flow measurements can help identify abnormal losses, improve asset maintenance, and assess continuity of supply. Reviews of IoT-based water-quality monitoring identify technical and operational constraints including calibration, power, communications, cost, and security [8]. These limitations are especially material in rural and remote settings, where maintenance and replacement logistics can determine whether a pilot system remains usable.

3. Decision support, forecasting, and digital models

Statistical and machine-learning approaches can support demand forecasting, anomaly detection, irrigation scheduling, drought indicators, and asset maintenance. Hydrological and hydraulic models can combine field observations with weather data and infrastructure characteristics to compare management scenarios. Forecasts should be treated as uncertain inputs to human decisions: model performance can deteriorate when catchment conditions, behavior, or climate shift beyond the training data. Documentation of data provenance, validation periods, error metrics, and uncertainty is essential for operational use.

4. Digital platforms and community participation

Water data portals can improve access for researchers, agencies, and the public when datasets are machine-readable and accompanied by definitions, units, dates, spatial references, and quality metadata [5,6]. Mobile channels can enable users to report leaks, service interruptions, and suspected contamination. Such reporting is most useful when communities receive feedback on action taken and when mechanisms are accessible in local languages and usable without persistent connectivity. Crowdsourced observations complement, but do not replace, accredited sampling and formal complaint systems.

5. Benefits and limits

The principal potential benefit is improved observability: timely information can reveal changes that periodic surveys miss. Better observation may support earlier detection of contamination, leaks, infrastructure failures, or emerging shortages. When linked to clear procedures, analytics can support preventive maintenance and more transparent investment priorities. Geospatial tools can help target field surveys and compare conditions across administrative boundaries [7]. Public-facing data systems can make water decisions more visible and support accountability [5,6].

These benefits are conditional. Sensors require calibration and maintenance; remote products require validation; and models require representative, well-documented data. A digital system may reproduce existing inequities if monitoring is concentrated in well-served urban or commercial areas. Data integration raises issues of interoperability, ownership, privacy, and cybersecurity. Efficiency gains may be offset if saved water is used to expand demand or if operational optimization ignores environmental flows and distributional consequences. Performance should therefore be judged against outcomes such as reduced non-revenue water, improved service continuity, reliable quality compliance, reduced groundwater extraction in stressed areas, and equitable access—not the number of devices installed.

Implementation priorities for India

Begin with decisions and baselines

Each deployment should specify the management decision to be improved, the responsible institution, the spatial and temporal scale, and baseline indicators. A groundwater monitoring program, for example, should state how measurements will affect abstraction planning, recharge priorities, or drought response. Baselines and comparison locations enable evaluation of whether technology changed outcomes.

Build interoperable and maintainable systems

Procurement should require open interfaces, common units and metadata, documented calibration, secure data transfer, and exportable records. Life-cycle budgets should include installation, field visits, calibration, connectivity, power, replacement parts, software support, and

staff training. Existing public infrastructure such as India-WRIS and the National Water Data Portal can inform integration planning, but local agencies need clear stewardship roles and update schedules [5,6].

Match tools to water-management scales

Remote sensing and basin-scale models suit regional patterns and prioritization; wells, gauges, and laboratory sampling remain necessary for local verification; utility telemetry supports network operations; and community-level systems can surface service problems and local knowledge. A tiered architecture connecting these scales is more defensible than reliance on any single data source. Ground observations remain essential for validating satellite-derived estimates and model outputs [4,7].

Make participation, equity, and safeguards operational

Local water users, utilities, researchers, and civil-society organizations should help define indicators, interpret results, and review outcomes. Agencies should publish understandable quality information, uncertainty, and response responsibilities. Data minimization, role-based access, audit logs, retention limits, and incident procedures should be incorporated where systems handle personal or infrastructure-sensitive information. Inclusion requires accessible interfaces, offline alternatives, and training that reaches groups often excluded from digital services.

Evaluate pilots before scaling

Pilots should specify technical reliability, cost per monitored unit, data completeness, response time, decision uptake, and distributional effects. Independent evaluation should compare the pilot with a baseline or suitable comparison site and report limitations. Scaling should proceed when the operating agency can demonstrate continuing maintenance capacity and a credible path from alerts to action.

Research gaps and future directions

Priority research areas include long-term evaluations of digital interventions in Indian water systems; low-cost, low-power sensors with locally supported calibration; methods to fuse satellite, well, utility, and citizen data while quantifying uncertainty; and decision models that represent institutional rules and competing demands. Research should examine how technology affects groundwater extraction, irrigation choices, water-quality compliance, utility losses, and access across socioeconomic groups. Studies need transparent datasets and reproducible methods so results can be compared across states and hydrogeological settings.

Digital twins and AI-enabled optimization may become more useful as data quality and operational integration improve, but they should be introduced incrementally. Their outputs need to be explainable to operators, tested under failure conditions, and governed through clear human accountability. Traditional water knowledge and local institutions can add information about seasonal reliability, customary access, and ecological change that sensor networks alone do not capture.

V. CONCLUSION

Digital water technologies can strengthen India's water resources management by improving observation, connecting data across scales, and supporting timely operational decisions. Official assessments show that India's water risks are heterogeneous, with groundwater pressure concentrated in particular regions and agriculture accounting for most national groundwater extraction [1,2]. A robust digital strategy should prioritize decision relevance, validated data, interoperability, maintenance, transparent uncertainty, and equitable participation. Technology is most likely to produce durable public value when embedded in accountable institutions and linked to demand management, pollution control, infrastructure renewal, and ecological protection.

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