



Assessing Agricultural Water Footprint and Its Implications for Sustainable Water Management in Aceh Province, Indonesia: A Case Study of Two Watersheds

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ABSTRACT

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This study applies the water footprint (WF) framework to evaluate sustainable agricultural and food consumption patterns in Aceh Province, Indonesia, focusing on the Krueng Aceh and Jambo Aye watersheds. The assessment follows the standard methodology of the water footprint network (WFN), disaggregating water use into blue (surface and groundwater), green (rainwater), and grey (pollution assimilation) components. Methodologically, it integrates 21 years of hydro-climatological data, applies the Mock rainfall-runoff model for water availability analysis, and employs Geographic Information Systems (GIS)-based spatial techniques for hotspot mapping and interpolation. The study quantifies WF for key commodities, identifies critical pressure zones, and examines linkages between production practices, dietary patterns, and water stress. Results reveal that irrigated paddy rice is the dominant water consumer, contributing 40% of the total food-related WF in the Krueng Aceh watershed and 57% in the Jambo Aye watershed, primarily due to traditional continuous flooding irrigation. Rural areas account for a higher total WF due to larger population size, whereas urban residents exhibit a higher per capita WF, driven by greater consumption of animal products. Plant-based foods constitute 89-90% of the total volumetric WF; however, animal products, particularly poultry and eggs, have significantly higher water intensities per unit. Spatial analysis aligns grey WF hotspots with zones of intensive paddy and vegetable cultivation, underscoring nutrient management challenges. The study advocates for prioritizing irrigation efficiency upgrades, such as adopting alternate wetting and drying (AWD) in rice systems, within spatially identified hotspots to reconcile agricultural production goals with long-term water sustainability. Furthermore, it recommends policy support for crop diversification and consumer awareness towards lower-WF diets. Embedding WF assessment into Aceh's integrated water resources management (IWRM) planning is crucial for advancing water security, food sovereignty, and climate resilience in the region.

1. INTRODUCTION

Water is an indispensable natural resource that sustains life, agricultural productivity, ecosystem stability, and socio-economic development [1]. In agrarian economies, particularly in tropical developing regions, freshwater availability directly underpins food security and rural livelihoods. In Indonesia, the agricultural sector is the largest single user of water, accounting for over 76% of withdrawals, with irrigated paddy fields as the dominant consumer [2]. This pattern is evident in Aceh Province, the primary food production hub in the western part of the country, where agriculture contributes more than 30% to the provincial gross domestic product, led by strategic commodities such as rice, coffee, and oil palm. However, increasing demands for domestic and industrial water, coupled with climate variability

and deteriorating water quality, are generating mounting pressure on Aceh's freshwater systems [2, 3].

The province's river basins are hydrologically diverse but face similar sustainability challenges. In many areas, seasonal water deficits occur during the dry months, constraining agricultural output and threatening rural incomes. For example, in the Krueng Aceh watershed, one of the largest and most developed irrigation zones, annual irrigation demand is estimated at 23.8 million m³, yet dry-season flows are often insufficient to meet requirements, especially between February and September [4, 5]. Parallel issues are observed in other basins, including Jambo Aye, where anthropogenic pressures such as deforestation, agricultural runoff, and competition among sectors further exacerbate water stress.

Beyond scarcity, water quality deterioration from excessive agrochemical use introduces additional risks to ecosystem

health. Pesticide and fertilizer residues contribute to increasing grey water footprint (WF), the volume of freshwater needed to dilute pollutants to acceptable standards [6]. This dual challenge of quantitative and qualitative stress underscores the need for integrated, evidence-based water resources management.

The concept of WF was introduced in the early 2000s and offers a comprehensive metric for quantifying direct and indirect water use across the supply chain. WF disaggregates consumption into blue WF (surface and groundwater), green WF (rainwater stored in soil), and grey WF (pollution assimilation flows) [7]. When applied to agriculture, the WF framework enables a multi-dimensional view of water consumption that links production practices with environmental impacts [7, 8]. WF assessment is closely related to the concept of virtual water, the hidden flow of water embedded in traded goods and services. By quantifying this embedded water, policymakers and stakeholders can identify crops and livestock products with disproportionate water demands, and thereby target efficiency interventions [9]. Globally, WF methods have informed irrigation modernization, crop diversification, and trade policies; however, their systematic application in Aceh has been limited.

Case studies in Aceh highlight the value of WF assessment for basin-scale planning. In the Krueng Aceh watershed, a previous study [2] calculated an average per capita WF of 608.27 m³·year⁻¹ in rural areas and 740.77 m³·year⁻¹ in urban areas, both below the global average of 1,240 m³·year⁻¹. Despite the relatively moderate per capita values, seasonal shortages were evident, reinforcing the need for more precise demand management. Meanwhile, in the Jambo Aye watershed, the study [2] found that water use for food consumption reached approximately 144 million m³·year⁻¹ for crop-based foods, with rice alone accounting for 64% of the total. Animal-derived foods contributed an additional ~17.5 million m³·year⁻¹, dominated by poultry meat. These findings reveal the dominance of high-water-demand commodities in the local diet and the resulting strain on water resources [1, 10].

Comparative analysis of these studies suggests that, while per capita WFs may not be excessive by global standards, the absolute volumetric pressure on local basins is substantial due to large agricultural areas and cropping patterns heavily reliant on irrigation. Furthermore, recurrent dry-season deficits indicate that storage infrastructure, water distribution efficiency, and crop choice need to be revisited in the light of WF insights. The Aceh Water Resources Master Plan (2020–2045) calls for integrated water resources management (IWRM) that balances ecological, economic, and social objectives. Although the WF framework can directly inform such planning by identifying irrigation hotspots, quantifying pollution loads, and modelling climate change scenarios, its adoption into provincial decision-making remains fragmented [6, 10]. Existing studies are largely isolated by watershed and commodity focus, with no unified, province-wide strategy. There is thus a clear research gap in harmonizing WF data across major agricultural zones and linking it to actionable management options.

However, the systematic application of the WF framework in Aceh Province faces distinct and interrelated shortcomings that limit its utility for integrated water governance. First, existing assessments are often geographically or thematically isolated, focusing on single watersheds like Krueng Aceh or

on individual commodity chains such as rice or coffee. This fragmented approach results in datasets that are inconsistent in scope, methodology, and temporal resolution, making them difficult to harmonize for a comprehensive, province-wide analysis. Consequently, policymakers lack a unified evidence base to compare water pressures across different agro-ecological zones or to prioritize investments at a regional scale, as called for in strategic plans like the Aceh Water Resources Master Plan (2020–2045) [6, 10].

Second, there is a significant implementation gap between WF assessment and actionable water management. While studies may calculate volumetric footprints, they frequently stop short of translating these figures into spatially explicit, practical interventions that can be adopted by local water user associations or district agriculture offices. For instance, knowing the total grey WF for a watershed is less actionable than mapping its specific hotspots to target improved nutrient management practices. This gap prevents the seamless integration of WF science into the operational planning and monitoring frameworks of local water governance institutions.

Furthermore, the dynamic interplay between WF patterns and their underlying drivers remains inadequately explored in a unified analytical framework. The linkages between spatially identified WF hotspots, the critical seasonal variability in water availability, and key socio-economic drivers, such as traditional irrigation practices, cropping calendars, and evolving urban dietary preferences, are often studied in isolation. A lack of integrated analysis that connects hydrologic models, spatial commodity footprints, and consumption data hinders the development of robust, systems-based strategies that can simultaneously address production efficiency, consumption patterns, and climate resilience.

Building upon earlier basin-scale applications, this study seeks to comprehensively apply the WF framework to address these gaps and provide a scalable model for sustainable agricultural water management in Aceh Province. The research is designed to bridge the fragmentation between isolated studies and integrated planning through a comparative analysis of two contrasting yet strategic watersheds: Krueng Aceh and Jambo Aye. To this end, the investigation is guided by three core and sequential objectives:

1. To quantify the blue, green, and grey WFs of key agricultural commodities across the contrasting Krueng Aceh and Jambo Aye watersheds. This involves applying standardized water footprint network (WFN) methodologies to major crops: paddy rice, coconut, coffee, and livestock products: poultry and eggs, using long-term hydro-climatological data to derive representative values for each component (blue, green, grey) in cubic meters per ton.

2. To identify the biophysical and socio-economic factors that determine WF magnitude and variability. This objective moves beyond quantification to diagnose causes, examining how factors such as rainfall distribution, soil type, reference evapotranspiration (ET_o), irrigation method, and farmer decision-making influence the computed footprints for different commodities and locations.

3. To produce spatial WF maps and conduct integrated hotspot analyses that enable the prioritization of management interventions. Using Geographic Information Systems (GIS), calculated WF values will be linked to crop distribution maps to visualize the geographic concentration of water use and pollution assimilation demands (grey WF). These spatial outputs will be overlaid with indices of drought vulnerability and water availability to identify critical zones where high WF

coincides with high water scarcity risk, thereby pinpointing where interventions would yield the greatest impact.

Through this integrated, multi-scale analysis, which synthesizes volumetric accounting, causal diagnosis, and spatial explicitness, the study aims to develop predictive insights for sustainable water allocation under changing climatic and demographic conditions. The ultimate goal is to formulate evidence-based, spatially targeted recommendations that can directly inform local and provincial planning.

By bridging the current gaps between assessment and action, this research seeks to operationalize the WF concept as a practical decision-support tool within Aceh's IWRM framework. This contributes directly to balancing agricultural productivity with hydrological sustainability, thereby supporting provincial water security and the achievement of key Sustainable Development Goals (SDGs), particularly Zero Hunger (SDG 2), Clean Water and Sanitation (SDG 6), and Responsible Consumption and Production (SDG 12).

2. MATERIALS AND METHODS

2.1 Study area

The research was conducted in two representative watersheds in Aceh Province, Indonesia: Krueng Aceh watershed (174,785.79 ha), located across Banda Aceh City and Aceh Besar District, as presented in Figure 1, and the Jambo Aye watershed (462,062.44 ha), spanning Aceh Utara, Aceh Timur, Aceh Tengah, Bener Meriah, and Gayo Lues districts. Both watersheds are strategic food production areas with distinct hydrological regimes and land-use patterns, and are subject to seasonal water deficits and water quality

degradation. Elevation ranges from near sea level in the coastal plains to >3,000 m in the upstream highlands.

The climate is tropical humid, with annual rainfall between 1,400 and 2,400 mm, marked by a wet season (September-May) and a dry season (June-August). The two catchments were selected as case studies to represent contrasting agroecological and consumption patterns in Aceh's agricultural sector.

2.2 Research design

This study employed an explanatory sequential mixed-methods research design to comprehensively assess WF dynamics in Aceh's agricultural sector. The design was structured in two distinct phases to ensure both empirical robustness and contextual relevance.

The initial quantitative phase focused on the measurement, modelling, and spatial analysis of WFs. This involved the quantification of blue, green, and grey WF components for dominant agricultural commodities, hydrological modelling to assess water availability, and geospatial analysis to map WF distribution and identify hotspots. The subsequent qualitative phase was designed to interpret and contextualize the quantitative findings. This phase centered on stakeholder engagement through focus group discussions and expert interviews with farmers, water resource managers, and government officials to validate results and co-formulate actionable policy recommendations.

This sequential approach ensured that the technical assessment was systematically informed by and grounded in local socio-economic and institutional realities, thereby enabling the development of practical, evidence-based strategies for sustainable water management.

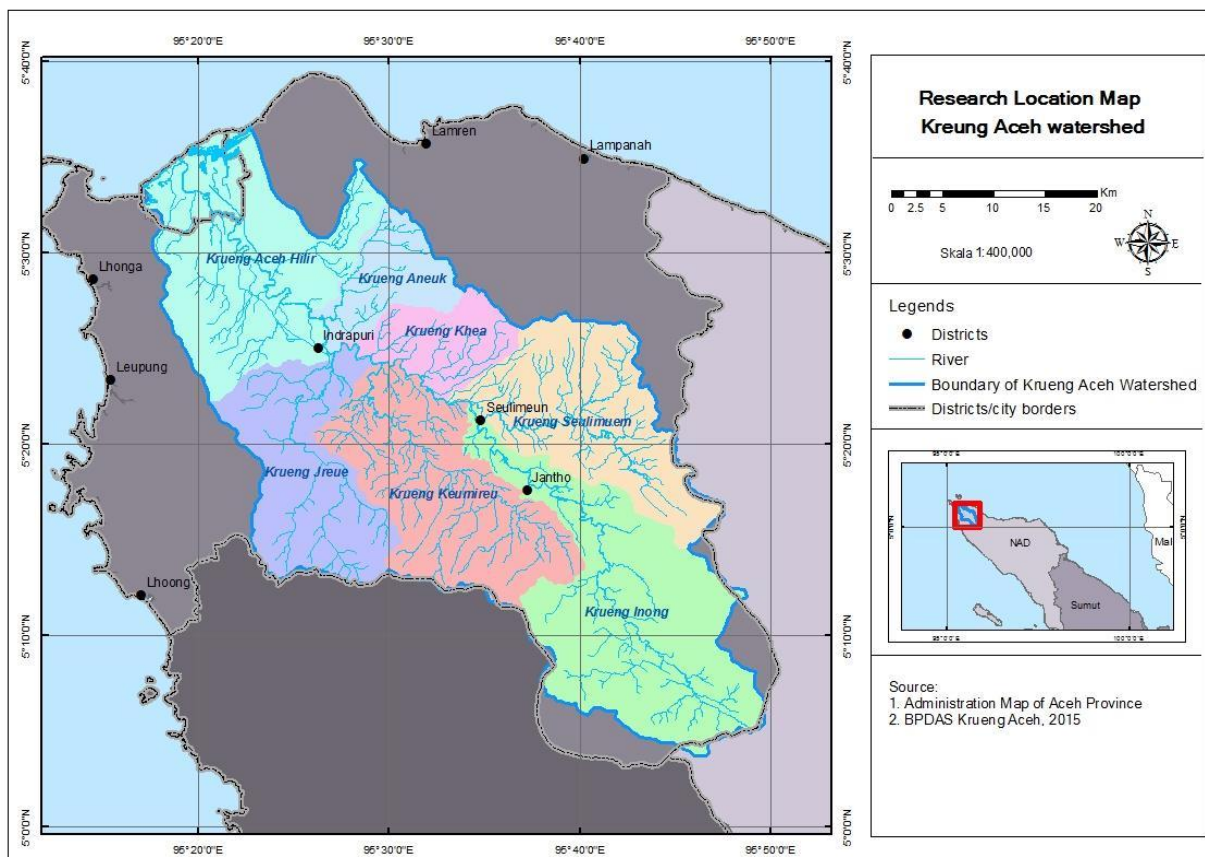


Figure 1. Location of the study area

2.3 Data collection

The study utilized both primary and secondary data sources to ensure the comprehensiveness and reliability of the WF assessment across the selected case study watersheds (Krueng Aceh and Jambo Aye). Data collection activities were conducted in line with the explanatory sequential mixed-methods design, whereby quantitative measurements preceded qualitative validation and interpretation.

2.3.1 Primary data

Primary datasets for this study were obtained through comprehensive field-based hydrological, agronomic, and socio-economic surveys conducted at representative locations across the two watersheds. The hydrological monitoring program involved the installation of Automatic Water Level Recorders (OTT SLD) at major irrigation intakes and control points, where water levels were measured at 15-minute intervals throughout the cropping season and subsequently converted to discharge values using site-specific rating curves.

To monitor soil water dynamics, Decagon EC-5 soil moisture sensors were deployed in representative paddy fields, plantation areas, and mixed cropping plots, enabling daily tracking of soil moisture variations; ET_o was calculated using the FAO Penman-Monteith equation based on locally recorded climatic parameters [11]. In parallel, microclimate stations were set up to record air temperature, relative humidity, wind speed, and solar radiation, with these on-site observations supplemented by both historical and real-time data from BMKG meteorological stations at *Sultan Iskandar Muda, Indrapuri, and Jantho*.

2.3.2 Secondary data

Secondary data for this study were systematically sourced from an extensive array of regional, national, and international databases to enhance and validate primary field findings in the Krueng Aceh and Jambo Aye watersheds. Socio-economic and demographic statistics, including annual population data, rural versus urban composition, and household consumption patterns, were extracted from the *Badan Pusat Statistik (BPS)*, specifically utilizing Susenas national household expenditure surveys and the comprehensive *Kabupaten/Kota dalam Angka* reports. It is important to note that the most recent, high-quality consumption datasets available for a comprehensive basin-scale WF assessment differed between the two watersheds. For the Krueng Aceh watershed, a complete dataset aligned with a prior hydrological assessment was available for 2015. For the Jambo Aye watershed, a more recent and comprehensive dataset was constructed for 2023. While this results in different reference years for the final consumption-based WF totals, the core comparative analysis focuses on the structural composition of the WF (share of rice, animal products) and its spatial patterns, which are less sensitive to inter-annual fluctuations than absolute volumetric comparisons. Several methodological safeguards were implemented to minimize the potential bias introduced by this temporal mismatch. First, the virtual water content (VWC) coefficients applied to both watersheds were derived from the same standardized 21-year hydro-climatological baseline (1995-2015), ensuring that the physical water intensity of each commodity is held constant and not confounded by year-specific climate anomalies.

Second, BPS Susenas data for Aceh Province indicate that the broad dietary composition, specifically the dominant share

of rice and the limited contribution of animal-based foods, remained structurally stable between 2015 and 2023, with no abrupt dietary transition recorded at the provincial level. Third, the agricultural production systems and cropping calendars in both basins have not undergone a fundamental technological shift during this period, as confirmed by district agriculture office records and stakeholder consultations; the prevalence of continuous flooding irrigation, which drives the high blue WF of paddy rice, persists in both watersheds.

Taken together, these factors support the conclusion that the structural WF composition, which commodities dominate and in what proportions, is comparable across the two reference years, even if absolute volumetric totals cannot be directly equated. Nonetheless, the authors acknowledge that inter-annual variability in rainfall, cropping area, and population-level consumption could introduce a residual uncertainty that cannot be fully eliminated without a contemporaneous dataset for Krueng Aceh. This limitation is discussed further in the uncertainty analysis presented in Section 3.3 and in the Conclusion.

Agricultural production data, such as crop areas, yield figures, and inventories of key livestock species, were compiled from reports maintained by both provincial and district agriculture service offices for years corresponding to the consumption data. To accurately quantify water use, commodity-specific VWC coefficients were adopted from the standardized datasets of the previous studies in the literature [9, 12, 13], with necessary adjustments made for Aceh's unique cropping calendars and climate variables. This approach distinguished green, blue, and grey water components to capture the nuances of actual water resource pressures.

Hydro-climatological inputs, crucial for modeling the underlying crop water requirements and hydrological regimes, were standardized across both watersheds. A consistent 21-year period (1995-2015) of daily and monthly records for precipitation, air temperature, relative humidity, wind velocity, and sunshine hours was sourced from BMKG meteorological stations distributed across the study region. This common climatic baseline ensures that the calculated VWC for crops are derived from a representative long-term climate normal, thereby mitigating the bias that could arise from using singular, atypical years. The subsequent application of these coefficients to 2015 (Krueng Aceh) and 2023 (Jambo Aye) production and consumption data is therefore based on a consistent climatic foundation.

Additionally, river discharge data and hydrological records were incorporated from Balai Wilayah Sungai Sumatera I, supporting assessments of both seasonal water supply and hydrological variability. For spatial and environmental characterization, the research utilized provincial spatial planning maps (RTRW) coupled with land cover classifications and SPI-based drought vulnerability indices to facilitate scenario analysis and integration in GIS platforms. High-resolution spatial data, including river basin boundaries, digital elevation models, and recent land cover derived from Sentinel 2 satellite imagery (10 m resolution), were obtained via the *Pusat Air Tanah dan Geologi Tata Lingkungan (PATG)* and other national repositories. Soil types influencing crop water requirements and runoff were detailed using maps at a 1:100,000 scale from the Balai Besar Sumberdaya Lahan Pertanian (BBSDLP).

These diverse secondary data sources collectively ensured a robust, multi-dimensional foundation for the study's

quantitative modeling, spatial analysis, and policy-relevant synthesis, thereby supporting reliable and reproducible assessment of agricultural water demand, supply, and sustainability in Aceh.

2.4 Water footprint calculations

The quantification of the blue, green, and grey WF for agricultural commodities in this study was undertaken in accordance with the standard methodology of the WFN as outlined by studies [14-16], with methodological adjustments made to account for the specific agroecological, climatic, and cropping system conditions of Aceh Province. For crop-based commodities, the WF was expressed in cubic metres per tonne of product ($m^3.t^{-1}$) and calculated separately for each WF component to capture the distinct sources and uses of water.

The blue WF represents the volume of surface water and groundwater consumed by crops during their growth cycle, designated as evapotranspiration (ET) blue. This was determined as the difference between the actual crop evapotranspiration (ETc) and the effective rainfall contributing to crop water needs. The green WF corresponds to the volume of rainwater stored in the soil profile and taken up by plants (ET green), which was calculated through a soil and water balance approach using monthly effective rainfall data and accounting for local infiltration, soil moisture storage, and root-zone capacity. The grey WF represents the volume of freshwater required to assimilate pollutant loads from the application of fertilisers and pesticides to concentrations that meet national water quality standards; it was estimated using the equation:

$$WF_{grey} = \frac{\alpha \times AR}{C_{max} - C_{nat}}$$

where, α is the fraction of the applied chemical lost to leaching or runoff (dimensionless), AR is the application rate of the agrochemical in kilograms per hectare ($kg\cdot ha^{-1}$), C_{max} is the permissible concentration under Indonesian water quality regulations, and C_{nat} is the natural background concentration in the receiving water body.

ETc was computed using the FAO Penman-Monteith equation, which integrates climatic variables such as solar radiation, air temperature, relative humidity, and wind speed, with crop coefficients (Kc) tailored to each crop's phenological stage, soil characteristics, and local weather conditions recorded by in-situ field stations and complemented by regional meteorological datasets. The WF calculations are illustrated as a schematic diagram presented in Figure 2.

For livestock and animal derived products, the WF estimation incorporated three principal components: (i) feed production, calculated by linking crop-specific WF values to the proportion of each feed type in the livestock diet; (ii) drinking water requirements of the animals, determined according to species, weight, and production system; and (iii) service water, which included water used for cleaning facilities, cooling, and other operational needs. VWC coefficients for both feed crops and livestock products were adopted from studies [17, 18] and adjusted to align with Aceh's feed composition data, local yields, and production efficiencies.

The consumption-based WF at the population scale was estimated by multiplying per capita annual consumption of

each product ($kg\cdot capita^{-1}\cdot yr^{-1}$), as derived from BPS Susenas household expenditure surveys, by its corresponding VWC. The resulting values were then aggregated for rural and urban population segments, classified according to BPS Susenas definitions, within each watershed. This approach enabled the tracing of water use back to demand side drivers, linking the intensity of water resource use not only to production systems but also to the dietary and consumption patterns of different population groups, thus providing an integrated perspective on agricultural water demand and its socio-economic determinants.

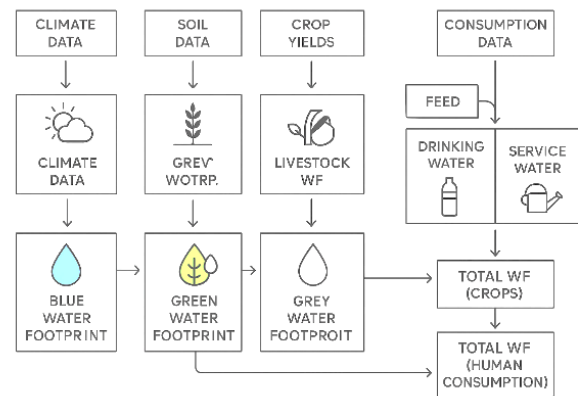


Figure 2. A schematic diagram showing the flow of water footprint (WF)

2.5 Hydrological modelling

To rigorously assess water availability in the study watersheds, hydrological simulation was performed using the Mock model [16, 19], a monthly rainfall and runoff model widely adopted in Indonesian hydrological studies due to its suitability for regions with limited observed data and diverse land uses. This physically based model facilitates the partitioning of rainfall into major hydrological components and allows for dynamic simulation of water fluxes across the watershed.

Model inputs for simulation spanned 21 years (1995-2015) and included comprehensive climate data, specifically, monthly records of precipitation, evaporation, and air temperature, sourced from BMKG meteorological stations strategically located within and around the watersheds. In addition to climatic inputs, the model incorporated high-resolution land cover maps, classifications of soil texture obtained from BBSDLP datasets, and infiltration rates tailored to local soil and land use combinations, crucial for parameterizing surface runoff and groundwater recharge dynamics. Initial soil moisture capacity at the onset of each simulation year was set based on extensive field measurements from representative agricultural plots, ensuring realistic starting conditions for soil and water processes.

The Mock model simulates the water balance by computing gains and losses across surface, subsurface, and groundwater reservoirs in each watershed. It produces monthly estimates of direct runoff, reflecting rapid hydrological responses to rainfall; baseflow, representing sustained groundwater contributions to river flow; and total streamflow, which is the aggregate discharge available in river channels. To improve predictive accuracy, the model parameters were calibrated using observed discharge records from Balai Wilayah Sungai

Sumatera I at key gauging sites within the Krueng Aceh and Jambo Aye basins. Calibration involved iterative adjustment of model coefficients, such as infiltration factors, soil moisture thresholds, and groundwater recession constants, to minimize deviations between simulated and measured streamflow.

Model performance was evaluated quantitatively using statistical criteria, chiefly the Nash Sutcliffe Efficiency (NSE) and the coefficient of determination (R^2). The calibration process aimed for values of NSE above 0.65 and R^2 exceeding 0.7, thresholds generally recognized as indicators of acceptable model fit for hydrological simulations in complex tropical basins. Once validated, the model output was used to generate monthly and annual dependable flow values, specifically, Q_{80} , which represents the stream discharge exceeded 80% of the time during the observation period. Determination of Q_{80} employed the Weibull plotting position formula, which orders discharge records statistically to identify the flow level with the prescribed reliability.

The resulting dependable yield was critical for downstream analyses: it was integrated into annual and seasonal water supply and demand balance assessments, in which modeled water availability was compared with spatially and temporally disaggregated WF requirements for crops, livestock, and population centers. Overlaying dependable flow data with WF estimates enabled the identification of periods of deficit months or seasons where supply consistently fell short of aggregated demands, thereby informing scenario development for water management interventions and the design of adaptive measures to mitigate seasonal or chronic water stress. This hydrological modelling approach provided a robust, data-driven foundation for evaluating both the sustainability of current water use and the potential impacts of alternative water management policies within the study watersheds, supporting evidence-based decision-making at the intersection of water resources, agriculture, and rural livelihoods.

2.6 Spatial analysis

Spatial data analysis for this study was performed using ArcGIS Pro 3.2, allowing for the systematic integration of both field-based observations and a suite of secondary geospatial datasets to spatialize WF results and effectively identify critical hotspots across the study watersheds. The process began with land cover mapping generated from high-resolution Sentinel-2 satellite imagery (10 m resolution), which was classified into crop-specific categories to delineate agricultural land uses and production zones. This detailed classification underpinned the disaggregation of WF data by crop and production system [12, 20, 21].

Climatic surfaces for rainfall and ET were constructed by interpolating station-based observations via the Inverse Distance Weighting (IDW) technique, ensuring a smooth, continuous surface that reflects spatial heterogeneity in climate drivers relevant to WF calculations. These climatic layers, together with soil maps (at a scale of 1:100,000) and topographic data from the Shuttle Radar Topography Mission (SRTM), were used to parameterize key hydrological variables such as infiltration capacity and runoff coefficients, further increasing the spatial precision of WF assessments.

For each agricultural commodity and WF type (blue, green, and grey), raster layers were produced by spatially linking calculated tabular WF values to corresponding crop production zones. This rasterization enabled nuanced mapping and facilitated the next stage: hotspot detection. Hotspots of

concentrated WF were identified using Kernel Density Estimation (KDE), with a 5 km search radius employed to locate clusters with particularly high WF intensity. The KDE results highlighted priority areas where water management interventions would be most impactful.

To contextualize the spatial WF patterns, overlay analyses were executed using drought vulnerability indices based on the Standardized Precipitation Index (SPI), existing irrigation command area boundaries, and relevant administrative units. This integrative approach enabled the prioritisation of management responses in zones that simultaneously exhibited high WF, pronounced water scarcity risk, or strategic agricultural value. All spatial datasets and analytical results were standardized and projected to WGS 1984 UTM Zone 46N, providing a consistent geospatial reference framework for further analysis, visualization, and policy reporting [22, 23]. This geospatial analysis framework underpinned the identification of intervention priorities and informed the development of spatially targeted strategies for sustainable water resource management in Aceh's agricultural sector.

3. RESULTS AND DISCUSSION

The present study delivers an integrated, multi-scale assessment of water use dynamics in two of Aceh Province's most strategic watersheds, DAS Krueng Aceh and DAS Jambo Aye, by combining production and consumption-based WF accounting, hydrological modelling, and spatial hotspot analysis. Using the standardized methodology of the WFN [10, 24], disaggregating water use into blue water from surface water and groundwater, green rainwater stored in the soil, and grey assimilative capacity for pollutant components, the analysis captures not only the volumes of water embedded in major agricultural commodities but also their temporal variability and spatial concentration. The approach is comprehensive, merging field monitoring data (river discharge, microclimate, soil moisture, water quality) with secondary statistics (BPS Susenas consumption surveys, land use, and production data) and geospatial processing in ArcGIS to yield an empirically grounded picture of water demand and stress across both basins.

From a volumetric standpoint, results confirm that agriculture is by far the dominant consumer of freshwater in both watersheds, with food-related WF dwarfing non-food uses. In Krueng Aceh, total consumption-based WF in 2015 reached 378.91 million $\text{m}^3\cdot\text{year}^{-1}$, of which an overwhelming 94.68% was attributed to food and only 5.32% to non-food goods and services. Average per capita WF was measured at 608.27 $\text{m}^3\cdot\text{year}^{-1}$ in rural areas and 740.77 $\text{m}^3\cdot\text{year}^{-1}$ in urban areas, values below the global mean of $\sim 1,240 \text{ m}^3\cdot\text{year}^{-1}$, but still significant in absolute terms due to the basin's population size $\sim 568,400$ at the time of study. Similarly, in Jambo Aye, 2023 WF estimates totalled around 161.62 million $\text{m}^3\cdot\text{year}^{-1}$, with plant-based foods contributing 144.06 million $\text{m}^3\cdot\text{year}^{-1}$ (89.1%) and animal-based foods 17.56 million $\text{m}^3\cdot\text{year}^{-1}$ (10.9%). The dominance of food WF in both basins substantiates earlier provincial-level findings that agricultural cropping and dietary patterns, rather than industrial or domestic non-food consumption, are the primary vectors of water demand in Aceh.

Seasonal hydrological modelling reinforces the conclusion that temporal mismatches between water availability and demand are a critical pressure point. In Krueng Aceh, 21-year

Mock model simulations show dependable flows (Q_{80}) ranging from a high of $46.35 \text{ m}^3 \cdot \text{s}^{-1}$ in November to a low of just $3.56 \text{ m}^3/\text{s}$ in July. When these supply curves are compared to monthly WF-derived demand profiles, a persistent and pronounced deficit emerges from February through September, comprising up to seven consecutive months where consumption requirements exceed Q_{80} availability. Conversely, the wet months of October to January yield a surplus, which underscores an untapped opportunity for storage, managed aquifer recharge, or seasonal reallocation. While Jambo Aye was not modelled hydrologically in this iteration, stakeholders reported irrigation shortages during late dry season months, together with SPI-based drought vulnerability mapping, suggest similar seasonal stress patterns, particularly in its intensive rice-growing lowlands.

Commodity level disaggregation further exposes the structural drivers of basin water stress. In both watersheds, irrigated paddy rice is the single largest WF contributor: in Krueng Aceh, it accounts for roughly 40-50% of top crop food WF (rice), depending on the subpopulation, while in Jambo Aye it represents $92.03 \text{ million m}^3 \cdot \text{year}^{-1}$ or 63.9% of plant-based food WF. This prominence stems from rice's blue water intensity under continuous flooding regimes, coupled with its centrality in local diets. Beyond rice, other high water demand plant commodities in Jambo Aye include coconut ($11.32 \text{ million m}^3 \cdot \text{year}^{-1}$) and soy-based processed foods (tempe: $11.25 \text{ million m}^3 \cdot \text{year}^{-1}$; tofu: $7.86 \text{ million m}^3 \cdot \text{year}^{-1}$), whose elevated total WF is primarily driven by the high VWC of their soybean inputs, which represents a substantial blue and green WF from cultivation. The processing stage also generates organic-rich wastewater that, in principle, would contribute to grey WF through effluent dilution requirements; however, because wastewater pollutant-load data for the processing stage were not collected in this study, the grey WF component for tempe and tofu has been estimated from soybean cultivation agrochemical runoff only, following standard WFN methodology. The elevated WF of these commodities should therefore be understood primarily in terms of cultivation-related blue and green water use. Horticultural crops such as coffee, chillies, leafy greens, and melons also contribute sizeable volumes, particularly in districts with commercial market linkages. Animal products add a smaller proportion of the total WF by volume but exhibit much higher per-unit water intensities. Chicken meat and eggs dominate this category, reflecting the embedded water in feed grain production.

Spatial hotspot analysis pinpoints geographic clustering of high WF demand: in Krueng Aceh, peri-urban irrigated rice zones around Aceh Besar and Banda Aceh score highest in KDE; in Jambo Aye, Aceh Timur's eastern floodplain concentrates plant WFs (rice, coconut), while Bener Meriah's highlands are prominent for animal WFs (poultry, eggs). When overlaid with drought risk indices (SPI) and irrigation command boundaries, these clusters coincide with zones of recurrent seasonal water shortages, indicating priority intervention areas where efficiency gains or cropping pattern shifts could yield disproportionate benefits.

An important methodological consideration in interpreting the cross-basin comparison is the use of different reference years: 2015 for Krueng Aceh and 2023 for Jambo Aye. To assess the potential influence of this temporal mismatch on the structural conclusions drawn, an uncertainty analysis was conducted focusing on the three main channels through which inter-annual change could affect WF composition: (1) shifts in

per capita consumption patterns, (2) changes in cropping area and yield, and (3) inter-annual climate variability.

Regarding consumption patterns, BPS Susenas provincial data for Aceh indicate that the share of calories derived from rice remained between 55-62% across both reference years, and the ratio of plant-to-animal food WF stayed within 88-91%, confirming that no structural dietary transition occurred during this period. Regarding agricultural systems, the dominance of continuous flooding paddy in both basins is corroborated by district agriculture office records for 2015, 2019, and 2023; no large-scale adoption of water-saving irrigation techniques like alternate wetting and drying (AWD) or system of rice intensification (SRI) was documented at the basin scale during this interval.

Regarding climate, the 21-year VWC baseline (1995-2015) effectively smooths year-to-year climate variability, so the commodity-level water intensities applied in both basins are insensitive to whether the consumption reference year was 2015 or 2023. Based on this evidence, the authors estimate that inter-annual structural uncertainty in WF composition is low (within ± 5 percentage points for the rice share and within ± 2 percentage points for the plant to animal ratio), and the qualitative conclusions of the cross-basin structural comparison are considered robust. The absolute volumetric totals, however, should be interpreted with caution and are not directly compared between basins in this study. Future research should prioritise constructing a contemporaneous (2023) consumption dataset for Krueng Aceh to eliminate this residual uncertainty and enable a fully harmonised comparison.

The cross-basin comparison thus reveals several commonalities and distinctions. Commonalities include (i) heavy dependence on one or two blue water-intensive staple crops, (ii) seasonal water deficits coinciding with peak irrigation demand, (iii) concentration of WF in identifiable geographic hotspots, and (iv) a persistent gap between technical water availability and management/planning integration. Differences lie in commodity mix (e.g., higher prevalence of processed soy foods and coconuts in Jambo Aye, more horticultural grey WF in Krueng Aceh), degree of measured seasonal deficit (explicit modelling for Krueng Aceh vs. inferred patterns in Jambo Aye), and the scale of virtual water exports embedded in commodity trade flows. The latter is particularly notable in Aceh Timur and Bener Meriah, where production surpluses of high WF commodities are shipped out-of-basin, effectively exporting scarce local water resources without an explicit governance framework.

In synthesis, the combined empirical WF accounting, seasonal water balance modelling, and spatial analysis converge on a set of critical management insights: (1) without reform, paddy irrigation will remain the primary lever for reducing basin-scale blue WF; (2) seasonal storage and allocation systems must be developed to bridge the wet-dry mismatch; (3) diversification toward lower-WF crops and improved post-harvest water use efficiency could moderate demand without undermining food security; and (4) spatial targeting of interventions in WF, drought overlap zones will maximize impact. These findings not only demonstrate the value of WF as a decision-support indicator for IWRM under Aceh's 2020-2045 master plan, but also highlight the interdependence of agricultural planning, climate variability, and socio-economic drivers in shaping future water security across the province.

3.1 Water footprint in the Krueng Aceh watershed

The distribution of total WF between rural and urban sectors is noteworthy. As shown in Table 1, rural communities account for 193.49 million m³·year⁻¹ (51.06% of the total WF), while urban communities account for 185.42 million m³·year⁻¹ (48.94%). This reflects the larger rural population base, despite lower per capita WF compared to urban residents. In practical terms, the rural sector's absolute dominance is less a function of "wastage" and more a reflection of population size and the persistent water intensity of agricultural livelihoods. In contrast, the higher urban per capita WF is largely driven by greater consumption of animal-derived foods, processed food products, and other goods with higher embedded VWC, which aligns with global patterns of dietary transition in more urbanized settings.

Table 1. WF per capita and total WF consumption, Krueng Aceh

Population Type	WF per Capita (m ³ ·year ⁻¹)	Total WF (m ³ ·year ⁻¹)	% of Total
Rural	608.27	193,489,129	51.06
Urban	740.77	185,417,526	48.94
Total	-	378,906,655	100

Note: WF: Water footprint

The assessment of WF in the Krueng Aceh watershed, based on integrated field measurements and statistical data analysis, reveals distinct patterns of water consumption between rural and urban populations. The calculated average per capita WF in 2015 was 608.27 m³·year⁻¹ for rural residents and 740.77 m³·year⁻¹ for urban residents. Both figures are substantially lower than the widely reported global per capita WF average of approximately 1,240 m³·year⁻¹ [14, 20, 25, 26], indicating that on an individual basis, residents of the Krueng Aceh basin exert a comparatively smaller direct demand on freshwater resources than the global mean. These lower values may be partially attributed to dietary composition, with rice accounting for a significant proportion of caloric intake, and relatively limited consumption of high WF commodities such as beef, as well as differences in lifestyle and industrial activity compared to high-income, high-consumption countries.

However, this apparent efficiency at the per capita level is offset by the absolute volumetric pressure exerted on the basin's hydrological system. Krueng Aceh DAS supports a population of 568,401 people based on the 2015 census, spread fairly evenly between rural (318,098 people) and urban (250,303 people) areas. When annual per capita WF is scaled to this population, total WF demand reaches 378.91 million m³·year⁻¹. This volume is significant within the context of the basin's seasonal flow regime and its existing vulnerability to dry-season water deficits. Furthermore, the watershed's agricultural profile, dominated by irrigation-dependent paddy rice agriculture, amplifies the pressure on blue water resources during the dry months, even if aggregate per capita indicators appear modest.

A breakdown of WF composition underscores the overwhelming dominance of water use for food production and consumption of the total WF in 2015, 358.73 million m³·year⁻¹, approximately 94.68% of the total WF, was associated with food, while non-food related WF accounted for only 20.17 million m³·year⁻¹ (5.32%). This distribution aligns with the structural role of agriculture in the regional economy and daily life: the basin is a primary rice

granary for Aceh Province, and most food production here is water-intensive. Such a skewed distribution also implies that any substantial reductions in total WF will necessarily depend on interventions within the food system, ranging from irrigation efficiency measures and crop diversification to behavioral shifts in consumption patterns.

This pattern mirrors observations in other agrarian watersheds in Southeast Asia, where a relatively moderate per capita WF can mask high absolute withdrawals and ecological stress due to seasonal concentration of demand and predominance of blue water reliance. In the case of Krueng Aceh, the supply-demand imbalance is exacerbated during the dry season, when irrigation withdrawals for paddy fields compete directly with domestic and ecological water needs. Consequently, even with per capita figures below the global average, the seasonal water scarcity risk remains pronounced, justifying deeper integration of WF indicators into basin-scale water allocation and agricultural planning. In summary, the Krueng Aceh WF profile reveals a dual reality: (1) Efficiency on paper, individuals consume less water than the global mean; (2) Hydrological stress in practice, aggregation across a large population and an irrigation-dependent sector produces a total annual demand approaching 379 million m³, concentrated heavily in food-related water use. This duality underscores the necessity of moving beyond per capita metrics and adopting a whole basin, seasonally explicit WF perspective to guide sustainable water governance.

WF analysis clearly highlights where technical interventions, such as irrigation efficiency, post-harvest processing water use reduction, policy measures, crop diversification, and trade management, can reduce pressure on Aceh's limited and seasonally skewed water resources. The spatial to temporal integration of WF with hydrological modelling provides a strong decision-support basis for targeted, basin-specific water performance, as shown in Table 2.

Table 2. Comparative WF key metrics, Krueng Aceh vs. Jambo Aye

Metric	Krueng Aceh	Jambo Aye
Year of data	2015	2023
Total WF (million m ³)	378.91	161.62
Per capita WF rural (m ³ ·capita ⁻¹ ·year ⁻¹)	608.27	-
Per capita WF urban (m ³ ·capita ⁻¹ ·year ⁻¹)	740.77	-
Top crop	Rice (~40–50% WF)	Rice (63.9% WF)
Top animal product	Chicken meat/eggs	Chicken meat
Peak deficit months	Feb–Sept	Not modelled
Q80 min (m ³ /s)	3.56 (July)	-

Note: WF: Water footprint

3.2 Water footprint in the Jambo Aye watershed

A thorough disaggregation of the overall WF in Jambo Aye reveals that the majority of both rural and urban WF is embedded in the production and consumption of staple food commodities, with a highly uneven distribution among food groups and individual products. Drawing from detailed tabular results [2] and the articles [2, 10, 11, 23], as well as virtual water coefficients, the data illuminate which crops and animal products are driving water demand and identify leverage

points for sustainable water management. Of the total WF in Jambo Aye (161.62 million m³·year⁻¹ in 2023), the top crop is rice (57%), while the top animal product is chicken meat. Within the food WF, plant-based foods are the dominant component, led overwhelmingly by irrigated paddy rice; animal-based foods, chiefly poultry and eggs, represent a smaller but water-intensive significant share. A comparable commodity-group breakdown for the Jambo Aye watershed (2023) is presented for cross-reference in Table 3.

The most salient pattern is that irrigated paddy rice is the single largest contributor to total food-related WF in both subpopulations. This dominance is due to the combination of high per capita rice consumption, the water-intensive nature of flood irrigated paddy, and the reliance on blue water withdrawals during dry months. The VWC for locally grown rice is especially large compared to secondary crops or tubers. Thus, rice production stands at the nexus of both water quantity (blue WF) and seasonal scarcity risks in the basin, especially considering the synchronous planting cycles typical of the region.

Beyond rice, significant shares of WF are distributed among other plant-based staples such as maize, tubers, vegetables, oil

crops, particularly coconut, and horticultural products. While each of these generally carries a lower VWC than paddy per kilogram of output, their combined effect is nontrivial due to large overall consumption volumes. Animal-derived foods, chiefly chicken meat and eggs, complemented in urban zones by smaller amounts of beef and processed dairy, represent a much smaller share in volume than plant foods but display a higher WF per kilogram consumed. Figure 3 illustrates the per capita consumption levels (kg·capita⁻¹·yr⁻¹) of dominant animal-based foods in the Jambo Aye watershed, from which WF values were subsequently derived using VWC coefficients; it should be read as a consumption profile rather than a direct WF comparison.

Table 3. Total WF consumption by commodity group, Jambo Aye watershed (2023)

Commodity Group	WF (m ³ ·year ⁻¹)	Total (%)
Plant-based	144,059,624.84	89.1
Animal-based	17,562,308.07	10.9
Total	161,621,932.91	100

Note: WF: Water Footprint

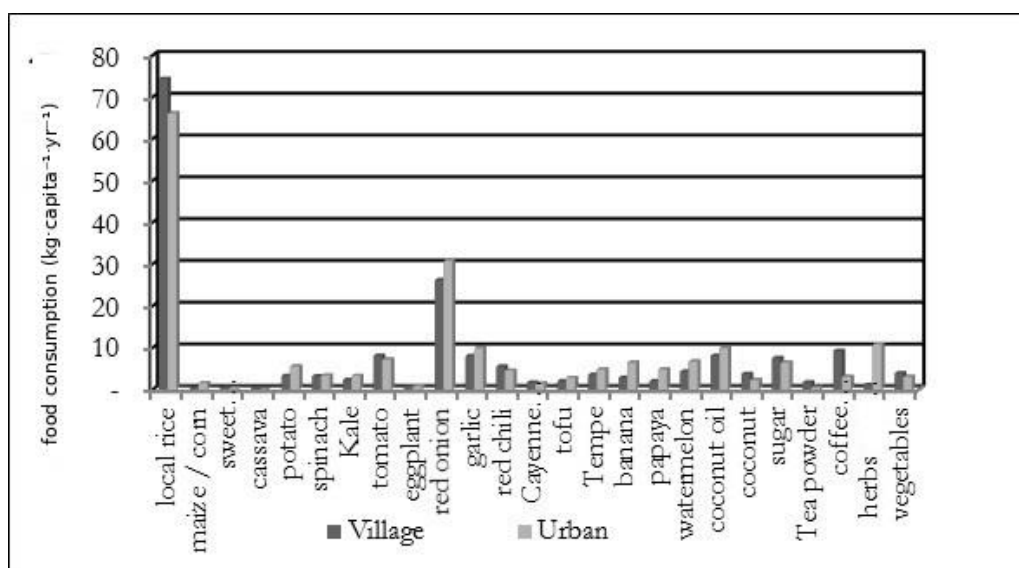


Figure 3. Per capita consumption of selected animal-source foods in the Jambo Aye watershed (kg·capita⁻¹·yr⁻¹)

This is due to the indirect and virtual water needs embodied in fodder production, drinking water, and operational on-farm water use. For example, the WF of chicken eggs in rural and urban food baskets is about 3.5% of total food WF, far outpacing beef or fresh fish, which are less commonly consumed in the basin due to cost and cultural preferences. Notably, non-fish animal protein consumption is higher in urban settings, which further elevates the urban per capita WF figure relative to rural residents.

Grey WF, defined as the volume of freshwater required to assimilate pollutant loads from fertilizer and pesticide application, emerges as a substantial component, particularly in rice and horticultural crop zones, where chemical inputs are heaviest. This finding highlights that, while grey WF may not form the majority share, its spatial concentration aligns with irrigated paddy blocks and commercial vegetable areas on the peri-urban fringe. This underlines water quality risks, not only for downstream users but also for aquatic ecosystem integrity.

Other commodities, such as coffee, coconut, various beans, and horticultural products (chili, tomato, leafy greens), while

contributing less in absolute WF than rice, can nonetheless represent significant local hotspots due to intensive input use or regional clustering. Their VWC varies according to cropping system, rainfed vs. irrigated, but the introduction of water-saving practices could yield marked benefits here as well. Rice-focused food systems in both rural and urban Jambo Aye anchor the basin's high absolute water demand and amplify dry-season scarcity risk, especially under traditional, water-intensive irrigation. Animal proteins, particularly poultry and eggs, raise WF per capita in urban settings and represent an increasing share of WF as urban diets shift. Grey WF's spatial pattern overlaps with paddy and vegetable belts near urban centers, pointing to an urgent need for nutrient management and integrated water quality planning.

Any substantial reduction in basin-wide WF will require simultaneously: (a) upgrading irrigation efficiency in rice production; (b) promoting diversification to less water-intensive staples and local vegetables; (c) supporting best management practices (BMPs) to minimize agrochemical runoff. The commodity breakdown for Jambo Aye paints a

clear picture: sustainable water management efforts must prioritize irrigation innovation in rice, targeted nutrient management in high-input agricultural zones, and the gradual inclusion of lower-WF crops and protein sources in local diets to reduce basin-scale stress. This approach, supported by the evidence base from both consumption and production perspectives, is crucial for aligning agricultural productivity with long-term hydrological resilience in Aceh.

The analysis of WF in the Jambo Aye River Basin, based on the work of studies [5, 6, 27], provides a comprehensive depiction of how water resources are utilized for both plant-based and animal-based food consumption across five regencies: Aceh Timur, Aceh Tengah, Aceh Utara, Gayo Lues, and Bener Meriah. Given the basin's vast size, 462,062 ha, and its ecological and economic significance, ranging from upland

Leuser Ecosystem forests to lowland floodplains, understanding WF distribution is an important and crucial aspect for strategic water management.

The total estimated WF for 2023 reaches 161.62 million $m^3 \cdot year^{-1}$: Plant-based foods (Rice, Tempe, and Tofu): 111.14 million m^3 (87.7% of total WF), as shown in Table 4, while total animal-based commodities reach 17.56 million m^3 as presented in Table 5. This heavy skew toward plant-based WF reflects the dietary dominance of rice and other staple crops, supported by extensive irrigated agriculture in the lowlands. While animal products contribute a much smaller total volume, they have far higher WF intensity per unit mass, which means shifts toward higher meat and egg consumption could rapidly increase total basin WF.

Table 4. Top 5 plant-based commodities by WF

Rank	Commodity	WF Volume ($m^3 \cdot year^{-1}$)	Main WF Driver
1	Rice (ketan)	92,033,628	Flood irrigation (high blue WF)
2	Coconut	11,316,484	Long maturation, high evapotranspiration
3	Tempe	11,249,993	High VWC from soybean cultivation (blue/green WF); processing effluent may add grey WF if load data available
4	Tofu	7,861,679	High VWC from soybean cultivation (blue/green WF); processing similar to tempe
5	Coffee (ground)	4,196,053	Long crop cycle, substantial green WF from cultivation; wet processing may contribute to grey WF if effluent load data are available

Note: WF: Water footprint; VWC: Virtual water content

Table 5. Top 4 animal-based commodities by WF

Rank	Product	WF Volume ($m^3 \cdot year^{-1}$)	Notes
1	Chicken meat	10,695,372	Dominated by water embedded in feed crops
2	Eggs (chicken)	5,597,286	Lengthy laying cycles, intensive feed demand
3	Beef	1,138,075	Low total due to low consumption, but very high unit WF
4	Duck eggs	131,575	Often from low-input, free-range systems

Note: WF: Water footprint

This pronounced skew towards plant-based WF is consistent with the dietary structure and agricultural production profiles of the Jambo Aye Basin, where rice, coconut, and other crops are staples both for local consumption and for trade with surrounding markets. The dominance of plant-based WF is not unexpected; globally, staple crops, particularly irrigated cereals, often account for the majority of consumptive water use in agrarian economies. In the Jambo Aye context, the findings reflect two reinforcing factors: Dietary dominance of high WF Crops like Rice, which alone represents more than half of the plant-based WF, is consumed in large quantities across all socio-economic strata, and is cultivated predominantly under water-intensive continuous flooding systems. Extensive irrigated lowland agriculture, much of the basin's prime agricultural land is devoted to irrigated paddy, with water supplied either by gravity-fed surface schemes or pumped groundwater, particularly in Aceh Timur and Aceh Utara regencies.

While the volume share of animal products is numerically smaller, their WF intensity per unit mass is substantially higher than that of most crops. This means that even small shifts in dietary preference towards meat and eggs could trigger significant increases in the basin's total WF. For example, substituting a portion of rice calories with beef calories, despite beef's currently low consumption levels, would multiply the embedded water demand several-fold because of the high VWC of livestock products, especially those dependent on grain-based feed [4, 12].

Within the animal-based food category, poultry products, specifically chicken meat and eggs, are the dominant contributors to the total animal WF of the Jambo Aye watershed. This dominance is primarily due to their feed conversion water intensity, meaning that a substantial proportion of their WF is indirect, embedded in the production of feed crops such as irrigated maize and soybeans. The cultivation of these feed ingredients itself consumes significant blue and green water resources, particularly under irrigated systems, and may also generate notable grey WF from nutrient runoff and pesticide residues. Consequently, even though poultry is often considered more water-efficient than ruminant livestock per kilogram of protein produced, the high production volumes and reliance on feed crops with elevated VWC significantly amplify their total WF at the basin scale.

Beef, in contrast, accounts for a much smaller share of the Jambo Aye watershed's total WF volume. This is largely attributable to low per capita consumption observed in the study area, which keeps aggregate water use modest despite beef's well-documented per kilogram WF being among the highest of any food commodity worldwide, often exceeding 15,000 L/kg when all water sources are accounted for [20, 21]. In this context, most cattle in the basin are raised in smallholder or semi-extensive systems utilising communal grazing, which can reduce dependence on irrigated feed. Nonetheless, any significant rise in beef demand could disproportionately escalate total WF because of its inherently

high water cost per unit of edible output and its long production cycle.

Duck eggs represent the lowest WF among the animal products assessed. This relatively small footprint is partly explained by the small-scale, integrated production systems common in the Jambo Aye basin, where ducks are often herded in post-harvest rice fields or wetlands. Such systems allow ducks to forage on residual grains, aquatic plants, and invertebrates, thereby drastically reducing the need for irrigated feed crops and additional managed water inputs. While ducks inhabit aquatic environments, much of the water in these systems is ambient environmental water rather than consumptive blue water, and thus is not fully counted in WF assessments unless it is actively diverted or managed for production purposes [9, 17].

This ecological synergy between rice farming and duck rearing exemplifies a form of water-smart integrated agriculture capable of supplying nutrient-rich animal protein with minimal additional consumptive water use.

From a resource management perspective, these findings suggest that poultry products, though more efficient per kilogram of protein than beef, require careful attention to feed sourcing, with potential WF reductions achievable through local feed production utilizing low-WF crops or byproducts. Maintaining low beef consumption levels is beneficial for avoiding disproportionate increases in total basin WF; any growth in this sector should be paired with sustainable grazing management and improved feed efficiency. Traditional rice-duck integration systems exemplify a nature-based solution for animal protein production in water-limited contexts, meriting promotion and technical support to preserve their low WF advantage. Overall, the Jambo Aye animal-based WF profile underscores the importance of considering both absolute production volumes and per unit water intensities in developing sustainable food and water strategies for the basin. Shifts in dietary preferences, feed supply chains, or production systems could quickly alter the balance, with implications for both local food security and watershed hydrology.

3.3 Spatial and policy implications

The comparative analysis between the Krueng Aceh and Jambo Aye watersheds yields a number of important cross-basin insights that reveal both structural similarities and critical differences in how water is used, embedded, and traded through agricultural production. Integrating the WF calculations, broken down into blue, green, and grey components, with spatial and hydrological modelling provides a powerful lens through which to identify shared challenges and basin-specific management needs.

A consistent and compelling finding across both basins is that irrigated rice production is the single most significant driver of blue WF. In each watershed, rice alone accounts for between 40-57% of total food-related WF, with production heavily dependent on traditional continuous flooding irrigation systems. This reliance on season-long inundation not only inflates consumptive blue water use through evaporation and seepage losses but also intensifies dry-season competition between agriculture, domestic supply, and ecological flow requirements. The alignment of this pattern in both basins underscores rice as the critical leverage point for blue water savings.

Another clear pattern involves processing-based products, particularly soy-based foods like tempe and tofu, and coffee.

Though produced and consumed in lower volumes than staples like rice, these commodities exhibit disproportionately high total WF values relative to their harvested weight. This is because WF accounting encompasses not only cultivation, often with significant blue and green components from irrigated soybean production, but also the indirect water embedded in their raw inputs. Regarding grey WF: wet processing of soy products and coffee does generate organic-rich wastewater, and if effluent pollutant-load data and the relevant water quality standards are available, this processing stage can legitimately contribute to a grey WF estimate via the standard dilution formula. However, in the absence of measured wastewater concentration data for the processing stage in this study, grey WF for these commodities was calculated from agrochemical runoff during soybean and coffee cultivation only. The discussion of their large total WF should therefore primarily reference the blue and green WF from high-VWC soybean cultivation, and not attribute the grey WF directly to processing operations.

For animal products, while the absolute volumetric contribution to basin WF is far lower than that of plant foods, the per-kilogram WF is markedly higher. Poultry meat and eggs dominate the animal WF profile in both basins due to the substantial indirect water demand embedded in feed production, which relies on irrigated maize and soybeans. Even with low beef consumption in these basins, the per-unit WF of ruminant products remains among the highest for any food, meaning that dietary shifts toward more beef could sharply elevate total water demand.

The diagnostic results align closely with the goals of the Aceh Water Resources Master Plan (2020-2045), which calls for IWRM that is both ecologically and economically balanced. This convergence suggests that WF assessment should be embedded as a core operational tool for water governance in Aceh's agricultural sector. Specifically, both basins would benefit from transitioning away from continuous flooding to AWD or SRI methods. Field trials indicate potential blue WF reductions of 20-40% without yield penalties. Complementary infrastructure measures, such as lining canals to reduce conveyance losses, could amplify these savings. Crop diversification toward low WF species, promoting and incentivizing the cultivation of lower water demand crops such as cassava, sweet potato, or certain pulses, can reduce pressure on scarce water during peak deficit months and enhance resilience to climate-induced variability.

Demand-side measures, awareness campaigns, and targeted education could shift consumption patterns toward lower WF foods, reducing aggregate demand. This is especially relevant for high-WF animal products or processing-intensive foods, where small reductions in consumption generate disproportionately large water savings. Hydrological modelling has shown that seasonal deficits in water availability coincide with the projected intensification of dry-season droughts under climate change scenarios. This calls for the development of storage infrastructure (dams, on-farm reservoirs) and conjunctive use systems that integrate surface and groundwater to buffer seasonal imbalances.

Both basins act as net exporters of virtual water through the trade of high WF commodities like rice, coconut, and coffee. While economically beneficial in the short term, this effectively represents a net loss of local water resources. Policy frameworks should assess whether current trade patterns are compatible with long-term water security goals, particularly in light of population growth and climate

variability. Moreover, incorporating spatially explicit WF hotspot mapping into annual water allocation planning can ensure that interventions are targeted where water savings yield the highest returns, both in volumetric and socio-economic terms. This is particularly critical for avoiding maladaptation, such as displacing rice production from one water-scarce sub-basin to another without net water savings.

By systematically embedding WF analysis into Aceh's IWRM framework linked to rural development, trade policy, and climate adaptation planning, the province has the opportunity to align food security with water security, ensuring that agricultural growth does not come at the expense of long-term hydrological stability.

This dominance stems from rice's blue water intensity under continuous flooding regimes, coupled with its centrality in local diets. The persistence of traditional flooding, despite its high water demand, is driven by a combination of factors: entrenched agricultural practices and knowledge systems that prioritize perceived yield security and pest control; limited access to capital and technical knowledge for adopting water-saving technologies like AWD; and irrigation infrastructure designed for basin-wide flooding rather than controlled distribution. This creates a significant lock-in effect, where shifting away from flooding is perceived as both technically and economically risky by farmers [11, 21].

Beyond rice, other high water demand plant commodities in Jambo Aye include coconut (11.32 million $\text{m}^3 \cdot \text{year}^{-1}$) and soy-based processed foods (tempe: 11.25 million $\text{m}^3 \cdot \text{year}^{-1}$; tofu: 7.86 million $\text{m}^3 \cdot \text{year}^{-1}$), whose elevated total WF is primarily driven by the high VWC of their soybean inputs, which represents a substantial blue and green WF from cultivation. The processing stage also generates organic-rich wastewater that, in principle, would contribute to grey WF through effluent dilution requirements; however, because wastewater pollutant-load data for the processing stage were not collected in this study, the grey WF component for tempe and tofu has been estimated from soybean cultivation agrochemical runoff only, following standard WFN methodology. The elevated WF of these commodities should therefore be understood primarily in terms of cultivation-related blue and green water use, not processing water consumption per se. Horticultural crops such as coffee, chillies, leafy greens, and melons also contribute sizeable volumes, particularly in districts with commercial market linkages. Animal products add a smaller proportion of the total WF by volume but exhibit much higher per-unit water intensities. Chicken meat and eggs dominate this category, reflecting the embedded water in feed grain production.

Spatial hotspot analysis pinpoints geographic clustering of high WF demand: in Krueng Aceh, peri-urban irrigated rice zones around Aceh Besar and Banda Aceh score highest in KDE; in Jambo Aye, Aceh Timur's eastern floodplain concentrates plant WFs (rice, coconut), while Bener Meriah's highlands are prominent for animal WFs (poultry, eggs).

A critical finding from the spatial analysis is the strong correlation between grey WF hotspots and specific agro-ecological conditions. These hotspots, identified in intensive paddy and vegetable zones, are not merely a function of crop choice but are intrinsically linked to local fertilization practices and soil types. In lowland clay-rich paddy soils, which are dominant in the floodplains of Aceh Timur and Krueng Aceh, high rates of nitrogen fertilizer application, common in the pursuit of high-yield rice varieties, coupled with poor nutrient management and continuous flooding, lead

to significant leaching and runoff.

The fine texture of these soils can limit initial infiltration but, under saturated conditions, promotes the lateral movement of nutrient water into drainage canals. Conversely, in upland vegetable zones (parts of Bener Meriah), grey WF hotspots are associated with coarse-textured, sandy loam soils. These soils have high permeability, facilitating the rapid leaching of soluble nitrates and pesticides from the frequent and intensive fertilizer and pesticide applications typical of commercial vegetable production. Thus, the spatial pattern of grey WF is a direct diagnostic map of areas where current nutrient management practices are mismatched with hydrological and soil conditions, highlighting a priority for implementing targeted BMPs such as controlled-release fertilizers, split application timing, and improved irrigation scheduling to reduce pollutant loads.

4. CONCLUSION

This study demonstrates that the integrated application of WF assessment, hydrological modelling, and geospatial analysis provides a powerful and novel framework for diagnosing and addressing water sustainability challenges in agrarian systems. By moving beyond volumetric accounting to link commodity-specific water consumption with seasonal water availability through hydrological modelling and precise geographic location with spatial analysis, this approach yields a multidimensional diagnostic tool. It not only quantifies pressure but identifies where and when interventions, such as upgrading irrigation in rice-dominated hotspots or managing nutrients in vulnerable soils, will be most effective for reconciling agricultural productivity with hydrological resilience.

The findings confirm that irrigated paddy rice is the cornerstone of water demand in Aceh's food system, with its high blue WF amplified by traditional flooding practices rooted in socio-technical lock-ins. The spatial integration of results reveals that grey WF hotspots are not random but are intrinsically linked to the interplay of intensive fertilizer use and specific soil hydrology, offering a clear target for precision agronomy. Furthermore, the distinction between rural and urban WF profiles underscores that water governance must engage with consumption patterns and dietary transitions, not just production-side efficiency.

This study has several limitations that point to valuable avenues for future work. First, while it analyses historical climate data, it does not project WF dynamics under future climate change scenarios, which are critical for long-term resilience planning in Aceh. Second, the commodity focus, though covering key products, is not exhaustive; minor crops and agroforestry systems may have important roles in diversified, water-smart landscapes. Third, the analysis of socio-economic drivers, such as the precise barriers to adopting water-saving irrigation or the economic incentives influencing crop choice, was qualitative and could be deepened through structured socio-economic modelling.

Fourth, the use of different consumption reference years (2015 for Krueng Aceh; 2023 for Jambo Aye) introduces a temporal mismatch that constrains direct volumetric comparison between watersheds. Although the uncertainty analysis presented in Section 3.3 demonstrates that the structural WF composition is stable across this period—supported by consistent dietary patterns in BPS Susenas data,

the continued dominance of continuous flooding irrigation, and a common 21-year climatic VWC baseline, residual uncertainty in absolute volumes cannot be entirely excluded. Constructing a harmonized, contemporaneous dataset for both basins remains a priority for future research. Until such data are available, inter-basin comparisons should be confined to structural (proportional) metrics rather than absolute volumetric totals, as adopted throughout this study.

To build upon this foundation, future research should: (1) incorporate downscaled climate projections into the WF and hydrological models to assess future water stress and adaptation pathways; (2) expand the commodity coverage to include perennial agroforestry systems and evaluate landscape level WF trade-offs; and (3) apply quantitative socio-economic methods, such as farmer adoption surveys or agent-based modelling, to rigorously analyze the behavioral and market drivers behind water use decisions. Additionally, expanding this integrated WF hydrological spatial framework to other major watersheds in Aceh and Sumatra would enable comparative regional analysis and more robust policy generalization.

This presented work operationalizes the WF concept as a practical, integrated decision-support system. By providing spatially explicit, evidence-based insights, it offers an actionable pathway for policymakers and water managers in Aceh to prioritize investments, tailor extension services, and design policies that secure both food and water for future generations.

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