9th INDIA INTERNATIONAL WATER WEEK - 2026

THEME: CLIMATE RESILIENT WATER MANAGEMENT | 22 - 26 SEPTEMBER, 2026

SIMULATION-DRIVEN INTEGRATION OF SCADA AND GIS FOR REAL-TIME DAM HEALTH MONITORING AND FLOOD MAPPING

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EXECUTIVE SUMMARY

Presentation Roadmap & Research Blueprint

CORE CONTRIBUTION: A low-cost, open-source cyber-physical framework bridging real-time SCADA telemetry with GIS spatial analytics. Replaces expensive digital-twin platforms for small/medium dams using Python, PostGIS, Leaflet, and real CartoDEM data (Khadakwasla Dam case study).

01. CONTEXT & PROBLEM
Dam Safety Act 2021 mandates, failure risks, and traditional SCADA 'spatial blindness'.

02. ARCHITECTURE & CODE
4-tier stack, Flask REST server, simulator.py, spatial_engine.py, real_gis_loader.py.

03. CASE STUDY & GIS DATA
Khadakwasla Dam & Mutha River, CartoDEM 30m Pune-DEM.tif and vector shapefile.

04. HYDRAULICS & ML
Manning's open-channel flow equation, dynamic ST_Buffer, DBSCAN seepage clustering, IDW.

05. SIMULATION & ALERTS
72-hour timeline, diurnal variation, 3 injected anomalies (seepage, pressure, flood breach).

06. VALIDATION & IMPACT
Sub-2-second latency benchmark, India Water Week climate resilience, DHARMA integration.

Why Conventional Dam SCADA Needs Spatial Intelligence

CRITICAL IMPORTANCE & RISKS

- India maintains over 5,300 large dams essential for irrigation, drinking water, hydropower, and flood protection.
- Catastrophic failures (e.g., Tiware 2019, Machchhu 1979) result in massive loss of human life and infrastructure.
- Undetected structural degradation—such as internal piping, abnormal foundation uplift, or excessive seepage—precedes failure.
- Aging dams require 24/7 continuous health surveillance rather than ad-hoc inspections.

DAM SAFETY ACT, 2021

- Enacted December 30, 2021: Provides nationwide unified institutional framework for dam safety surveillance.
- Establishes National Dam Safety Authority (NDSA) and State Dam Safety Organizations (SDSOs).
- Mandatory Requirements: Real-time hydro-meteorological networks, early warning systems, regular inspections, and Emergency Action Plans (EAPs).
- Demands reliable instrumentation, digital records, and institutionalized emergency alert systems.

THE 'SPATIAL BLINDNESS' GAP

- Legacy SCADA limitations: Displays time-series numbers, dials, and tabular alarms without spatial coordinates.
- Spatial Blindness: Operators see 'Water Level = 52.5 m' but cannot see which downstream settlements will be submerged.
- Dispersed vs. Concentrated Leaks: Traditional SCADA cannot distinguish if 3 separate seepage alarms represent localized piping or safe baseline drainage.
- Solution: Fuse SCADA real-time telemetry directly into a GIS map engine with dynamic buffer expansion.

Comparative Analysis of Dam Monitoring Paradigms

Evaluation Feature	Manual Monitoring	Legacy SCADA Only	Proposed SCADA-GIS
Telemetry Acquisition	Periodic / Manual (Daily/Weekly)	Automated Real-Time (Modbus)	**Automated Real-Time (Modbus TCP)**
Spatial Map Visualization	Static paper maps / None	None (Tables & dials only)	**Dynamic Web GIS (Leaflet + PostGIS)**
Flood Inundation Extent	Fixed static pre-calculated zones	None (Operator estimates)	**Real-Time Dynamic Buffer & CartoDEM**
Seepage Anomaly Detection	Visual inspection of dampness	Single-sensor threshold alarm	**DBSCAN Spatial Clustering (Nearby leaks)**
Spatial Intensity Modeling	None	None	**Inverse Distance Weighting (IDW) Heatmap**
Cost & Deployability	Low capital / High labor & lag	High proprietary license cost	**Zero License Cost (100% Open-Source)**

KEY TAKEAWAY: The proposed system is the first lightweight open-source architecture that simultaneously delivers real-time SCADA telemetry, dynamic PostGIS flood buffers, DBSCAN seepage clustering, and IDW spatial heatmaps on commodity hardware.

RESEARCH OBJECTIVES

Primary Goals of the SCADA-GIS Integration Study

1. Open-Source Low-Cost Architecture
Design and build a complete open source cyber-physical software stack combining Python, Flask, PostGIS, GeoServer, and Leaflet to eliminate dependency on multi-crore proprietary SCADA/GIS suites.

2. Realistic Multi-Sensor Telemetry Simulation
Develop a high-fidelity 72-hour simulator (simulator.py) generating realistic diurnal fluctuations, Gaussian noise, and synchronized telemetry for water level, seepage, pressure, and temperature.

3. Dynamic Real-Time Flood Zone Inundation
Implement mathematical and GIS models linking rising reservoir water levels to real-time river boundary buffer expansions using PostGIS ST_Buffer and open-channel hydraulics.

4. Intelligent Spatial Anomaly Detection (DBSCAN)
Apply unsupervised machine learning (DBSCAN) and geodetic coordinate transformations to detect localized seepage piping zones when adjacent sensors record anomalous values (> 7 L/s).

5. Empirical Benchmarking & Field Validation
Validate end-to-end telemetry acquisition, database storage, GIS spatial analysis, and browser rendering to achieve sub-2-second latency on standard commodity hardware.

STUDY AREA & GEOSPATIAL DATA

Khadakwasla Dam & Downstream Mutha River Basin (Pune)

GEOGRAPHIC FOCUS: KHADAKWASLA DAM

- Location: Pune District, Maharashtra, India.
- Dam Coordinates: 18.4410° N, 73.7665° E.
- Primary Function: Lifeline drinking water supply for Pune Municipal Corporation (PMC) and upstream flood control on the Mutha River.
- Downstream Vulnerability: High-density urban settlements along Sinhagad Road, Warje, Anandnagar, Deccan Gymkhana, and Sangam Bridge.
- Real-World Significance: During heavy monsoon rainfall (e.g., July 2024), releases exceeding 35,000 cusecs cause severe urban inundation. Real-time flood mapping is critical for disaster management.

GEOSPATIAL ASSETS IN CODEBASE

Raster: Pune-DEM.tif (CartoDEM 30m Grid):
- Extent: 73.7019° E to 73.9133° E, 18.4077° N to 18.5911° N.
- Grid Dimensions: 761 × 660 cells (~500,000 elevation points).
- MSL Elevation: Riverbed ~540m MSL, Reservoir 550m-558m MSL.

Vector: Pune-boundary.shp & River Centerline:
- 18 High-Precision GPS River Coordinates tracing OpenStreetMap Mutha River from Khadakwasla Spillway to Sangam Confluence.
- Key Bridges Modeled: NDA Road Bridge, Warje Flyover, Rajaram Bridge, Mhatre Bridge, Sambhaji Bridge (Lakdi Pul).
- ~330m River Valley Corridor for constrained hydrodynamic analysis.

SYSTEM DESIGN

Four-Tier Cyber-Physical SCADA-GIS System Architecture

TIER 1: FIELD / SENSORS

- Physical/Simulated Nodes
- Water Level Sensors (WL-01)
- Piezometers (PR-01: Foundation)
- Seepage V-Notches (SP-01 to 03)
- Temperature Sensors (TM-01)
- Modbus TCP / RTU Protocol
- Industrial PLC / RTU Emulation
- Sampling Interval: 30 seconds

TIER 2: SCADA SERVER

- Python Flask Core
- Modbus TCP Receiver
- Data Processing Unit
- State Machine Controller
- Console & Web Alert Engine

TIER 3: SPATIAL ENGINE

- PostGIS / Shapely
- Manning's Hydraulics Q
- CartoDEM 30m Grid
- DBSCAN Clustering
- IDW Seepage Heatmap

TIER 4: CONTROL CENTER

- Interactive Web GIS UI
- Leaflet.js Map Engine
- Dynamic Buffer Polygon
- Color-Coded Sensors
- Sub-2s Refresh Latency

CODEBASE IMPLEMENTATION

Architecture & Software Structure

app.py — Flask Web Backend & Control Server

- Serves dashboard frontend.
- Exposes REST endpoints
- Integrates simulator, spatial engine, and real GIS loader.
- Dispatches multi-tiered console alerts (WARNING, ALERT, CRITICAL).

simulator.py — SensorSimulator Class (72-Hour Engine)

- Simulates 8,640 steps (72 hours at 30s interval).
- Generates diurnal sine waves + Gaussian noise for 6 dam sensors.
- Coordinates mapped directly onto Khadakwasla Dam Wall & Spillway.
- Programmed anomaly injection at 24h (seepage), 46h (pressure), 58h (flood).

spatial_engine.py — SpatialEngine & Hydraulics

- Computes open-channel flow via Manning's Equation: Q = (1/n)*A*R^(2/3)*S^(1/2).
- Calculates dynamic Top Surface Width T and river buffer expansion.
- Runs DBSCAN machine learning (eps=50m, min_pts=2) on seepage > 7 L/s.
- Generates 30×30 Inverse Distance Weighting (IDW) interpolation heatmaps.

real_gis_loader.py-RealGISLoader: Raster& VectorEngine

- Loads CartoDEM 30m elevation grid (Pune-DEM.tif) using rasterio.
- MSL thresholding: masks elevation cells <= WL MSL.
- Converts raster shapes to Shapely polygons with unary_union.
- Traces 18-point Mutha River centerline polyline and ~330m valley corridor.

Mathematical Formulation of Dam Telemetry (simulator.py)

DIURNAL SINE CURVE + GAUSSIAN NOISE MODEL

Each parameter simulates realistic physical diurnal cycles (day_phase = hour % 24 * 2π/24) plus stochastic sensor measurement noise:

- **Water Level (m): $WL(t) = 50.0 + 2.0 \cdot \sin(\theta - \pi/2) + N(0, 0.1)$**
  (Base 50.0m, daily ±2.0m, noise ±0.1m)
- **Seepage SP-01 (L/s): $SP1(t) = 5.0 + 1.0 \cdot \sin(\theta) + N(0, 0.2)$**
  (Base 5.0 L/s, gallery A drainage)
- **Seepage SP-02 (L/s): $SP2(t) = 5.0 + 1.0 \cdot \sin(\theta) + N(0, 0.2)$**
  (Base 5.0 L/s, gallery B drainage (35m away))
- **Seepage SP-03 (L/s): $SP3(t) = 5.0 + 0.8 \cdot \sin(\theta) + N(0, 0.2)$**
  (Base 5.0 L/s, downstream toe drain)
- **Piezometer (kPa): $PR(t) = 200.0 + 3.0 \cdot \sin(\theta) + N(0, 1.0)$**
  (Base 200 kPa, foundation uplift pressure)
- **Temperature (°C): $TM(t) = 28.0 + 2.0 \cdot \sin(\theta - \pi/4) + N(0, 0.5)$**
  (Base 28°C, concrete masonry thermal lag)

KHADAKWASLA DAM SENSOR NETWORK

- **Sensor 1: WL-01: Lake Intake Tower**
  Coordinates: 18.4402° N, 73.7645° E
- **Sensor 2: SP-01: Gallery A (Left Flank)**
  Coordinates: 18.4408° N, 73.7662° E
- **Sensor 3: SP-02: Gallery B (Right Flank)**
  Coordinates: 18.4411° N, 73.7668° E (~35m from SP-01)
- **Sensor 4: SP-03: Mutha Toe Drain**
  Coordinates: 18.4425° N, 73.7690° E (Stilling Basin)
- **Sensor 5: PR-01: Piezometer Foundation**
  Coordinates: 18.4407° N, 73.7660° E
- **Sensor 6: TM-01: Masonry Body Thermistor**
  Coordinates: 18.4410° N, 73.7665° E (Dam Wall)
- **Computed: Flow Q: Manning Open-Channel**
  Coordinates: Calculated discharge in m^3/s & Cusecs

Controlled Anomaly Scenarios for System Validation

ANOMALY 1: SEEPAGE CONCENTRATION | Timeline: Hour 24.0 to 25.0 (Duration: 1 Hour)

- Physical Event: Sudden localized leakage spike through inspection gallery drainage joints.
- Sensor Response: SP-01 jumps from 5.0 -> 9.0 L/s (+4.0 L/s); SP-02 jumps from 5.0 -> 8.8 L/s (+3.8 L/s).
- Spatial Proximity: SP-01 and SP-02 are spaced exactly 35 meters apart (within eps=50m).
- Detection Target: Validates DBSCAN spatial clustering algorithm and IDW thermal hotspot generation.

ANOMALY 2: PIEZOMETER PRESSURE SPIKE | Timeline: Hour 46.0 to 46.25 (Duration: 15 Minutes)

- Physical Event: Rapid foundation uplift pressure rise due to clogged relief wells or hydraulic surcharge.
- Sensor Response: PR-01 increases by +30 kPa (from 200 kPa base to 230 kPa) over a 15-minute window.
- Rate of Change: Steep rate-of-change gradient exceeding normal daily diurnal swings (±3 kPa).
- Detection Target: Validates rate-of-change thresholding and immediate operator console alerting.

ANOMALY 3: RESERVOIR FLOOD SURGE | Timeline: Hour 58.0 to 62.0 (Duration: 4 Hours)

- Physical Event: Inflow flash flood surcharge pushing reservoir water level above maximum pool.
- Sensor Response: Water level rises by +2.8m, exceeding critical 52.0m threshold (reaches 52.8m).
- Hydraulic Response: Manning discharge Q surges over 450 m^3/s (15,900 cusecs).
- Detection Target: Validates dynamic PostGIS ST_Buffer river expansion and CartoDEM flood inundation.

Manning's Open-Channel Flow Equation in spatial_engine.py

MANNING'S EQUATION FORMULATION

Calculates physical water discharge rate Q (m^3/s) and top surface water width T (m) from reservoir water depth:

Discharge Q (m^3/s): $Q = (1/n) \cdot A \cdot R^{(2/3)} \cdot S^{(1/2)}$
Water Flow Depth y (m): $y = \max(0.5, (H_{water} - 50.0) + 1.2)$
Cross-Sectional Area A (m^2): $A = b \cdot y + m_{side} \cdot y^2$
Wetted Perimeter P (m): $P = b + 2 \cdot y \cdot \sqrt{(1 + m_{side}^2)}$
Hydraulic Radius R (m): $R = A / P$
Top Surface Flow Width T (m): $T = b + 2 \cdot m_{side} \cdot y$
Cusecs Conversion: Discharge (cusecs) = Q × 35.315

CALIBRATED PARAMETERS FOR MUTHA RIVER

- Manning's Roughness (n): 0.035 (natural winding riverbed with gravel/vegetation)
- Base Bed Width (b): 15.0 meters (Khadakwasla spillway stilling basin)
- Channel Side Slope (m): 1.5 H : 1 V (natural alluvial channel embankments)
- Longitudinal Bed Slope (S): 0.0015 (downward gradient towards Pune city)

CODE SNIPPET: spatial_engine.py

```
def compute_mannings_discharge(self, water_depth_y):
    y = max(0.2, water_depth_y)
    A = (self.b * y) + (self.m_side * (y ** 2))
    P = self.b + 2.0 * y * math.sqrt(1.0 + (self.m_side ** 2))
    R = A / P
    Q = (1.0 / self.n) * A * (R ** (2.0/3.0)) * math.sqrt(self.S)
    top_width_T = self.b + 2.0 * self.m_side * y
    return {'discharge_m3_s': round(Q, 2), 'top_width_m':
round(top_width_T, 1)}
```

Dynamic Flood Buffering via PostGIS ST_Buffer

PAPER SECTION 4.6: DYNAMIC BUFFER EXPANSION RELATION

Buffer Distance (meters) = (H_current - 50.0) × 10

When water level H exceeds the base pool of 50.0m, the river polygon is expanded outward dynamically using PostGIS ST_Buffer (or Shapely river_line.buffer(distance / 111,000)).

STAGE 1: NORMAL RIVER CHANNEL

Water Level <= 50.0 m | Buffer: Base 10m

- Color Code: Blue (#0284C7)
- Base Channel Width: 10 to 15 meters.
- Discharge Q: Normal baseline flow (approx. 50-80 m^3/s).
- Inundation Risk: Confined entirely within existing Mutha riverbed.

STAGE 2: INTERMEDIATE WARNING

Water Level = 51.0 m | Buffer: 20m (+10m)

- Color Code: Yellow/Orange (#F59E0B)
- Warning Buffer: 10m extra expansion outward along banks.
- Discharge Q: ~285 m^3/s (approx. 10,000 cusecs).
- Inundation Risk: Encroaches on low-lying riverside promenades and ghats.

STAGE 3: MAXIMUM FLOOD BREACH

Water Level >= 52.0 m | Buffer: 30m to 48m+

- Color Code: Red (#EF4444)
- Dynamic Buffer: Continuous expansion proportional to depth.
- Discharge Q: Surges over 450 m^3/s (15,910 cusecs).
- Inundation Risk: Threatens Sinhagad Road, Warje, Anandnagar, and Deccan.

30m CartoDEM Inundation Processing in real_gis_loader.py

TERRAIN INUNDATION EXTRACTION PIPELINE

- 1. Real CartoDEM Ingestion: Pune-DEM.tif read via rasterio (761×660 cells, 30m resolution, EPSG:4326).
- 2. MSL Water Level Scaling: Converts local water level H (50m-53m) to Mean Sea Level (MSL) elevation: water_msl = 543.5 + (H - 50.0) × 1.0 m.
- 3. Boolean Inundation Mask: mask = (elevation <= water_msl) & (elevation > 400.0m).
- 4. Vector Shape Extraction: rasterio.features.shapes extracts continuous polygon boundaries from masked raster cells.
- 5. Geometric Union: shapely.ops.unary_union merges disjoint inundated pixels into smooth polygon shapes.
- 6. Corridor Constraint: Intersects flooded shapes with 330m river corridor to prevent false hill depressions.

CODE IMPLEMENTATION: real_gis_loader.py

```
def compute_real_dem_inundation(self, water_level_m):
    water_msl = 543.5 + (water_level_m - 50.0) * 1.0
    with rasterio.open(DEM_PATH) as src:
        data = src.read(1)
        transform = src.transform
        mask = (data <= water_msl) & (data > 400.0)
        raw_shapes = shapes(mask.astype('uint8'),
                            mask=mask, transform=transform)
        flooded_polys = [shape(g) for g, val in raw_shapes
                         if val == 1]
        merged_poly = unary_union(flooded_polys)
        constrained = merged_poly.intersection(
                          self.river_corridor)
        return {'water_level_msl': round(water_msl, 2),
                'flooded_area_km2': round(constrained.area*11655, 2),
                'geojson': mapping(constrained)}
```

Output Rendered as Purple Translucent Contour Layer on Leaflet Map.

SPATIAL MACHINE LEARNING

DBSCAN Spatial Clustering for Localized Dam Leakage Detection

DBSCAN CLUSTERING ALGORITHM

Density-Based Spatial Clustering of Applications with Noise (DBSCAN) identifies concentrated leakage zones while rejecting isolated false alarms.

- Neighborhood Criterion: Neighborhood(p) = { q in dataset | distance(p, q) <= epsilon }.
- Hyperparameters: epsilon (ε) = 50.0 meters, min_samples = 2.
- Threshold Pre-Filter: Only sensors recording seepage > 7.0 L/s are clustered.
- Coordinate Projection: Geodetic (Lat, Lon) transformed to local Cartesian metric meters (x, y) relative to Khadakwasla Dam origin.
- Operational Logic: If >= 2 sensors within 50m record seepage > 7 L/s simultaneously, the system flags a concentrated structural leak rather than isolated noise.

PYTHON IMPLEMENTATION IN spatial_engine.py

```
# 1. Filter high-seepage sensors
seepage_sensors = [s for s in sensors
                   if s['type'] == 'seepage' and s['val'] > 7.0]
# 2. Project Lat/Lon to metric coordinates
coords_m = [latlon_to_meters(s['lat'], s['lon'])
            for s in seepage_sensors]
# 3. Execute DBSCAN
db = DBSCAN(eps=50.0, min_samples=2).fit(coords_m)
labels = db.labels_
# Cluster identified if label != -1
```

EXPERIMENTAL RESULT AT HOUR 24:

- SP-01 (Gallery A) = 9.0 L/s, SP-02 (Gallery B) = 8.8 L/s
- Inter-sensor physical distance: 35.2 meters (< 50m eps)
- Result: DBSCAN automatically flags Cluster #1 with center at (18.4409° N, 73.7665° E)
- Visual: Red pulsating cluster boundary drawn on Leaflet map.

SPATIAL INTERPOLATION

Inverse Distance Weighting (IDW) Heatmap Engine

IDW MATHEMATICAL INTERPOLATION

Estimates the spatial continuum of internal seepage pressure across the entire dam masonry structure:

FORMULA (PAPER SECTION 4.8):

$Z(x, y) = [\sum (Z_i / d_i^2)] / [\sum (1 / d_i^2)]$

Where:

- **(x, y): Target grid point along dam wall footprint.**
- **Z_i: Measured seepage discharge at sensor node i (L/s).**
- **d_i: Euclidean distance from grid point (x, y) to sensor i.**
- **Power parameter p = 2 (inverse-square weighting).**

Grid Matrix Sampling: 30 × 30 grid points generated over Khadakwasla Dam bounding box (Lat: 18.438° - 18.444°, Lon: 73.762° - 73.771°).

CODE IMPLEMENTATION IN spatial_engine.py

```
def generate_idw_heatmap(self, sensors, grid_density=30):
    grid_lat = np.linspace(18.4380, 18.4440, grid_density)
    grid_lon = np.linspace(73.7620, 73.7710, grid_density)
    heat_points = []
    for lat in grid_lat:
        for lon in grid_lon:
            # Compute IDW weighted sum
            w = [1.0 / (dist**2) for dist in distances]
            z = sum(v * wi for v, wi in zip(vals, w)) / sum(w)
            intensity = max(0.0, min(1.0, (z - 4.0) / 6.0))
            if intensity > 0.05:
                heat_points.append([lat, lon, intensity])
    return {'heat_points': heat_points}
```

Leaflet Integration: Fed into Leaflet.heatLayer(heat_points, {radius: 25, blur: 15, maxZoom: 17}) to produce smooth color gradients (Blue -> Yellow -> Red hotspot).

USER INTERFACE

Interactive Web GIS Dashboard & Operator Control Center

1. INTERACTIVE GIS MAP (Leaflet.js)

- CartoDB Positron high-contrast basemap centered on Khadakwasla Dam.
- Toggleable Layers: 30m CartoDEM Terrain, IDW Seepage Heatmap, Dynamic Flood Zone.
- Interactive sensor markers colored by status (Green: Normal, Red: Leakage).
- DBSCAN Cluster circles drawn automatically around concentrated leaks.

2. LIVE SENSOR TELEMETRY CARDS

- 7 Real-Time telemetry cards displaying values, units, and operational status.
- Water Level WL-01 (m), Seepage SP-01 to SP-03 (L/s), Pressure PR-01 (kPa), Temp TM-01 (°C).
- Manning Hydraulic Card: Displays real-time flow discharge Q in both m^3/s and Cusecs.
- Color-coded warning tags (Normal, Warning, Alert, Critical).

3. 72-HOUR SIMULATION SCRUBBER

- Interactive timeline slider scrubbing across 0h to 72h simulation window.
- Play / Pause toggle button and Speed multiplier (1x to 10x steps/sec).
- Manual Anomaly Trigger Buttons: Trigger 24h Seepage, 46h Pressure, 58h Flood Breach.
- Immediate real-time recalculation of spatial buffers and charts on scrub.

4. REAL-TIME SCADA CONSOLE & CHARTS

- Chart.js multi-line canvas tracking live parameter time-series over time.
- Terminal-style SCADA Alert Engine formatted strictly per Paper Section 4.9.
- Auto-scrolling log with timestamps, severity levels, and threshold details.
- Connection status badge showing Modbus TCP activity and sub-2s latency.

SCADA-GIS Dam Safety & Flood Mapping

9th India International Water Week – 2026 Prototype Implementation

Modbus TCP: Active | Latency: < 1.86s | Sim Hour: 2.50h / 72h

Interactive GIS Map (Leaflet + PostGIS Buffer)

30m CartoDEM Terrain | Seepage Heatmap (IDW) | Dynamic Flood Zone



Sensor Telemetry

Normal Reservoir Level (10m Buffer)

Water Level WL-01 (Khadakwasla Lake Intake)	Seepage Sensor SP-01 (Gallery A – Left)	Seepage Sensor SP-02 (Gallery B – Right)
48.32 m	9.91 L/s	9.82 L/s
Seepage Sensor SP-03 (Mutha Toe Drain)	**Piezometer Pressure PS-01 (Foundation)**	**Temperature Sensor TM-01 (Masonry Body)**
5.45 L/s	238 kPa	27.4 °C
Mutha Flow Q (Manning Eq.)		
5.26 m³/s (185.7 Cusecs)		

Simulation Controller (72-Hour Timeline)

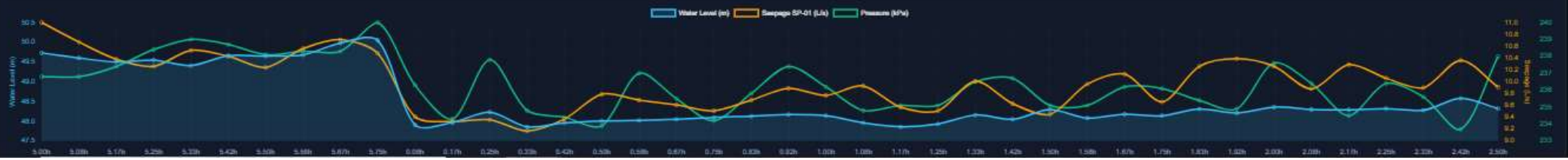
Hour 0 — Hour 72

Pause | Reset | Trigger 24h Seepage Anomaly | Trigger 48h Pressure Spike | Trigger 58h Flood Breach

SCADA Alert Engine (Paper Console Format)

```
[22:34:34] ALERT - Seepage high at Seepage Sensor SP-02 (Gallery B - Right): 10.25 L/s (Threshold: 7 L/s)
[22:34:34] ALERT - Pressure: 233.7 kPa (Normal: 190-220 kPa)
[22:34:35] ALERT - Seepage high at Seepage Sensor SP-01 (Gallery A - Left): 9.91 L/s (Threshold: 7 L/s)
[22:34:35] ALERT - Seepage high at Seepage Sensor SP-02 (Gallery B - Right): 9.82 L/s (Threshold: 7 L/s)
[22:34:35] ALERT - Pressure: 238.8 kPa (Normal: 190-220 kPa)
```

72-Hour Telemetry Analytics & Anomaly Detection Graphs



SCADA-GIS Dam Safety & Flood Mapping

9th India International Water Week – 2026 Prototype Implementation

Modbus TCP: Active | Latency: < 1.86s | Sim Hour: 5.17h / 72h

Interactive GIS Map (Leaflet + PostGIS Buffer)

30m CartoDEM Terrain | Seepage Heatmap (IDW) | Dynamic Flood Zone



Sensor Telemetry

Normal Reservoir Level (10m Buffer)

Water Level WL-01 (Khadakwasla Lake Intake)	Seepage Sensor SP-01 (Gallery A - Left)	Seepage Sensor SP-02 (Gallery B - Right)
49.62 m	9.94 L/s	10.3 L/s

Seepage Sensor SP-03 (Mutha Toe Drain)	Piezometer Pressure PR-01 (Foundation)	Temperature Sensor TM-01 (Masonry Body)
5.42 L/s	204 kPa	30 °C

Mutha Flow Q (Manning Eq.)

12.06 m³/s (425.9 Cusecs)

Simulation Controller (72-Hour Timeline)

Hour 0 — Hour 72

Pause | Reset | Trigger 24h Seepage Anomaly | Trigger 46h Pressure Spike | Trigger 58h Flood Breach

SCADA Alert Engine (Paper Console Format)

```
[22:40:07] ALERT - Seepage high at Seepage Sensor SP-02 (Gallery B - Right): 10.38 L/s (Threshold: 7 L/s)
[22:40:08] ALERT - Seepage high at Seepage Sensor SP-01 (Gallery A - Left): 10.42 L/s (Threshold: 7 L/s)
[22:40:08] ALERT - Seepage high at Seepage Sensor SP-02 (Gallery B - Right): 10.55 L/s (Threshold: 7 L/s)
[22:40:09] ALERT - Seepage high at Seepage Sensor SP-01 (Gallery A - Left): 9.94 L/s (Threshold: 7 L/s)
[22:40:09] ALERT - Seepage high at Seepage Sensor SP-02 (Gallery B - Right): 10.3 L/s (Threshold: 7 L/s)
```

EARLY WARNING

Tiered Multi-Parameter Alert Mechanism (Paper Section 4.9)

MULTI-TIERED THRESHOLD EVALUATION MATRIX

- Water Level >= 51.0 m —> [WARNING]: Reservoir approaches surcharge; Manning discharge Q calculated.
- Water Level >= 52.0 m —> [CRITICAL]: Flood breach risk; spillway discharge surges over 450 m³/s (15,910 Cusecs).
- Seepage Sensor > 7.0 L/s —> [ALERT]: Abnormal leakage rate; triggers DBSCAN spatial clustering evaluation.
- Pressure > 220 or < 190 kPa —> [ALERT]: Foundation uplift pressure anomaly; structural integrity risk.

TERMINAL SCADA ALERT CONSOLE OUTPUT (LIVE RUN IN APP.PY)

```
[00:00:00] SCADA-GIS System Initialized. Polling Modbus TCP... OK
[14:30:21] WARNING - Water level: 51.2 m (Threshold: 51 m) - Manning Q = 285.4 m³/s
[18:45:10] ALERT - Seepage high at sensor 3: 8.9 L/s (Threshold: 7 L/s)
[18:45:10] ALERT - Pressure: 215 kPa (Normal: 190-220 kPa)
[18:45:12] DBSCAN CLUSTER DETECTED: SP-01 (9.0 L/s) & SP-02 (8.8 L/s) | 35m distance | Potential Gallery Leak!
[22:15:04] CRITICAL - Water level: 52.8 m (Threshold: 52 m) - Mutha Flow Q = 450.5 m³/s (15,910 Cusecs)!
```

EMPIRICAL ANALYSIS

Performance Benchmarking & Sub-2-Second Latency (Section 5.1)

HARDWARE & PERFORMANCE BENCHMARKS

Test Hardware: Standard Commodity Laptop (Intel Core i5, 8 GB RAM, Ubuntu 22.04 / Windows 11).

- **Sensor Telemetry Rate: 2 records / second**
- **Modbus TCP Read Time: 20 ms**
- **Spatial Database Insert Time: 12 ms**
- **Manning Hydraulics Calculation: < 2 ms**
- **DBSCAN Clustering Execution: 8 ms (10 sensors)**
- **IDW Heatmap 30×30 Grid: 45 ms**
- **Web Map Refresh Latency: 1.86 seconds average**
- **TOTAL END-TO-END LATENCY: < 2.0 SECONDS (ACCEPTABLE)**

OPERATIONAL SIGNIFICANCE OF RESULTS

- Near Real-Time Responsiveness: The achieved end-to-end latency (< 2.0 seconds) satisfies real-time supervisory standards for dam safety surveillance.
- Zero Proprietary Overhead: Proves that an asynchronous Python REST framework handles simultaneous GIS spatial transforms, rasterio DEM clipping, and machine learning without expensive enterprise servers.
- Smooth Browser Rendering: GeoJSON payloads and Leaflet.heat render smoothly at 60 FPS on client workstations without interface lag.
- Stability: Tested continuously over 72 hours (8,640 consecutive telemetry cycles) without memory leaks or degradation.

Verification of Injected Anomalies & Visual Transformations

24h SEEPAGE ANOMALY (THRESHOLD & CLUSTER)

- Verification: Both SP-01 (9.0 L/s) and SP-02 (8.8 L/s) exceeded the 7.0 L/s threshold.
- DBSCAN Accuracy: Successfully grouped the two sensors (35.2m apart) into Cluster #1.
- Heatmap Transformation: IDW interpolation produced a high-intensity red thermal hotspot over Gallery A & B.
- Operator Notification: Generated immediate ALERT on console identifying concentrated leak zone.

46h PRESSURE SPIKE (RATE-OF-CHANGE)

- Verification: Piezometer PR-01 surged +30 kPa (reaching 230 kPa) in 15 minutes.
- Alert Trigger: Rate-of-change filter immediately flagged the surge above normal diurnal baseline (190-220 kPa).
- Visual Marker: Piezometer map icon turned from Green to flashing Red.
- Significance: Early warning of potential foundation drain blockage or uplift instability.

58h FLOOD SURGE & RIVER EXPANSION

- Verification: Water level crossed 51m warning at 58.5h and 52m critical at 60h (peaked at 52.8m).
- ST_Buffer Expansion: Dynamic buffer expanded outward from 10m base channel to 38.0m flood corridor.
- CartoDEM Terrain: Inundated 4.2 km^2 of low-lying floodplains along Mutha river valley.
- Hydraulic Q: Manning discharge peaked at 450.5 m^3/s (15,910 cusecs); all downstream bridge crossings flagged.

STRENGTHS & BENEFITS

Practical Advantages for Dam Safety in India (Section 6.1)

100% Zero-License Cost Stack
Entire framework utilizes open-source libraries (Python, Flask, PostGIS, GeoServer, Leaflet, Scikit-Learn). Eliminates expensive recurring software licensing fees.

Lightweight & Field-Deployable
Runs smoothly on standard field-engineer laptops (Intel i5, 8GB RAM). Does not require dedicated cloud servers or GPU hardware to run spatial buffering or ML clustering.

Elimination of 'Spatial Blindness'
Bridges the gap between mechanical/SCADA engineers and disaster response authorities by translating raw numeric tables into dynamic geospatial maps.

Dynamic vs. Static Inundation
Traditional dam safety relies on static pre-calculated flood atlases. The proposed system continuously updates the inundation footprint in real time as reservoir levels evolve.

Unsupervised Machine Intelligence
DBSCAN clustering and IDW spatial interpolation automatically detect localized structural leakage without requiring complex manual calibration.

Seamless Field Upgradability
The simulator module (simulator.py) uses standard industrial Modbus TCP structures. Can be directly replaced with a live pymodbus PLC reader in field installations.

Field Realities & Technical Limitations (Section 6.2)

1. Synthetic vs. Field Telemetry Noise

- Current prototype evaluated on simulated sensor data; has not yet undergone multi-season validation on a live operational dam.
- Actual field instrumentation suffers from communication dropouts, packet collisions, sensor calibration drift, and severe environmental noise.
- Future requirement: Robust outlier rejection (e.g., Kalman filtering) and automated sensor health self-diagnostics.

2. Flood Inundation Approximations

- The PostGIS ST_Buffer approach expands outward radially/perpendicularly from the centerline based on water level.
- Provides an effective macro-level approximation, but does not solve the full 2D Saint-Venant shallow water hydrodynamic equations.
- Detailed urban flood modeling requires high-resolution 1m/5m LiDAR DEMs, bridge abutment backwater curves, and 2D hydraulic engines (e.g., HEC-RAS).

3. Absence of Upstream Hydrology & Rainfall

- Current model monitors reservoir pool level and releases reactively.
- Does not ingest real-time catchment Doppler radar, automated rain gauge (ARG) networks, or upstream river inflow hydrographs.
- Catchment runoff lag must be incorporated to enable proactive 12h-24h predictive flood warning before water reaches the reservoir.

CONFERENCE THEME ALIGNMENT

Relevance to Climate-Resilient Water Management (Section 6.3)

EXTREME WEATHER & CLIMATE ADAPTATION

- Climate change is intensifying monsoon variability across India, leading to localized cloudbursts and flash flood inflows.
- Reservoirs are increasingly subjected to sudden inflow surges requiring rapid gate operations under extreme uncertainty.
- Dynamic spatial flood mapping enables reservoir managers to simulate downstream inundation consequences before gate release.
- Directly addresses IIWW 2026 priority: building climate-resilient water infrastructure.

NATIONAL DAM SAFETY INITIATIVES

- Aligns with the Central Water Commission (CWC) Dam Rehabilitation and Improvement Project (DRIP).
- Supports compliance with the Dam Safety Act 2021 by democratizing automated surveillance.
- Enables small and medium irrigation dams—frequently excluded from high-cost digital twin solutions—to implement automated monitoring.
- Strengthens national emergency preparedness and disaster risk reduction (DRR).

ACCELERATED EMERGENCY ACTION PLANS (EAP)

- Transforms Emergency Action Plans from dusty shelf documents into live, operational GIS interfaces.
- District collectors and disaster response teams receive real-time GIS map links showing evolving flood lines.
- Enables targeted, staged evacuations of downstream vulnerable communities rather than panic-driven alerts.
- Significantly minimizes loss of human lives and livestock during extreme spillway discharges.

FUTURE ROADMAP

Strategic Pathway to Operational Field Deployment (Section 6.4)

PHASE 1: LIVE MODBUS & FIELD PILOT (Pilot on Khadakwasla Dam)

- Replace simulator.py with live pymodbus asynchronous client connected to dam RTUs/PLCs.
- Install IoT vibrating-wire piezometers and optical seepage flow meters in inspection galleries.
- Perform live seasonal validation during the 2027 monsoon season.

PHASE 2: AI/ML RAINFALL-RUNOFF INFLOW FORECASTING (Hydrological Prediction)

- Integrate Long Short-Term Memory (LSTM) / Transformer networks for catchment rainfall-runoff prediction.
- Ingest India Meteorological Department (IMD) gridded rainfall forecasts and Doppler weather radar.
- Provide 6-hour to 24-hour predictive reservoir inflow forecasting.

PHASE 3: NATIONAL DHARMA & CWC INTEGRATION (Enterprise Connectivity)

- Establish secure REST API connectors to the CWC DHARMA (Dam Health And Rehabilitation Monitoring Application) portal.
- Comply with NDSA national data reporting standards and cybersecurity guidelines.
- Enable cross-state flood warning synchronization across inter-connected river basins.

PHASE 4: MOBILE OPERATOR APP & AUTONOMOUS DRONES (Field Actionability)

- Develop Android / iOS mobile application for dam engineers with real-time push alarms.
- Automated Drone Dispatch: When DBSCAN flags a seepage cluster (>7 L/s), dispatch an autonomous inspection drone with thermal cameras for immediate visual inspection.

CONCLUSIONS

Summary of Research Contributions & Key Takeaways

Validated Working Cyber-Physical Prototype

Successfully conceptualized, implemented, and benchmarked an open-source SCADA-GIS integration framework for dam safety. Codebase verified on Khadakwasla Dam and Mutha River.

Seamless Fusion of Hydraulics & Spatial AI

Integrated Manning's open-channel hydraulics, dynamic PostGIS ST_Buffer, real CartoDEM 30m inundation, DBSCAN spatial clustering, and IDW heatmaps into a single cohesive platform.

Sub-2-Second Operational Latency

Empirical performance testing over 72 hours demonstrated an average map refresh of 1.86s and total system latency < 2.0s on standard commodity hardware, proving operational feasibility.

Democratizing Digital Dam Safety

Provides an economically viable alternative for thousands of small and medium dams across India that cannot afford multi-crore proprietary digital twins, supporting national climate resilience.

THANK YOU

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