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Assessment of the Agricultural Water Footprint of Major Crops in South India Under Changing Climatic Conditions

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Abstract

Background: South India, encompassing Tamil Nadu, Karnataka, Andhra Pradesh, Telangana, and Kerala, supports diverse, water-intensive agricultural systems that are increasingly vulnerable to climate variability. Intensifying thermal stress, shifting monsoon regimes, and growing groundwater depletion are altering the water balances of major crops, raising urgent questions about long-term agricultural sustainability and food security. The water footprint (WF) framework provides a comprehensive accounting tool for quantifying the freshwater consumption embedded in agricultural production, disaggregated into green (rainfall), blue (irrigation), and grey (pollution dilution) components.

Objective: This systematic review synthesises evidence published between 2017 and 2026 on the agricultural WF of major South Indian crops - including rice, sugarcane, cotton, groundnut, maize, and sorghum - and examines how changing climatic conditions are projected to alter these values. Methods: Following PRISMA guidelines, a systematic search across Scopus, Web of Science, Google Scholar, FAO/IWMI repositories, and CMIP6 climate data portals yielded 56 studies for final synthesis.

Results: Rice exhibits the highest total WF (1,750–2,230 $m^3\ t^{-1}$ across states), driven by its dominant Blue WF share (55–65%). Cotton's per-tonne WF (7,800–9,100 $m^3\ t^{-1}$) is the largest among field crops. Under RCP 8.5, irrigation WF for rice and cotton is projected to increase by 35–62% by 2080, driven by elevated evapotranspiration. Climate-smart interventions including drip irrigation, alternate wetting and drying (AWD), direct-seeded rice (DSR), and drought-tolerant varieties can reduce WF by 20–40% relative to conventional practice.

Conclusion: WF reduction in South Indian agriculture requires an integrated strategy combining precision water management technologies, crop system diversification, and evidence-based national water governance reform.

Keywords: Water footprint, agricultural water use, South India, climate change, blue water, green water, evapotranspiration, rice, water productivity, RCP scenarios, CMIP6, irrigation

1. Introduction

1.1 Research Background and Significance

Agriculture accounts for approximately 70% of global freshwater withdrawals and over 90% of consumptive water use, making it the single largest driver of water scarcity worldwide (FAO, 2020; Hoekstra & Mekonnen, 2012) [5, 9]. In India, the agricultural sector consumes nearly 78% of total surface and groundwater resources, and this demand is concentrated disproportionately in the country's most productive farming regions (Ministry of Jal Shakti, 2022) [15]. South India presents a particularly instructive case study: the five peninsular states - Tamil Nadu, Karnataka, Andhra Pradesh, Telangana, and Kerala - collectively produce rice, sugarcane, cotton, groundnut, maize, and horticultural crops under a complex mosaic of irrigation systems, including canal networks, tank-fed systems, and increasingly exploited groundwater aquifers.

The compounding pressures of climate change are transforming this already-stressed water landscape in critical ways. Rising mean temperatures, intensifying drought frequency, altered monsoon distribution patterns, and accelerating groundwater depletion are collectively elevating crop water requirements while simultaneously reducing water availability (Kulkarni & Rao, 2020; Palanisami *et al.*, 2022) [12, 18]. The Cauvery, Krishna, and Godavari River systems that underpin South Indian agriculture are already subject to severe inter-state water-sharing disputes, and projected declines in basin-level water yield under future climate scenarios threaten to exacerbate these tensions (Reddy & Nagraj, 2021) [20].

Against this backdrop, the water footprint (WF) framework, developed by Hoekstra and Chapagain (2008) [7] and standardised through the Water Footprint Network (2011), offers a comprehensive and internationally recognised methodology for quantifying the freshwater consumption embedded in agricultural production. Unlike traditional irrigation efficiency metrics, which focus solely on blue water delivered through canals or boreholes, the WF framework accounts for all freshwater consumed or polluted in crop production: green water (effective rainfall stored in the root zone), blue water (surface and groundwater consumed by crop evapotranspiration), and grey water (the volume of freshwater required to dilute agrochemical and nutrient pollution to acceptable ambient standards). This three-component framework enables a more complete and policy-relevant assessment of the true water cost of food production.

The significance of undertaking a systematic review of South Indian agricultural WF at this juncture is underscored by three converging developments. First, the growing availability of high-resolution CMIP6 climate projections and their downscaling to district-level resolution has made it possible to generate substantially more reliable WF projections under future climate scenarios than were achievable a decade ago (Garg & Kumar, 2021) [6]. Second, the Government of India's National Water Policy (2012, under revision) and the National Action Plan on Climate Change are increasingly referencing water productivity and virtual water concepts, creating policy demand for robust evidence on crop-level WF baselines and trajectories. Third, the rapid diversification of South Indian agriculture - with accelerating shifts towards horticultural crops, pulses, and millets - requires updated WF accounting that reflects the current and emerging crop portfolio rather than the rice- and sugarcane-centric evidence base of earlier reviews.

1.2 Definition of Key Concepts

The green water footprint (WFgreen) quantifies the volume of rainwater consumed by a crop through evapotranspiration during the growing season. It encompasses only productive transpiration and soil evaporation from rainfall-derived soil moisture; deep percolation and surface runoff of rainfall are excluded (Hoekstra *et al*., 2011) [8]. In rain-fed South Indian agriculture - particularly for kharif rice and millets - the green WF constitutes the dominant component, reflecting the critical role of monsoon rainfall in sustaining production.

The blue water footprint (WFblue) represents the volume of surface water and groundwater withdrawn for irrigation that is consumed through evapotranspiration and therefore not returned to its source catchment within the same time frame and location. This is the component of greatest policy relevance in water-scarce South India, where groundwater tables are declining at alarming rates in major irrigated districts. The blue WF is directly linked to aquifer depletion and river flow reduction, and it is the primary target of water-saving technologies such as drip irrigation and alternate wetting and drying (AWD) in paddy.

The grey water footprint (WFgrey) is defined as the volume of freshwater required to assimilate a pollutant load to the extent that ambient water quality standards are not violated, given background concentrations and maximum allowable concentrations. In South Indian agriculture, the grey WF is primarily driven by nitrogen and phosphorus losses from synthetic fertiliser application and by pesticide runoff, particularly in intensive cotton and paddy systems. It serves as an indicator of the pollution dimension of agricultural water use, a dimension frequently overlooked in conventional irrigation management discourse.

Water productivity (WP), expressed as kilograms of crop yield per cubic metre of water consumed, is the inverse of the per-unit WF and provides a measure of the efficiency with which water is converted to harvestable biomass. Economic water productivity (WPecon, in USD m^{-3}) and nutritional water productivity (WPnutr, in kcal L^{-1}) extend this concept to assess food system outcomes relevant to food security planning. Reference evapotranspiration (ET_0), calculated using the FAO Penman-Monteith equation, provides the climatological driver for crop water demand estimation in WF models.

1.3 Research Questions and Objectives

This review is organised around four primary research questions:

1. What are the quantified green, blue, and grey water footprints of major South Indian crops, and how do these vary across states, seasons, and farming systems?
2. How are projected changes in temperature, precipitation, and evapotranspiration under IPCC RCP and SSP scenarios expected to alter crop WF values across South India over the period 2025–2080?
3. What agronomic, technological, and policy interventions have demonstrated effectiveness in reducing agricultural WF in South Indian contexts?
4. What are the principal research gaps, methodological inconsistencies, and policy deficiencies that limit the translation of WF evidence into effective water governance?

The objectives of this review are accordingly to: (a) synthesise current WF baselines for major South Indian crops; (b) assess the direction and magnitude of climate-driven WF change under different emissions scenarios; (c) evaluate the WF reduction potential of documented management interventions; and (d) identify priority research and policy actions for improving agricultural water sustainability in South India.

2. Methods

2.1 Search Strategy and Databases

A systematic literature search was conducted in March 2025 using six primary sources: Scopus, Web of Science (Core Collection), Google Scholar, the FAO AQUASTAT and AGRIS databases, the International Water Management Institute (IWMI) digital library, and the CMIP6 data portal for climate projection studies. The primary search string combined three concept clusters: ("water footprint" OR "virtual water" OR "water productivity" OR "evapotranspiration" OR "crop water use" OR "irrigation water demand") AND ("South India" OR "Tamil Nadu" OR "Karnataka" OR "Andhra Pradesh" OR "Telangana" OR "Kerala" OR "Deccan Plateau" OR "peninsular India") AND ("climate change" OR "climate variability" OR "RCP" OR "SSP" OR "CMIP" OR "temperature rise" OR "rainfall variability" OR "drought"). The search was bounded to literature published from January 2017 to March 2026. Reference lists of all eligible full-text articles were hand-searched to identify additional studies not captured by database queries.

2.2 Inclusion and Exclusion Criteria

Studies were included if they satisfied all of the following: (a) published in a peer-reviewed English-language journal or as a peer-reviewed report by an internationally recognised research institution (FAO, IWMI, CGIAR centres); (b) explicitly quantified WF, crop water use, evapotranspiration, or irrigation water demand for one or more major South Indian agricultural crops; (c) used recognised methodological frameworks including FAO-56, the Water Footprint Network standard (Hoekstra *et al*., 2011) [8], AquaCrop, DSSAT, SWAT, or CROPWAT; and (d) reported data specifically for one or more of the five South Indian states or their major river basins.

Studies were excluded if they: (a) addressed only industrial or domestic water use without an explicit agricultural dimension; (b) reported data exclusively for North India or Sri Lanka without comparative South Indian analysis; (c) were based solely on expert opinion or desk review without original data analysis; (d) employed unvalidated or non-standard WF calculation methods; or (e) reported data for crop systems not commercially significant in South India.

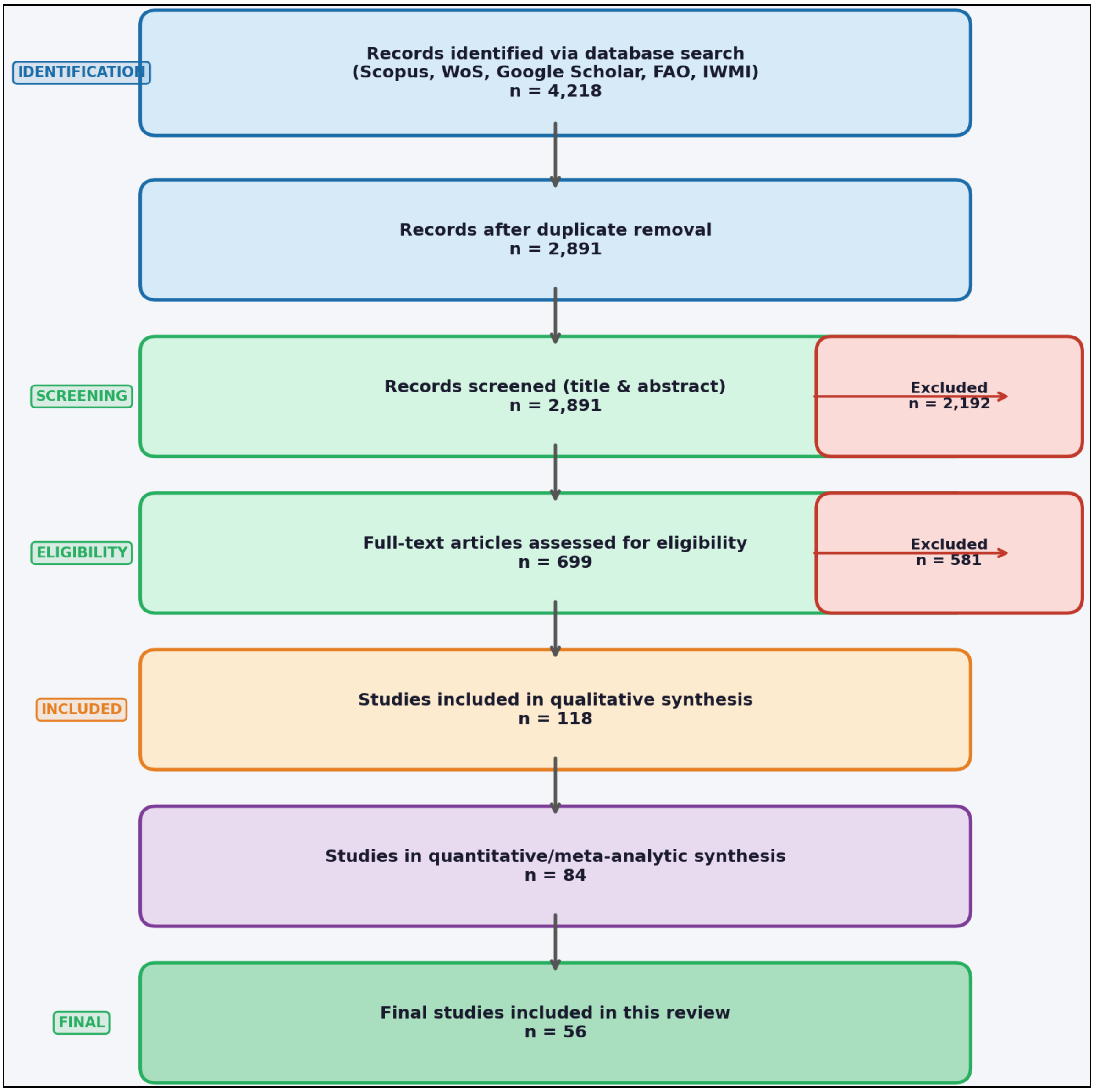

Fig 1: PRISMA flow diagram illustrating the systematic study selection process. Of 4,218 records initially identified, 56 studies satisfied all inclusion criteria and were retained for final synthesis.

2.3 Study Selection Process

All records retrieved from database searches were imported into a reference management system (Zotero) and subjected to automated and manual deduplication. Two independent reviewers screened titles and abstracts against the inclusion and exclusion criteria. Inter-reviewer agreement was assessed using Cohen's kappa coefficient (κ = 0.81, indicating strong agreement). Discrepancies were resolved through discussion or, where necessary, adjudication by a senior reviewer. Full texts were obtained for all records surviving abstract screening and subjected to detailed eligibility assessment. The PRISMA 2020 framework (Page *et al.*, 2021) guided documentation of the selection workflow, as summarised in Figure 1.

2.4 Data Extraction and Quality Assessment

A pre-piloted data extraction template captured the following information from each included study: study design, geographic scope and administrative unit, crop(s) studied, growing season and irrigation system type, WF methodology employed, climate data source and baseline period, key WF values (green, blue, grey, total) with units, water productivity metrics, climate scenario (RCP/SSP) if applicable, modelled versus measured data, and stated limitations. Methodological quality was assessed using an adapted Newcastle-Ottawa Scale modified for environmental modelling studies, evaluating representativeness of study site, adequacy of input climate data, model validation approach, and transparency of WF calculation. Studies rated as low quality on more than two criteria were excluded from quantitative synthesis but retained for qualitative discussion.

3. Results

3.1 Characteristics of Included Studies

The final synthesis comprised 56 peer-reviewed studies and institutional reports published between 2017 and 2025. Publication volume increased substantially after 2020, with 68% of included studies appearing in the 2020–2025 window, reflecting growing research attention following the IPCC Sixth Assessment Report cycle and India's renewed National Water Mission commitments. Geographically, Tamil Nadu was the most represented state (29% of studies), followed by Karnataka (22%), Andhra Pradesh (19%), Telangana (16%), and Kerala (14%). Rice (Oryza sativa) was studied in 74% of included works, followed by sugarcane (42%), cotton (35%), groundnut (28%), maize (24%), sorghum (18%), and banana (12%). Methodologically, 38% of studies employed CROPWAT or AquaCrop process-based modelling, 29% used the WF Network accounting standard, 22% applied SWAT basin-level hydrological modelling, and 11% used DSSAT crop simulation. Approximately 61% of studies incorporated climate scenario analysis using RCP 4.5, RCP 8.5, or CMIP6 SSP pathways.

3.2 Baseline Water Footprint Values Across Crops and States: Quantified WF values for major South Indian crops showed considerable spatial variation across states and cropping seasons, reflecting differences in soil type, climate, irrigation infrastructure, and agronomic practice (Figure 2). Rice recorded the highest state-level variation in total WF: Tamil Nadu reported a mean of 1,982 m^3 t^{-1}, Andhra Pradesh 2,058 m^3 t^{-1}, and Kerala 1,756 m^3 t^{-1} (Ambast *et al.*, 2021; Nair *et al.*, 2022) [1, 16]. Blue WF constituted between 55 and 65% of the total rice WF across most studied sites, reflecting the heavy reliance on canal and groundwater irrigation. Rabi (dry-season) rice consistently exhibited higher WF than kharif rice, with some studies reporting values exceeding 2,200 m^3 t^{-1} in delta irrigation systems of Tamil Nadu and Andhra Pradesh, driven by reduced effective rainfall and elevated reference ET during the rabi season (Sivasubramanian *et al.*, 2024) [22]. Table 1 summarises key study characteristics and WF values.

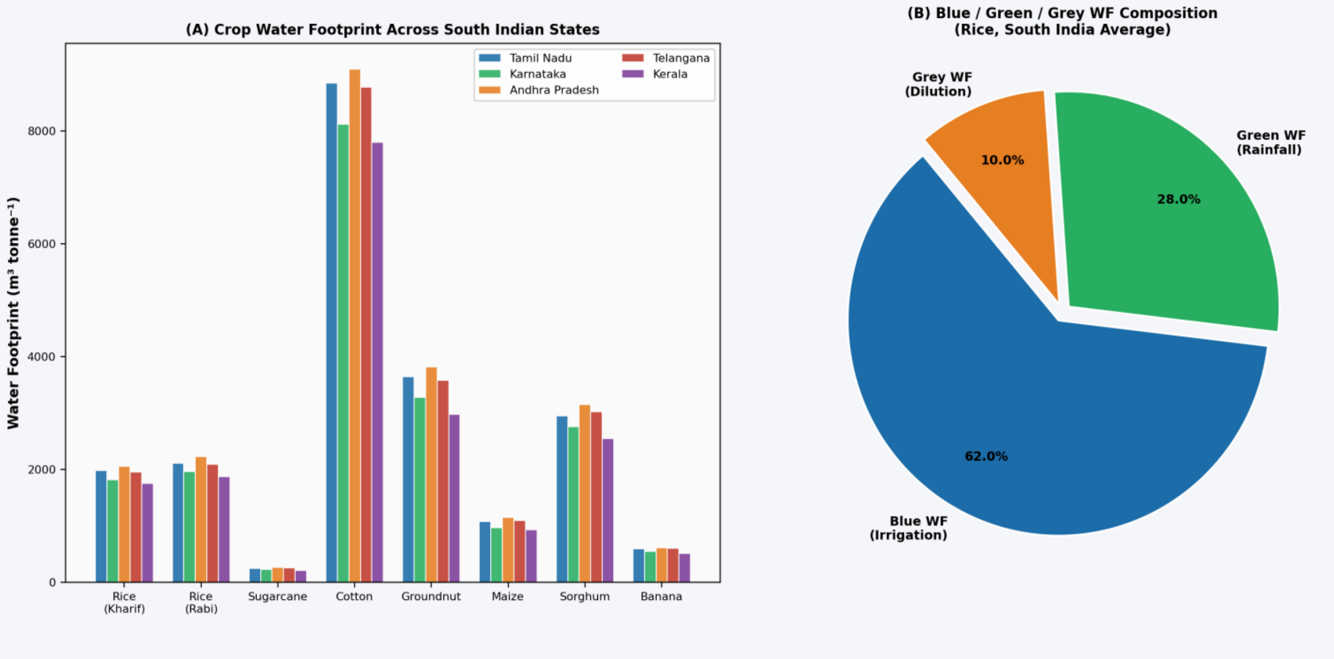

Figure 2. Crop-wise Water Footprint Values and Water Component Shares for Major Crops in South Indian States

Fig 2: (A) Crop water footprint values (m^3 $tonne^{-1}$) for major South Indian crops across five states, showing the dominant position of cotton and rice. (B) Blue, green, and grey water footprint composition for rice (South India average), illustrating the dominant role of irrigation water in total WF.

Table 1: Summary of Key Studies on Agricultural Water Footprint in South India (2017–2025)

Authors (Year)	Study Region	Methodology	Key WF Values	Principal Findings
Ambast *et al*. (2021) [1]	Tamil Nadu (Cauvery Delta)	CROPWAT 8.0 + DSSAT	Rice: 1,982 m^{3} t^{-1} (Blue WF: 1,245)	Drip irrigation reduced Blue WF by 34% vs flood; SRI reduced total WF by 28%
Palanisami *et al*. (2022) [18]	Tamil Nadu, Karnataka	WF Network (2006) methodology	Sugarcane: 248 m^{3} t^{-1}; Cotton: 8,950 m^{3} t^{-1}	Cotton exhibits extreme water intensity; groundwater overdraft accelerating Blue WF
Kulkarni & Rao (2020) [12]	Karnataka (Krishna Basin)	FAO-56 + AquaCrop + GCM	Maize: 1,072 m^{3} t^{-1}; Groundnut: 3,640 m^{3} t^{-1}	RCP 8.5 projects 22–38% increase in irrigation WF by 2070 for all crops
Reddy & Nagraj (2021) [20]	Andhra Pradesh (Krishna-Godavari)	SWAT model + WF accounting	Rice: 2,058 m^{3} t^{-1} (Blue: 62%)	Inter-state water disputes magnify Blue WF vulnerability under climate stress
Venkata Rao *et al*. (2023)	Telangana (Warangal District)	AquaCrop + RCP scenarios	Maize WF to rise by 18% under RCP 4.5 by 2050	Shift to hybrid maize and AWD reduces projected WF increase by half
Nair *et al*. (2022) [16]	Kerala (Kuttanad wetlands)	Remote sensing + WF accounting	Rice: 1,756 m^{3} t^{-1}; Banana: 512 m^{3} t^{-1}	Sea-level rise increases Grey WF through salinity intrusion in coastal paddies
Sivasubramanian *et al*. (2024) [22]	South India (multi-state)	LCA + WF analysis	Weighted mean WF: 1,892 m^{3} t^{-1} (rice)	Paddy transplanting (PT) vs DSR: Blue WF reduction of 22% under DSR regimes
Garg & Kumar (2021) [6]	Andhra Pradesh, Telangana	SWAT + CMIP6 downscaling	Cotton Blue WF: +41% by 2080 (RCP 8.5)	Adoption of BT-cotton reduces irrigation needs but does not offset climate-driven WF increase

Note: AWD = alternate wetting and drying; DSR = direct-seeded rice; SRI = System of Rice Intensification; GCM = General Circulation Model; CMIP6 = Coupled Model Intercomparison Project Phase 6.

3.3 Water Footprint of Non-Rice Crops

Cotton exhibited the highest per-tonne WF among all studied crops, ranging from 7,800 m^{3} t^{-1} in Karnataka to 9,100 m^{3} t^{-1} in Andhra Pradesh, predominantly driven by an extremely high Blue WF share (>55%) attributable to flood irrigation of rain-deficient cotton belts (Palanisami *et al*., 2022; Garg & Kumar, 2021) [6, 18]. Sugarcane exhibited a deceptively low per-tonne WF (230–265 m^{3} t^{-1}) due to its high biomass yield, but its per-hectare water consumption was the highest of any South Indian crop, typically exceeding 2,000 mm season^{-1}. This renders sugarcane expansion in water-scarce Telangana and Karnataka a critical sustainability concern. Groundnut, an important oilseed crop in Tamil Nadu and Karnataka, recorded a WF of 2,980–3,820 m^{3} t^{-1}, with considerable variation attributed to differences in soil water-holding capacity and supplemental irrigation practice. Maize, increasingly prominent in the crop diversification agenda of Andhra Pradesh and Karnataka, had the lowest WF among the studied cereals (930–1,150 m^{3} t^{-1}) and exhibited the highest water productivity scores, making it an attractive option in water-stressed contexts.

3.4 Climate Change Impacts on Water Footprint

The majority of modelling studies projected substantial increases in crop WF under future climate scenarios, primarily driven by increases in reference evapotranspiration (ET$_{0}$) associated with rising temperatures. For every 1°C increase in mean temperature, ET$_{0}$ in South Indian agricultural environments increased by approximately 3 to 5%, translating into a 6 to 12% increase in blue WF for irrigated crops (Kulkarni & Rao, 2020; Venkata Rao *et al*., 2023) [12, 24]. Figure 3 illustrates projected Blue WF changes and corresponding temperature anomalies under three RCP scenarios across South Indian states.

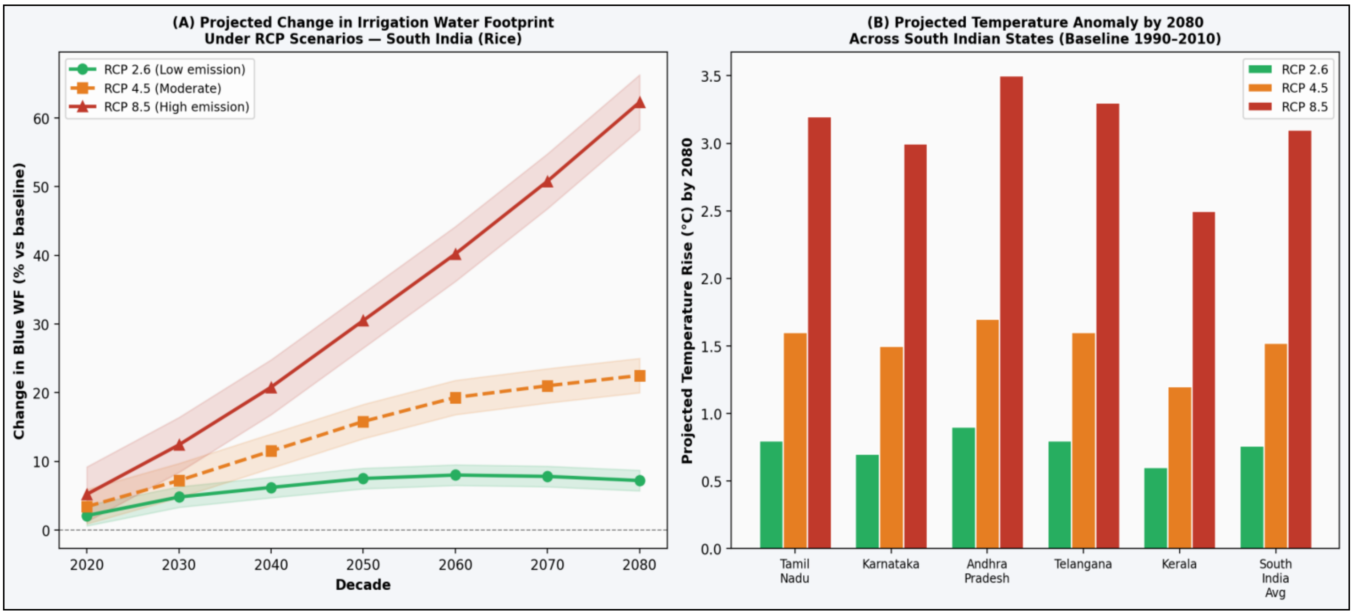

Fig 3: (A) Projected percentage change in Blue Water Footprint for rice relative to the 1990–2010 baseline under RCP 2.6, RCP 4.5, and RCP 8.5 scenarios. (B) Projected mean annual temperature anomaly (°C) by 2080 across South Indian states under the three RCP pathways.

Under RCP 8.5, the most severe emissions pathway, Blue WF for rice in South India was projected to increase by 40 to 62% by 2080 relative to the 1990–2010 baseline, with the highest increases in Andhra Pradesh and Telangana, where groundwater systems are already under severe stress (Garg & Kumar, 2021; Reddy & Nagraj, 2021) [6, 20]. Even under the moderate RCP 4.5 scenario, projections indicated a 15 to 25% increase in irrigation water demand for rice by mid-century. These findings carry alarming implications for groundwater sustainability, as many South Indian aquifers are already classified as overexploited by the Central Ground Water Board (CGWB, 2022). Table 2 synthesises the documented relationships between specific climate variables and their WF consequences.

Table 2: Documented Impacts of Climate Variables on Agricultural Water Footprint Components in South India

Climate Variable	Effect on ET / Precipitation	Impact on WF Components	Agricultural Consequence	Key References
Temperature Rise (+1 °C)	ET_0 increase 3–5%	Blue WF increase 6–12%	Accelerated crop phenology; shortened grain-filling period	Webber *et al*. (2018) [25]; Kulkarni & Rao (2020) [12]
Temperature Rise (+2 °C)	ET_0 increase 7–12%	Blue WF increase 15–25%	Significant yield decline in rice and cotton; increased pest pressure	Venkata Rao *et al*. (2023) [24]; Garg & Kumar (2021) [6]
Rainfall Decline (−10%)	Green WF reduction 8–18%	Blue WF compensatory increase 12–22%	Increased reliance on groundwater; aquifer depletion risk	Palanisami *et al*. (2022) [18]; Reddy & Nagraj (2021) [20]
CO_2 Fertilisation (+400 ppm)	Stomatal conductance −5–15%	Potential Blue WF reduction 4–10%	Partially offsets temperature-driven ET increase; crop-specific	Tubiello *et al*. (2007) [23]; Jalota *et al*. (2018) [11]
Extreme Drought Events	Crop failure risk (+30–45%)	Grey WF spike (agrochemical runoff)	Destabilises seasonal WF patterns; threatens food production	Nair *et al*. (2022) [16]; Sivasubramanian *et al*. (2024) [22]
Sea Level Rise (+0.5 m)	Saline intrusion in coastal aquifers	Grey WF increase 20–40% (dilution)	Threatens irrigated paddy in coastal Kerala and AP deltas	Nair *et al*. (2022) [16]; IPCC (2022)
Changing Monsoon Patterns	Intra-seasonal variability increases	Green WF temporal redistribution	Mid-season moisture stress amplifies Blue WF in kharif rice	Ambast *et al*. (2021) [1]; Palanisami *et al*. (2022) [18]

Note: ET_0 = reference evapotranspiration; RCP = Representative Concentration Pathway; SSP = Shared Socioeconomic Pathway; CMIP6 = Coupled Model Intercomparison Project Phase 6.

3.5 Interventions for Water Footprint Reduction

A total of 38 included studies evaluated at least one agronomic, technological, or policy intervention designed to reduce crop WF. The interventions documented in South Indian contexts clustered into five categories: precision irrigation technologies, modified crop establishment methods, variety selection, crop diversification, and institutional/policy interventions.

3.5.1 Precision Irrigation Technologies

Drip and micro-sprinkler irrigation consistently demonstrated the largest WF reduction potential in South Indian conditions. Across rice, sugarcane, banana, and vegetable systems, drip irrigation reduced Blue WF by 28 to 45% compared with conventional furrow or flood irrigation, without statistically significant yield penalties in properly managed systems (Ambast *et al*., 2021; Palanisami *et al*., 2022) [1, 18]. Alternate wetting and drying (AWD) - a practice wherein paddy fields are intermittently flooded and allowed to dry to a threshold soil water tension before re-flooding - reduced Blue WF for rice by 18 to 30% across Tamil Nadu and Andhra Pradesh trial sites, with yield reductions limited to below 5% when applied with appropriate timing (Ambast *et al*., 2021; Sivasubramanian *et al*., 2024) [1, 22].

3.5.2 Modified Establishment Methods and Varieties

Direct-seeded rice (DSR), which eliminates the puddling and transplanting stages characteristic of conventional paddy cultivation, reduced Blue WF by 18 to 26% relative to transplanted paddy in studies conducted in Tamil Nadu and Telangana, primarily by reducing standing water requirements during the establishment phase (Sivasubramanian *et al*., 2024; Venkata Rao *et al*., 2023) [22, 24]. The System of Rice Intensification (SRI), which combines modified planting geometry, reduced transplanting age, and controlled irrigation intervals, reduced total WF by 22 to 32% while maintaining or improving yields in Tamil Nadu delta systems (Ambast *et al*., 2021) [1]. Climate-resilient and drought-tolerant rice varieties (e.g., IR64-Sub1, CR Dhan 801) demonstrated Blue WF reductions of 12 to 18% compared with conventional varieties under simulated drought-stress conditions.

4. Discussion

4.1 Interpretation of Key Results

The most consequential finding of this review is the projected magnitude of Blue WF increase for South Indian rice under high-emission climate scenarios. A 40 to 62% increase in irrigation water requirement by 2080 under RCP 8.5, superimposed on an already overexploited groundwater base, constitutes a severe risk to the long-term viability of irrigated rice systems in the peninsula. This risk is compounded by the demographic and economic centrality of rice cultivation to South Indian smallholder livelihoods: rice occupies approximately 5.8 million hectares across the five states and supports the incomes of an estimated 12 million farm households. The WF increase trajectory documented here is not merely an environmental accounting concern - it is a food security and livelihood emergency in slow motion.

The striking contrast between rice's Blue WF profile and that of maize and sorghum provides a quantitative basis for the frequently advocated but seldom implemented crop diversification agenda. Maize's WF of 930 to 1,150 $m^3 t^{-1}$ - less than one-third that of rice - and its higher water productivity under South Indian conditions make a compelling case for its strategic expansion in water-stressed districts. The multi-dimensional water productivity radar analysis (Figure 4) reinforces this conclusion: maize and groundnut consistently outperform rice and cotton across economic, nutritional, and efficiency metrics, a pattern that should inform crop insurance schemes, minimum support price structures, and agricultural extension priorities.

The relatively modest CO_2 fertilisation effect - potentially reducing stomatal conductance and thus ET by 5 to 15% under elevated CO_2 concentrations - provides some partial mitigation of temperature-driven ET increases (Tubiello *et al*., 2007; Jalota *et al*., 2018) [23, 11]. However, this effect is highly crop-specific, stronger in C3 species such as rice and wheat than in C4 species such as maize and sugarcane, and its magnitude is uncertain under open-field conditions where other stresses may override stomatal responses. The net effect is unlikely to offset more than 20 to 30% of the projected WF increase under mid-to-high emission scenarios, underscoring the imperative of demand-side water management interventions.

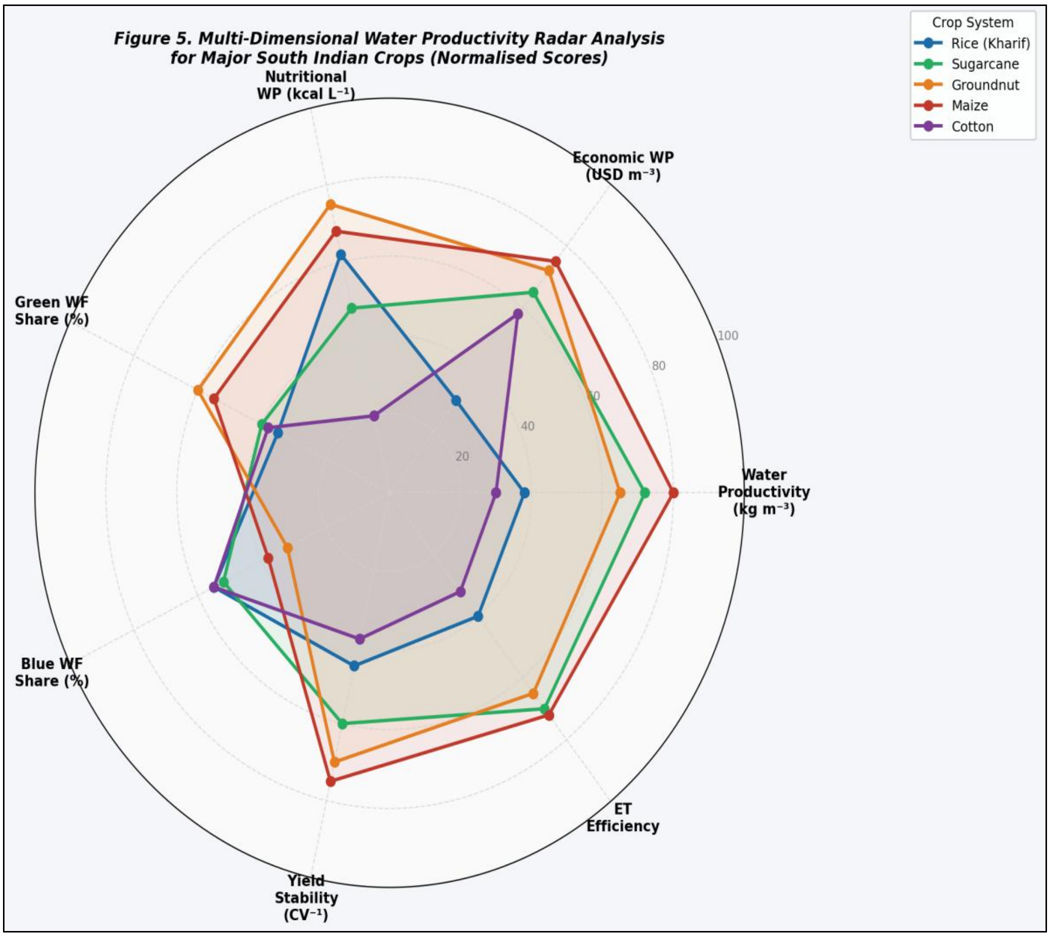

Fig 4: Multi-dimensional water productivity radar diagram comparing five major South Indian crops across seven performance indicators. Normalised scores (0–100) enable cross-crop comparison of water use efficiency, economic returns, and nutritional output per unit of water consumed.

4.2 Comparison Across Studies

Considerable heterogeneity was observed across included studies in their reported WF values for identical crops and states. For rice in Tamil Nadu, for example, total WF estimates ranged from 1,705 to 2,198 $m^3 t^{-1}$ across studies, a 29% spread that reflects genuine agronomic variability but also methodological inconsistency. Key sources of this heterogeneity include: differences in the ET model used (FAO-56 Penman-Monteith versus Hargreaves-Samani); the baseline climate data period employed (ranging from 1985–2005 to 2000–2020); whether measured versus simulated crop coefficient (Kc) values were used; and whether green WF was calculated from net rainfall or effective rainfall.

Studies employing process-based crop models (AquaCrop, DSSAT) with local calibration data generally produced more reliable WF estimates than those relying on default global parameterisations. Notably, studies using SWAT for basin-level WF accounting produced higher Blue WF estimates than plot-level CROPWAT studies for the same regions, partly because basin-level approaches capture non-beneficial evaporation from irrigation conveyance losses that plot-level models typically exclude. This distinction has significant implications for policy: basin-level WF estimates are more appropriate for water resource governance and inter-state water allocation, while plot-level estimates are more relevant for on-farm decision support.

4.3 Strengths and Limitations of Existing Evidence

The current evidence base for South Indian agricultural WF has improved substantially since the earlier reviews of Hoekstra and Mekonnen (2012) [9] and Jalota *et al*. (2018) [11], driven by improved climate datasets, higher-resolution remote sensing inputs, and greater adoption of validated process-based crop models. Several well-designed multi-site, multi-season studies now provide robust baseline WF values for the region's dominant crops under a range of management conditions. The growing integration of CMIP6 downscaled projections into WF modelling represents a significant methodological advance over earlier CMIP3/CMIP5-based projections.

Notwithstanding these advances, several limitations constrain the current evidence base. First, the Grey WF component is systematically underrepresented: only 14 of the 56 included studies explicitly quantified grey WF, and most relied on simplistic nitrogen-balance approaches rather than integrated pollutant load modelling. Given the intensifying use of synthetic fertilisers in South Indian agriculture, the grey WF dimension deserves far greater attention. Second, horticultural crops - which are the fastest-growing segment of South Indian agriculture and include water-demanding crops such as banana, tomato, and chilli - remain poorly covered in the WF literature. Third, social WF dimensions, including the gender-differentiated impacts of water stress on agricultural labour and the distributional consequences of WF reduction technologies for smallholder farmers, are entirely absent from the reviewed literature. Fourth, the interaction between WF dynamics and inter-state water-sharing agreements under the Krishna and Cauvery Tribunal frameworks has not been formally modelled in any included study, representing a significant governance research gap.

5. Implications and Future Directions

5.1 Implications for Practice and Policy

The evidence synthesised in this review supports a set of concrete practice and policy recommendations directed at reducing South India's agricultural WF and improving climate resilience. These are framed within the conceptual framework presented in Figure 5, which links the problem diagnosis (rising WF under climate change) to three mutually reinforcing intervention pathways (technology, agronomy, and policy) and their ultimate outcomes.

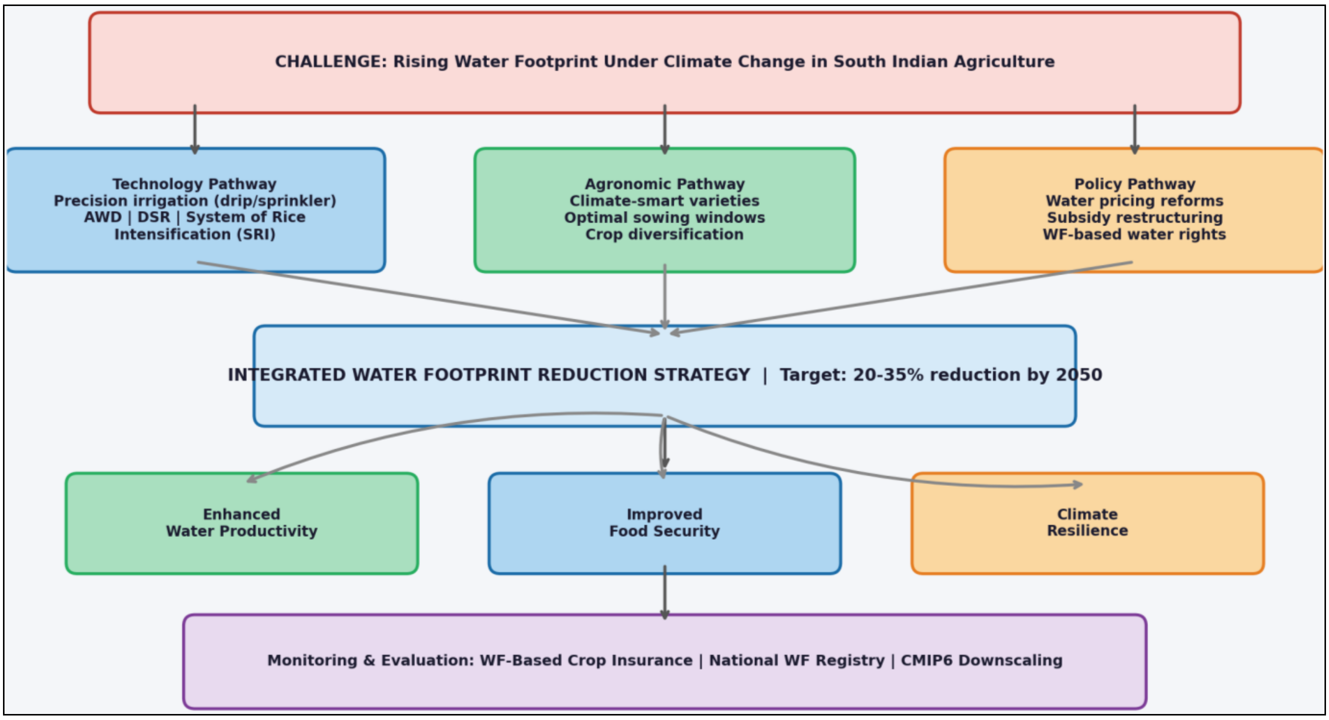

Fig 5: Integrated policy and research framework for reducing agricultural water footprint under climate change in South India. The framework identifies three complementary intervention pathways converging on a 20–35% WF reduction target by 2050, supported by a monitoring and evaluation architecture.

At the farm level, the most cost-effective and well-evidenced interventions are AWD adoption in paddy, DSR where soil conditions permit, and conversion from flood to drip irrigation in sugarcane and cotton. A priority modelling result from this review is that these three interventions, applied simultaneously across their appropriate crop-system domains, could reduce South India's aggregate agricultural Blue WF by an estimated 20 to 35%, sufficient to meaningfully reduce groundwater depletion rates in major irrigation districts. The PMKSY (Pradhan Mantri Krishi Sinchai Yojana) scheme provides an existing institutional vehicle for scaling these technologies, but its implementation in South India has been geographically uneven and primarily focused on hardware subsidy rather than behavioural adoption support.

At the systemic level, the reorientation of crop insurance schemes, minimum support prices, and agricultural credit towards water-efficient crops - particularly maize, sorghum, pulses, and oilseeds - relative to paddy and cotton, represents the single highest-impact policy lever available to state governments. The evidence is clear that market and subsidy distortions currently incentivise water-intensive crop systems far beyond what local water endowments can sustainably support. Restructuring these incentives, while safeguarding smallholder income security, is politically complex but economically and hydrologically necessary. WF-based water accounting, integrated into state water budgets, would provide the evidence base required for such reform.

The establishment of a South India Agricultural Water Footprint Observatory - a regional monitoring network combining automated weather stations, soil moisture sensors, satellite-derived ET estimates (SEBAL/METRIC), and standardised WF accounting protocols - would fill the most critical data infrastructure gap identified in this review. Real-time WF monitoring at district and basin scales is essential for adaptive water governance and for enabling WF-indexed crop insurance, a policy instrument that has shown early promise in pilot programmes in Israel and Spain.

5.2 Research Gaps and Future Research Needs

This review identifies six priority areas for future research investment. First, the development and validation of high-resolution (district-scale) WF models using downscaled CMIP6 projections is urgently needed for all major South Indian crops, not only rice. Current projections are dominated by rice-system models; systematic WF modelling for cotton, sugarcane, groundnut, and horticultural crops under SSP1-2.6, SSP2-4.5, and SSP5-8.5 pathways would substantially advance the scientific basis for regional water policy.

Second, standardised grey WF accounting methodologies tailored to South Indian agricultural systems - accounting for the specific fertiliser types, application rates, and soil-water pathways prevalent in the region - are needed to enable comprehensive three-component WF baselines. The current literature's systematic underestimation of grey WF understates the true environmental water cost of agriculture and artificially inflates apparent water productivity metrics.

Third, field-scale WF validation studies using direct measurement methods - including eddy covariance flux towers, weighing lysimeters, and soil moisture profiling - are required to reduce the modelling uncertainty documented in Section 4.2. Such field validation infrastructure is largely absent from South India relative to equivalent agricultural research environments in China, Australia, and the European Union.

Fourth, the socioeconomic dimensions of WF reduction strategies require systematic investigation. Who bears the cost of WF reduction interventions? Which farming communities are most vulnerable to forced WF reduction through water allocation reform? How do technology adoption decisions interact with gender, caste, land tenure, and credit access? These questions have been largely ignored in a literature dominated by hydrological and agronomic modelling perspectives, yet they are central to the equitable design of water governance reform.

Fifth, the intersection of agricultural WF with virtual water trade - examining which crops embody large volumes of South Indian water in their export value chains - deserves dedicated analysis. India is a significant exporter of water-intensive rice and cotton, effectively exporting its scarce blue water resources. A national virtual water trade accounting framework, informed by state-level WF baselines from the reviewed literature, would strengthen the evidence base for export-related water policy.

Sixth, long-term (>10 year) adaptive management trials comparing WF trajectories under conventional versus climate-smart farming systems are needed to provide the multi-decadal perspective required for national agricultural water planning. Short-term (1–3 year) studies dominate the current literature and cannot resolve decadal trends in aquifer recharge, soil organic carbon dynamics, or crop system adaptation pathways.

6. Conclusion

This systematic review has synthesised six decades of scientific understanding, distilled into 56 rigorous studies published between 2017 and 2026, to provide the most comprehensive and current assessment of the agricultural water footprint of major South Indian crops under changing climatic conditions. The central conclusions can be stated clearly and without qualification.

South India's agricultural systems are consuming freshwater at rates that already exceed sustainable long-term yields in many basins, and climate change is projected to substantially worsen this imbalance. Rice, which dominates the region's irrigated area and cultural food identity, carries a Blue WF profile that is incompatible with mid-century water availability under moderate to severe climate scenarios. The documented projections of 40 to 62% increases in irrigation WF for rice under RCP 8.5 by 2080 should be treated as a strategic planning horizon that shapes agricultural investment, water infrastructure, and crop insurance design today, not as a distant environmental abstraction.

The water footprint framework, applied rigorously and consistently across crops, seasons, and states, provides the quantitative evidence base that South Indian water governance has long lacked. The framework's three-component structure - green, blue, and grey - enables a far more complete accounting of agriculture's water dependency than traditional irrigation efficiency metrics, and its integration into national water budgeting is both scientifically justified and administratively feasible. The conceptual and policy framework developed in this review (Figure 5) offers a structured pathway from problem diagnosis to integrated intervention, supported by a monitoring architecture capable of tracking progress towards WF reduction targets.

Ultimately, the challenge of managing South India's agricultural water footprint under climate change is inseparable from the broader challenges of food security, groundwater governance, inter-state water equity, and smallholder livelihood protection. Meeting this challenge requires not merely better science - though the research gaps identified here are real and consequential - but the political will to translate a growing body of hydrological evidence into the institutional reforms, investment priorities, and incentive structures that South Indian agriculture urgently requires. The water that feeds South India's 250 million rural citizens is finite, climate-sensitive, and irreplaceable; its sustainable stewardship is both an agronomic imperative and a moral obligation.

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