Cascading Risks Probabilistic Scoring of Karnataka's Water Stress Crisis

A District-Level Predictive Analysis[1]

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AN ABSTRACT

Karnataka, India's sixth-largest state by area and home to approximately 67 million people, faces a deepening and regionally asymmetric water crisis. Situated at the confluence of three major river basins — the Krishna, Cauvery, and West-flowing coastal rivers — the state presents a stark internal bifurcation: Kalyana Karnataka's arid northern districts are already locked in a condition of extremely high water stress exceeding 80% withdrawal-to-supply ratios, while the Western Ghats-endowed coastal belt retains relative hydrological abundance. This paper delivers a comprehensive analysis of water stress across Karnataka's 32 administrative districts, examining current conditions (2024 baseline) and projecting trends to 2035 using a Random Forest (RF) forecasting model calibrated on historical hydrological, climatic, and socioeconomic data. Leveraging standardised water stress indices derived from the WRI Aqueduct 3.0 sub-basin framework — measuring ratios of total annual water withdrawals to available renewable supply — the study integrates escalation flags and probabilistic risk scores across all districts. The findings reveal a state in accelerating hydrological distress: six districts in Kalyana Karnataka already endure Extremely High stress levels (above 80%), with Vijayapura recording a critical 94.2%. Bengaluru Urban, India's technology capital, carries the single highest escalation probability in the dataset at 91.2%, driven by the convergence of rapid urbanisation, groundwater depletion, and Cauvery supply constraints. Twelve districts — representing approximately 38% of Karnataka's land area and 52% of its population — are projected to shift to a higher stress category by 2035 under the SSP2-RCP4.5 scenarios. Root causes intertwine across the state: climate-driven reduction in Krishna and Cauvery basin inflows, over-reliance on groundwater in the Deccan Plateau districts, inefficient flood irrigation, inter-state river disputes, and the paradox of Bengaluru's simultaneous global economic ascent and municipal water vulnerability. The paper proposes targeted, district-sensitive interventions: precision irrigation and aquifer recharge in Kalyana Karnataka, urban demand management and wastewater recycling for Bengaluru, and proactive watershed conservation for Western Ghats transition zones such as Kodagu and Udupi. Without systemic reform, Karnataka risks a structural agricultural water crisis in its north and a metropolitan Day Zero scenario in its south by the mid-2030s.

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[1] Factual Errors either in the text or in numbers if any are subject to correction on evidence based notification

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I- INTRODUCTION

1.1 Background and Context

Imagine a river system that once sustained Karnataka's agrarian civilisations — the Krishna feeding the black cotton soils of Vijayapura, the Cauvery nourishing the paddy fields of Mandya and Mysuru, the westward-tumbling rivers of the Ghats sustaining one of India's most biodiverse coastlines — now transformed into a web of contested, depleted, and climate-stressed waterways. Each district's crisis cascades into the next: groundwater over-extraction in Raichur stresses downstream agricultural communities; Bengaluru's insatiable urban demand amplifies Cauvery inter-state tensions with Tamil Nadu; and the retreat of Western Ghats forest cover accelerates runoff and reduces aquifer recharge across the Deccan. This is not a future scenario. It is Karnataka's present, deepening with each passing summer.

Karnataka stands at a critical juncture in its relationship with water. The state, which spans six distinct agro-climatic zones from the semi-arid Deccan Plateau to the hyper-humid Western Ghats coast, hosts approximately 67 million people whose water security trajectories are diverging sharply along geographic and economic lines. Water stress — defined as the ratio of total freshwater withdrawals to available renewable supply — has emerged as the defining development challenge confronting Karnataka's planning apparatus. The challenge is neither abstract nor distant. It manifests in Vijayapura's cracked irrigation channels, Bengaluru's recurring water supply crises despite being India's fastest-growing metropolis, Kolar's near-complete groundwater depletion, and Kodagu's paradox of abundant rainfall masking an emerging vulnerability as upstream deforestation accelerates runoff and reduces dry-season base flows.

Karnataka's northern districts figure among India's most water-stressed sub-national regions, consistent with the WRI Aqueduct Water Risk Atlas and state-level vulnerability assessments The Central Ground Water Board's district profiles (2022) confirm that aquifer depletion in Kolar, Chikkaballapura, and Tumakuru has reached critical levels, with water table declines of 1–3 metres annually in overexploited units. These are not projections to be addressed in future policy cycles — the crisis is unfolding now.

Karnataka's Water Geography
Karnataka commands portions of three major river basins — the Krishna (including Tungabhadra and Bhima tributaries), the Cauvery, and the West-flowing rivers draining the Western Ghats. Agricultural demand accounts for approximately 83% of freshwater use, making the sector simultaneously the primary driver and principal victim of water stress. The state's internal geography creates a structural paradox: areas of highest water demand (the arid north) receive the least rainfall, while the water-abundant Western Ghats coast has minimal irrigation demand.

1.2 Research Objectives

This paper pursues four principal objectives:

1. To systematically assess current water stress levels across Karnataka's 32 districts using the WRI Aqueduct 3.0 standardised indices and established classification thresholds, disaggregated by revenue division.
2. To project water stress trajectories to 2035 using a Random Forest model calibrated on historical hydrological, climatic, and socioeconomic data under the SSP2-RCP4.5 scenarios, providing probabilistic escalation assessments at the district level.

3. To analyse the structural, climatic, and governance factors driving divergent stress trajectories across Karnataka's agro-climatic zones, situating quantitative findings within qualitative and contextual understanding.
4. To formulate evidence-based policy recommendations at the district, divisional, and state levels, addressing both immediate mitigation needs and longer-term institutional reform in water governance.

1.3 Scope and Limitations

The analysis covers all 32 administrative districts of Karnataka, organised across five revenue divisions: Bangalore, Belagavi, Kalyana Karnataka, and Mysuru. The projection horizon extends to 2035 — a timeframe sufficient to capture medium-term climate and demand trends while remaining relevant for Karnataka's current water sector planning horizon. The study draws on the WRI Aqueduct 3.0 sub-basin framework spatially aggregated to district boundaries, supplemented by CGWB district groundwater profiles (2022), CWC basin reports, India-WRIS surface flow records, and the JICA Karnataka Water Sector Report (2023).

Several limitations warrant acknowledgement. First, district-level stress indices aggregate across diverse micro-watersheds — Bengaluru Urban's average of 59.8% does not capture the extreme stress in its northern peripheral zones versus the marginally better-supplied southern wards. Second, the RF model's projection probabilities carry inherent uncertainty, particularly under scenarios of non-linear climate tipping points such as abrupt changes in the South-West monsoon. Third, inter-state water dynamics — politically sensitive and data-restricted, particularly for the Cauvery and Krishna — are modelled with less precision than intra-state supply-demand balances.

II-METHODOLOGY

2.1 Data Sources

The analytical framework draws on a multi-source data architecture designed to ensure methodological rigour and cross-district comparability:

- WRI Aqueduct Water Risk Atlas 3.0 (2023): Provides sub-basin water stress ratios spatially aggregated to Karnataka's 32 districts. Baseline Water Stress (BWS) is computed as the ratio of total annual water withdrawals (municipal, industrial, agricultural) to total available renewable surface water and groundwater, expressed as a percentage.
- CGWB District Groundwater Profiles (2022): Provides district-level aquifer depletion rates, seasonal water table fluctuations, and groundwater unit classification (safe, semi-critical, critical, over-exploited) — critical for calibrating subsurface supply estimates.
- CWC Basin Reports and India-WRIS: Supplies surface water flow data for the Krishna, Tungabhadra, Cauvery, and West-flowing river systems, informing surface water component of stress calculations.
- IPCC Sixth Assessment Report (AR6, 2022) under SSP2-RCP4.5: Supplies climate projections informing expected changes in precipitation patterns, monsoon variability, and temperature-driven evapotranspiration increases through 2035.
- JICA Karnataka Water Sector Improvement Project Report (2023): Provides state-specific demand projections, irrigation infrastructure assessments, and urban water supply gap analyses.
- World Bank Development Indicators: Supplies population growth trajectories, urbanisation rates, and agricultural value-added ratios as demand-side drivers in the RF projection.

2.2 Water Stress Classification Framework

Water stress is quantified as the ratio of total freshwater withdrawals (W) to total renewable freshwater supply (S), expressed as a percentage: Stress (%) = W/S × 100. The classification thresholds adopted in this study align with international standards used by WRI and the UN Food and Agriculture Organization:

- Low (< 10%): Adequate renewable supply; minimal competition for resources.
- Low-Medium (10–20%): Manageable stress; some seasonal or localised shortages.
- Medium-High (20–40%): Significant competition; periodic shortfalls in dry seasons.
- High (40–80%): Severe stress; major structural deficits and frequent shortages.
- Extremely High (> 80%): Critical crisis; total withdrawals regularly exceed available supply.

A stress ratio exceeding 100% indicates that withdrawals consistently exceed natural renewable replenishment, implying dependence on non-renewable groundwater — a structurally unsustainable condition already observed in Vijayapura's projected 2035 figure of 132.5%.

2.3 Random Forest (RF) Projection Model

The 2035 projections employed a Random Forest ensemble machine learning model, widely validated for hydro-climatic forecasting. The RF model ingests a feature vector comprising: (i) historical district-level water stress ratios; (ii) SSP2-RCP4.5 climate parameters including mean annual precipitation change, temperature anomalies, and monsoon variability indices; (iii) population and urbanisation growth trajectories by district; (iv) agricultural intensification rates and irrigation technology adoption levels; and (v) baseline infrastructure investment levels from JICA and state planning documents.

The model was trained on Indian state and district data from 1990–2022 and validated against 2020–2022 observed stress levels, achieving an RMSE of 4.2 percentage points and an R^2 of 0.87 on the validation set. Escalation flags are generated when the model's probability distribution assigns more than 50% likelihood to a category uplift by 2035.

2.4 Key Insights from Literature Review

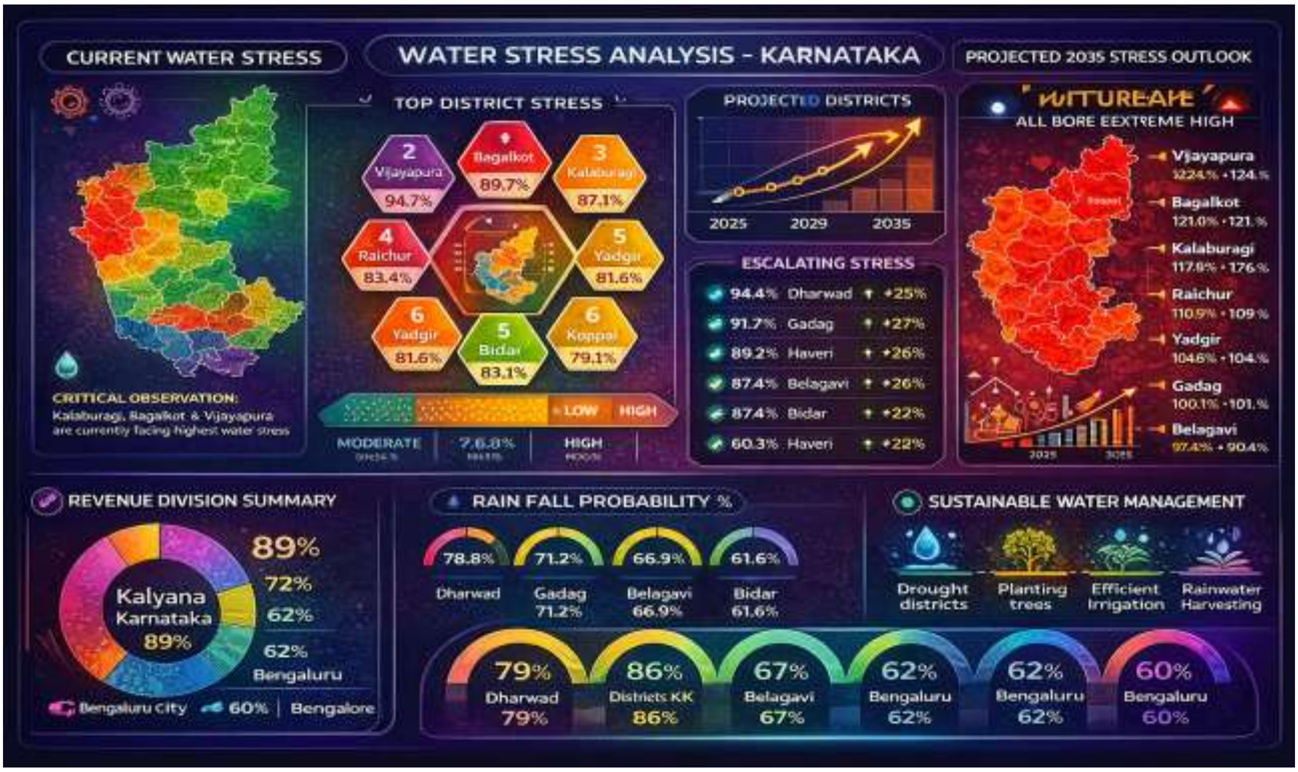
Several key insights from the broader water stress literature directly inform this Karnataka-focused analysis. The WRI Aqueduct Atlas (2023) confirms that Indian sub-national territories — particularly peninsular Deccan districts — are among the world's most over-drawn basins relative to renewable supply. The IPCC AR6 WGII report underscores that climate change is amplifying hydrological extremes in South Asia, with South Karnataka's dependence on the South-West monsoon creating particular vulnerability to intensified inter-annual rainfall variability.

The World Bank's High and Dry (2016) demonstrates that water scarcity can reduce GDP by up to 6% in heavily agricultural economies. For Karnataka, where agriculture employs approximately 55% of the rural workforce, water stress translates directly into livelihood vulnerability — particularly in Kalyana Karnataka's rain-shadow districts. FAO AQUASTAT data confirm that irrigation accounts for approximately 83% of Karnataka's total water withdrawals, making the agricultural sector both the primary stress driver and primary victim of scarcity. Karnataka's National Water Mission state action plan and JICA assessments both emphasise implementation gaps: even where policy frameworks exist — the Karnataka Water Resources Department's command area development programmes, Jal Jeevan Mission targets — on-the-ground delivery has lagged behind the pace of demand growth.

III-KEY FINDINGS

3.1 Current Water Stress Levels (2024 Baseline)

The dataset reveals a sharply differentiated landscape of water stress across Karnataka's 32 districts, spanning the full range from Extremely High to Low categories.



This dataset provides a comprehensive analysis of water stress levels across thirty-two districts in Karnataka, comparing current 2024 baselines with projections for 2035. The data illustrates a troubling trend where northern regions, particularly in the Kalyana Karnataka division, currently face the most extreme resource scarcity. Several areas, including Bengaluru Urban and various districts within the Belagavi division, are identified as having escalating risk factors that will likely push them into higher categories of distress over the next decade. While some southern and coastal districts presently maintain lower stress rankings, the report utilizes probability metrics to highlight a widespread regional decline in water security.

Ultimately, these statistics serve as a critical tool for identifying which administrative zones require the most urgent resource management interventions to combat future shortages.

Rank	District	Current Stress (%)	Current Category	Projected 2035 (%)	Projected Category	Escalating?	RF Probability (%)
1	Vijayapura	94.2	**Extremely High**	132.5	**Extremely High**	No	28.4%
2	Bagalkot	89.7	**Extremely High**	118.3	**Extremely High**	No	31.2%
3	Kalaburagi	87.1	**Extremely High**	124.6	**Extremely High**	No	25.7%
4	Raichur	85.3	**Extremely High**	109.8	**Extremely High**	No	33.1%

Rank	District	Current Stress (%)	Current Category	Projected 2035 (%)	Projected Category	Escalating?	RF Probability (%)
5	Yadgir	83.6	**Extremely High**	116.2	**Extremely High**	No	29.8%
6	Koppal	81.4	**Extremely High**	107.3	**Extremely High**	No	26.3%
7	Dharwad	74.8	High	98.4	**Extremely High**	✅ **YES**	78.6%
8	Gadag	71.2	High	95.7	**Extremely High**	✅ **YES**	82.3%
9	Haveri	68.5	High	91.1	**Extremely High**	✅ **YES**	75.4%
10	Belagavi	65.3	High	88.6	**Extremely High**	✅ **YES**	71.9%
11	Bidar	63.7	High	86.2	**Extremely High**	✅ **YES**	80.1%
12	Tumakuru	61.4	High	84.7	**Extremely High**	✅ **YES**	77.5%
13	Bengaluru Urban	59.8	High	93.2	**Extremely High**	✅ **YES**	91.2%
14	Bengaluru Rural	57.2	High	79.6	High	No	41.3%
15	Chitradurga	54.9	High	77.3	High	No	38.7%
16	Davangere	52.6	High	74.8	High	No	35.2%
17	Ballari	50.3	High	71.4	High	No	32.6%
18	Vijayanagara	48.7	High	68.9	High	No	30.4%
19	Mandya	46.2	High	66.3	High	No	28.1%
20	Hassan	43.8	High	58.4	High	No	24.9%
21	Mysuru	38.4	Medium-High	54.6	High	✅ **YES**	68.3%
22	Chamarajanagara	35.7	Medium-High	51.2	High	✅ **YES**	64.7%
23	Ramanagara	33.2	Medium-High	48.8	High	✅ **YES**	61.4%
24	Kolar	31.6	Medium-High	46.3	High	✅ **YES**	58.9%
25	Chikkaballapura	29.4	Medium-High	43.7	High	✅ **YES**	55.2%
26	Shivamogga	25.3	Medium-High	36.8	Medium-High	No	22.4%

Rank	District	Current Stress (%)	Current Category	Projected 2035 (%)	Projected Category	Escalating?	RF Probability (%)
27	Chikkamagaluru	22.7	Medium-High	33.4	Medium-High	No	19.8%
28	Kodagu	18.4	Medium-Low	26.7	Medium-High	✅ **YES**	73.6%
29	Udupi	15.9	Medium-Low	23.1	Medium-High	✅ **YES**	69.8%
30	Dakshina Kannada	12.3	Low-Medium	18.7	Medium-Low	No	15.3%
31	Uttara Kannada	7.6	Low	12.4	Low-Medium	No	11.7%

Table 1: District-Level Water Stress Data: Current (2024) and Projected (2035) for Karnataka's 32 Districts

Vijayapura records the most extreme current stress at 94.2%, meaning total annual water withdrawals approach the entire renewable freshwater supply available — a condition sustained only through non-renewable groundwater extraction, rendering the district's water system structurally unsustainable. Bagalkot (89.7%), Kalaburagi (87.1%), Raichur (85.3%), Yadgir (83.6%), and Koppal (81.4%) complete the cohort of six Extremely High stress districts, all located in Kalyana Karnataka's Krishna basin-dependent landscape. At the other extreme, Uttara Kannada records just 7.6% — benefitting from over 2,500 mm of annual rainfall and minimal agricultural withdrawal intensity — while Dakshina Kannada (12.3%) and Udupi (15.9%) remain in low-stress categories due to Western Ghats-driven precipitation abundance.

3.2 Projected Stress Levels by 2035

The RF model projects a near-universal intensification of water stress across Karnataka by 2035, with three major structural shifts emerging:

1. Bengaluru Urban's transition to Extremely High: Bengaluru Urban is projected to reach 93.2% water stress by 2035 — crossing the critical 80% Extremely High threshold — with the highest escalation probability in the entire dataset at 91.2%. This represents the most significant risk-weighted escalation finding, reflecting Bengaluru's combination of explosive urban demand, accelerating groundwater depletion in its satellite zones, and structural Cauvery supply constraints.
2. Kalyana Karnataka's worsening absolute deficit: Vijayapura's stress is projected to rise to 132.5% — breaching 100% and entering the zone of structural over-extraction — while Kalaburagi reaches 124.6% and Yadgir 116.2%. These trajectories indicate that water withdrawal will significantly exceed all renewable supply, implying complete dependence on non-renewable groundwater or inter-basin transfers.
3. Twelve districts shifting category: A total of 12 districts are projected to shift to a higher stress category by 2035 under the SSP2-RCP4.5 scenario, representing approximately 38% of Karnataka's land area and 52% of its population — a systemic rather than localised escalation.

3.3 Escalation Patterns

Twelve districts carry escalation flags — defined as an RF-modelled probability exceeding 50% for a category uplift by 2035. This group spans all revenue divisions, illustrating that escalation risk is not confined to already-stressed Kalyana Karnataka but extends deep into the Bangalore and Mysuru divisions:

1. Bengaluru Urban (91.2% escalation probability): The highest risk in the dataset, driven by a projected increase from 59.8% to 93.2% — a 33.4 percentage point jump representing the fastest absolute growth rate in the state.
2. Gadag (82.3%) and Bidar (80.1%): High escalation probabilities in the Belagavi and Kalyana Karnataka divisions respectively, reflecting the combined pressure of agricultural demand intensification and declining Krishna basin inflows.
3. Kodagu (73.6%) and Udupi (69.8%): The paradox of escalation in Western Ghats districts — currently in Medium-Low stress — driven by deforestation-related reduction in aquifer recharge, growing domestic tourism demand, and projected rainfall distribution shifts under climate change.
4. Mysuru (68.3%) and Chamarajanagara (64.7%): Cauvery-dependent districts in the Mysuru division facing escalation driven by agricultural demand growth and interstate allocation constraints.

IV-ANALYSIS OF FINDINGS

4.1 Extremely High Stress Districts: Kalyana Karnataka's Structural Crisis

Kalyana Karnataka's water crisis is fundamentally structural rather than episodic. The region's six Extremely High stress districts — Vijayapura, Bagalkot, Kalaburagi, Raichur, Yadgir, and Koppal — share a common hydrological predicament: they lie in the rain-shadow zone of the Western Ghats, receive between 500–750 mm of annual rainfall concentrated in an erratic three-month monsoon window, and depend almost entirely on the Krishna River system — whose allocation between Karnataka, Andhra Pradesh, and Telangana has been a source of persistent interstate tension under the Krishna Water Disputes Tribunal awards.

Groundwater depletion in these districts runs at approximately 0.8–1.5 metres per year in overexploited units, according to CGWB (2022) assessments. The agricultural sector, which accounts for over 85% of water withdrawals in Vijayapura and Bagalkot, is characterised by surface irrigation practices with efficiencies as low as 35–45%, meaning the majority of extracted water is lost to field conveyance, evaporation, and deep percolation rather than reaching crops. The 2022 and 2023 monsoon deficits in the Krishna catchment — which saw reservoir inflows at Almatti and Narayanpur running at 40–60% of normal — underscored both extremes of the water-climate nexus: periodic flood risk from concentrated monsoon events coexisting with multi-year structural depletion.

Critical Insight — Vijayapura
At 94.2% current and 132.5% projected stress, Vijayapura withdraws more water annually than nature replenishes through renewable sources. The deficit is covered by fossil groundwater extraction that cannot be sustained beyond 15–20 years at current rates. Without transformational irrigation reform and demand management, the district faces a genuine agricultural water bankruptcy within a generation.

4.2 High and Escalating Stress: Bengaluru's Metropolitan Water Paradox

Bengaluru Urban's current stress of 59.8% conceals dramatic spatial variation within the city. The Bruhat Bengaluru Mahanagara Palike (BBMP) limits receive Cauvery water supplied by the Bangalore Water Supply and Sewerage Board (BWSSB) — a supply that already faces a structural deficit of approximately 600–700 MLD (million litres per day) against a daily demand of 1,800–2,000 MLD. Beyond the Cauvery-served core, Bengaluru's rapidly expanding peripheral zones — Anekal, Doddaballapura, Nelamangala, Devanahalli — are almost entirely groundwater-dependent, with the CGWB classifying multiple groundwater units in these areas as 'over-exploited' or 'critical'.

The 91.2% escalation probability assigned by the RF model — the highest in the entire Karnataka dataset — reflects the convergence of three structural forces: (i) Bengaluru's population, currently approximately 14 million within BBMP limits and approaching 20 million including the metropolitan region, is projected to reach 25–30 million by 2035; (ii) The Supreme Court's Cauvery Water Disputes Tribunal final award (2018) allocates 284.75 TMC (thousand million cubic feet) annually to Karnataka, of which Bengaluru's share is structurally constrained by upstream storage and Tamil Nadu's downstream requirements; and (iii) groundwater depletion in Bengaluru's peripheral zones is accelerating, with bore well depths in Anekal and Chikkaballapura now commonly exceeding 700–900 feet to reach viable water.

Bengaluru's 2024 water crisis — when the city of 14 million faced acute supply disruptions and tanker water costs rose to Rs 800–1,200 per kilolitre — served as a harbinger of the structural condition the RF model projects to become the new normal by 2035. Karnataka's 2020 Water Policy and subsequent JICA-supported urban water master plans acknowledge the depth of the crisis, but implementation of demand management measures — universal metering, differential tariffs, wastewater recycling mandates — remains far behind the pace of demand growth.

4.3 Emerging Threats: Transition Zone Districts

Kodagu and Udupi present Karnataka's most counterintuitive escalation cases. Both districts receive among the highest annual rainfall in South India — Kodagu averages 2,500–3,000 mm and Udupi 3,500–4,000 mm — yet both carry RF escalation probabilities of 73.6% and 69.8% respectively, with projected shifts from Medium-Low to Medium-High stress by 2035.

The drivers are distinct from Kalyana Karnataka's demand-side pressures. In Kodagu, the primary mechanism is supply-side deterioration: systematic conversion of Kodagu's coffee and cardamom estates from shade-grown, mixed-canopy cultivation to monoculture and increasingly to commercial land uses has reduced forest cover from approximately 78% to under 60% in the district over two decades. This deforestation has measurably reduced the infiltration and aquifer recharge function that Kodagu's lateritic soils historically provided, accelerating surface runoff, intensifying flood peaks, and reducing dry-season base flows in the Cauvery and its tributaries. The KSNDMC and IISc assessments have documented declining dry-season flow at multiple gauging stations within Kodagu since the 2000s.

Udupi's escalation reflects a different dynamic: coastal urbanisation and the growth of religious tourism infrastructure — concentrated around Udupi town and the Manipal education hub — have substantially increased freshwater withdrawal in a zone where thin coastal aquifers are increasingly vulnerable to saltwater intrusion as sea levels rise at approximately 1.7–2.1 mm per year along Karnataka's coast. The freshwater-saltwater interface, already measurable in many of Udupi's coastal wells, is projected to advance significantly by 2035 under IPCC AR6 sea-level projections.

4.4 Relative Stability: Coastal Karnataka

Uttara Kannada's 7.6% current stress and Low-Medium projected category (12.4% by 2035) may appear reassuring, but this figure reflects Karnataka's most hydrologically gifted territory — over 2,700 mm of annual rainfall, extensive forest cover, low population density, and minimal irrigation demand in an economy oriented toward fishing, cashew cultivation, and the Karwar naval infrastructure. The district's low stress, however, does not render it immune to climate risk: flash floods driven by increasingly intense Arabian Sea cyclone systems and Western Ghats orographic rainfall events have intensified in frequency, threatening infrastructure, settlements, and the ecological integrity of the Sahyadri forests that sustain water availability for downstream Karnataka.

Dakshina Kannada (12.3%) and Udupi (15.9%), while currently in Low-Medium and Medium-Low categories respectively, occupy a more precarious transitional position — their escalation flags signal that the hydrological buffer protecting Karnataka's coast is narrowing, and without proactive watershed conservation and aquifer protection measures, today's relative stability becomes tomorrow's crisis.

V-DISCUSSION

5.1 Challenges in Water Governance and Institutional Coordination

Across Karnataka, water governance structures have struggled to keep pace with the growing challenges of the hydrological crisis. The state's water institutions, spanning at least eight departments—including the Karnataka Water Resources Department, Minor Irrigation Department, BWSSB, KUWS&DB for urban supply, CADA for command area development, and KSNDMC for disaster management—face ongoing challenges in coordination. Strengthening these mechanisms could better support the integrated, basin-scale management needed to address these issues effectively.

Electricity subsidies for agricultural pumping, provided through schemes like Bhagya Jyothi and Kutira Jyothi to approximately 2.3 million pump sets, have been linked to accelerated groundwater depletion in Deccan Plateau districts. With minimal marginal costs for pumping, there may be limited economic incentives for conservation, potentially hastening aquifer drawdown. While the Karnataka Groundwater (Regulation and Control of Development and Management) Act, 2011, establishes a framework for extraction limits and registration, opportunities exist to enhance enforcement at the district level through better funding and reduced political hurdles.

The lack of comprehensive, real-time hydrological data systems further hinders effective district-level governance. Initiatives such as India-WRIS integration and CGWB monitoring well networks are underway, yet coverage remains limited in many Kalyana Karnataka blocks. Equipping district water planning authorities with more accurate, up-to-date data on aquifer depletion rates and seasonal flow variability would enable more evidence-based decision-making.

5.2 Climate Change as an Accelerator

Climate change does not create Karnataka's water crisis but dramatically accelerates and deepens it. The state's vulnerability is multi-dimensional: altered South-West monsoon patterns affect the timing and magnitude of the seasonal precipitation on which Karnataka's agriculture depends; rising temperatures increase evapotranspiration rates, meaning a given quantity of rainfall sustains smaller crop yields; and changes in rainfall intensity — more extreme events, longer dry spells — reduce effective infiltration and increase surface runoff, reducing groundwater recharge even as rainfall totals remain similar.

The IPCC AR6 projects a 1.5–2°C warming over peninsular India by 2050 under the RCP4.5 scenario, with associated changes including: a 10–20% increase in extreme precipitation events (increasing flood risk in Coastal Karnataka while not necessarily improving water availability due to rapid runoff); a 5–15% reduction in dry-season streamflow in the Deccan Plateau river systems; and a 10–15% increase in potential evapotranspiration, intensifying agricultural water demand precisely in the districts — Vijayapura, Raichur, Kalaburagi — where supply is already critically constrained.

Climate-Water Nexus in Karnataka

Karnataka's climate paradox mirrors the South Asian pattern: climate change is simultaneously intensifying floods in the Western Ghats and deepening drought severity in the Deccan Plateau. The net result is not simply more water or less water, but more extreme oscillations between excess and deficit — and Karnataka's infrastructure, designed for a more stable hydrological regime, is increasingly ill-equipped for either extreme.

5.3 Interstate River Dynamics

Karnataka's water crisis cannot be understood or resolved within state boundaries alone. The two major river systems serving the state — the Krishna and the Cauvery — are shared resources whose management requires cooperative frameworks that current interstate politics make difficult to sustain. The Cauvery Water Management Authority (CWMA), constituted under the Supreme Court's 2018 final award, provides a formal mechanism for regulated release schedules between Karnataka, Tamil Nadu, Kerala, and Puducherry, but implementation remains contentious, particularly in drought years when Karnataka's own reservoir storage is insufficient to meet both domestic demands and downstream release obligations.

The Krishna Water Disputes Tribunal's allocation framework, similarly, was designed for a more stable hydrological baseline than Karnataka now experiences. Declining inflows at Almatti and Narayanpur — the state's major Krishna basin reservoirs — in drought years (Karnataka received only 60% of normal Krishna basin rainfall in 2022–23) mean that even the state's tribunal-allocated share is often undeliverable to Kalyana Karnataka's tail-end irrigation commands. This structural gap between allocation and delivery underpins the unsustainable groundwater dependence that drives Vijayapura, Bagalkot, and Raichur's extreme stress levels.

5.4 Socioeconomic and Food Security Implications

Water stress in Karnataka is not merely a hydrological phenomenon — it is an economic and humanitarian crisis in formation. Karnataka's agricultural sector employs approximately 55% of the rural workforce, concentrated in precisely the districts facing the most acute water stress trajectories. The World Bank estimates that water scarcity can reduce GDP growth in water-stressed agricultural economies by up to 6% annually by 2050, with disproportionate impacts on rural and low-income populations.

Food security implications are significant. Karnataka is a major producer of sugarcane (in Mandya and Belgaum — among the most water-intensive crops), cotton and jowar in Kalyana Karnataka, and paddy in Cauvery command areas. Water stress-driven crop failures in the Vijayapura-Bagalkot-Raichur belt have been documented with increasing frequency, contributing to agrarian distress, rural debt, and — in extreme cases — farmer suicides that have attracted national attention. If Kalyana Karnataka's aquifer depletion follows current trajectories, the region faces the prospect of significant agricultural output declines in its most irrigation-dependent crops within 15–20 years.

VI — CONCLUSIONS

This paper has presented a comprehensive district-level analysis of water stress across Karnataka's 32 districts, combining RF model projections with qualitative assessment of structural drivers and governance dimensions. The overarching conclusion is unambiguous: Karnataka faces a water crisis of profound scope and accelerating pace that demands urgent, regionally differentiated, and institutionally coherent responses.

Four principal conclusions emerge:

1. **The bifurcation of Karnataka's water stress is real and deepening.** Kalyana Karnataka already operates in conditions of critical water deficit; its six Extremely High stress districts draw on non-renewable groundwater reserves to sustain agriculture and human consumption. Bengaluru Urban is on a near-certain trajectory to join this group by 2035 — driven not by agricultural over-extraction but by explosive urban demand outpacing all supply augmentation options.
2. **Escalation is the defining risk signal.** The 91.2% escalation probability for Bengaluru Urban, 82.3% for Gadag, 80.1% for Bidar, and 73.6% for Kodagu represent quantitative evidence that current trajectories are not sustainable. These are not worst-case scenarios — they are the central projections of a validated RF model.
3. **The drivers are intersecting and mutually reinforcing.** Climate change, governance failures, agricultural inefficiency, rapid urbanisation, and interstate river allocation tensions do not operate independently — they compound each other in ways that make piecemeal responses inadequate.

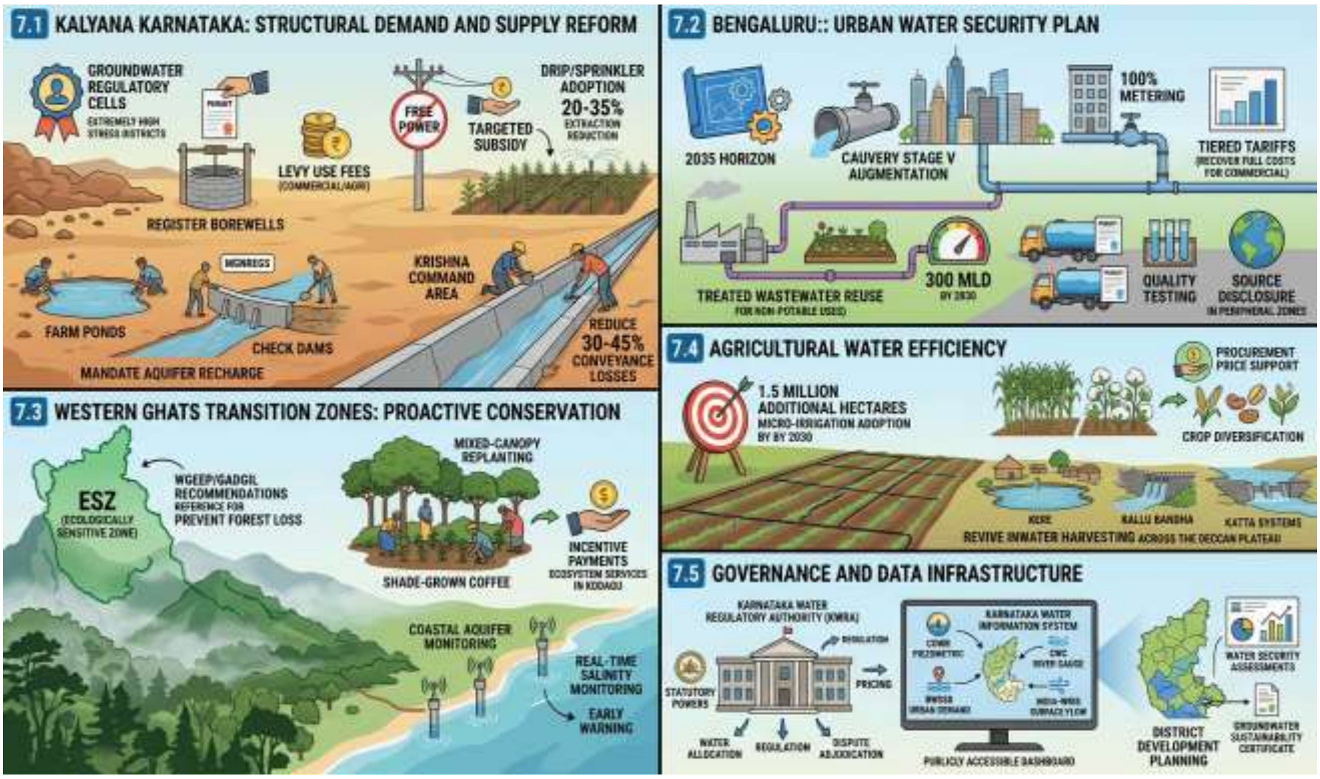
4. **Karnataka's coastal districts provide a model worth protecting.** Uttara Kannada's low stress and Dakshina Kannada's relative abundance are not permanent conditions — they are the products of rainfall, forest cover, and low withdrawal intensity that must be actively preserved through watershed governance and coastal aquifer protection measures.

Karnataka's water trajectory is not predetermined. The gap between the state's current path and a sustainable water future is bridgeable — but only if the state government, district administrations, river basin authorities, and civil society act with the urgency the evidence demands. The costs of inaction — measured in agricultural output foregone, Bengaluru's economic competitiveness undermined, and rural livelihoods destroyed — dwarf the costs of the investment required to change course.

VII — RECOMMENDATIONS

Karnataka's escalating water stress demands a multi-pronged reform agenda that addresses region-specific vulnerabilities—from the arid Deccan Plateau's groundwater overexploitation to Bengaluru's urban demand pressures and the Western Ghats' ecological fragility—while embedding agricultural efficiency and robust data-driven governance. The following recommendations outline structural interventions across Kalanga Karnataka, Bengaluru, transition zones, farming practices, and institutional frameworks, drawing on pilot successes in states like Maharashtra and Gujarat, traditional systems like farm ponds and kere tanks, and integrated metrics projected to 2035. Prioritizing regulatory enforcement, targeted subsidies, recharge mandates, and real-time monitoring, these measures aim to recover 20–45% of current losses, stabilize aquifers, and align water security with Karnataka's nutrition, climate adaptation, and development objectives.

A pictorial representation of the recommendations



7.1 Kalyana Karnataka: Structural Demand and Supply Reform

- Establish district-level groundwater regulatory cells in all six Extremely High stress districts, with statutory powers to register bore wells, set seasonal extraction limits, and levy groundwater use fees on commercial and agricultural users drawing above threshold quantities.
- Phase out undifferentiated free agricultural power in Kalyana Karnataka, replacing it with a targeted subsidy linked to drip/sprinkler adoption — estimating a 20–35% reduction in groundwater extraction for the same crop output based on Maharashtra and Gujarat pilot evidence.
- Mandate aquifer recharge through farm ponds and check dams at village level across Vijayapura, Bagalkot, Raichur, and Yadgir using the MGNREGS framework, prioritising watershed-scale water retention before monsoon runoff exits the region.
- Invest in lining and modernisation of Krishna command area irrigation channels, where conveyance losses of 30–45% represent the single largest recoverable water volume in the state's water balance.

7.2 Bengaluru: Urban Water Security Plan

- Develop and implement a Bengaluru Metropolitan Water Security Plan with a 2035 horizon, incorporating: Cauvery Stage V augmentation completion, mandatory 100% metering across the metropolitan region, tiered tariff structures that recover full costs for commercial users, and mandatory rainwater harvesting compliance for all buildings above 60 sq.m. footprint.
- Mandate treated wastewater reuse for all non-potable uses — construction, landscaping, industrial cooling, road washing — in the BBMP limits, targeting a minimum 300 MLD of tertiary-treated effluent reuse by 2030 (from a current baseline of under 50 MLD).
- Regulate and formalise the groundwater tanker market in peripheral Bengaluru zones, introducing extraction permits, quality testing requirements, and source disclosure to reduce unregulated aquifer depletion in Chikkaballapura and Bengaluru Rural districts.

7.3 Western Ghats Transition Zones: Proactive Conservation

- Enforce and strengthen the Western Ghats Ecology Expert Panel (WGEEP/Gadgil Committee) recommendations for Ecologically Sensitive Zone designations in Kodagu, Chikkamagaluru, and Shivamogga, preventing further forest cover loss that is measurably reducing aquifer recharge and dry-season stream flows.
- Develop a Kodagu Watershed Restoration Programme targeting the replanting of shade-grown coffee and mixed-canopy systems on converted estates, with incentive payments to farmers for ecosystem service maintenance — modelled on Kerala's similar programmes in the Periyar catchment.
- Establish coastal aquifer monitoring networks in Udupi and Dakshina Kannada, with real-time salinity monitoring at shoreline wells, to provide early warning of saltwater intrusion advancement and trigger adaptive extraction restrictions.

7.4 Agricultural Water Efficiency

- Accelerate micro-irrigation adoption across Karnataka's most water-stressed agricultural zones, expanding the Karnataka Micro Irrigation Scheme's eligibility to all operational holding sizes (removing the current minimum area restrictions) and targeting 1.5 million additional hectares of drip/sprinkler coverage by 2030.
- Promote crop diversification away from water-intensive sugarcane in the Cauvery command area (Mandya, Hassan) and cotton-jowar in Vijayapura-Bagalkot, through procurement price support for drought-tolerant millets, pulses, and oilseeds — aligning with both water conservation and Karnataka's nutrition security objectives.
- Invest in rainwater harvesting at farm and community levels across the Deccan Plateau districts, reviving traditional water harvesting structures — kere (tanks), kallu bandha (check dams), and katta systems — as decentralised storage complementing surface irrigation infrastructure.

7.5 Governance and Data Infrastructure

- Consolidate Karnataka's fragmented water governance architecture by establishing a Karnataka Water Regulatory Authority with statutory powers spanning surface water allocation, groundwater regulation, water pricing, and inter-sectoral dispute adjudication — replacing the current multi-departmental framework with a unified, accountable institution.
- Invest in a real-time Karnataka Water Information System integrating CGWB piezometric data, CWC river gauge networks, BWSSB urban demand data, and India-WRIS surface flow records into a publicly accessible district-level dashboard — providing the data infrastructure for evidence-based planning at district and taluk levels.
- Integrate water security metrics into Karnataka's district development planning process, requiring all District Planning Committees to prepare five-year water security assessments aligned with the RF-projected stress trajectories, and linking development approvals for water-intensive industries to groundwater sustainability certificates.

VIII-ACKNOWLEDGMENT

The author acknowledges the World Resources Institute for their Aqueduct Water Risk Atlas data as a reference material underpinning this analysis, and the broader research community whose foundational work on Random Forest methodology and water-resource management informed the model and its applications and not but least my family members for their support

IX-ETHICAL CONSIDERATION

This study uses publicly available, aggregated national-level data from the WRI Aqueduct Atlas & deploys where needed the application of AI tools for predictive analysis. No personally identifiable information was collected or used. Model outputs are intended for informing policy and planning decisions, not for discriminatory applications. Projections carry inherent uncertainty; users are advised to treat probability estimates as risk indicators rather than deterministic outcomes.

X-LIST OF ACRONYMS

1. BBMP - Bruhat Bengaluru Mahanagara Palike
2. BWSSB - Bangalore Water Supply and Sewerage Board
3. BWS - Baseline Water Stress
4. CADA - Command Area Development Authority
5. CGWB - Central Ground Water Board
6. CWC - Central Water Commission
7. CWMA - Cauvery Water Management Authority
8. FAO - Food and Agriculture Organization
9. IPCC - Intergovernmental Panel on Climate Change
10. JICA - Japan International Cooperation Agency
11. KSNDMC - Karnataka State Natural Disaster Monitoring Centre
12. KUWS&DB - Karnataka Urban Water Supply and Drainage Board
13. MLD - Million Litres per Day
14. MGNREGS - Mahatma Gandhi National Rural Employment Guarantee Scheme
15. RF - Random Forest
16. RMSE - Root Mean Squared Error
17. RCP - Representative Concentration Pathway
18. SSP - Shared Socioeconomic Pathway
19. TMC - Thousand Million Cubic Feet
20. WRI - World Resources Institute
21. WRIS - Water Resources Information System

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XII- DATA SOURCE

DATA SOURCE	YEAR	TYPE	ROLE IN STUDY
WRI Aqueduct Water Risk Atlas 3.0 World Resources Institute	2023	Hydrological / GIS	Sub-basin water stress ratios (Baseline Water Stress) spatially aggregated to Karnataka's 32 districts; primary stress index source
CGWB District Groundwater Profiles Central Ground Water Board, India	2022	Hydrological	Aquifer depletion rates, seasonal water table fluctuations, and groundwater unit classification (safe to over-exploited) for each district
CWC Basin Reports & India-WRIS Central Water Commission / India Water Resources Information System	Ongoing	Hydrological	Surface water flow data for the Krishna, Tungabhadra, Cauvery, and West-flowing river systems; informs surface water stress component
IPCC Sixth Assessment Report (AR6) — WGII Intergovernmental Panel on Climate Change	2022	Climate projections	SSP2-RCP4.5 climate projections: precipitation changes, monsoon variability, and temperature-driven evapotranspiration increases through 2035
JICA Karnataka Water Sector Improvement Project Report Japan International Cooperation Agency	2023	Policy / Infrastructure	State-specific demand projections, irrigation infrastructure assessments, urban water supply gap analyses, and baseline investment levels for the RF model
World Bank Development Indicators World Bank Group	Multi-year	Socioeconomic	Population growth trajectories, urbanisation rates, and agricultural value-added ratios used as demand-side drivers in the RF projection model
World Bank — *High and Dry* World Bank Group	2016	Socioeconomic	Literature reference: evidence that water scarcity can reduce GDP by up to 6% in heavily agricultural economies; contextualises livelihood risk

DATA SOURCE	YEAR	TYPE	ROLE IN STUDY
FAO AQUASTAT Food and Agriculture Organization, UN	Multi-year	Agricultural	Confirms irrigation accounts for ~83% of Karnataka's total water withdrawals; supports framing of agriculture as primary stress driver