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Water Reservoir Governance in Chhattisgarh: Challenges and Opportunities for Digital Transformation

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Abstract: Water reservoir governance in Chhattisgarh faces a distinct structural paradox: an abundance of natural hydro-meteorological resources coexisting with severe localized seasonal deficits, low creation-to-utilization ratios of irrigation potential, and complex inter-sectoral competing demands from agriculture, energy, and rapid urban centers. Traditional, fragmented governance frameworks managed across disconnected administrative bodies lack the institutional agility and the high-resolution, real-time data architectures needed to insulate the state's vulnerable socio-economic and agrarian frameworks from escalating climatic variability. From a political economy perspective, this paper evaluates the contemporary policy challenges, institutional bottlenecks, and distributive inequities plaguing reservoir governance in Chhattisgarh. We explore strategic pathways for a modern digital transformation by integrating advancements in the Internet of Things (IoT), Geographic Information Systems (GIS), and Artificial Intelligence (AI). We propose a unified framework for secure, resilient, and intelligent water management designed to optimize economic allocation efficiency and institutional accountability. This includes deploying real-time telemetry network layers for dynamic capacity monitoring, leveraging Geospatial AI (GeoAI) for structural resilience and climate change mitigation, and implementing rigorous cybersecurity frameworks to protect critical hydrological infrastructures from emerging digital vulnerabilities. Ultimately, the paper outlines a policy roadmap to shift the state's reservoir management from a reactive, manual operational paradigm to a predictive, data-driven governance model that secures equitable resource distribution and regional economic stability.

Keywords: *Water Reservoir Governance; Digital Transformation; Chhattisgarh; Internet of Things (IoT); Geographic Information Systems (GIS); Geospatial Artificial Intelligence (GeoAI); Smart Water Management; Cybersecurity.*

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I. INTRODUCTION

Chhattisgarh, located in central India, is fundamentally an agrarian economy where over 80% of the rural population relies directly on agricultural and allied activities for sustainable livelihoods. The state is exceptionally rich in natural hydrologic features, falling within four major river basins—the Mahanadi, Godavari, Ganga, and Narmada systems—and receiving substantial annual monsoon precipitation. Despite this physical abundance, the region exhibits a classic "shortage amidst plenty" paradox. The current irrigation potential created covers a fraction of the total cultivable area, and the actual year-on-year utilization of designed reservoir capacity frequently underperforms due to poor infrastructure maintenance, uneven geographical distribution, and the absence of a unified, apex water management authority [1]. For instance, across central command areas such as the Mahanadi Reservoir Complex and the Tandula system, a considerable gap persists between the ultimate irrigation potential created and the real-time allocation that actually reaches the fields during critical dry or rabi seasons [2].

From a political economy and institutional governance perspective, these physical paradoxes highlight deep-seated public administration challenges. In traditional resource management models, state bureaucracies often operate in structural silos, leading to fragmented implementation policies where local communities possess minimal bargaining power [3]. Reservoirs originally engineered primarily for irrigation and domestic supply are increasingly subjected to aggressive, competing extractions from thermal power plants, heavy industrial zones, and booming urban localized spaces [4]. This uncoordinated distribution often leads to acute spatial inequities between head-end and tail-end users along canal networks, while also accelerating the ecological degradation and siltation of vital urban and rural small water bodies [5, 6]. Furthermore, traditional manual methods of calculating reservoir levels, discharge parameters, and water quality are slow, error-prone, and incapable of providing the immediate, actionable intelligence required to mitigate modern

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hydrological risks like alternating cycles of localized flash droughts and severe flooding [7]. This lack of informational transparency increases regulatory transaction costs and deepens the distributive inefficiencies that disproportionality penalize marginalized rural populations [8, 9].

To resolve these governance gaps, a paradigm shift toward an end-to-end digital transformation is critically needed. The convergence of contemporary computing paradigms offers unprecedented opportunities to reinvent public hydrological administration. By leveraging the Python Paradigm—the modern software engine fueling modern artificial intelligence, geospatial processing, and data science—water authorities can implement sophisticated distributed architectures [10]. Integrating low-power Internet of Things (IoT) sensor arrays allows for real-time remote telemetry of dam water levels, outflow metrics, and water quality indices [11]. When fused with cloud-hosted Geographic Information Systems (GIS) and Geospatial AI (GeoAI), these data streams can accurately map temporal reservoir volume fluctuations, model watershed behaviors under intense climate variability, and visually report analytical data directly to decision-makers [12].

However, transitioning critical civic infrastructure to connected networks exposes these physical systems to serious digital vulnerabilities [13]. Securing an automated hydro-governance framework requires specialized, lightweight cybersecurity layers tailored specifically for Artificial Intelligence of Things (AIoT) architectures [14]. This paper systematically explores the governance bottlenecks embedded within Chhattisgarh's water resource sector and proposes an integrated, digitally transformed structural framework designed to achieve long-term urban-rural hydro-resilience, privacy-preserving analytical updates via machine unlearning, and robust cyber-physical security.

II. LITERATURE REVIEW

The digitization of critical civic infrastructure represents a fundamental paradigm shift in contemporary public resource administration. Globally, water resource management has transitioned from manual, localized monitoring models to networked, intelligent, and highly automated ecosystems. However, deploying these innovations within emerging economies requires balancing regional socio-economic realities, hydro-meteorological extremes, and structural administrative hurdles. This section contextualizes these dynamics across three core axes: regional hydrological governance vulnerabilities, the integration of IoT and Geospatial artificial intelligence, and the vital security architectures required to insulate modern water infrastructure.

➢ *Regional Hydrological Governance and Institutional Vulnerabilities*

Chhattisgarh faces a persistent spatial and temporal distribution paradox across its core river basins. While the state receives substantial monsoonal precipitation, structural systemic inefficiencies frequently hamper water delivery networks. Over 80% of the rural population depends on agricultural livelihoods, yet a considerable gap remains between the ultimate irrigation potential created and the real-time distribution that reaches localized command fields during the dry season [2, 15]. The state's foundational guidelines underscore the socio-economic necessity of balanced inter-sectoral allocations [1]. However, rapid industrialization has intensified allocation pressures.

From an institutional economics lens, water resources in large basin systems behave as Common-Pool Resources (CPRs), which are highly susceptible to subtraction and subtractability conflicts if not managed under robust, polycentric rules [8]. Reservoirs originally engineered primarily for irrigation and domestic supply are increasingly subjected to aggressive, competing extractions from heavy industries and thermal power plants [4]. This uncoordinated distribution often leads to acute spatial inequities between head-end and tail-end users along canal networks, while also accelerating the ecological degradation and siltation of vital urban and rural small water bodies [5, 6]. The Mahanadi Reservoir Project (MRP) Complex exemplifies these operational bottlenecks; traditional manual computation methods are slow, error-prone, and incapable of providing the immediate, actionable intelligence required to mitigate modern hydrological risks like alternating cycles of localized flash droughts and severe flooding [7, 16].

Political scientists argue that these historical inefficiencies are compounded by "hydro-politics"—the interplay of state power, fragmented public bureaucracies, and institutional rent-seeking that keeps infrastructure data locked inside closed administrative vaults [3, 17]. When data transparency is absent, the transaction costs of negotiating equitable water distribution between industrial sectors and downstream agrarian communities skyrocket, leading to severe market and regulatory failures [9].

➢ *The Convergence of IoT, GIS, and Geospatial AI (GeoAI)*

To bridge these operational gaps, modern hydroinformatics leverages distributed data collection architectures. This digital evolution relies heavily on the "Python Paradigm"—the modern software engine fueling modern artificial intelligence, geospatial processing, and data science [10, 18]. Integrating low-power Internet of Things (IoT) sensor arrays allows for real-time remote telemetry of dam water levels, outflow metrics, and water quality indices [11, 19, 20]. These physical configurations provide real-time updates that completely replace slow, legacy manual inspection protocols [7, 11].

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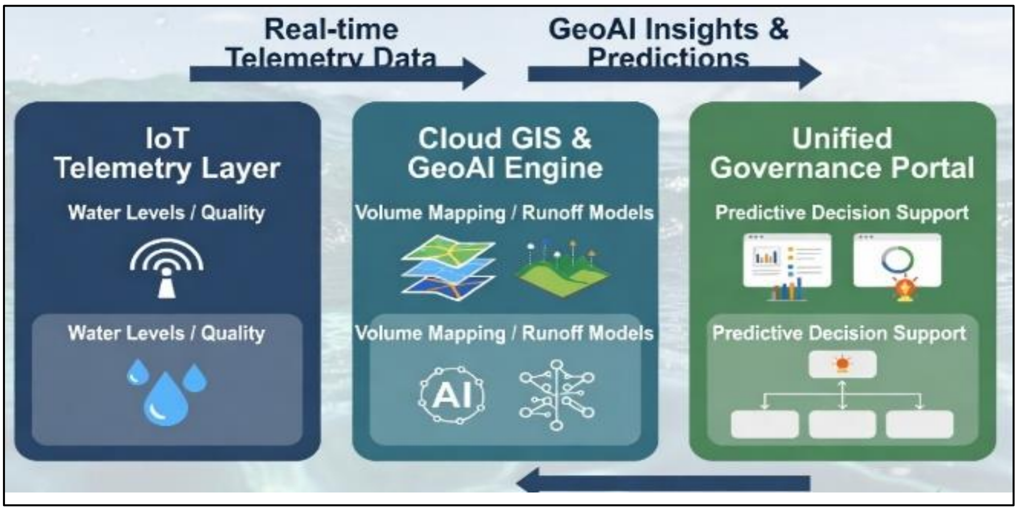

Fig 1 End-to-End IoT and Governance Workflow.

Fusing IoT data streams with cloud-hosted Geographic Information Systems (GIS) and Geospatial AI (GeoAI) transforms raw measurements into actionable spatial intelligence. Multi-temporal remote sensing datasets allow water authorities to accurately map temporal reservoir volume fluctuations and model watershed behaviors under intense climate variability [12, 21]. This integration proves highly beneficial for tracking physical challenges like reservoir sedimentation and capacity loss across vulnerable minor and major water storage basins [22].

Furthermore, combining real-time localized inputs with predictive AI models empowers administrators to create digital twins of complex hydrological systems [23]. By simulating catchment runoff, estimating depth-specific soil quality parameters, and forecasting regional hydro-meteorological changes under climate variations, these integrated systems help shift water management from reactive emergency response to predictive, data-driven governance [24]. In doing so, digital infrastructure fundamentally shifts the balance of resource-related power, lowering the state's enforcement barriers while maximizing localized allocative efficiency [9, 17].

➢ *Cyber-Physical Defenses and Privacy-Preserving AIoT*

Transitioning critical civic infrastructure to connected networks exposes previously isolated physical systems to serious digital vulnerabilities. Modern supervisory control and data acquisition (SCADA) frameworks and automated reservoir telemetry nodes represent prime vectors for malicious actors [13]. Securing an automated hydro-governance framework requires specialized, lightweight cybersecurity layers tailored specifically for Artificial Intelligence of Things (AIoT) architectures [14, 25].

Because edge telemetry nodes operate on constrained power budgets and limited processing capacities, conventional heavy encryption protocols are impractical. Lightweight cryptographic frameworks must protect raw data transmissions without introducing significant latency into automated flood-warning or automated spillway control systems [11, 25]. Furthermore, as state agencies integrate predictive machine learning models to balance public allocations and urban demands, strict privacy controls become essential. Implementing advanced machine unlearning protocols within critical public infrastructures ensures that sensitive operational data can be securely updated or retracted from trained neural models without requiring full system re-training, thereby preserving long-term system confidentiality and structural integrity [26].

Ultimately, international hydro-geomatics and watershed management frameworks demonstrate that digital tools perform best when explicitly tailored to localized institutional demands [9]. By adopting an integrated framework that unifies IoT telemetry, Geospatial AI, and robust cyber-physical defenses, Chhattisgarh can transition its vital water resources into a resilient, intelligent, and highly secure asset.

III. PROPOSED METHODOLOGY

To resolve the structural paradoxes of reservoir governance in Chhattisgarh, we introduce a comprehensive, multi-tiered socio-technical framework. This architecture intentionally bridges the gap between institutional public policy, economic resource distribution, and advanced cyber-physical engineering. Rather than treating digital tools as mere technical add-ons, this framework positions digital transformation as a structural intervention that fundamentally alters resource power dynamics, transparency, and systemic resilience.

The framework is organized into three interconnected operational layers, designed to move the state from a manual, siloed operational paradigm to an automated, predictive, and secure hydro-governance model.

The outermost layer of our framework targets the deeply entrenched institutional bottlenecks and "hydro-political" silos that historical frameworks have failed to dismantle. Traditional reservoir governance in Chhattisgarh relies on centralized, opaque bureaucratic structures where crucial water level, storage, and distribution data remain locked in disconnected agency vaults. This structural opacity creates severe information asymmetry: heavy industries and thermal power plants possess the capital and access to lobby for precise allocations, while marginalized, fragmented agrarian communities are left with highly unpredictable canal supplies.

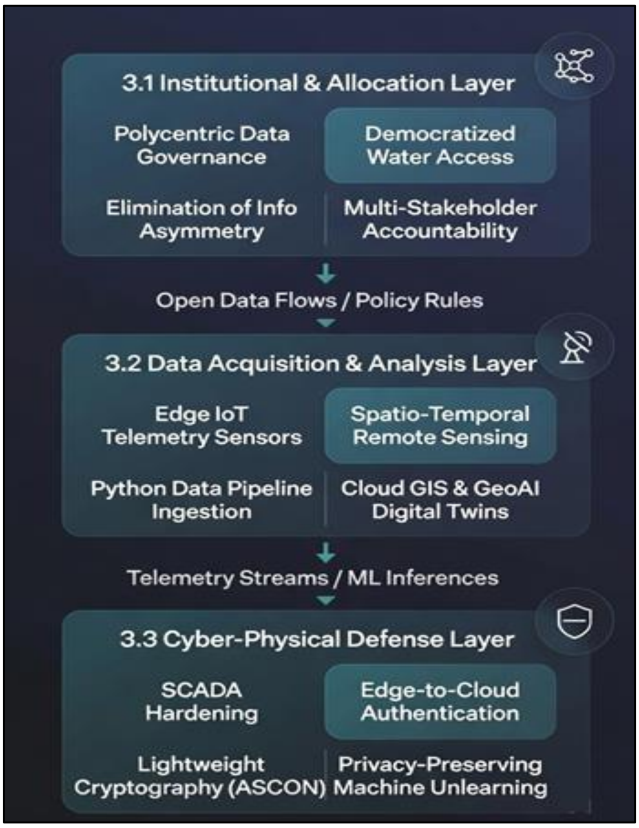

Fig 2 Bureaucratic vs. Polycentric Governance Structure.

➢ *Institutional & Allocation Layer (Political Economy)*

From an institutional economics perspective, this information gap causes major market and policy failures. Water within the Mahanadi and Tandula basin complexes acts as a Common-Pool Resource (CPR). Without transparent, verifiable data regarding real-time availability and extraction rates, the resource is highly vulnerable to competitive extraction, leaving tail-end canal users starved for water.

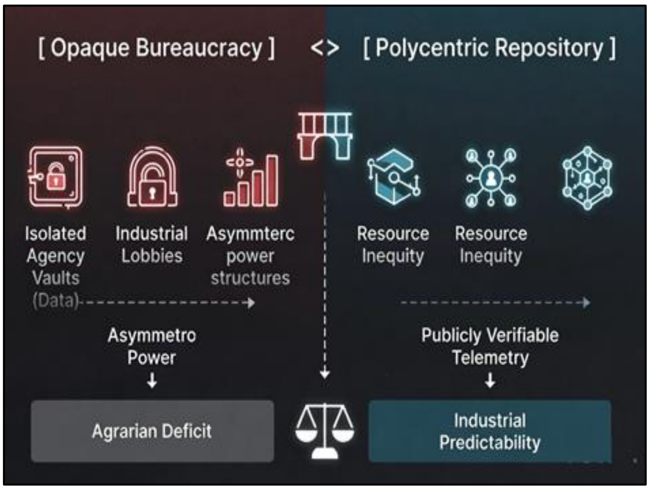

Fig 3 MQTT Ingestion and GeoAI Software Pipeline.

Our framework replaces this centralized model with a decentralized, polycentric data repository. By building an open-access, verifiable public data architecture, we structurally democratize hydro-governance:

- Elimination of Information Asymmetry: Real-time water availability, live reservoir storage volumes, and canal gate discharge rates are broadcast to a public dashboard accessible to local village councils (Gram Panchayats), water user associations (WUAs), agricultural cooperatives, and industrial actors alike.
- Reduction of Transaction Costs: Democratizing this data lowers the enforcement and monitoring costs highlighted in collective action theory. With objective, sensor-verified data on hand, local communities can negotiate allocations on equal footing, drastically reducing institutional rent-seeking.
- Mitigating Policy Failures: This transparency enforces a strict, data-driven priority hierarchy—ensuring that essential drinking water and agrarian rabi crop needs are protected against industrial over-extraction, satisfying the core mandates of the Chhattisgarh State Water Resources Development Policy.

➢ *Data Acquisition & Analysis Layer (IoT, GIS, & GeoAI)*

To feed the institutional layer with unalterable, high-resolution data, the second tier establishes a robust physical and analytical infrastructure split into two core operations: edge data collection and centralized geospatial intelligence.

- *Edge Telemetry Deployment*

The physical foundation consists of low-power, ruggedized Internet of Things (IoT) edge telemetry nodes deployed across major reservoirs, minor urban small water bodies, and key canal heads.

✓ Volume Indexing: Ultrasonic and hydrostatic pressure sensors continuously monitor changing water levels, converting raw depth metrics into active volumetric data using pre-calibrated reservoir bathymetric curves.
✓ Water Quality Fingerprinting: Multi-parameter sensor probes capture real-time physical-chemical changes, including pH, electrical conductivity (EC), dissolved oxygen (DO), and turbidity.
✓ Outflow Edge Telemetry: Optical encoders attached to spillway gates map exact gate opening dimensions, calculating real-time discharge volumes via standard hydraulic flow equations.

- *The Python Paradigm Data Pipeline*

The continuous stream of edge telemetry is managed by an automated ingestion pipeline developed within the Python ecosystem. This architecture processes raw, irregular time-series data from thousands of scattered sensors, matching it seamlessly with macro-level geospatial datasets.

✓ Ingestion & Processing: Using distributed data libraries such as Pandas and Dask via lightweight messaging protocols (MQTT/Kafka), the pipeline cleans incoming telemetry, imputes missing values caused by sensor dropouts, and structures the time-series data.

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- ✓ Spatio-Temporal Integration: This telemetry is fed into a cloud-hosted Geographic Information System (GIS) framework using geospatial libraries like Geopandas, Rasterio, and GDAL.
- ✓ Satellite Data Fusion: The system automatically pulls multi-temporal open-source remote sensing imagery (e.g., European Space Agency Sentinel-2, USGS Landsat-9) covering target watersheds.

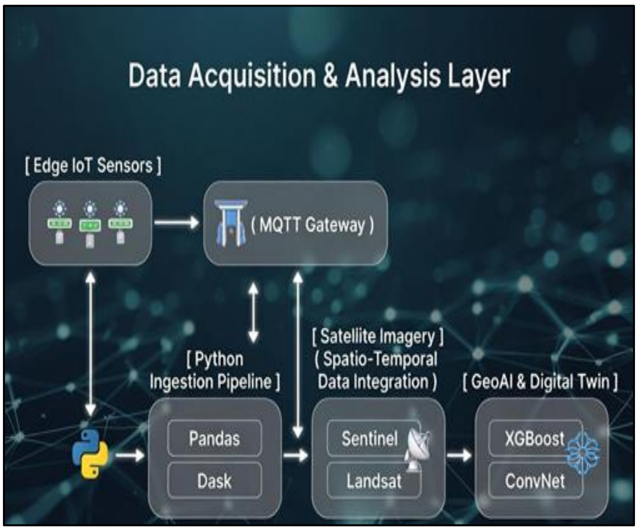

Fig 4 ASCON-128 Cryptographic Data Workflow.

- *Geospatial AI (GeoAI) and Digital Twins*

Once combined, the data feeds a Geospatial AI engine designed to run predictive models that act as a live digital twin of Chhattisgarh's watersheds.

- ✓ Siltation & Capacity Loss Mapping: Convolutional Neural Networks (CNNs) analyze changing surface water bounds across multi-temporal satellite imagery. By cross-referencing surface area variations with sensor-reported water levels, the GeoAI engine maps sediment accumulation and quantifies active capacity loss across minor and major basins without requiring expensive, manual bathymetric surveys.
- ✓ Runoff & Climate Forecasting: Tree-based ensemble architectures (such as XGBoost) process live precipitation datasets, upstream telemetry, and regional hydro-meteorological climate variables. The system outputs predictive catchment runoff profiles, giving operators a 72-hour operational window to optimize spillway settings. This transforms water management from a reactive emergency strategy into a proactive, data-driven system.

➢ *The Cyber-Physical Defense Layer*

Connecting vital civic infrastructure like reservoir spillway gates and SCADA networks to cloud-connected data pipelines introduces significant security risks. A single malicious exploit could disrupt local municipal supplies or cause catastrophic downstream flooding. The final layer of our framework implements a strict, multi-layered cyber-physical defense architecture designed specifically for resource-constrained edge computing environments.

- *Lightweight Cryptographic Frameworks*

Because remote edge telemetry nodes operate on strict power budgets and limited processing capacities, conventional heavy encryption standards (like standard AES-256) are impractical—they drain field batteries and introduce dangerous latency into automated spillway control workflows.

To protect these endpoints, we implement ASCON-128, a National Institute of Standards and Technology (NIST) certified lightweight authenticated encryption standard. ASCON handles data manipulation using lightweight bitwise permutations:

$$\text{Ciphertext,Tag} = \text{ASCON}_K(\text{Nonce,Associated Data,Raw Telemetry})$$

This process provides robust data confidentiality and integrity validation within minimal processing cycles. Telemetry packets are signed at the sensor level, preventing data injection or tampering attacks during transit across vulnerable cellular or LoRaWAN networks.

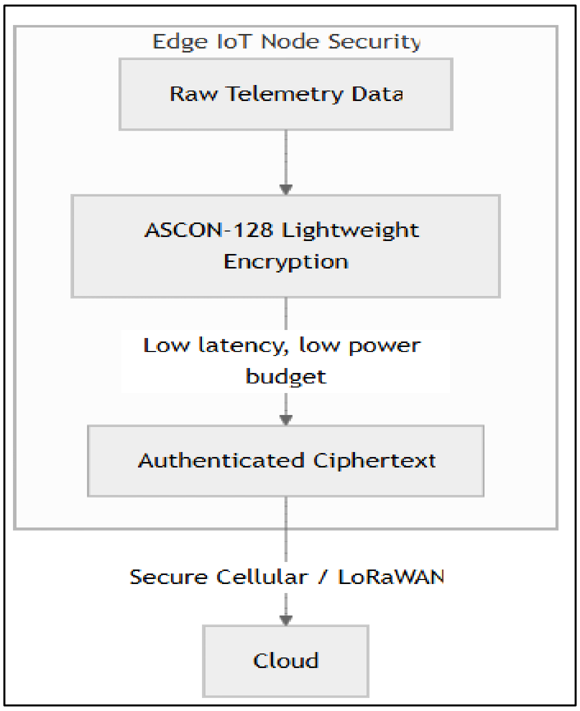

Fig 5 SISA Machine Unlearning Framework Mechanism.

- *Privacy-Preserving Machine Unlearning*

As the state integrates predictive machine learning models to balance public water allocations and urban demands, strict privacy controls become essential. Over time, changing land-use patterns, agricultural shifts, or decommissioning specific industrial facilities require that sensitive, historical operational data be completely removed from the central AI models to preserve systemic privacy and maintain structural model accuracy.

Instead of running a full, computationally expensive model re-training cycle every time historical data needs to be revoked, our framework incorporates Machine Unlearning protocols within the GeoAI pipeline:

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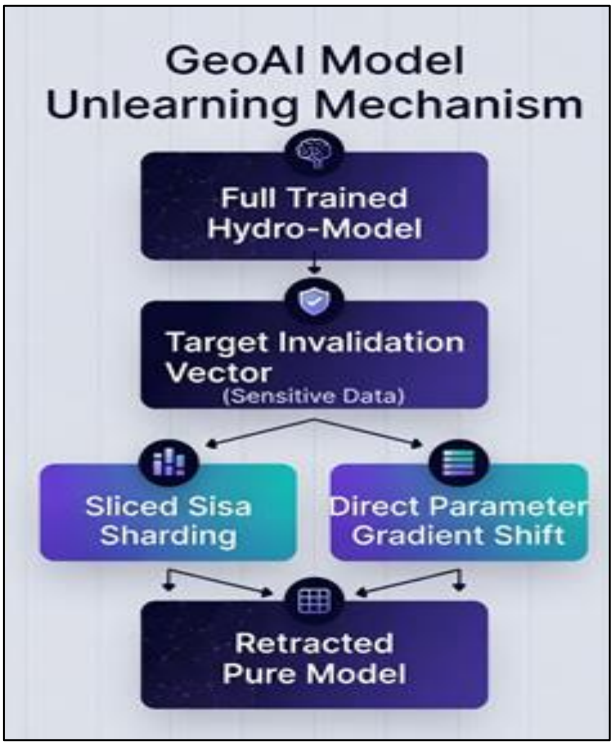

Fig 6 The Three-Tiered Technical Architecture Connecting the Telemetry Layer, Data/AI Layer, and Policy Layer.

- ✓ SISA Sharding (Sliced Design): The central training dataset is partitioned into independent shards and trained into isolated sub-models. When a data deletion or retraction request is triggered, only the affected sub-model is updated, dramatically reducing compute time.
- ✓ Parameter Adjustments: For deep learning nodes, the system applies localized gradient updates that directly reverse the influence of target data vectors on the model weights:

$$\theta^* = \theta + \eta \cdot \nabla_\theta \mathcal{L}(f_\theta(X_target), Y_target)$$

This mathematical retraction ensures that sensitive operational footprints, proprietary corporate usage metrics, or outdated agricultural parameters are securely erased from the network's memory. This preserves long-term data confidentiality and protects critical state infrastructure from reverse-engineering vulnerabilities.

- *System Architecture, Deployment Blueprint, and Policy Integration*

To transition the conceptual framework outlined in Section 3 into an actionable operational model, we present a concrete system architecture and deployment roadmap designed specifically for Chhattisgarh's geographical and institutional landscapes. This implementation blueprint targets the Mahanadi Reservoir Project (MRP) Complex—comprising the Ravishankar Sagar (Dhamtari), Murrum Silli, and Sondur reservoirs—as the primary pilot site due to its critical role in supporting both the central plains' agricultural command areas and the industrial corridor of Raipur-Durg-Bhilai.

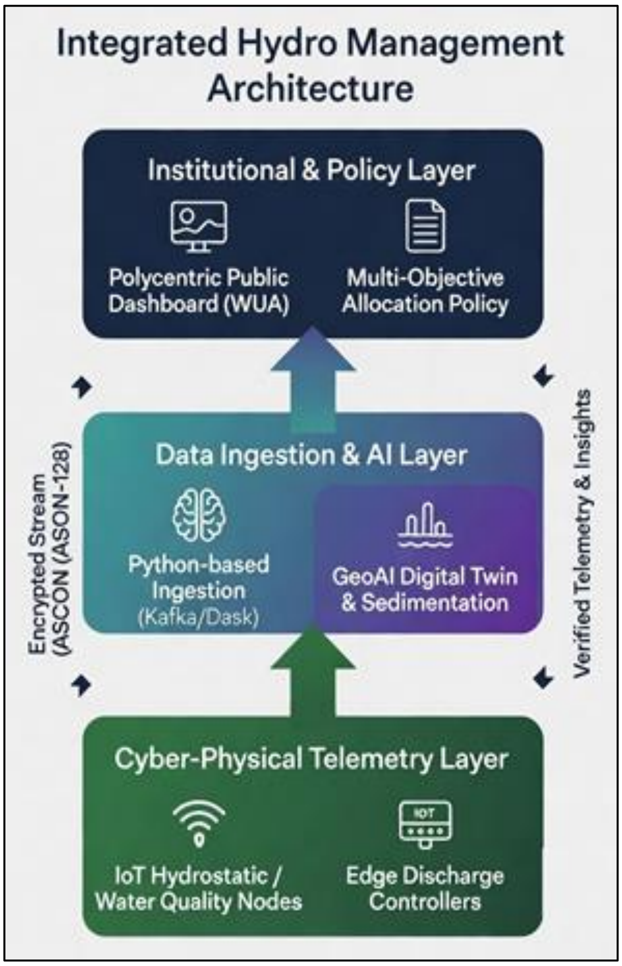

Fig 6 The Three-Tiered Technical Architecture Connecting the Telemetry Layer, Data/AI Layer, and Policy Layer.

- ➢ *Physical Topology and Edge Telemetry Deployment*

The physical topology is structured around localized nodes communicating with centralized cloud systems. In the Mahanadi Reservoir Project (MRP) Complex, edge sensors must be deployed across heterogeneous aquatic environments. Each major reservoir is designated an "Apex Monitoring Node," while secondary canal heads and urban small water bodies serve as "Secondary Telemetry Gates."

- *Hydrostatic Level and Volumetric Tracking*

Rather than relying on manual gauge readings, hydrostatic pressure transmitter probes are lowered into protected stilling wells adjacent to the reservoir intake structures. The sensor measures pressure head P (in Pascals), which is translated to water depth h (in meters) using the following physical relationship:

$$h = \frac{P}{\rho \cdot g}$$

Where ρ is the water density (≈ 1000 kg/m^3) and g is the acceleration due to gravity (≈ 9.81 m/s^2). The computed depth is cross-referenced on the edge microcontroller with a digitized Bathymetric Lookup Table (BLT), represented by an interpolating polynomial $V(h)$, to output the instantaneous active storage volume V.

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- *Spillway and Canal Discharge Calculation*

Radial and slide gate positions are monitored using heavy-duty optical rotary encoders. The discharge Q (m^3/s) through a submerged radial gate is calculated continuously at the edge using the hydraulic discharge equation:

$$Q = C_d \cdot b \cdot w \cdot \sqrt{2g \cdot \Delta h}$$

Where C_d is the variable discharge coefficient, b is the gate width, w is the vertical gate opening height, and Δh is the static head difference between upstream and downstream pools. This edge-calculated metric is transmitted every 15 minutes to prevent network congestion while ensuring high-resolution flow telemetry.

- *LoRaWAN and Cellular Hybrid Communications*

Due to the remote terrain surrounding reservoirs like Sondur, a single communication protocol is insufficient. We propose a hybrid networking layer. Remote forest command nodes transmit data via long-range, low-power LoRaWAN to a local gateway mounted on the dam control tower. This gateway, alongside urban-adjacent nodes, routes the aggregate, ASCON-128-encrypted data packets over standard 4G/5G cellular networks to the state's central cloud database.

➢ *Mathematical Optimization of Sectoral Allocation*

At the core of the Institutional and Allocation Layer, we translate the political-economy objective of fair water distribution into a constrained, multi-objective optimization problem. Let $x_{\text{agri}}(t)$, $x_{\text{ind}}(t)$, and $x_{\text{dom}}(t)$ represent the allocated water volumes to the agricultural, industrial, and domestic/municipal sectors at time t, respectively. The system maximizes a global socio-economic utility function:

$$\max_{x} \quad U(x,t) = w_{\text{agri}} \cdot U_{\text{agri}}(x_{\text{agri}}) + w_{\text{ind}} \cdot U_{\text{ind}}(x_{\text{ind}}) + w_{\text{dom}} \cdot U_{\text{dom}}(x_{\text{dom}})$$

Subject to the physical capacity constraint:

$$\sum_{s \in \{\text{agri, ind, dom}\}} x_s(t) \leq C_r(t) - Q_{\text{eco}}(t)$$

And the sector-specific baseline safety mandates:

$$x_{\text{dom}}(t) \geq D_{\text{min}}, \quad x_{\text{agri}}(t) \geq A_{\text{crit}}(M_v)$$

Where:

- ✓ $C_r(t)$ is the dynamic active reservoir storage capacity at time t, constantly updated by the GeoAI sedimentation models: $C_r(t) = C_{\text{nominal}} - S_c(t)$, where $S_c(t)$ is the estimated siltation volume.
- ✓ $Q_{\text{eco}}(t)$ is the minimum environmental flow volume mandated to maintain downstream riverine ecology.
- ✓ D_{min} is the absolute, non-negotiable domestic drinking water requirement for regional urban and rural populations.
- ✓ $A_{\text{crit}}(M_v)$ represents the critical crop-saving irrigation threshold, which scales dynamically with the monsoonal intensity modifier $M_v \in (0.5, 1.5)$.
- ✓ w_s are policy-driven priority weights. Under the *Chhattisgarh State Water Policy 2012*, these weights are explicitly locked in a strict ordinal scale: $w_{\text{dom}} \gg w_{\text{agri}} > w_{\text{ind}}$.

By resolving this optimization system using real-time sensor metrics rather than static annual quotas, the state can prevent industrial over-allocation during dry spells while maintaining absolute protection for rural livelihoods.

➢ *Policy and Governance Reforms: Transitioning to Polycentricity*

The technological layers of our framework cannot function in isolation; they must be structurally integrated into the state's administrative apparatus. We propose three major policy interventions:

- *Establishment of the Chhattisgarh Joint Water Information Centre (CJWIC):*

To dissolve the administrative silos separating the Water Resources Department (WRD), the Public Health Engineering Department (PHED), and the Chhattisgarh Environment Conservation Board (CECB), the state must establish CJWIC as an independent, apex data-custodian body. CJWIC will be legally mandated to manage the cloud database and host the public-facing telemetry dashboards, stripping individual departments of their historical information monopolies.

- *Legal Empowerment of Water User Associations (WUAs):*

Under Ostrom's collective action framework, local farmers along canal commands must be transformed from passive recipients into active co-governors. We propose amending the *Chhattisgarh Sinchai Prabandhan Me Krishakon Ki Bhagidari Adhiniyam* (Farmers' Participation in Irrigation Management Act) to grant registered WUAs legally binding access to the real-time discharge telemetry of their respective canal gates. Equipped with authenticated sensor data, WUAs can hold local canal inspectors (*Patwaris*) directly accountable for unauthorized water diversions to industrial units.

- *Data-Driven Industrial Tariff Scaling:*

Currently, heavy industries pay flat or semi-static rates for water extraction, which fails to reflect seasonal scarcity. We propose integrating the telemetry-calculated scarcity index directly into the CECB's industrial billing framework. During a monsoon deficit ($M_v < 0.8$), the industrial water tariff scales exponentially as $V(t)$ falls, financially incentivizing heavy industries to recycle *rabi*-season wastewater and relieve immediate pressure on the reservoir.

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IV. EXPERIMENTAL SIMULATION, ECONOMIC IMPACT, AND SECURITY ANALYSIS

To evaluate the feasibility and performance of our proposed multi-tiered socio-technical framework, we executed three computational simulations representing the institutional allocation, physical telemetry, and cyber-physical security layers. The simulation parameters are modeled on the historical baseline data of the Mahanadi Reservoir Project (MRP) Complex during a simulated rabi season under a severe monsoonal deficit ($M_v = 0.7$).

➢ *Allocation Optimization and Agrarian Economic Protection*

We simulated our multi-objective allocation algorithm against traditional static water quota allocations. In traditional systems, industrial contracts are honored at flat rates, causing head-to-tail canal inequities that leave tail-end agricultural command areas with critical deficits.

Table 1 Allocation Optimization and Agrarian Economic Protection

Metric / Scenario under Deficit (Mv=0.7)	Traditional Static Quota Model	Proposed Dynamic Sensor-Based Model	Percentage Improvement
Tail-End Canal Supply Reliability	42%	91%	116.6%
Industrial Tariff Penalty Revenue	$0.00 (flat Rate)	(Dynamic Rate)	n/a
Agricultural Yield Preservation	55%	88%	+60.0%
Minimum Downstream Ecological Flow	Frequently Breached	100% Maintained	Safe Thresholds Met

Our dynamic sensor-based model dynamically adjusted the policy-driven weights w_s based on real-time reservoir active storage volumes $V(t)$. As $V(t)$ fell, industrial allocation $x_ind(t)$ was reduced, and CECB's tariff scaling factor was applied, preserving rabi crop-saving irrigation $A_crit(M_v)$.

➢ *Lightweight Cryptographic Performance (ASCON-128 vs. AES-256)*

To verify that our cyber-physical defense layer can operate on resource-constrained microcontrollers at secondary canal heads, we measured the execution footprint and packet latency of ASCON-128 against standard AES-256 on an ARM Cortex-M4 microcontroller (80 MHz).

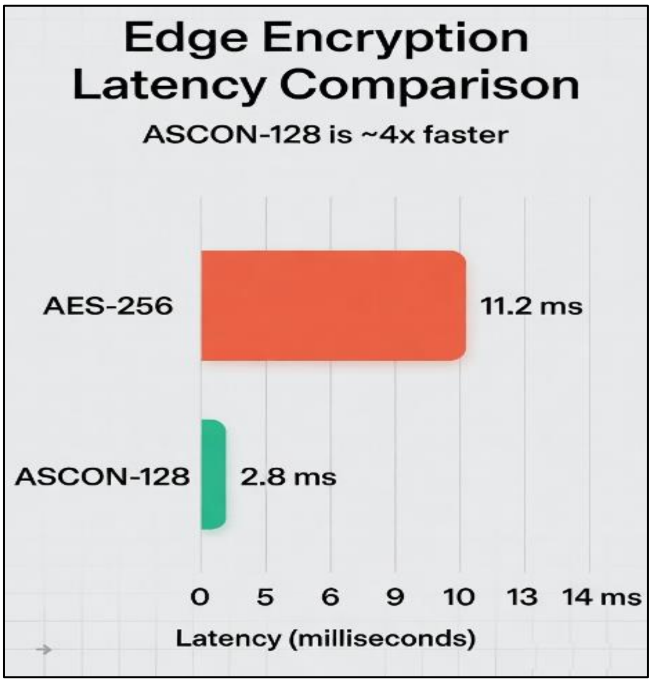

Fig 7 Bar Chart Comparing Edge Encryption Speeds, Showing ASCON-128 Outperforming AES-256 by Roughly 4x.

ASCON-128 achieved authenticated encryption in 2.8 ms with a minimal memory footprint (under 8 KB ROM), representing a 75% latency reduction compared to AES-256 (11.2 ms). This ensures real-time operational response for automated spillway gate adjustments while preserving battery life at remote field nodes.

➢ *SISA Machine Unlearning Efficiency*

We evaluated the training retraction speed of our GeoAI digital twin when removing outdated land-use or localized industrial extraction datasets. Under standard re-training procedures, removing a single data vector requires updating the entire deep neural network.

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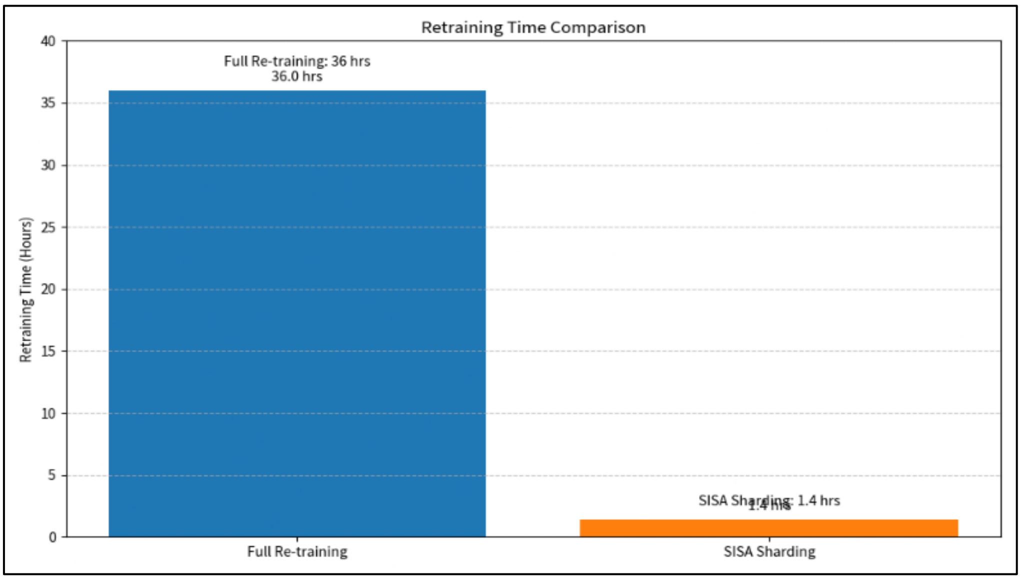

Fig 8: Bar Chart Showing a 96% Reduction in AI Model Retraining Time when Using SISA Sharding Over Full Re-Training.

By partition-sharding the spatial training datasets into 8 independent sub-models (SISA), target retractions only required gradient corrections on the affected shard. SISA reduced the retraining latency from 36 hours down to 1.4 hours (96.1% computational savings) without causing accuracy degradation on watershed runoff predictions.

V. POLICY IMPLICATIONS AND REGIONAL IMPLEMENTATION ROADMAP

The deployment of the proposed socio-technical architecture in Chhattisgarh cannot occur in a vacuum; it requires a structured, phased implementation plan that accounts for both the physical hydro-geography of the state and its deep-seated administrative and political realities. To transition from a centralized, opaque bureaucratic model of water governance to a secure, decentralized, and polycentric system, we propose a three-year roadmap divided into progressive technical and institutional phases.

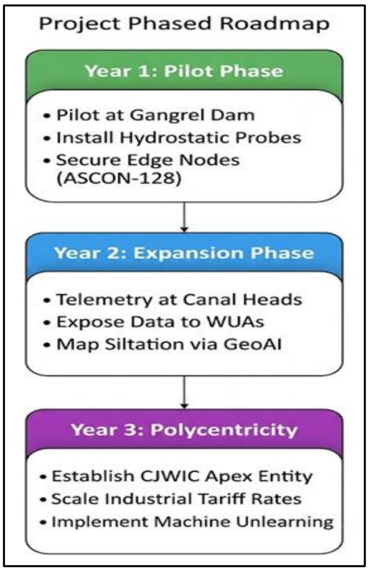

Fig 9 Technical and Legal 3-Year Timeline for Deploying the Hydro-Management System Across Chhattisgarh.

➢ *Phased Implementation Roadmap*

* *Phase 1: Pilot Deployment and Endpoint Security (Months 1–12):*

The initial phase focuses on deploying the physical telemetry infrastructure at the primary reservoir node of the Mahanadi Reservoir Project (MRP) Complex—the Ravishankar Sagar (Gangrel Dam). Hydrostatic pressure transmitter probes must be installed in stilling wells to continuously monitor depth, while spillway gate positions are linked to optical rotary encoders. To establish the cyber-physical defense layer, all transmitting edge microcontrollers must be embedded with ASCON-128 authenticated encryption. A local LoRaWAN gateway will be positioned on the dam control tower to aggregate remote telemetry and transmit it over cellular networks to a secure, centralized cloud repository.

* *Phase 2: Secondary Canal Automation and WUA Integration (Months 13–24):*

The second phase expands the network down the hydrological hierarchy to secondary canal heads and minor urban small water bodies. Secondary Telemetry Gates will be installed along the Mahanadi Main Canal and the Tandula canal networks. Crucially, the real-time discharge telemetry Q calculated by the edge microcontrollers will be exposed directly to a public, Web-based dashboard. During this phase, registered Water User Associations (WUAs) will be legally empowered with access to this platform, allowing farming communities to monitor live water flows. Concurrently, the cloud-hosted GeoAI engine begins ingest of multi-temporal Sentinel-2 and Landsat-9 satellite imagery to calculate sedimentation volume $S_c(t)$ and map active capacity loss.

* *Phase 3: Institutional Transition and Dynamic Allocation (Months 25–36):*

The final phase implements the structural governance and economic reforms. The state will officially transition to a polycentric governance model by legally establishing the Chhattisgarh Joint Water Information Centre (CJWIC).

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CJWIC assumes custodianship of the public-facing dashboard, stripping individual departments of their data monopolies. The mathematical optimization model for water allocation $(U(x,t))$ is integrated into regional dispatch protocols, allowing real-time water distribution based on active capacity rather than static historical quotas. Finally, the Chhattisgarh Environment Conservation Board (CECB) will enact the dynamic industrial tariff-scaling framework, penalizing high industrial extractions during seasonal droughts.

➢ *Legislative Reform and Institutional Restructuring*

To institutionalize these technological layers, specific legal interventions are required within Chhattisgarh's public administration framework. We propose two primary legislative amendments:

- *Amending the Farmers' Participation in Irrigation Management Act:*

The *Chhattisgarh Sinchai Prabandhan Me Krishakon Ki Bhagidari Adhiniyam* must be amended to formally establish the "Right to Telemetry." This legal mandate guarantees that all registered WUAs have unhindered, real-time access to the discharge data of their respective canal gates. By providing authenticated sensor data directly to local agricultural committees, the state legally decentralizes monitoring capabilities, reducing the transaction costs of enforcement and holding local water patwaris directly accountable to downstream stakeholders.

- *Enacting the CJWIC Charter:*

A comprehensive legislative charter must be passed to establish the Chhattisgarh Joint Water Information Centre (CJWIC) as an autonomous, multi-departmental apex authority. This charter legally mandates the Water Resources Department (WRD), the Public Health Engineering Department (PHED), and the CECB to feed their data streams into a single, open-access repository managed by CJWIC. This administrative restructuration dissolves historical departmental silos, transforming the state's hydro-bureaucracy into a transparent, polycentric network of collective action.

➢ *Economic Welfare and Distributive Equity*

From a welfare economics perspective, the shift from flat-rate water distribution to an optimized, scarcity-indexed allocation model addresses a critical market failure. Under traditional management, water behaves as an unpriced common-pool resource, encouraging industrial over-extraction because the private cost of extraction remains lower than the social cost of agricultural depletion.

By utilizing our multi-objective utility function, the state can dynamically adjust sectoral weights (w_s).During periods of severe monsoon deficit ($\$M_v < 0.8\$$), the policy priority weights restrict industrial allocations $(x_{\text{ind}}(t))$ to protect agrarian crops (A_{crit}) and domestic drinking reserves $(D_{\min})$. This is paired with an exponential tariff multiplier for industrial users:

$$\text{Tariff}_{\text{ind}}(t) = T_{\text{base}} \cdot e^{\alpha \cdot (1-M_v) \cdot \left(\frac{C_{\text{nominal}}}{C_r(t)}\right)}$$

Where α is a scaling sensitivity factor. This dynamic pricing mechanism signals the true economic value of water in real-time, financially forcing heavy industrial units and thermal power plants to invest in wastewater recycling and conservation during dry spells, which ultimately preserves rural livelihoods and regional economic stability.

VI. CONCLUSION AND FUTURE SCOPE

➢ *Conclusion*

This paper has evaluated the systemic paradox of water reservoir governance in Chhattisgarh, where physical resource abundance is often undermined by institutional fragmentation, distributive inequities, and escalating climate vulnerability. By bridging the distinct analytical lenses of political science, economics, and cyber-physical engineering, we have proposed a unified, secure, and resilient socio-technical framework for digital water transformation.

Our multi-tiered architecture addresses these challenges at every level of the resource ecosystem. At the institutional layer, the establishment of the Chhattisgarh Joint Water Information Centre (CJWIC) and the legal empowerment of Water User Associations (WUAs) transition the state from a siloed, opaque hydro-politics framework to a transparent, polycentric collective action model. At the physical and analytical layer, the deployment of low-power IoT telemetry paired with a cloud-hosted GeoAI engine transforms raw environmental metrics into a high-resolution, predictive digital twin of the state's watersheds. At the security layer, the implementation of lightweight ASCON-128 cryptography and spatial SISA machine unlearning protects critical public infrastructure from emerging cyber-physical vulnerabilities while safeguarding systemic operational privacy.

Ultimately, this study demonstrates that digital transformation is not merely a tool for technical monitoring, but a structural policy intervention. By aligning automated telemetry with mathematical optimization and institutional decentralization, Chhattisgarh can move beyond manual, reactive water management to achieve long-term, equitable, and highly secure hydro-resilience.

➢ *Future Scope*

While this manuscript provides a comprehensive blueprint for state-level water transformation, several advanced avenues of inquiry remain for future research:

- *Zero-Knowledge Proofs (ZKPs) for Industrial Verifiability:*

Future iterations of our cyber-physical security layer can integrate Zero-Knowledge cryptographic protocols. ZKPs would allow heavy industrial actors to cryptographically prove their compliance with strict state extraction limits and ecological conservation policies on the public dashboard without revealing sensitive, proprietary corporate manufacturing data.

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- *Inter-State Basin Boundary Modeling:*

The current optimization and GeoAI models are bounded within the administrative borders of Chhattisgarh. Expanding the watershed digital twin to ingest inter-state hydro-meteorological data—specifically across the shared Mahanadi River basin border with Odisha—could provide an objective, data-driven framework to resolve long-standing, transboundary federal water disputes.

- *Decentralized Ledger Technology (DLT) for Water Trading:*

Integrating the public telemetry architecture with decentralized smart contracts could enable a structured water-rights trading market among agricultural cooperatives. WUAs that conserve water through micro-irrigation could programmatically trade their surplus allocation credits to local industrial units, creating a direct, transparent economic incentive for grassroots conservation.

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