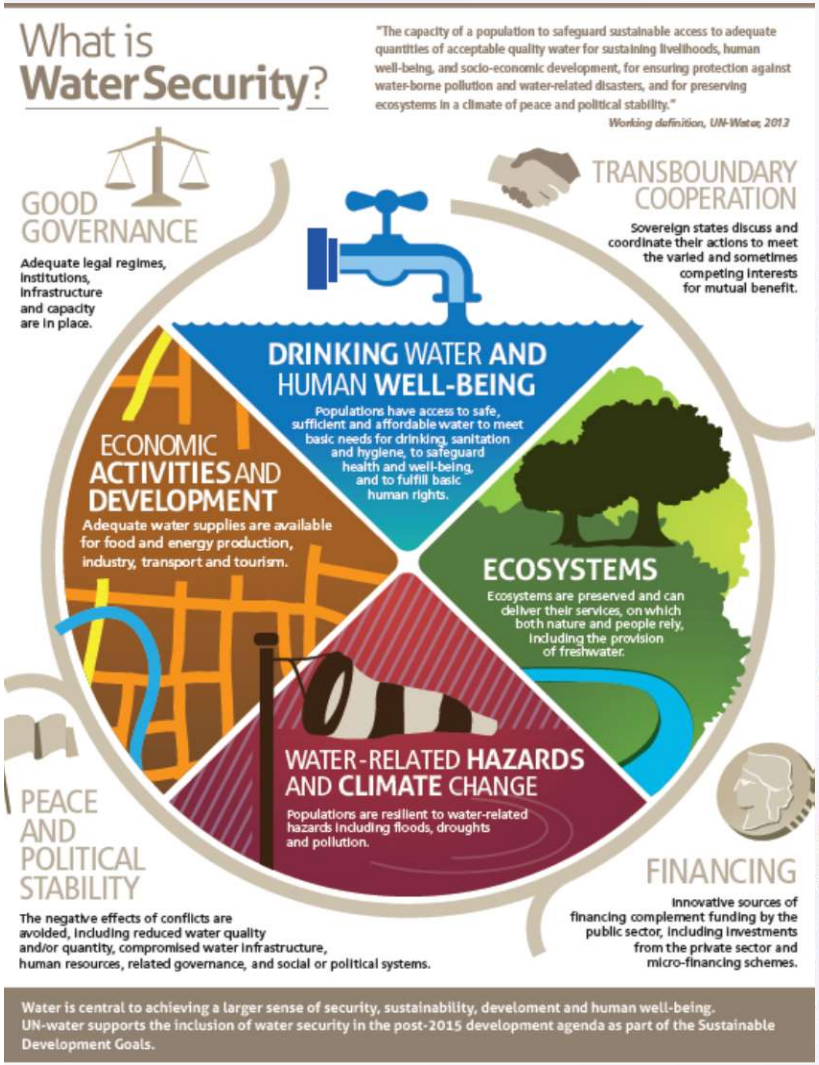


Transforming Water Security: Integrating AI, ML, Remote Sensing & Climate-Informed Modelling

Vinesh Katte, Kasturi Katte, Ramana Rao G.V — Central Water & Power Research Station, Pune.

This paper argues that conventional, reactive water-management systems—reliant on limited historical data—are inadequate under mounting climate variability, population growth, and hydrological complexity. The solution: data-driven, intelligent systems combining AI/ML, remote sensing, GIS, DEMs, and real-time monitoring to enable proactive, resilient resource management.

Why Change Is Urgent

Global hydrological systems face unprecedented pressure from climate extremes, population growth, and resource depletion. Traditional reactive approaches cannot manage systemic risks like catastrophic floods, prolonged droughts, and groundwater decline. This work demonstrates how integrating AI/ML, remote sensing, and real-time monitoring converts heterogeneous data into predictive insights, shifting governance from crisis response to proactive resilience and operational adaptation.



What Is Water Security?

Water security is the capacity to ensure sustainable access to adequate, acceptable-quality water for livelihoods, health, ecosystems, and socio-economic development while protecting communities from floods, droughts, and contamination. It demands integrated governance across sectors—agriculture, energy, planning, finance, health—to protect the vulnerable and support sustainable development, social justice, and peace.



Emerging Technologies: The New Toolbox



Forecasting & Early Warning

AI models analyze real-time rainfall and soil moisture to accelerate flood and drought response.



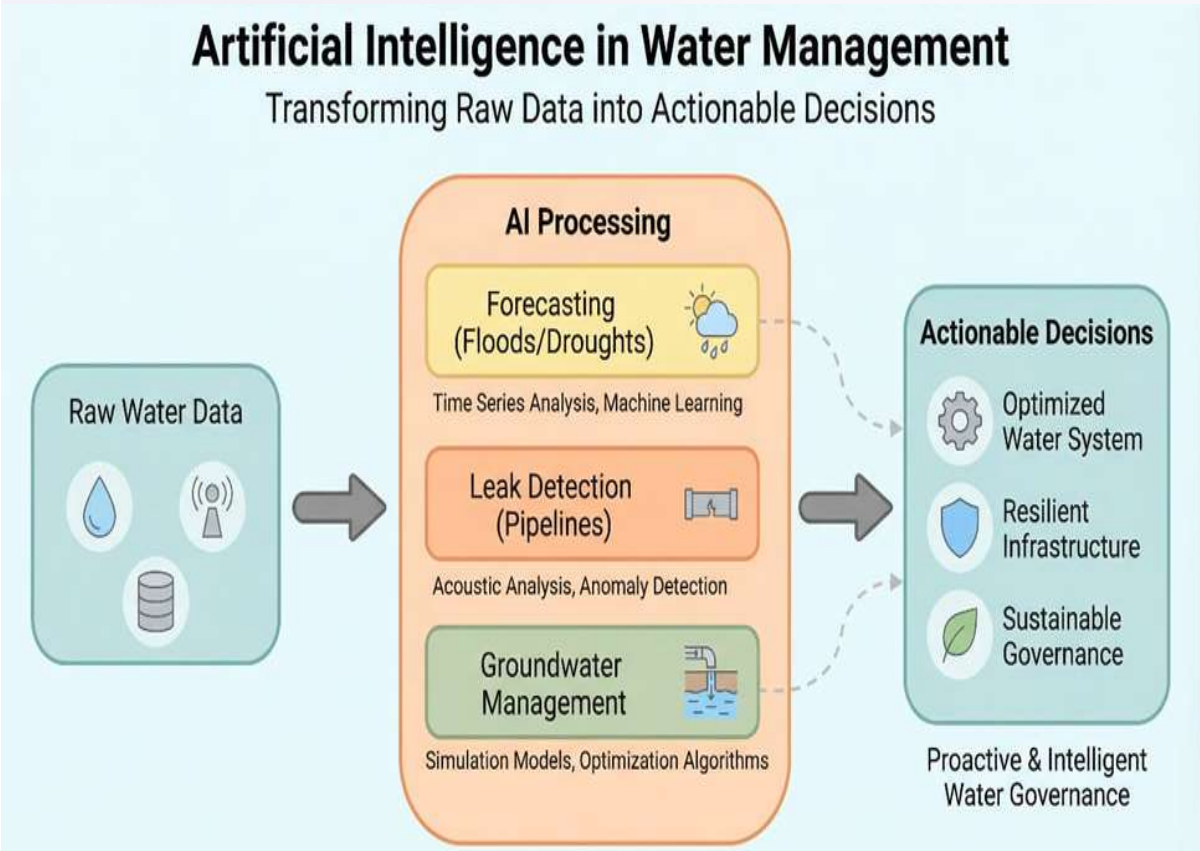
Infrastructure Optimization

AI detects leaks and losses in distribution networks, cutting operational costs and conserving treated water.

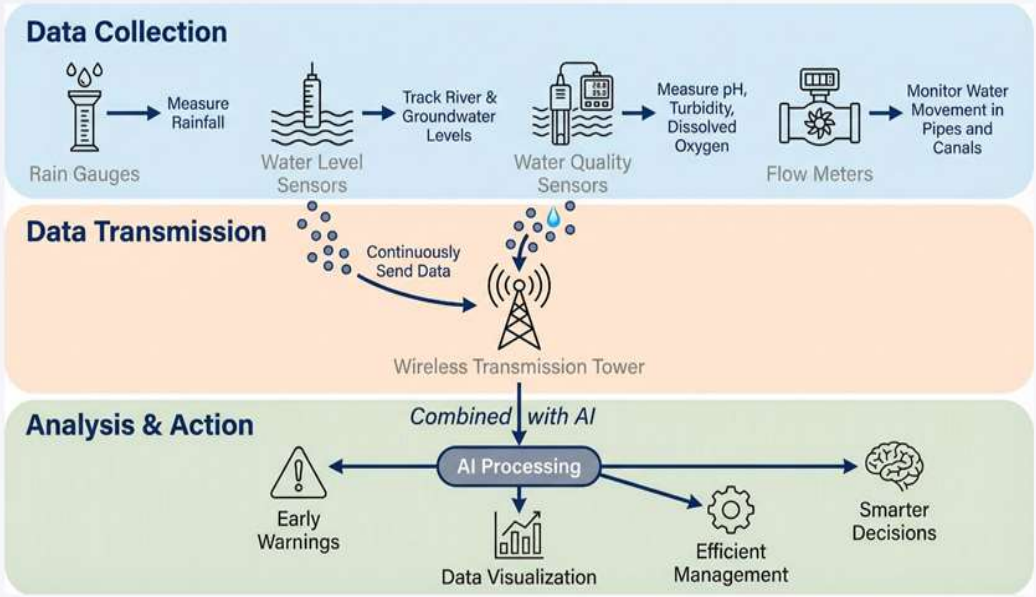


Groundwater Management

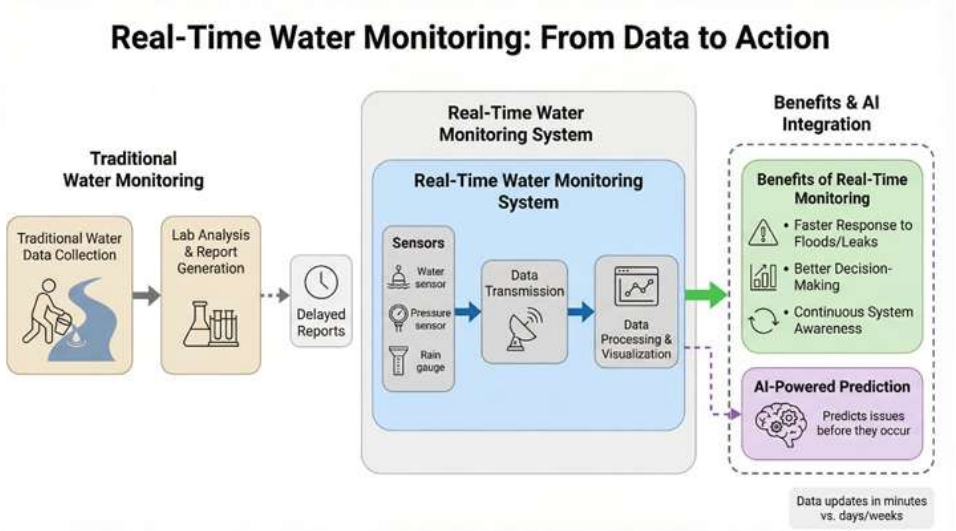
Simulation models and lifecycle data enable sustainable governance of aquifers for agriculture and industry.



Artificial Intelligence (AI) in water management means using data and smart algorithms to understand and manage water systems better. It helps in predicting floods, monitoring groundwater levels, detecting leaks, and optimizing water distribution.



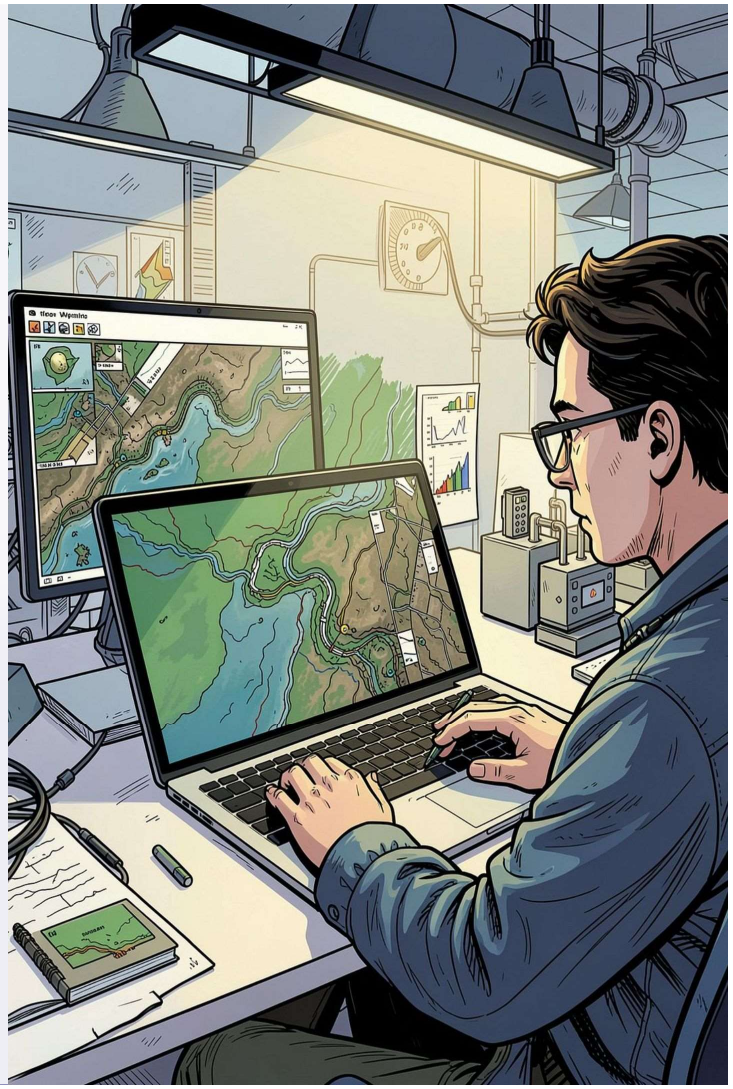
Sensors used in water monitoring Sensors are the backbone of modern water monitoring systems 💧 They help us collect real-time data such as: 🌧 Rain gauges → measure rainfall 💧 Water level sensors → track river & groundwater levels 🌡 Water quality sensors → measure pH, turbidity, dissolved oxygen 🚰 Flow meters → monitor water movement in pipes and canals. These sensors continuously send data, helping us understand what's happening on the ground. When combined with AI, this data becomes powerful for early warnings, efficient management, and smarter decisions



What is real-time water monitoring? Real-time water monitoring means tracking water data as it happens ⏱️💧Instead of waiting for reports, we get instant updates from sensors and systems. Examples:📡 River levels updating every few minutes🚰 Pipeline pressure monitored continuously🌧️ Rainfall data streaming live. Why it matters:⚠️ Faster response to floods or leaks📊 Better decision-making🔄 Continuous system awareness In simple terms:👉 No delays, only live data With AI, real-time monitoring becomes even more powerful by predicting issues before they occur.

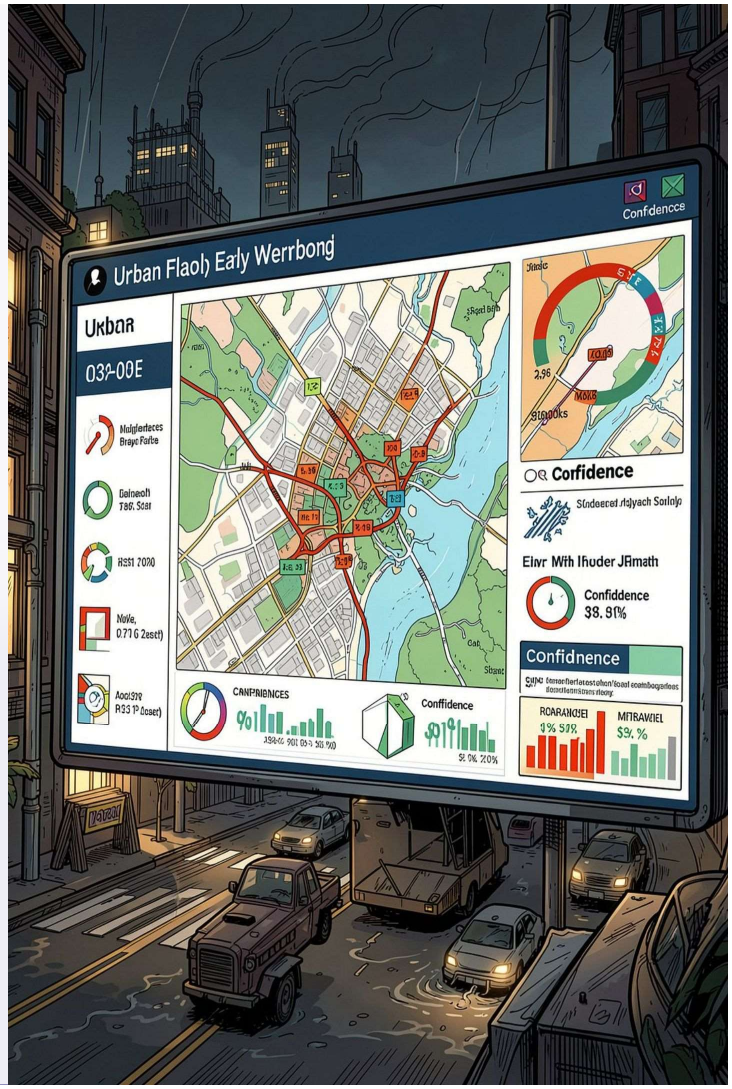
AI & ML: Capabilities and Applications

AI (broad) and ML (subset) enable pattern recognition and forecasting from large measured datasets. Techniques include supervised methods (SVM, RF, ANN), deep learning (CNNs, LSTMs), unsupervised clustering, and evolutionary optimization. Applications: streamflow forecasting, evapotranspiration, sediment transport, water-demand prediction, flood forecasting, groundwater-level forecasting, and real-time water-quality anomaly detection.



AI in Practice: Forecasting, Demand & Floods

Machine learning models (RNNs, LSTM, XGBoost, CNNs) improve water-demand forecasts using socioeconomic and climate variables, support hour/day/month predictions, and help utilities optimize operations. For flood prediction, ML trained on meteorological, discharge, and satellite inputs can rapidly predict occurrence, magnitude, and duration—with reported high accuracy—and integrate with early warning systems to reduce disaster impacts.



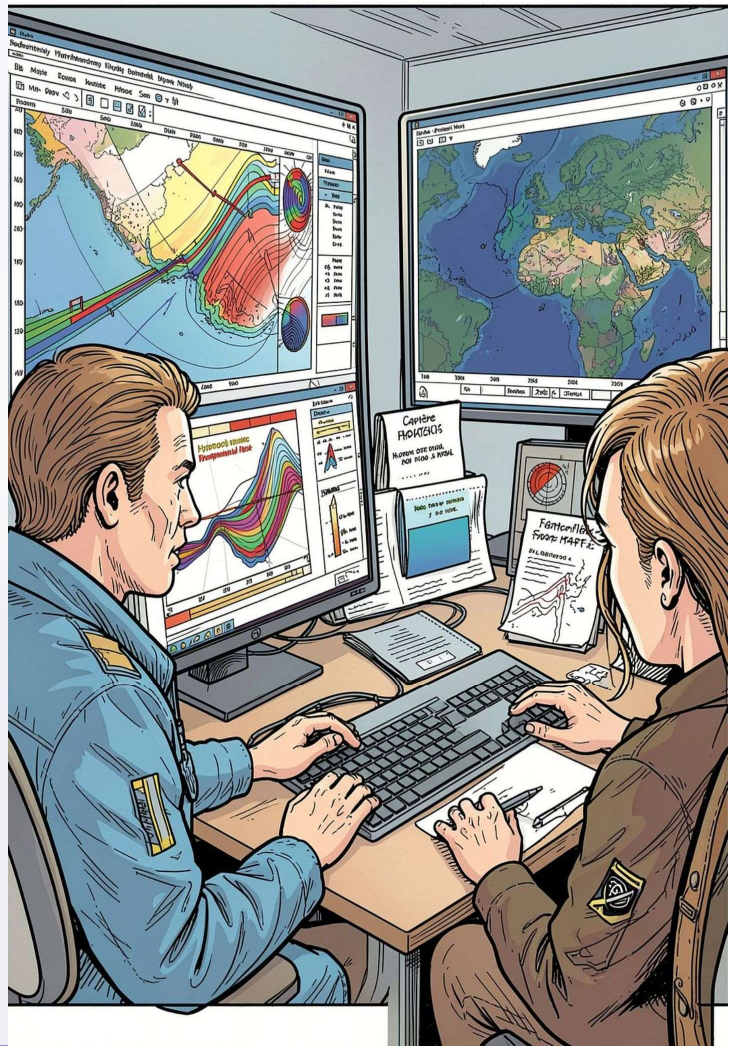
Remote Sensing, GIS & DEM: Observing Water at Scale

Remote sensing provides spatially and temporally explicit data—surface water extent, soil moisture, snow cover, turbidity, chlorophyll, and thermal anomalies—while GIS synthesizes layers (land use, precipitation, infrastructure) for analysis and visualization. DEMs (including LiDAR) underpin watershed delineation, flow routing, floodplain mapping, slope and erosion analysis, and sediment transport modelling—critical for flood risk assessment and site-specific interventions.



Hybrid Approaches: Combining Physics & Data

Physical hydrological models (SWAT, HEC-HMS, MODFLOW) remain essential but are data- and calibration-intensive. Hybrid solutions—coupling geospatial data, AI-driven parameter optimization, and real-time satellite inputs—yield dynamic flood-forecasting and groundwater-assessment systems. AI reduces uncertainty in model calibration and augments process understanding, producing more accurate, near-real-time actionable outputs for decision-makers.





Implementation, Stakeholders & Challenges

Technology

IoT sensors, satellites (Sentinel-2, GRACE, SWOT), cloud analytics, and ML pipelines make near-real-time monitoring possible.

Policy & Capacity

Successful deployment requires governance frameworks, training, stakeholder engagement, and science communication to integrate findings into policy.

Data & Equity

Harmonizing diverse data sources, addressing data uncertainty, and ensuring benefits reach vulnerable populations are ongoing challenges.

Conclusions & Next Steps

Integrating geospatial technology, AI/ML, and hydrological models offers a pathway from reactive to proactive water governance—improving flood forecasting, groundwater sustainability, and water-quality monitoring. Hybrid models balance physical understanding with data-driven predictive power. Moving forward requires investment in infrastructure, multisector collaboration, stakeholder training, and robust science-policy translation to achieve resilient, equitable water security.

Andhra Pradesh's 2025 Cyclone Montha Response Empowered by the APWRIMS System

Across India's water-stressed regions:
familiar pattern emerges during every monsoon and cyclone season:

fragmented data, delayed decisions, and cascading infrastructure failures.

The result is reactive crisis management rather than proactive preparation—and lives lost that could have been saved.
This wasn't always understood as a systemic problem.

For decades, India's approach to water governance and disaster preparedness treated it as a technology challenge: build better sensors, collect more data, improve forecasting models. But decades of cyclones, floods, and water crises revealed a deeper truth: the problem wasn't data scarcity. It was information fragmentation.

The Crisis Before the System: A Tale of Fragmented Response
Cyclone Hudhud's October 2014 strike on Andhra Pradesh exposed critical vulnerabilities in the state's fragmented water and disaster management systems.

Across four coastal districts:
claimed 61 lives
injured 43 others,
affected 20.93 lakh families
impacted pproximately 9.2 million people in over 7,285 villages

The damage was catastrophic:
over 2,250 kilometers of roads were destroyed,
45,000 electrical poles needed replacement.

The fundamental problem wasn't a lack of effort from government agencies. Rather, it was a crisis of data silos. Water resource managers operated in silos – those monitoring reservoirs had no real-time visibility into minor irrigation tank conditions; rainfall data arrived in fragments from disconnected stations; satellite observations existed but weren't integrated into decision-making workflows; and crucially, there was no unified platform that could translate raw environmental data into actionable intelligence for field coordinators and state command centers.

When early warnings arrived, they came too late or lacked the granularity needed for precision response. Evacuation decisions relied on broad forecasts rather than hyper-localized risk assessments. Water release schedules from reservoirs couldn't account for real-time rainfall changes across upstream catchments. Field teams lacked visibility into tank overflow risks, leading to reactive rather than proactive interventions. The 2014 response, while saving many lives through manual coordination, exposed a painful truth: data existed, but knowledge was absent.
The state government recognized that building resilience required something fundamentally different – not just better equipment, but an entirely new paradigm for how water, weather, and disaster information flowed through governance. There are many studies which have been performed in similar cases and few of them are also discussed below:

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Literature Review:
To mitigate these risks:

integrated adaptation strategies are essential. These include the development of localized early warning systems informed by oceanic and atmospheric monitoring, the promotion of drought- and heat-tolerant crop varieties, and the adoption of efficient **AI water management** practices such as rainwater harvesting and drip irrigation (**Islam *et al.*** 2025) .

Piezometric depth modeling for the Sarab Plain aquifer uses monthly precipitation and water consumption variables to predict groundwater levels. This approach, detailed in a 2024 study by ***S. Khosravi,*** innovates by integrating both recharge (precipitation) and abstraction (water consumption) factors simultaneously, unlike prior models focusing on one variable.

Borankulova *et al. 2025* presented a paper on a solar-powered IoT-based real-time water-level monitoring system designed to improve irrigation efficiency and **water management** in Kazakhstan's agriculture. It integrates multi-parameter sensors and cloud analytics to support sustainable water use and informed decision-making.

Bioresita *et al.* 2018 proposed a robust, automatic method for rapidly mapping water surfaces from single Sentinel-1 SAR images using adaptive thresholding on backscatter data, enhanced by fuzzy logic, region growing, and bimodality tests to reduce errors from low/high-backscatter areas. Validated across diverse sites, it achieves high accuracy (e.g., ~90% user's/producer's) and supports scalable applications like flood/drought monitoring, outperforming simpler thresholding in urban/complex terrain. It can be inferred from the above studies that the early warning system is essential for any disaster in addition to it, an integration of groundwater system , sensor and **IoT water management** will help in efficient future prediction. A well developed robust method is also essential in mapping water surface.

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Andhra Pradesh’s 2025 Cyclone Montha Response Empowered by the APWRIMS System

The Digital Transformation: APWRIMS 2.0 Emerges

India’s water security:

Demanded innovation aligned with the Digital India vision and Jal Shakti mission.

Andhra Pradesh launched APWRIMS (Andhra Pradesh Water Resources Information and Management System) in 2017 as a foundational step.

Built on the **aquaWISE technology** stack developed by Vassar Labs.,

APWRIMS represented India’s first state-scale **Digital Public Infrastructure (DPI)** for integrated water resource management.

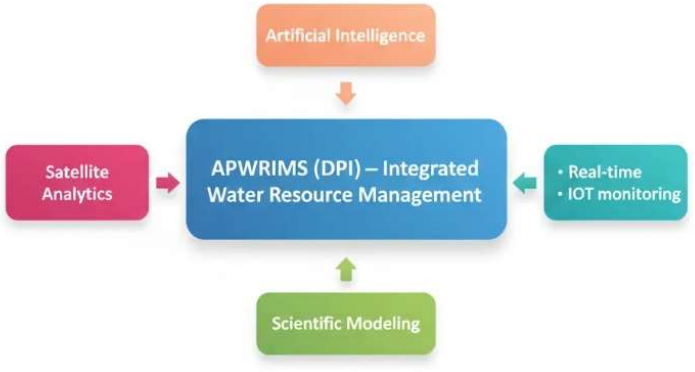


Figure 1: *APWRIMS an Integrated Water Resources Management System*

APWRIMS was a fundamentally new approach to governance.

By fused **AI, real-time IoT monitoring, satellite analytics, and scientific modeling** into a unified decision-support ecosystem as shown in Figure 1.

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Unlike traditional systems that stored historical data,

APWRIMS created a **living digital twin** of Andhra Pradesh's entire water system:

With
31,000+ minor irrigation (MI) tanks
100+ reservoirs,
2,000+ rainfall monitoring stations to groundwater conditions
17,334 villages covered

shown in **Figure 2.**



Figure 2: *APWRIMS a digital twin of AP entire water system*

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Real-Time Visibility at Scale: APWRIMS integrated data from,

- 2,000+ rainfall stations across
- 155 automatic water level sensors deployed in reservoirs and major water bodies
- 1,800 piezometers tracking groundwater
- satellite-based water spread detection across all 38,000 minor irrigation tanks using ESA's Sentinel-1 satellite imagery
- deep learning models.

The Reservoir, MI tanks and Rainfall module are shown in **Figure 3,4 and 5** respectively.

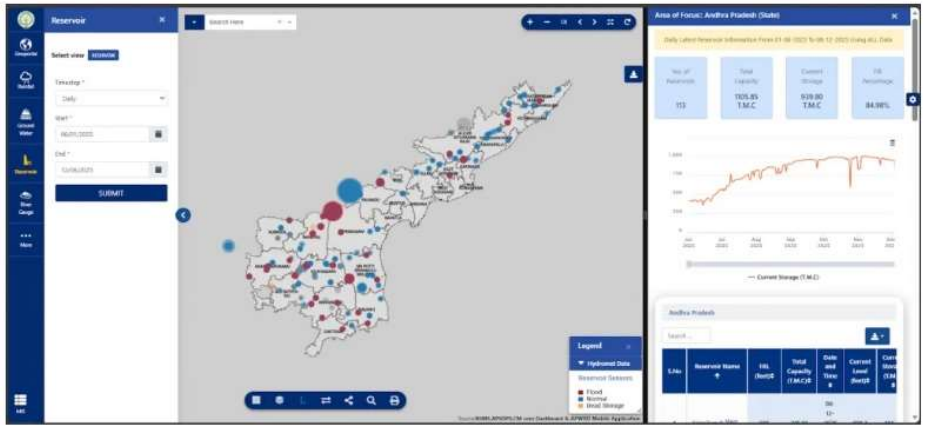


Figure 3: *Reservoir Module of APWRIMS*

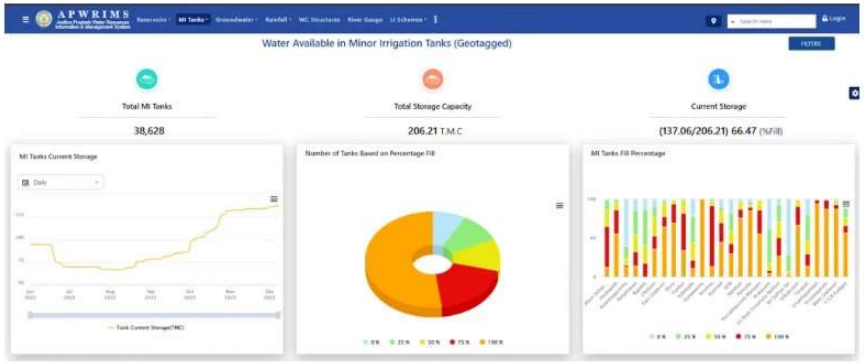


Figure 4: *Reservoir Module of APWRIMS*



Figure 5: *Rainfall Module of APWRIMS*

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AI-Powered Early Warning Generation: No waiting for emergencies.

three-hourly alerts on MI tank water levels and overflow risks, coupled with
twice-daily forecast-based advisories that predicted floods and droughts **7 days in advance**

Decision-Ready Intelligence: AI-enabled dashboard
consolidated alerts from
•tanks,
•reservoirs,
•weather systems, and
•cyclone tracking models,
•translating technical data into plain-language advisories

Governance with Accountability: Ensures transparency and ethical deployment of AI in public service.
co-managed by:
•Andhra Pradesh Water Resources Department
•Vassar Labs, Hyd

By 2024, the system had matured into APWRIMS 2.0, with more sophisticated modules included.
• **Nowcast integration for real-time cyclone tracking**
• **GenAI Copilot for conversational water intelligence**.

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•**When Crisis Tested the System: Cyclone Montha and the Power of Real-Time Intelligence**

On October 28-29, 2025,
•Severe Cyclonic Storm Montha made landfall near Narasapuram in Andhra Pradesh with
•wind speeds reaching 90-110 km/h at the coast,
•unleashing torrential rainfall

Hyper-Localized Risk Intelligence:
The **digital public infrastructure (DPI) of water** identified exactly
•5 reservoirs &
•1,307 MI tanks that were at elevated risk –

not a broad warning for all 31,000+ tanks,

This specificity allowed district collectors and field engineers to focus protective measures where they mattered most.

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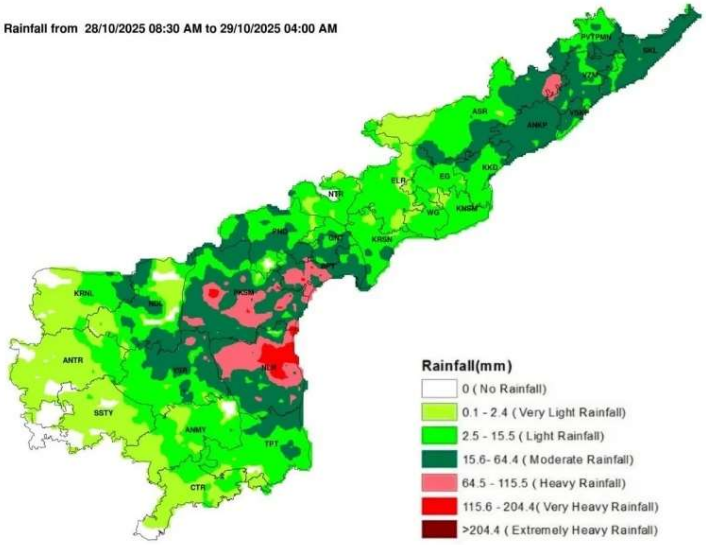


Figure 6: *Observed rainfall over the past 24 hours*

Figure 7: *Rainfall from 28th Oct to 29th Oct*

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Continuous Situational Awareness:
Throughout the cyclone event, APWRIMS delivered:

– Real-time cyclone path tracking and rainfall intensity projections integrated with Nowcast meteorological models

– Satellite-based water-spread analysis updated with high temporal frequency (every 5-10 days or post-rainfall) to assess actual tank storage conditions and identify potential breaches even under cloudy conditions

– Three-hourly automated alerts on rising water levels, overflow risks, and structural stress for all monitored water bodies

– Twice-daily forecast-based advisories projecting tank and reservoir conditions 48-72 hours ahead

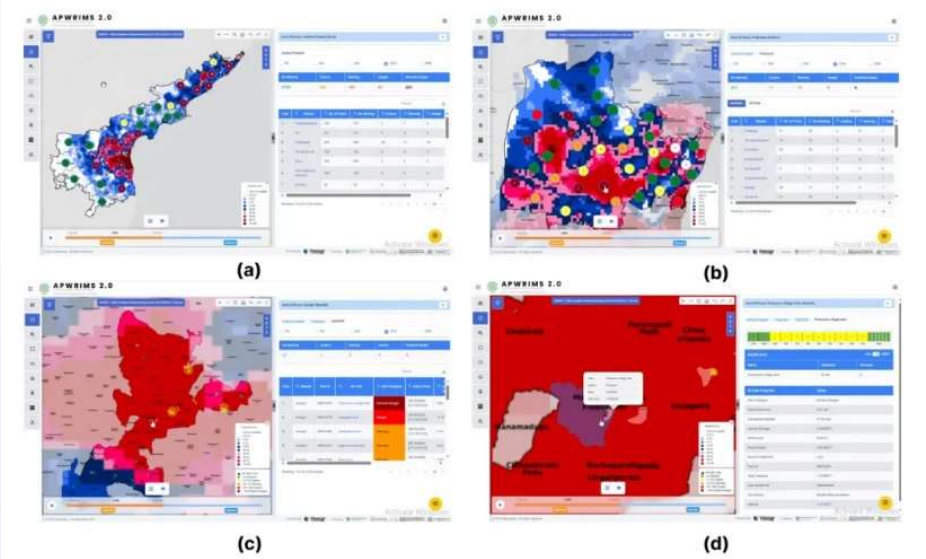


Figure 8: *Showing Montha at state level **(a)**, district level **(b)**, mandal level **(c)**, tank level **(d)***

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Coordinated Field Operations: The platform enabled real-time coordination between the State Control Room, Chief Engineers (CEs), Superintending Engineers (SEs), and Division Engineers (DEs) across all four irrigation regions by accessing the unified command dashboard showing:

– Priority tanks and reservoirs requiring immediate intervention (water releases, spillway operations, or emergency preparedness)
– Live rainfall intensity maps overlaid with tank locations and capacity thresholds
– Recommended water release schedules for reservoirs to prevent catastrophic spilling while maintaining supply to downstream command areas
– Status updates on field teams and interventions already underway

Decision Support in Real Time: Automated advisory bulletins dispatched to CEs, EEs, and DEs at critical moments,

translating complex hydrological data into actionable recommendations
For example :
• "Release 500 cusecs from Reservoir X within 2 hours to prevent spillway activation"
•"Tank Y has reached 95% capacity"
•"mobilize field teams for emergency spillway maintenance"

Achievements:
zero human fatalities occurred directly attributable to cyclone-related water disasters in the regions

While Cyclone Montha caused an estimated 53 billion rupees in total damage across Andhra Pradesh,
the vast majority was from agricultural losses and wind damage to infrastructure

– not from uncontrolled flooding, tank breaches, or cascading water-related emergencies.

Recognition from Government and the National Narrative

The effectiveness of APWRIMS and its use cases were deeply appreciated not only in AP but also across other states.

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This recognition was more than symbolic. It reflected a governance transformation for the first time in a major disaster event, a state-scale **DPI for water management** had proven its value in real operational conditions – not in pilot projects or controlled settings, but under the most demanding circumstances imaginable: a severe cyclone affecting millions of people and thousands of critical infrastructure points.

The Montha response also captured national attention as a case study in how modern governance should work during natural disasters : real-time data flowing seamlessly from sensors to command centers, AI translating complexity into clarity, multiple agencies coordinating through shared intelligence rather than operating in isolation, and critically, preventive action replacing reactive crisis management .

When Disaster Preparedness Technology Becomes Governance

The arc as shown in **Figure 10** from Cyclone Hudhud to Cyclone Montha, from fragmented emergency response to coordinated real-time action, tells a story about the future of governance in a climate-changing world. It is not ultimately a story about technology- sensors and satellite data and machine learning algorithms are tools. Rather, it is a story about how those tools can be assembled into systems that fundamentally change what governments can know and what they can do.

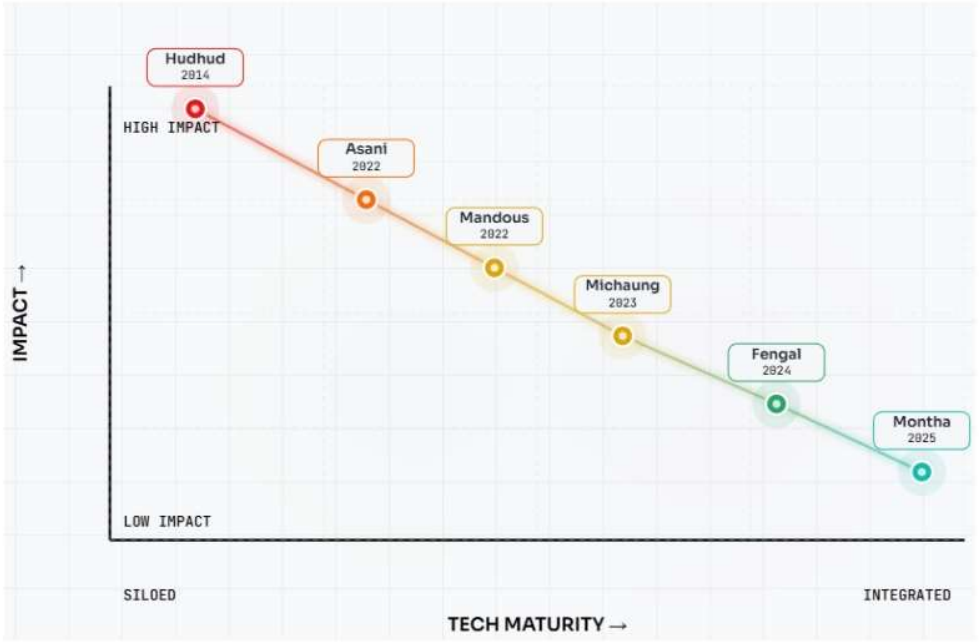


Figure 10: *Development of Technology and information from Cyclone Hudhud to Cyclone Montha*

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Andhra Pradesh's experience with APWRIMS 2.0 demonstrates that modern governance in the age of climate uncertainty requires three elements working in concert :

1. **Real-time environmental monitoring** at scale (thousands of sensors, satellite data, weather forecasts) that creates a continuous digital model of the physical world.

2. **AI and scientific modeling** that translates raw observations into predictions and recommendations, and does so at the speed and scale humans cannot match.

3. **Institutional coordination frameworks** that ensure this intelligence reaches decision-makers, field teams, and communities in time for action.

When Cyclone Montha struck, APWRIMS proved that these elements, properly assembled, can save lives, protect livelihoods, and minimize cascading failures in critical infrastructure. The platform's success during the crisis was not an exception but evidence of what becomes possible when governance infrastructure is designed for the 21st century – when data, intelligence, and decision-making are integrated into a seamless whole.

As climate change intensifies water-related hazards, similar systems will become standard practice, not cutting-edge innovation. The question is no longer whether states should build platforms like APWRIMS, but how quickly they can do so, how widely they can deploy them, and how effectively they can use them to protect and serve their citizens.

Andhra Pradesh's journey from the devastation of Cyclone Hudhud to the coordinated resilience demonstrated during Cyclone Montha offers the world a template: for how to govern water in an age of uncertainty, for how to make AI serve public good rather than perpetuate fragmentation, and for how to build the institutional infrastructure that allows communities to not merely survive disasters, but actively prepare for them.

Results

It can thus be summarized that APWRIMS has been an integrated platform which can thus be helpful during cyclones and other disasters. This platform helped in automated advisory bulletins generation at critical moments There were zero human fatalities related to disasters under APWRIMS **real-time water monitoring**. It also helped in reducing the impact on tanks which reduced the pressure on the entire water system: from the 31,000+ minor irrigation (MI) tanks scattered across the state to over 100+ reservoirs, from 2,000+ **rainfall monitoring** stations to groundwater conditions across 17,334 villages.

Case Detail

Client Name: Andhra Pradesh Water Resource Department

Area: Andhra Pradesh

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