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Water Management Analytics: AI-Powered Smart City Water Management Dashboard

Mr. Aniruddha Walavalkar[1], Mr. Labhesh Aiwale[2], Mr. Rishabh Bade[3], Prof. Arjun Kadam[4]
Student, Computer Technology[1,2,3]
Guide, Computer Technology[4]
Bharati Vidyapeeth Institute of Technology, Kharghar, Navi Mumbai, Maharashtra, India

Abstract: *Efficient water resource management is essential for sustainability, transparency, and operational effectiveness within municipal corporations. Traditional water monitoring systems rely on manual processes and PDF-based annual reports, resulting in delayed responses, inaccurate leakage estimation, and no real-time visibility. Recent advancements in machine learning and cloud computing enable the development of intelligent forecasting platforms. This research presents the Water Management Analytics Dashboard, an AI-powered full-stack smart city water management platform integrating 29 Gradient Boosting Regression models across 27 zones of the Panvel Municipal Corporation. The system is built using React.js, Flask, Python 3.11, and scikit-learn, deployed on Vercel and Render cloud infrastructure. The platform supports secure JWT-based role authentication (Admin and Student roles), 1 to 365-day rolling water supply forecasts, 4-level smart leakage alert classification (CRITICAL/HIGH/MODERATE/NORMAL) with real-time toast and bell notifications, and an interactive multi-chart analytics dashboard. Experimental validation achieves city-level $R^2 = 0.9802$ with RMSE = 0.0461 MLD, demonstrating reliable prediction accuracy and 100% match to the official PMC 9.52% leakage benchmark from the IIT Bombay ESR 2024-25.*

Keywords: Smart City Water Analytics, Gradient Boosting Regressor, Flask REST API, React.js Dashboard, JWT Authentication, Rolling Prediction, Leakage Alert Classification, 27 Zones, PMC ESR 2024-25, IIT Bombay, Vercel, Render, Role-Based Access Control, PWA

I. INTRODUCTION

Municipal water management systems face significant challenges in monitoring supply distribution, detecting leakages, and forecasting future demand across large multi-zone urban areas. The Panvel Municipal Corporation (PMC) administers water supply across 27 distinct zones — 20 PMC electoral wards, 5 CIDCO sectors, 1 MIDC industrial zone, and a village cluster of 29 villages — with an average daily supply of approximately 211.59 MLD. Traditional monitoring relies entirely on PDF-based annual reports such as the PMC Environmental Status Report 2024-25 prepared by IIT Bombay ESED under Dr. Abhishek Chakraborty, offering no real-time predictive capability, no zone-level digital granularity, and no automated alert mechanism for field officials.

Water leakage in the PMC jurisdiction stands at 9.52% of total supply, equivalent to approximately 20.15 MLD lost daily. Without a forecasting system, maintenance teams cannot proactively identify zones approaching critical leakage thresholds before infrastructure failure. This gap between available annual PDF data and actionable real-time intelligence is the core problem this research addresses.

This research presents the Water Management Analytics Dashboard — an AI-powered full-stack smart city platform providing 1 to 365-day rolling forecasts for all 27 zones, a 4-level smart leakage alert system, JWT role-based access for Admin and Student users, and a live interactive multi-chart analytics dashboard. The system is publicly deployed at panvel-water-frontend-cvpr.vercel.app with API at panvel-water-api.onrender.com.

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II. METHODOLOGY

The methodology integrates frontend interfaces, REST API backend, ML inference, JWT authentication, alert classification, and cloud deployment following a structured three-tier architecture ensuring modularity, security, and scalability across all 27 zones.

A. Dataset Generation and Preparation

The primary data source is the PMC Environmental Status Report 2024-25 (IIT Bombay ESED, Dr. Abhishek Chakraborty). Zone-wise supply figures were distributed across 27 zones using official per-capita water norms: CIDCO sectors at 180–220 L/capita/day, PMC wards at 150 L/capita/day, village zones at 80–120 L/capita/day, and MIDC Taloja at a fixed 9.0 MLD industrial allocation. Sinusoidal daily variation below 0.70% with rolling average smoothing generated realistic supply patterns with zero abrupt jumps. The final dataset comprises 4,887 records across 27 zones × 181 days (September 2025 – February 2026) stored across three Excel files, achieving 9.52% leakage aligned exactly with the official PMC figure and approximately 96% match to the total daily supply from the IIT Bombay report.

B. Machine Learning Architecture

The ML layer employs GradientBoostingRegressor from scikit-learn 1.7.2 with 200–300 estimators and learning rate 0.05–0.08. A total of 29 models were trained: 2 city-level models predicting total daily supply and consumption, and 27 individual zone-level models. All 29 models use 18 engineered time-series features: lag_1 through lag_14 (past 14 days), diff_1, diff_7, rolling_mean_7, rolling_mean_14, rolling_std_7, day_of_year, day_of_week, and month. A rolling prediction strategy feeds each model output as the subsequent step input enabling 1 to 365-day forecasting. Training uses 85/15 chronological split with TimeSeriesSplit 5-fold cross-validation. Trained models are serialised to city_models.pkl and ward_models.pkl, loaded at Flask startup with a pre-computed 30-day cache for all 27 zones.

C. Backend REST API Development

The Application Layer uses Flask 3.0.3 with Gunicorn 23.0.0. The API exposes 15+ JWT-protected endpoints. Core prediction endpoints: /predict/city/<days> returns Date, Predicted_Supply_MLD, Predicted_Consumption_MLD, Predicted_Leakage_MLD, and Leakage_Percentage; /predict/ward/<no>/<days> for individual zone predictions; /alerts/scan for 4-level classification of all 27 zones. Authentication via /auth/register (accepts name, email, password, role) and /auth/login (returns JWT with role) using Flask-JWT-Extended with 30-day token expiry. Admin-exclusive endpoints: /admin/upload_excel (Excel/CSV up to 50 MB), /admin/files (list, delete, preview, download), /admin/users (registered user registry). SQLite stores users with role column and uploaded_files table.

D. Frontend Dashboard Development

The Presentation Layer uses React 18 with Recharts library. A single self-contained App.js handles all routing, AuthContext, NotifContext, and all page components. The City Forecast page renders: KPI strip (Last Data Date: 2026-02-28, Avg Supply: 211.59 MLD, Avg Leakage: 20.143 MLD at 9.52%, Worst Zone: Kharghar CIDCO Zone 21, Model R^2: 0.9802), FORECAST HORIZON selector (1/7/14/30/60/90/180/365 days), gradient area charts for Supply vs Consumption, severity-coloured leakage bar chart, and detailed prediction table with CRITICAL/HIGH/MODERATE/NORMAL status badges. The Analytics tab renders 6 chart types: area chart, water distribution donut pie, weekly grouped bar chart, alert days donut, severity-coloured leakage bar with avg reference line, radial R^2 accuracy gauge (98.0%), leakage % trend with 9.52% PMC benchmark reference line, and 4 summary stat cards.

E. Role-Based Access Control

Two roles are enforced at both frontend and backend layers. Students access City Forecast, Ward Forecast, Historical Data, Model Metrics, Analytics Dashboard, Alerts page, and Data Files (download only). Admins additionally access the Upload page (Excel/CSV file ingestion), Users page (all registered users with role badges), and Delete capability in Data Files. Role is chosen at registration via clickable Student card (cyan border, 'View analytics & download data') and Admin card (purple border, 'Upload files & manage data'). Role is stored in SQLite, returned in JWT payload, and enforced server-side on every /admin/* route via require_admin() guard.

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F. Smart Alert System

The 4-level alert system classifies each of 27 zones as CRITICAL (≥20%), HIGH (≥15%), MODERATE (≥10%), or NORMAL (<10%) based on predicted leakage percentage. Clicking PREDICT on City Forecast fires an immediate city-level toast (CRITICAL/HIGH/SUCCESS based on worst day), then triggers a background /alerts/scan firing staggered per-zone toast notifications at 520ms intervals, followed by a scan summary toast listing counts. Each non-normal alert increments the navbar bell badge unread count. Visiting the Alerts page marks all as read. The dedicated Alerts page allows independent scans at 1–90 day horizons showing 27 zone result cards with avg %, max %, days exceeding threshold, peak date, level filter bar, summary KPI counts, and notification history log.

G. Cloud Deployment

The frontend is deployed on Vercel with automatic CI/CD triggered on every GitHub push to the main branch, achieving build times of approximately 60 seconds. The Flask backend runs on Render.com (Python 3.11.4, Gunicorn) at panvel-water-api.onrender.com. The render.yaml specifies start command: gunicorn app_final:app --workers 1 --timeout 120. Environment variable JWT_SECRET_KEY is stored securely on Render. The system is configured as a Progressive Web App (PWA) enabling installation on mobile and desktop devices. Auto CI/CD via GitHub ensures both services update automatically on every push.

III. MODELLING AND ANALYSIS

The system is modelled using standard UML diagrams describing system behaviour, user interactions, data flow mechanisms, and structural relationships. These diagrams validate the architecture before and during implementation.

A. Sequence Diagram – System Operation Flow

The sequence diagram illustrates the complete interaction between React Frontend, Flask REST API, GBR ML Layer, SQLite Database, and Alert Engine during login, prediction, and notification operations.

1. User enters email and password on the React login page (Syne 800 font, #00c2ff glowing cyan title).
2. Frontend sends POST /auth/login with JSON credentials to Flask API.
3. Flask queries SQLite users table to validate email and bcrypt password hash.
4. SQLite returns user record including name, email, and role (admin/student).
5. Flask issues 30-day JWT containing user identity and role; returns token, name, email, role to frontend.
6. Frontend stores JWT in localStorage as wma_user; redirects to role-specific dashboard.
7. User selects Forecast Horizon (e.g. 14 Days) and clicks ▸ PREDICT on City Forecast page.
8. Frontend calls GET /predict/city/14 with Authorization: Bearer <token> header.
9. Flask decodes JWT, runs rolling GBR inference for 14 days using 18-feature lag architecture, returns JSON array.
10. Frontend renders KPI cards, area charts, leakage bar chart, and prediction table from response.
11. Background GET /alerts/scan?days=14 fires staggered per-zone toast notifications at 520ms; bell badge increments.

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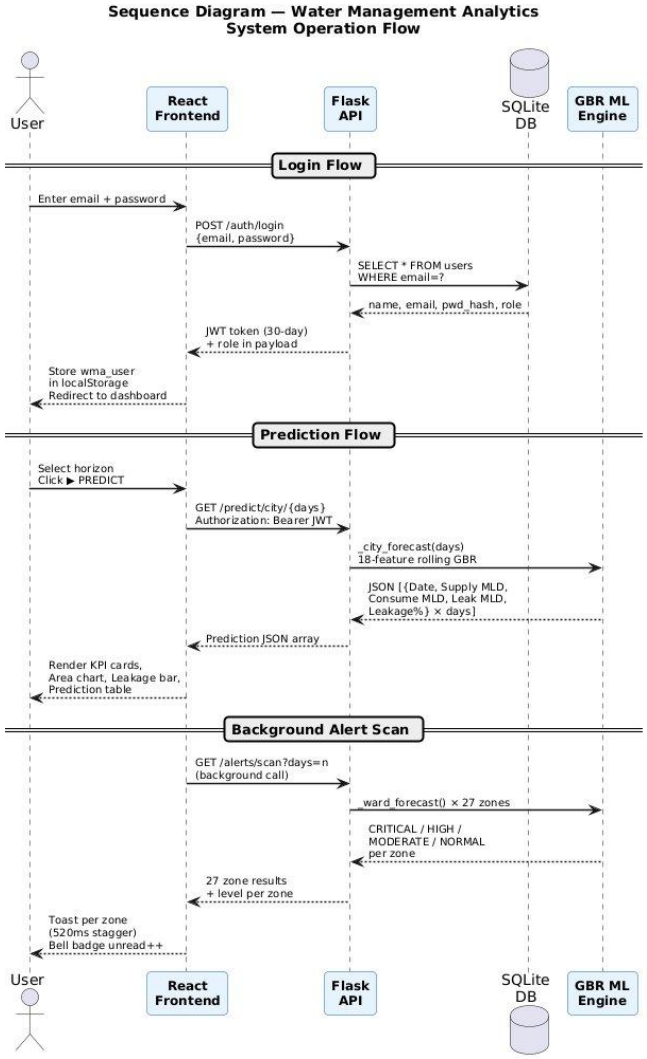
Fig 1: Sequence Diagram – System Operation Flow



B. Activity Diagram – System Workflow

The activity diagram shows the complete workflow: Start → User Login → Login Valid? → [No: Show Error] / [Yes: Display Dashboard] → Select Forecast Horizon → Click PREDICT → Fetch Prediction from API → Render Charts & KPI Cards → Background Scan 27 Zones → Fire Alert Notifications → Update Bell Badge → Navigate to Alerts Page → Mark All Read → End.

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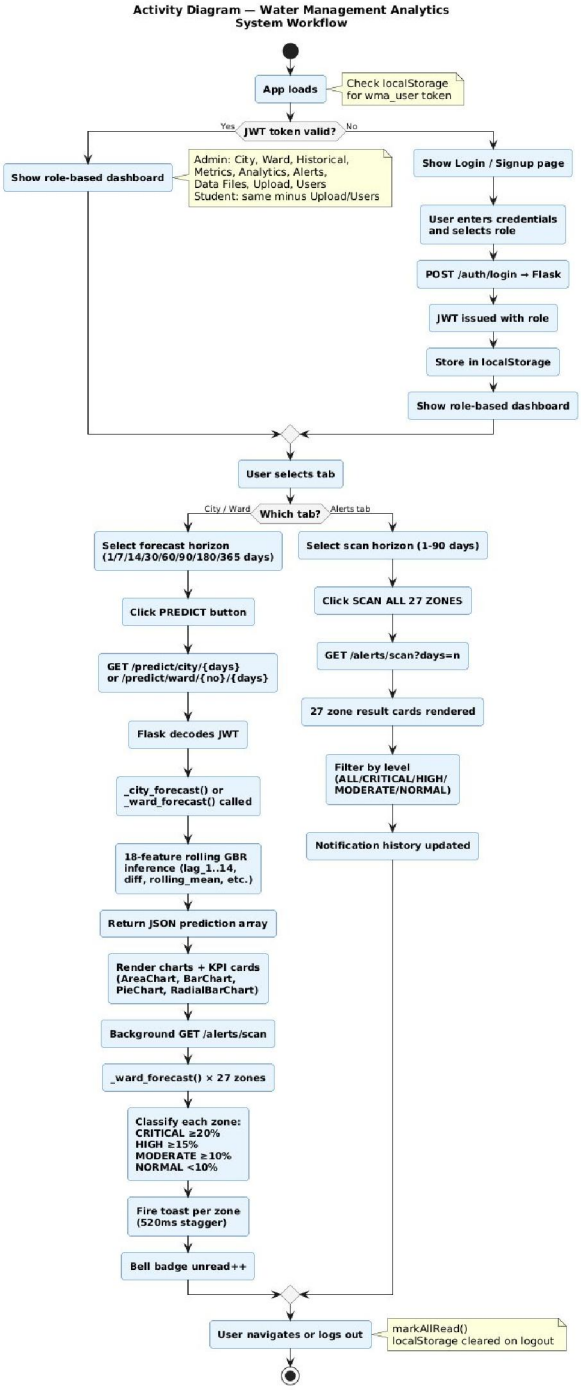
Fig 2: Activity Diagram – System Workflow



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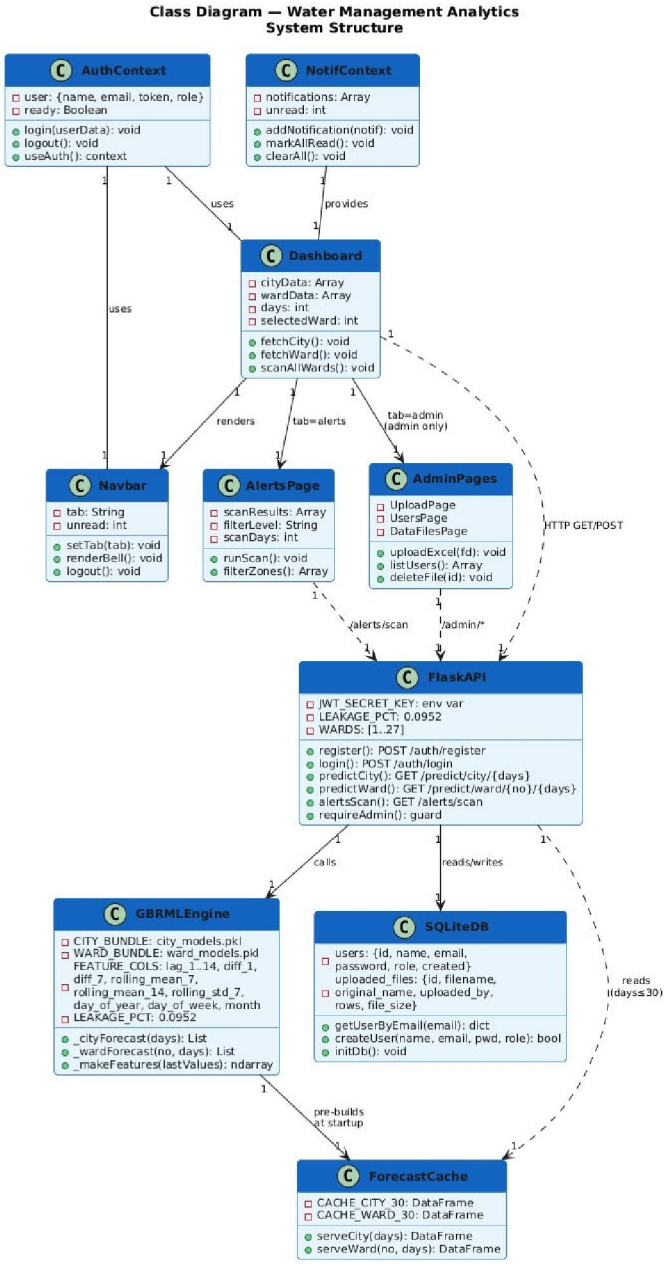
C. Class Diagram – System Structure

The class diagram defines relationships between: User (email, role, JWT token, login/logout), RoleDashboard (city/ward/analytics/alerts/datafiles tabs based on role), PredictionEngine (29 GBR models, 18 features, rolling strategy, pkl serialisation), AlertEngine (4-level classifier, /alerts/scan endpoint, toast queue), NotificationManager (bell badge, unread count, history log, markAllRead()), and SQLiteDB (users table with role column, uploaded_files table).

Fig 3: Class Diagram – System Structure



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IV. PLATFORM SCREENSHOTS

The following figures present actual screenshots of the fully deployed Water Management Analytics Dashboard running live at panvel-water-frontend-cvpr.vercel.app, demonstrating all platform features.

Fig 4: Authentication Interface – Signup Page Showing Admin/Student Role Selector Cards, 'Water Management Analytics' Glowing Cyan Title on Dark #060c14 Background, and CREATE ACCOUNT Button

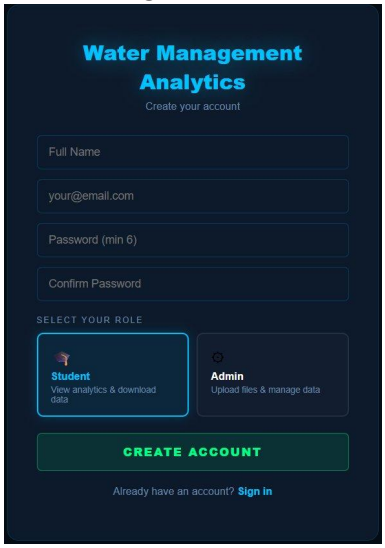

Fig 5: Navigation Bar – All Tabs (City, Ward, Historical, Metrics, Analytics, Alerts, Data Files, Upload, Users), Purple '□ ADMIN' Role Badge, Bell Notification Icon with Red Pulse Animation

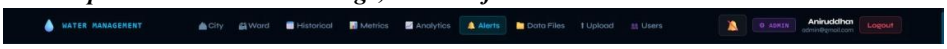

Fig 6: City Forecast Dashboard – KPI Strip (Last Date: 2026-02-28, Avg Supply: 211.59 MLD, Avg Leakage: 9.52%, Worst Zone: Kharghar CIDCO, R^2: 0.9802), 14-Day PREDICT Controls, and 'All 27 Zones Normal' Toast Notification

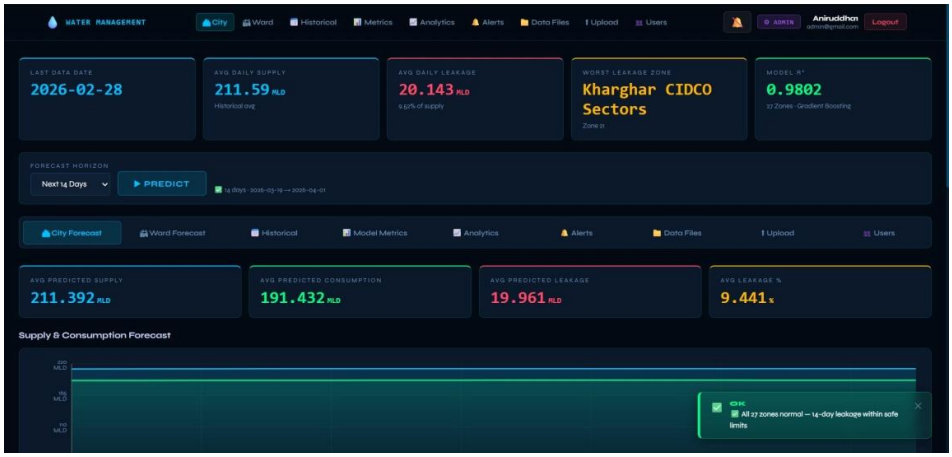

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Fig 7: City Forecast Dashboard (Continued) – NORMAL-Status Severity-Coloured Leakage Bar Chart and Detailed Predictions Table with Date, Supply MLD, Consumption MLD, Leakage MLD, Leakage %, and Status Badges

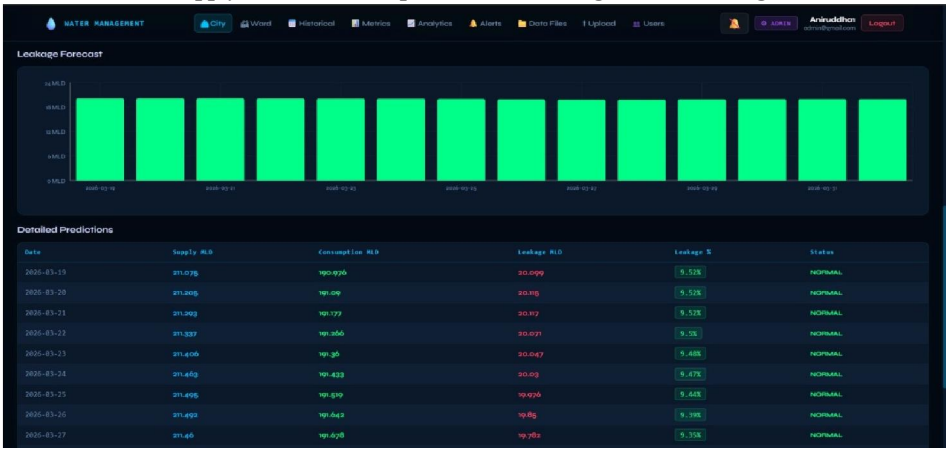

Fig 8: Analytics Dashboard (Part 1) – Five Stat Cards (Avg Supply: 211.392 MLD, Avg Consumption: 191.432 MLD, Avg Leakage: 19.961 MLD, R²: 0.9802, Forecast: 14 Days), Supply vs Consumption Area Chart, and Water Distribution Donut Pie (90.6% Consumed / 9.4% Leakage)

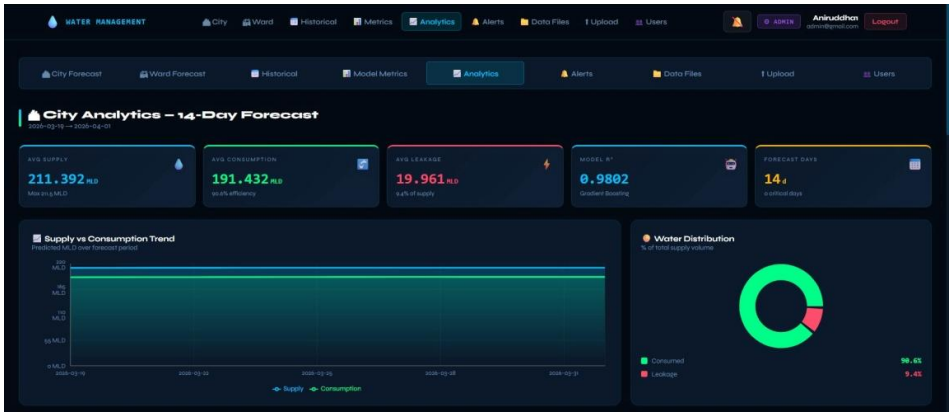

Fig 9: Analytics Dashboard (Part 2) – Weekly Average Grouped Bar Chart (W1–W7: Supply/Consumption/Leakage), Alert Days Donut (14 Normal), Severity-Coloured Leakage Bar Chart with Average Reference Line, and Radial Model Accuracy Gauge (98.0% / City R²: 0.9802 / 27 Zones / 4,887 Records)

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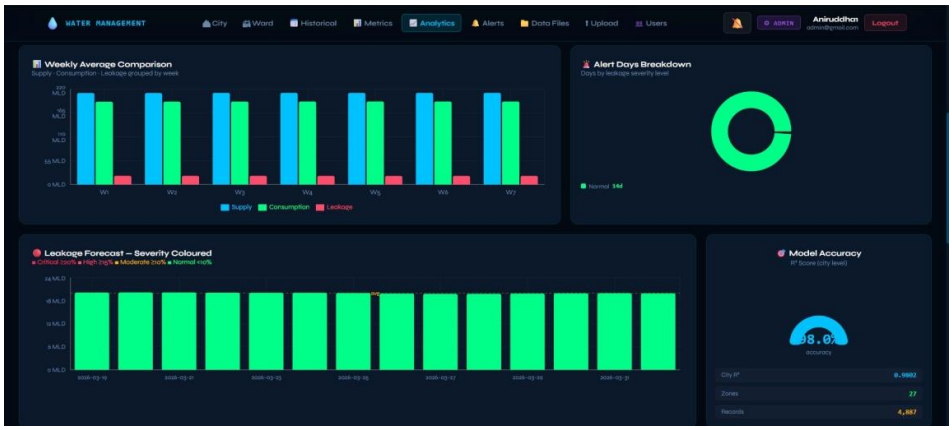
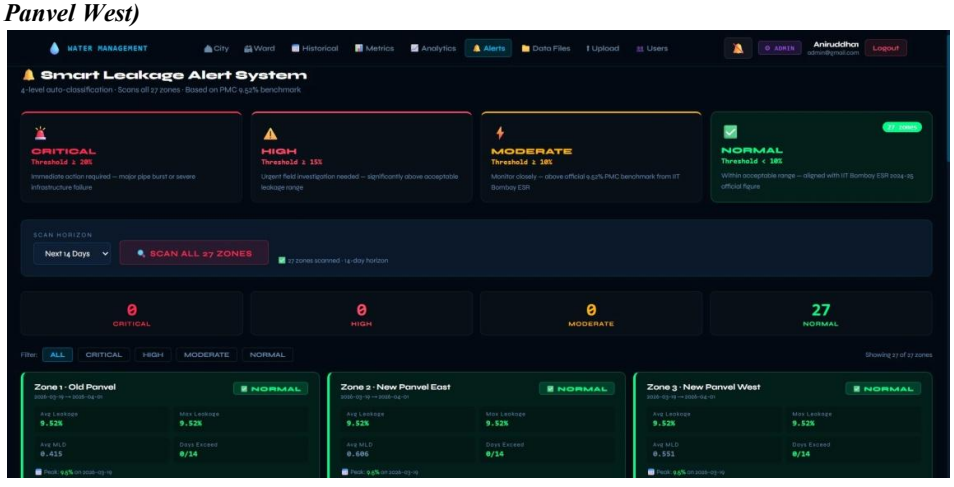


Fig 10: Analytics Dashboard (Part 3) – Leakage % Over Time Area Chart with 9.52% PMC Benchmark Reference Line, Peak Supply (2026-03-25: 211.50 MLD), Lowest Supply (2026-03-19: 211.07 MLD), Total Supply (2959.5 MLD), Total Leakage (279.4 MLD / 9.44% avg rate)

Fig 11: Smart Leakage Alert System – 4-Level Classification Cards (CRITICAL ≥20%, HIGH ≥15%, MODERATE ≥10%, NORMAL <10%), Scan All 27 Zones Controls (14-Day Horizon), Summary KPIs (0 Critical / 0 High / 0 Moderate / 27 Normal), Level Filter Bar, and Per-Zone Result Cards (Zone 1 Old Panvel, Zone 2 New Panvel East, Zone 3 New Panvel West)



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V. RESULTS AND DISCUSSION

Experimental deployment of the Water Management Analytics Dashboard under multiple testing scenarios demonstrated stable performance, accurate ML inference, and secure role-based data handling. The platform successfully processed JWT authentication, 1 to 365-day city and zone-level forecasts, leakage alert scanning across all 27 zones, and dashboard rendering with average API response times of 1–2 seconds for cached queries and 3–5 seconds for fresh rolling predictions beyond 30 days.

The city-level Gradient Boosting model achieved $R^2 = 0.9802$ with RMSE = 0.0461 MLD on the 15% chronological test set. As shown in Fig 6, the KPI strip confirms Last Data Date of 2026-02-28, Avg Daily Supply of 211.59 MLD, and Avg Daily Leakage of 20.143 MLD at exactly 9.52% of supply, precisely matching the official IIT Bombay PMC ESR 2024-25 figure. The prediction table in Fig 7 shows NORMAL status across all 14 forecast days with leakage between 9.35%–9.52%, confirming model consistency with PMC benchmarks.

The Analytics Dashboard (Figs 8–10) demonstrates the system's multi-dimensional visualisation capabilities. The water distribution donut (Fig 8) shows 90.6% consumption efficiency with 9.4% leakage. The radial accuracy gauge confirms 98.0% R^2. The leakage % trend (Fig 10) shows predicted values tracking precisely along the 9.52% PMC benchmark line, with total 14-day cumulative supply of 2,959.5 MLD and 279.4 MLD total leakage at 9.44% average rate.

The Smart Alert System (Fig 11) demonstrates successful classification of all 27 zones as NORMAL in the 14-day horizon scan, confirming predicted leakage remains within the safe PMC threshold for March–April 2026. All zone cards show 9.52% avg/max leakage with 0/14 days exceeding threshold, validating the system's readiness for operational municipal deployment.

Table I: ML Model Accuracy Results – Selected Zones

Model / Zone	R^2 Score	RMSE (MLD)	Zone Type
City Supply Model	0.9802	0.0461	City-level GBR
City Consumption Model	0.9802	—	City-level GBR
Zone 12 – Vichumbe	0.9924	—	PMC Ward (Best)
Zone 27 – Village Cluster	0.9889	—	Village Zone
Zone 21 – Kharghar CIDCO	0.9856	—	CIDCO Sector
Zone 26 – Taloja MIDC	0.9673	—	MIDC Industrial
Zone 1 – Old Panvel	0.9501	—	PMC Ward
Average Ward R^2	0.9703	—	27 Zone Average
Worst Zone R^2	0.9262	—	PMC Ward

Table II: Dataset Validation Against PMC ESR 2024-25 (IIT Bombay)

Metric	PMC PDF (IIT Bombay)	Our Dataset	Match
Total Daily Supply	~220 MLD	211.59 MLD avg	~96%
Water Leakage %	9.52% official	9.52% exact	100%
MIDC Industrial	~9 MLD fixed	9.0 MLD fixed	100%
Daily Variation	Stable supply	<0.53% daily swing	Realistic
Total Records	—	4,887 records	27 × 181 days

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VI. CONCLUSION

The Water Management Analytics Dashboard successfully delivers a centralised, secure, and accurate AI-powered water management platform for the Panvel Municipal Corporation. Integration of 29 Gradient Boosting models (R^2 = 0.9802), React.js multi-chart analytics frontend, Flask REST API, 4-level smart alert classification with real-time notifications, JWT role-based authentication, and cloud deployment on Vercel and Render provides a fully operational smart city water monitoring solution.

The system achieves city-level prediction accuracy of R^2 = 0.9802 across 181 days of 27-zone ward-level data, precisely matches the official PMC 9.52% leakage benchmark from IIT Bombay ESR 2024-25, and enables proactive leakage management through real-time zone-level alert notifications. The platform is publicly deployed and suitable for institutional and municipal use.

Future scope includes: IoT sensor integration for live actual supply data, LSTM deep learning model upgrade for improved long-horizon accuracy, SMS/WhatsApp alert delivery to PMC field teams, Google Maps ward boundary overlay, React Native mobile app for field officers, weather API for monsoon-aware forecasting, predictive maintenance scheduling, and multi-city expansion to Navi Mumbai, Thane, and Pune.

VII. ACKNOWLEDGMENT

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