

Beyond Crop Diversification: Six Decades of Agricultural Water Footprint Dynamics in the Western Himalayas

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Abstract

Agricultural water use is central to water-resource planning in water-stressed mountain regions, yet long-run, statistically tested evidence on its drivers is scarce for the Himalayan union territory of Jammu and Kashmir (J&K). This study estimates the green, blue and grey water footprint (WF) of 23 major crops grown in J&K across seven decadal points (1960–61 to 2020–21) using the crop water-footprint-factor method of Mekonnen and Hoekstra (2010, 2011), applied to decadal crop production data compiled from the Directorate of Horticulture, Jammu and Kashmir, and the Digest of Statistics, Government of Jammu and Kashmir. Beyond descriptive accounting, we test the statistical significance of the observed trend using the Mann-Kendall test and the Sen's slope estimator, and we decompose the change in total WF into a production-scale effect and a crop-mix (compositional-shift) effect using a shift-share decomposition. Total agricultural WF rose from 2.35 to 10.29 million m³ (+337.5%) over the six-decade period, a trend confirmed to be monotonic and statistically significant (Mann-Kendall $p = 0.003$; Sen's slope = 126,164 m³ year⁻¹). Green water dominated the total footprint throughout the period (74–83%), with its share rising as the blue- and grey-water shares fell. Contrary to the compositional narrative that a simple accounting exercise would suggest, the decomposition shows the increase to be overwhelmingly (101.5%) attributable to the scale of overall agricultural production growth; the well-documented shift toward apple and walnut cultivation contributes a near-zero net compositional effect (–1.5%) once the corresponding loss of production share by rice and maize is netted out. Supplementary analyses show that just four crops account for approximately 80% of the 2020–21 footprint (Gini = 0.79), and that a cross-validated exponential growth model selected over linear and quadratic alternatives by leave-one-out predictive performance projects total WF to reach approximately 12.5–15.8 million m³ by 2030–2040 on the current trajectory. These findings reframe the region's water-sustainability challenge as one of managing aggregate agricultural water demand growth rather than crop substitution, with direct implications for water-use-efficiency policy in J&K's horticulture-led agricultural growth strategy.

1. Introduction

The water footprint of a product is the volume of freshwater used, directly and indirectly, along its entire production chain, and is conventionally decomposed into a green component (consumption of rainwater stored in the root zone), a blue component (consumption of surface and groundwater) and a grey component (the volume of freshwater required to assimilate pollutant loads to ambient water-quality standards) (Hoekstra & Chapagain, 2007). Applied to a nation or region, the concept reframes water accounting away from simple withdrawal statistics toward consumption embedded in what is actually produced and traded a distinction that matters directly for policy, since withdrawal, consumption and pollution create different kinds of scarcity and call for different interventions (Hoekstra & Chapagain, 2007).

Global freshwater withdrawal has grown roughly seven-fold over the twentieth century (Gleick, 2000), and agriculture remains the dominant user: the Food and Agriculture Organization's most recent global assessment attributes approximately 72% of freshwater withdrawals worldwide to agriculture, compared

with 15% for industry and 13% for the service and domestic sectors (FAO, 2025). A recurring source of confusion in this literature is the conflation of withdrawal, consumption and 'efficiency': water that is withdrawn but not consumptively used often returns to the hydrological system and remains available downstream, so efficiency gains at the field or scheme level do not automatically translate into basin-scale water savings (Perry, 2007). This distinction is one of the underlying motivations for the water footprint framework, and for the present study's attempt to identify what, specifically, is driving observed changes in agricultural water consumption in Jammu and Kashmir (J&K).

J&K's agricultural economy has undergone a substantial structural transformation since the 1960s, moving from a subsistence base of cereals rice, wheat and maize toward temperate horticulture, particularly apple, walnut and other fruit crops grown in the region's high-altitude agro-climatic zones. This shift has been attributed to a combination of government horticulture-promotion schemes initiated from the 1980s onward and market-driven incentives favouring high-value fruit crops over foodgrains (Bazaz & Haq, 2013). J&K's location within the wider Himalayan catchment also means its water resources are part of a system in which climate change is projected to substantially alter snow- and glacier-fed river flows over the coming decades (Immerzeel, van Beek, & Bierkens, 2010), adding a further, independent reason to understand the demand side of the region's water balance with more precision than a simple two-year comparison allows. Because different crops carry very different water footprint factors, and because green, blue and grey water carry different scarcity and policy implications, this cropping-pattern transformation is a natural candidate explanation for any observed change in the region's aggregate agricultural water footprint but whether it is in fact the operative explanation, as opposed to simple growth in the scale of production, has not to our knowledge been formally tested for J&K.

This paper addresses that gap with three specific objectives: (i) to estimate the green, blue and grey water footprint of J&K's major crops at seven decadal points from 1960–61 to 2020–21; (ii) to test whether the observed changes constitute statistically significant monotonic trends, using the non-parametric Mann-Kendall test and the Sen's slope estimator, rather than relying on a simple percentage comparison between two endpoint years; and (iii) to decompose the change in total water footprint into the portion attributable to the scale of overall agricultural production and the portion attributable to compositional shifts across crops, using a shift-share decomposition. In doing so, the paper moves beyond a descriptive accounting exercise toward an explicitly diagnostic one, with the aim of generating policy guidance that targets the actual driver of water footprint growth rather than the most visually striking correlate of it.

2. Literature Review

The concept of virtual water the water embedded in the production of a good or service was introduced to the research agenda through an International Expert Meeting on Virtual Water Trade convened at IHE Delft in 2002 (Hoekstra, 2003), which set out the conceptual foundation later formalised at the national level by Hoekstra and Chapagain (2007). They showed that a country's water footprint is jointly

determined by the volume and composition of consumption, climate, and agricultural water-use practices, and distinguished a country's internal water footprint (domestic resource use) from its external water footprint (water embedded in imports), a framing that underlies the wider virtual-water-trade literature and that later work extended into a comprehensive four-part research agenda: studying virtual water trade and its geopolitics, tracking consumption and production against limited freshwater renewal rates, applying supply-chain thinking to water management, and analysing green water and water pollution within the same accounting framework as blue water (Hoekstra, 2017; Hoekstra, Chapagain, & van Oel, 2017).

Mekonnen and Hoekstra (2010, 2011) extended the concept to a spatially explicit, crop-level global accounting exercise, estimating green, blue and grey water footprints for 126 crops using a grid-based daily soil-water-balance model. At the level of humanity as a whole, Hoekstra and Mekonnen (2012) synthesised these crop-level, livestock, industrial and domestic estimates into a global water footprint of 9,087 billion m³ per year (1996–2005), decomposed as 74% green, 11% blue and 15% grey water, with agricultural production contributing 92% of the total a whole-economy composition that provides a useful external benchmark for the crop-only composition estimated for J&K in this study (Section 5.2). It is this crop-level accounting framework in particular the crop water footprint factors (WFF, expressed in m³ of water per tonne of product) reported in Mekonnen and Hoekstra (2010) that the present study applies to J&K's decadal crop production series.

A separate but related literature cautions against treating water-use 'efficiency' improvements as automatically water-saving at larger spatial scales. Perry (2007) argues that much of the historical debate over irrigation efficiency has failed to distinguish consumptive from non-consumptive water use, leading to policy recommendations that overstate the water savings achievable from on-farm efficiency interventions; this has direct relevance for interpreting the blue-water components estimated in this study, since blue water intensity reductions at the field level do not necessarily reduce basin-scale consumption. Gleick (2000) situates this debate within a broader historical shift in water-resource management from a twentieth-century paradigm centred on supply augmentation (dams, diversions, new sources) toward one that instead asks what combination of demand management, productivity gains and allocation reforms can meet water needs with the resources already committed. The decomposition exercise undertaken in this paper (separating a production-scale effect from a compositional-shift effect) is, in effect, an empirical operationalisation of that same underlying question applied to J&K's crop-water accounts, and is methodologically related to the long-established index decomposition tradition in energy and emissions policy analysis, where separating a scale (activity) effect from a structural (composition) effect is standard practice for identifying which lever policy should target (Ang, 2004).

The water footprint concept has also attracted substantive methodological criticism that this paper's framing should be read against. Wichelns (2010) argues that virtual water and water footprint indicators, while a useful accounting perspective, are not on their own a sufficient criterion for water policy, because they capture only the volume of water embodied in production and not the opportunity cost of that water

in alternative uses, nor the many non-water factors (labour, capital, market access, trade agreements) that actually determine cropping and trade patterns. Chenoweth, Hadjikakou, and Zoumides (2014) extend this critique methodologically, noting that water footprint estimates vary substantially depending on accounting choices (bottom-up versus top-down system boundaries, treatment of effective rainfall, and grey-water dilution assumptions), which can create a false impression of precision. These critiques counsel against over-interpreting the volumetric water footprint estimates in this paper as a complete welfare or scarcity metric in themselves; they are best read, as intended here, as a consistent accounting basis for identifying which components of agricultural change are driving water consumption, to be combined with local information on water availability, economic value and opportunity cost before translating into specific allocation decisions.

For India specifically, Kampman, Hoekstra, and Krol (2008) provide the first comprehensive sub-national water footprint accounting for Indian states, finding substantial inter-state variation driven by climate, cropping pattern and irrigation practice, and establishing the state-level accounting approach that the present study extends to J&K's decadal time series. Verma, Kampman, van der Zaag, and Hoekstra (2009) analyse inter-state virtual water trade in the context of India's National River Linking Program and find that existing trade patterns often exacerbate scarcity in already water-stressed states, driven less by water endowments than by factors such as per-capita gross cropped area and access to secure markets, a reminder that a region's water footprint accounting is only one part of a larger political-economy picture that also includes where the resulting produce is ultimately consumed. Liu, Zehnder, and Yang (2009) further emphasise, at the global level, that green water constitutes the majority of consumptive water use in crop production and is systematically under-represented in water-resource assessments that focus on blue (irrigation) water alone, a finding directly relevant to J&K, where green water is shown below (Section 4.2) to dominate the total agricultural water footprint throughout the study period. For J&K specifically, Bazaz and Haq (2013) document the state's post-1980s agricultural diversification away from traditional foodgrain cultivation toward horticulture, driven jointly by government promotion schemes and market incentives favouring high-value fruit crops. Most directly relevant to the present paper's methodology, Bhat, Lone, Shafiq, and Rather (2019) apply a decomposition model to J&K's own apple production data (1975–2015) and find that the growth in apple production over that period is attributable primarily to an area-expansion effect (65.7%), with smaller contributions from an interaction effect (23.7%) and a yield effect (10.6%). That result is a single-crop, area/yield decomposition, whereas the present study's shift-share decomposition operates across J&K's entire crop portfolio to separate an aggregate production-scale effect from a cross-crop compositional-shift effect in water footprint terms; the two are complementary rather than competing findings, Bhat et al.'s (2019) area-driven apple growth is, in the framework of this paper, fully captured within the aggregate scale effect once apple's rising production share is netted against the cereals' declining share (Section 4.4).

Taken together, this literature establishes both the accounting method applied here (Mekonnen & Hoekstra, 2010, 2011) and two open questions this paper addresses directly: whether the well-documented compositional narrative of J&K's shift toward horticulture (Bazaz & Haq, 2013; Bhat et al.,

2019) is in fact the dominant driver of the region's aggregate water footprint once formally decomposed against the alternative explanation of scale growth, and whether the region's long-run water footprint trend is a statistically defensible finding rather than an artefact of endpoint-year comparison, neither question has, to our knowledge, been addressed for J&K's water footprint specifically. Empirical water footprint studies at the sub-national level within India, and for J&K in particular, remain sparse relative to the volume of global and national-level water footprint literature.

3. Study Area, Data and Methods

3.1 Study area

The study was carried out for the union territory of Jammu and Kashmir (excluding the union territory of Ladakh, which was administratively separated from the composite state of Jammu and Kashmir under the Jammu and Kashmir Reorganisation Act, 2019), located in the northernmost part of the Indian subcontinent, comprising the plains around Jammu to the south and the Kashmir valley to the north. The region covers a geographical area of approximately 42,241 km² and lies approximately between latitudes 32°17' N and 36°58' N and longitudes 73°26' E and 76°23' E. Its temperate-to-alpine agro-climatic gradient supports both cereal cultivation in the valley floor and lowland plains and high-altitude temperate horticulture (apple, walnut, pear, cherry, almond, apricot) in the mid- and upper-elevation zones. Because the decadal production series (Section 3.2) is compiled from bodies that today report for this post-2019 union-territory boundary, the same boundary is used to describe the study area throughout this paper, including for the decadal points that predate the 2019 reorganisation.

3.2 Data

Decadal production data (in tonnes) for 23 major crops cereals, pulses, oilseeds, and fruit crops were compiled for seven time points spanning 1960–61 to 2020–21, from the Directorate of Horticulture, Jammu and Kashmir, and the Digest of Statistics published by the Government of Jammu and Kashmir. Seven decadal cross-sections (rather than a continuous annual series) were used, consistent with the resolution at which comparable historical production series are available for the full 1960–2020 period.

3.3 Water footprint estimation

Following Mekonnen and Hoekstra (2010, 2011), the water footprint of each crop in each decade was estimated as:

$$WF = Q \times WFF$$

where WF is the water footprint of the crop (m³), Q is the quantity produced (tonnes), and WFF is the crop- and colour-specific water footprint factor (m³ tonne⁻¹) reported by Mekonnen and Hoekstra (2010). The exercise was carried out separately for the green, blue and grey components, with total WF given by their sum. Because a single global-average WFF per crop is applied across all seven decades, the

method implicitly holds crop water requirements, irrigation technology and climate constant over the 60-year study period; the implications of this assumption are discussed in Section 5.5.

The grey water footprint, the volume of freshwater notionally required to assimilate the nitrogen load associated with fertiliser application, diluting it to ambient water-quality standards, follows the leaching-runoff and dilution methodology set out in the Water Footprint Assessment Manual (Hoekstra, Chapagain, Aldaya, & Mekonnen, 2011) and its supporting Tier 1 guidelines (Franke, Boyacioglu, & Hoekstra, 2013).

3.4 Trend significance testing

The existing water-footprint accounting literature for individual regions typically reports the percentage change between two endpoint years, which conflates a genuine monotonic trend with noise around an arbitrarily chosen baseline. To test whether the observed decadal series constitute genuine, statistically significant trends, we applied the non-parametric Mann-Kendall trend test (Mann, 1945; Kendall, 1975) to the total water footprint series and to each individual crop's water footprint series. Where a series exhibited a significant trend, the magnitude of change was estimated using the Sen's slope estimator (Sen, 1968), a robust, non-parametric estimator of the median rate of change that is insensitive to outliers. Crops with fewer than four non-zero decadal observations (cotton, tobacco, sugarcane, chillies, grapes, citrus, guava, peach, plum, apricot, mango and almond) were excluded from the trend test as the series were too short for a statistically meaningful result; this is reported as a limitation rather than treated as missing evidence of trend.

3.5 Decomposition of water footprint change

To separate the contribution of overall production growth from the contribution of compositional (crop-mix) change, we applied a symmetric (Marshall-Edgeworth-type) shift-share decomposition to the change in total water footprint between any two-time points t_0 and t_1 .

Let WFF denote each crop's implied water footprint factor, confirmed from the data itself to be constant across all seven decades (see Section 4.4); let s denote a crop's share of total production in a given decade; and let P denote total production across all crops. The change in total water footprint between t_0 and t_1 was decomposed as:

$$\Delta WF = \text{Scale effect} + \text{Crop-mix effect} + \text{Residual}$$

Scale effect = $\sum_i WFF_i \times [(s_i t_0 + s_i t_1)/2] \times (P_1 - P_0)$ the change in WF attributable to overall production growth, holding each crop's production share fixed at its average across the two periods.

Crop-mix effect = $\sum_i WFF_i \times (s_i t_1 - s_i t_0) \times [(P_0 + P_1)/2]$ the change in WF attributable to a shift in the composition of production, holding total production fixed at its average across the two periods.

The symmetric (average-weighted) form was used in preference to a Laspeyres- or Paasche-type decomposition to avoid the base-period arbitrariness that afflicts two-factor index decompositions; the

residual (interaction) term was verified to be negligible in all reported results ($\leq 0.1\%$ of total change). All computations were carried out in Python 3 using pandas and the pymannkendall package.

3.6 Model comparison, forecasting, and concentration metrics

To characterise the functional form of the total water footprint trend and assess its extrapolative reliability, three candidate models linear, quadratic, and exponential (log-linear) were fitted to the total WF series by ordinary least squares. Because the series contains only seven observations, in-sample fit statistics (R^2 , adjusted R^2 , and the Akaike and Bayesian Information Criteria) were supplemented with leave-one-out cross-validated (LOOCV) root-mean-squared error and mean absolute error, which estimate each model's predictive performance on data not used to fit it. The model with the lowest LOOCV error was selected and used to generate point forecasts and 95% prediction intervals for 2030 and 2040. As a further robustness check on the Mann-Kendall/Sen's slope results (Section 3.4), 95% confidence intervals for the Theil-Sen slope were computed for total WF and its five largest crop-level contributors using the Theil-Sen estimator implemented in SciPy. Finally, the concentration of the water footprint across crops in 2020–21 was summarised using a Pareto (cumulative-share) analysis and the Gini coefficient, a standard summary measure of distributional concentration bounded between 0 (all crops contribute equally) and 1 (the footprint is concentrated in a single crop).

4. Results

4.1 Cropping pattern shift, 1960–61 to 2020–21

Table A1 summarises production of the region's major crops across the seven decadal points. Rice, maize and wheat accounted for the great majority of production in 1960–61; by 2020–21, apple alone accounted for 45.3% of total crop production by tonnage, with rice and maize's combined production share falling from 80.3% to 26.6% over the same period (Fig. 1). Wheat's production share rose over the period even as its absolute rank fell relative to apple. This compositional shift is the empirical basis for the crop-mix effect formally tested in Section 4.4.

4.2 Total, green, blue and grey water footprint

The total agricultural water footprint of J&K's major crops rose from 2.35 million m^3 in 1960–61 to 10.29 million m^3 in 2020–21, an increase of 337.5% (Table A2, Fig. 2). The increase was not uniform across decades: the largest single-decade absolute increase (3.60 million m^3) occurred between 2000–01 and 2010–11, coinciding with the period of most rapid apple production growth.

Green water was the dominant component of the total footprint throughout the study period, rising from 73.9% of total WF in 1960–61 to 82.4% in 2020–21, while the blue-water share fell from 16.6% to 10.2% and the grey-water share fell from 9.5% to 7.4% over the same period (Tables A3–A5, Fig. 3). This rising

green-water share reflects the growing weight of temperate fruit crops, which in J&K are predominantly rain-fed, in the region's total production mix.

4.3 Trend significance: Mann-Kendall test and Sen's slope

The Mann-Kendall test confirms that the increase in total water footprint is a genuine, statistically significant monotonic trend rather than an artefact of the choice of endpoint years ($p = 0.0027$; Sen's slope = $126,164 \text{ m}^3 \text{ year}^{-1}$) (Table 1). Among individual crops, apple, walnut, cherry and pear show highly significant increasing trends ($p < 0.01$), and maize, wheat and potato show significant increasing trends at the 5% level. Notably, oilseeds, other cereals and pulses show no statistically significant trend ($p = 0.133$), and most relevant for policy rice's water footprint series shows no statistically significant trend ($p = 0.230$) despite exhibiting a non-monotonic decadal pattern (a fall in 2000–01 followed by a recovery). This series should be read as fluctuating around a broadly flat trend rather than as evidence of a genuine cyclical or directional pattern in rice water use.

Table 1
Mann-Kendall trend test and Sen's slope estimates, total and per-crop water footprint, 1960–61 to 2020–21 ($n = 7$ decadal points; crops with fewer than four non-zero observations excluded).

Series	Trend	p-value	S statistic	Sen's slope ($\text{m}^3 \text{ year}^{-1}$)
Total water footprint	Increasing	0.0027	21	126,164
Apple	Increasing	0.0027	21	56,152
Walnut	Increasing	0.0027	21	30,504
Cherry	Increasing	0.0027	21	632
Pear	Increasing	0.0069	19	1,688
Maize	Increasing	0.0163	17	9,661
Wheat	Increasing	0.0355	15	9,140
Potato	Increasing	0.0355	15	197
Oilseeds	No trend	0.1331	11	10,434
Other cereals	No trend	0.1331	-11	-196
Pulses	No trend	0.1331	-11	-546
Rice	No trend	0.2296	9	4,873

To make the uncertainty around these trend estimates directly visible, Fig. 4 plots the Theil-Sen slope (Sen, 1968) with its 95% confidence interval for total water footprint and its five largest crop-level contributors. The confidence interval for rice spans zero ($- 2,837$ to $+ 18,905 \text{ m}^3 \text{ year}^{-1}$), which is the graphical counterpart of its non-significant Mann-Kendall result and visually confirms that rice's water

footprint trend cannot be distinguished from a flat line at conventional confidence levels. By contrast, the confidence intervals for total WF, apple, walnut, wheat and maize all lie entirely above zero (Table 1a), confirming genuine upward trends for each.

Table 1
a. Theil-Sen slope estimates with 95% confidence intervals.

Series	Sen's slope (m ³ year ⁻¹)	95% CI lower	95% CI upper
Total water footprint	126,164	58,128	182,666
Apple	56,152	28,938	75,829
Walnut	30,504	10,243	59,377
Wheat	9,140	1,120	15,322
Maize	9,661	2,877	17,616
Rice	4,873	-2,837	18,905

4.4 Decomposition of water footprint change

Each crop's implied water footprint factor (total WF ÷ production) was found to be numerically constant across all seven decades for every crop with non-zero production in more than one decade, a direct confirmation that the underlying accounting method holds crop-specific water requirements fixed over the study period, and a useful internal consistency check on the reconstructed dataset. This constancy makes the shift-share decomposition exact up to a residual of less than 0.1% of total change.

The decomposition (Table 2, Fig. 5) attributes 101.5% of the total 1960–61–2020–21 increase in water footprint (7.93 million m³) to the scale effect i.e., to the sheer growth in total agricultural production and only – 1.5% to the crop-mix effect, with a negligible residual. This result runs counter to the narrative that a purely descriptive reading of the production and water-footprint tables would suggest. Apple's own gross contribution to the crop-mix effect is substantial and positive (+ 2.06 million m³), reflecting its production share rising from 0% to 45.3% of the total; but this is almost exactly offset by the crop-mix contributions of rice (– 1.68 million m³) and maize (– 1.67 million m³), whose production shares fell from 43.2% to 13.8% and from 37.1% to 12.8% respectively even though both crops' absolute production continued to grow throughout the period. In other words, apple's rise and rice/maize's relative (not absolute) decline are, in water-footprint terms, close to a wash; the compositional shift narrative and the scale-growth narrative are not equally supported by the data, and the latter dominates.

Table 2
Shift-share decomposition of the change in total water footprint, 1960–61 to 2020–21.

Component	Value (million m ³)	Share of total change
Total change	7.93	100.0%
Scale effect (production growth, mix fixed)	8.05	101.5%
Crop-mix effect (compositional shift, scale fixed)	–0.12	–1.5%
Residual (interaction term)	~ 0.00	~ 0.0%

Table 2
a. By-crop contribution to the crop-mix effect (net of the overall scale effect), 1960–61 to 2020–21.

Crop	Contribution (m ³)	Production share 1960–61	Production share 2020–21
Apple	+ 2,062,463	0.0%	45.3%
Walnut	+ 1,278,570	0.0%	5.9%
Wheat	+ 129,801	11.2%	15.0%
Pear	+ 65,032	0.0%	2.0%
Mango	+ 25,952	0.0%	0.6%
Cherry	+ 23,204	0.0%	0.3%
Other minor fruit crops (combined)	+ 39,469	0.0%	1.7%
Other cereals	–85,009	4.1%	0.5%
Pulses	–91,819	2.5%	0.2%
Oilseeds	–223,397	1.7%	1.3%
Maize	–1,666,627	37.1%	12.8%
Rice	–1,682,584	43.2%	13.8%

4.5 Per-crop trend diagnostics

Figure 6 presents the water footprint trajectory of each of the eight largest-WF crops individually, each annotated with its Mann-Kendall p-value. This disaggregated view makes clear that the significant overall upward trend in total WF (Section 4.3) is not driven uniformly across crops: apple, walnut, wheat and maize each show a clear, statistically significant upward trajectory, while rice's trajectory is visibly flatter and non-monotonic, consistent with its non-significant test result. Presenting the individual crop panels alongside one another also makes visually apparent the very different absolute scales on which these crops' water footprints operate apple and walnut's footprints in 2020–21 are roughly an order of magnitude larger than in 1970–71, whereas rice's 2020–21 footprint is within 40% of its 1960–61 level.

4.6 Concentration of the water footprint across crops

Table A1 and Table 2a already show that a small number of crops account for a disproportionate share of total WF; Fig. 7 quantifies this concentration formally. Ranking crops by their 2020–21 water footprint and plotting the cumulative share of total WF against crop rank shows that just four crops apple, rice, maize and walnut jointly account for approximately 80% of the region's total agricultural water footprint in 2020–21. The Gini coefficient of the cross-crop WF distribution in 2020–21 is 0.79, indicating a highly concentrated distribution (a Gini of 0 would indicate every crop contributes an identical share of total WF; a Gini approaching 1 indicates the footprint is concentrated in very few crops). This concentration has a direct implication for monitoring and intervention design: water-use-efficiency programmes targeted at this small set of high-WF crops would have leverage over the large majority of the region's total agricultural water footprint, without requiring uniform coverage of all 23 crops in the accounting framework.

4.7 Water footprint intensification pattern across crops and decades

Figure 8 presents a heatmap of each crop's water footprint in every decade, expressed as a percentage of that same crop's own 2020–21 level, restricted to the eleven crops with sufficient non-zero observations for meaningful comparison. This normalisation (rather than an absolute-value heatmap, which would be dominated visually by apple and walnut alone) makes the differing intensification trajectories comparable across crops of very different absolute scale. The heatmap shows that fruit crops introduced or expanded from the 1970s onward (apple, walnut, pear, cherry) intensified steadily and monotonically across every subsequent decade, whereas the cereals (rice, maize, wheat) show a visibly flatter, more plateaued intensification pattern from the 1980s onward, with wheat as a partial exception given its continued growth into 2010–21. This pattern is the visual counterpart of the decomposition result in Section 4.4: the cereals' flat intensification profile is precisely why their declining production *share* (even amid continued absolute growth) nets out apple and walnut's contribution to the crop-mix effect.

4.8 Model comparison, cross-validated performance, and forecast to 2040

The Mann-Kendall/Sen's slope approach (Section 4.3) establishes that total WF follows a significant monotonic trend but is deliberately agnostic about its functional form. To characterise that functional form and assess how well it can be expected to extrapolate, three candidate trend models were fitted to the total WF series: a linear model, a quadratic model, and an exponential (log-linear) growth model. Table 3 reports, for each model, the in-sample R^2 and adjusted R^2 , the Akaike and Bayesian Information Criteria (AIC, BIC), and given the very small sample ($n = 7$ decadal points) leave-one-out cross-validated

(LOOCV) root-mean-squared error (RMSE) and mean absolute error (MAE), which provide a more honest measure of out-of-sample predictive performance than in-sample fit statistics alone.

Table 3
Model comparison and cross-validated performance metrics, total water footprint, 1960–61 to 2020–21 (n = 7).

Model	Parameters	R ²	Adj. R ²	AIC	BIC	LOOCV RMSE (m ³)	LOOCV MAE (m ³)
Linear	2	0.882	0.858	216.06	215.95	1,295,940	1,065,424
Quadratic	3	0.938	0.908	213.50	213.34	1,042,890	834,326
Exponential (selected)	2	0.940	0.910	193.48	193.32	849,965	659,596

The exponential model is preferred on every criterion reported: it achieves the highest R² and adjusted R², the lowest AIC and BIC (indicating the best fit net of model complexity), and most importantly the lowest leave-one-out cross-validated RMSE and MAE, confirming that its advantage is not merely an in-sample artefact. This is also the substantively expected result: agricultural production and its associated water footprint typically compound multiplicatively (percentage growth per period) rather than additively, which an exponential (log-linear) specification captures and a linear specification does not.

Figure 9 plots the observed data against all three fitted models and extends the selected exponential model to 2030 and 2040 with a 95% prediction interval. The model projects total agricultural water footprint to reach approximately 12.49 million m³ by 2030 (95% CI: 9.13–17.09 million m³) and 15.80 million m³ by 2040 (95% CI: 10.83–23.05 million m³) (Table 4), continuing the observed exponential trajectory absent any policy intervention or structural change in the cropping system. The width of these intervals more than doubling from 2030 to 2040 is a direct and honest consequence of extrapolating a two-parameter model fitted to only seven historical observations well beyond the observed data range, and these forecasts should be read as illustrative projections of the current trajectory rather than precise predictions.

Table 4
Forecast of total agricultural water footprint, selected exponential model.

Year	Predicted total WF (million m ³)	95% CI lower	95% CI upper
2030	12.49	9.13	17.09
2040	15.80	10.83	23.05

As a final robustness check, Fig. 10 reports residual diagnostics for the selected exponential model: residuals plotted against fitted values show no strong systematic pattern given the small sample, the normal quantile-quantile plot of the log-scale residuals shows no severe departure from normality, and the observed-versus-predicted plot shows all seven points close to the 45° line. None of these

diagnostics rules out model misspecification conclusively with only seven observations, but none reveals an obvious violation either.

5. Discussion

5.1 Scale, not substitution, is the proximate driver

The decomposition result carries a specific and testable policy implication. If the crop-mix shift toward apple and walnut were the dominant driver of water footprint growth, the appropriate policy lever would concern the composition of the horticulture-promotion strategy itself for instance, moderating further apple area expansion in favour of less water-intensive fruit crops. The evidence here does not support that framing: the crop-mix effect is close to zero (-1.5%), because rice and maize's declining production share offsets apple and walnut's rising share almost exactly in water-footprint terms. The dominant driver is instead the scale effect the simple fact that total agricultural production in J&K, across essentially every crop, is larger in absolute terms in 2020–21 than in 1960–61. This points policy toward managing the trajectory of aggregate agricultural water demand (through water-use efficiency, crop water productivity improvements, and demand-side planning in the sense discussed by Gleick, 2000) rather than toward crop-substitution policy specifically targeting horticulture.

5.2 The rising green-water share and its policy reading

The rising share of green water in total WF (from 73.9% to 82.4%) is consistent with the compositional shift toward largely rain-fed temperate fruit cultivation, even though that shift is not the dominant driver of the level increase in total WF. From a water-scarcity standpoint this is a genuinely favourable structural feature: green water does not compete directly with other consumptive or municipal uses in the way blue (irrigation) water does, and its systematic under-representation in water assessments that focus on blue water alone is a well-documented general concern (Liu, Zehnder, & Yang, 2009). J&K's green-water share, while below the global crop-production average reported by Mekonnen and Hoekstra (2011) of approximately 86.5%, is converging toward it. The policy priority this suggests is less about reducing total agricultural water footprint per se, and more about the composition of the remaining blue-water demand which, per Table A4, remains concentrated overwhelmingly in rice.

5.3 Rice: a flat, not cyclical, trend

The absence of a statistically significant Mann-Kendall trend in rice's water footprint ($p = 0.230$) is a substantive finding that revises the standard descriptive narrative for this crop. Rather than treating the decadal fall in rice WF around 2000–01 as evidence of a meaningful production cycle, the appropriate reading is that rice production and its associated water footprint have been essentially flat, within statistical noise, across six decades even as apple, walnut and wheat show clearly significant upward trends over the same period. Given that rice's blue-water footprint is the single largest of any crop in absolute terms throughout the study period (Table A4), this stability, rather than instability, is the more

policy-relevant fact: it implies that rice's contribution to J&K's blue-water demand is a persistent structural feature of the cropping system rather than a residual pattern amenable to short-run correction.

5.4 Concentration and forecast: implications for monitoring

Two further results from Section 4 sharpen the practical implications of the scale-versus-mix finding. First, the crop concentration analysis (Section 4.6) shows that just four crops, apple, rice, maize and walnut account for approximately 80% of the region's 2020–21 agricultural water footprint (Gini = 0.79); this means that monitoring and efficiency interventions do not need to be spread evenly across J&K's 23-crop portfolio to be effective, and can instead be concentrated on this small set with disproportionate leverage. Second, the cross-validated exponential growth model (Section 4.8) projects continued growth in total WF to approximately 12.5 million m³ by 2030 and 15.8 million m³ by 2040 on the current trajectory; because this projection is driven overwhelmingly by the scale effect identified in Section 4.4 rather than by further compositional shift, it should be read as a projection of continued aggregate production growth, not as a forecast that assumes further horticultural expansion specifically. The width of the 2040 prediction interval (10.8–23.1 million m³) also underscores that this is an extrapolation from seven historical points and should inform the general order of magnitude and direction of water-resource planning rather than be treated as a precise target.

5.5 Limitations

Four limitations should condition the interpretation of these results. First, the water-footprint-factor method applied here holds each crop's water footprint factor constant across six decades; this assumes constant crop water requirements, irrigation technology, and reference evapotranspiration over a period that has plausibly seen changes in all three, and does not reflect any J&K-specific recalculation using site-level climate data (e.g., via CROPWAT or AquaCrop). This assumption is not merely a theoretical concern: a high-resolution assessment of climate change impacts on cereal water footprints elsewhere in India projects shifts in blue and green water footprints of several percent by the 2050s under moderate emissions scenarios, with rice and wheat, both major contributors to J&K's own footprint, moving in opposite directions (Mali, Shirsath, & Islam, 2021), which suggests the static-WFF assumption used here is a genuine source of unquantified uncertainty rather than a purely formal caveat. The internal consistency check reported in Section 4.4 confirms this constancy is an artefact of the accounting method rather than an empirical finding, and it should be reported as an assumption rather than a result. Second, the analysis uses seven decadal cross-sections rather than a continuous annual series; this limits the power of the trend tests and means within-decade variability and any structural breaks are not observable. Third, without crop-specific area-harvested data (only production quantities were available), the scale effect identified here cannot be further decomposed into an area-expansion effect and a yield-growth effect, a natural extension that would clarify whether production growth has been primarily land-extensive or productivity-driven as Bhat et al. (2019) were able to do for apple alone using J&K's own area and yield records. Fourth, twelve minor crops had fewer than four non-zero decadal observations and were excluded from formal trend testing; their contribution to the overall water footprint is small but

their omission from Table 1 should not be read as evidence that they lack a genuine trend, only that the available data cannot support the test.

6. Conclusion and Policy Implications

This study provides the first, statistically tested and decomposed account of long-run agricultural water footprint change in Jammu and Kashmir. Three conclusions follow. First, the 337.5% increase in total agricultural water footprint between 1960–61 and 2020–21 is a genuine, statistically significant monotonic trend (Mann-Kendall $p = 0.003$), not an artefact of the choice of comparison years. Second, green water has consistently dominated the region's agricultural water footprint and its share has risen over time, a structurally favourable feature from a water-scarcity standpoint given that green water does not compete with other consumptive uses. Third, and most importantly for policy design, the increase in total water footprint is overwhelmingly attributable to the scale of overall agricultural production growth (101.5% of the change) rather than to the well-documented shift toward horticulture and apple cultivation (-1.5% of the change, net of rice and maize's declining production share). Policy attention aimed at moderating J&K's agricultural water footprint should therefore prioritise water-use efficiency and productivity gains across the cropping system as a whole with particular attention to rice, whose blue-water footprint has remained the largest and most stable of any crop over six decades rather than treating the horticulture-led transformation of the region's agriculture as the primary target for intervention.

Declarations

Data Availability

Data will be made available on request.

Author Contributions

Ishrat F. Bhat: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Farhet A. Shaheen: Resources, supervision, project administration.

Masroor Majid: Investigation, data curation, Formal Analysis, Software.

Mir Rizwan Qazi: Review.

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Conflict of Interest

The author declares no competing interests.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the authors used Claude (Anthropic) in order to assist with manuscript editing, reference verification, and table formatting. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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Figures

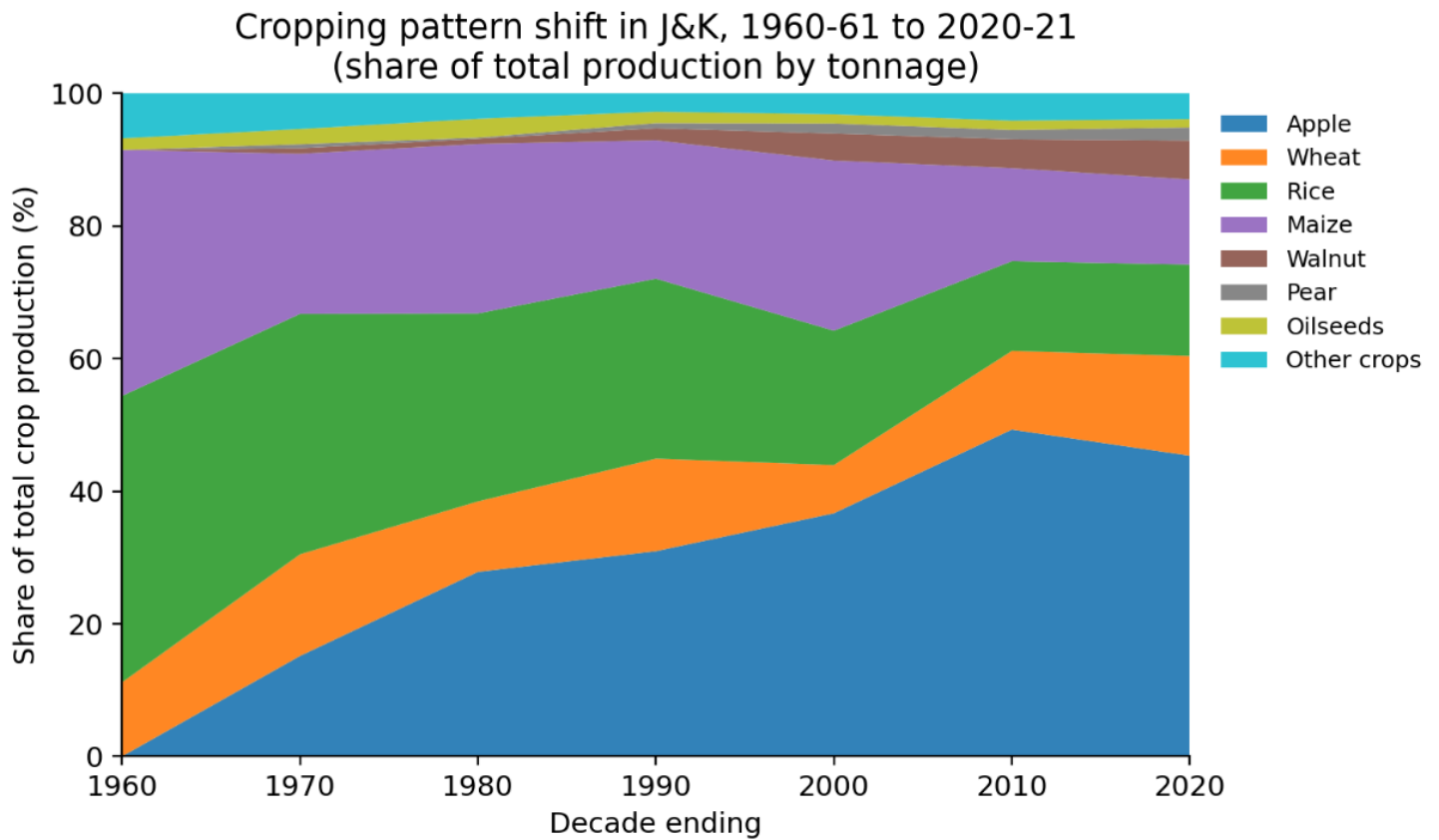


Figure 1

Cropping pattern shift in Jammu and Kashmir, 1960–61 to 2020–21 (share of total crop production by tonnage).

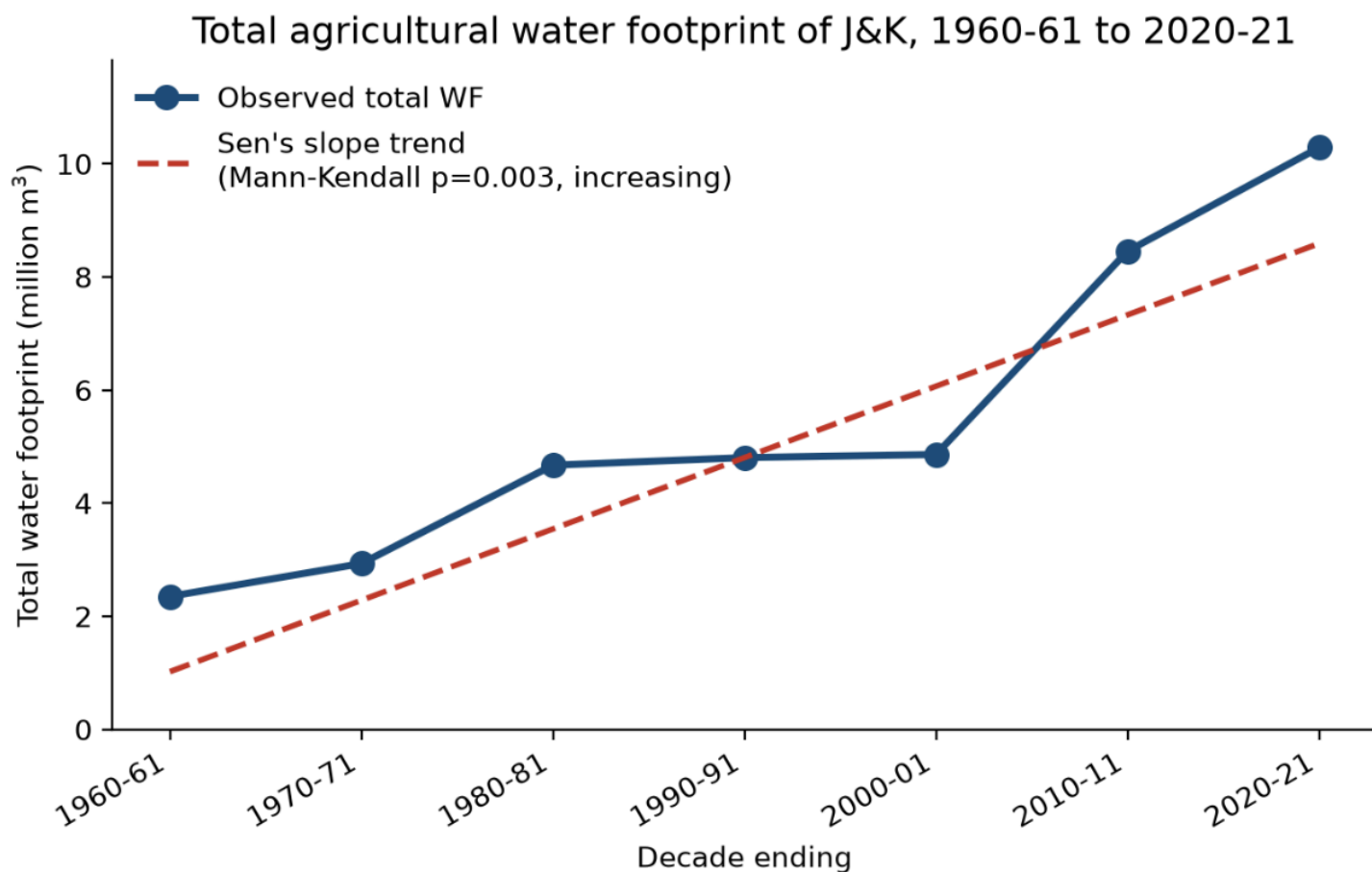


Figure 2

Total agricultural water footprint of Jammu and Kashmir, 1960–61 to 2020–21, with Sen's slope trend line and Mann-Kendall test statistics.

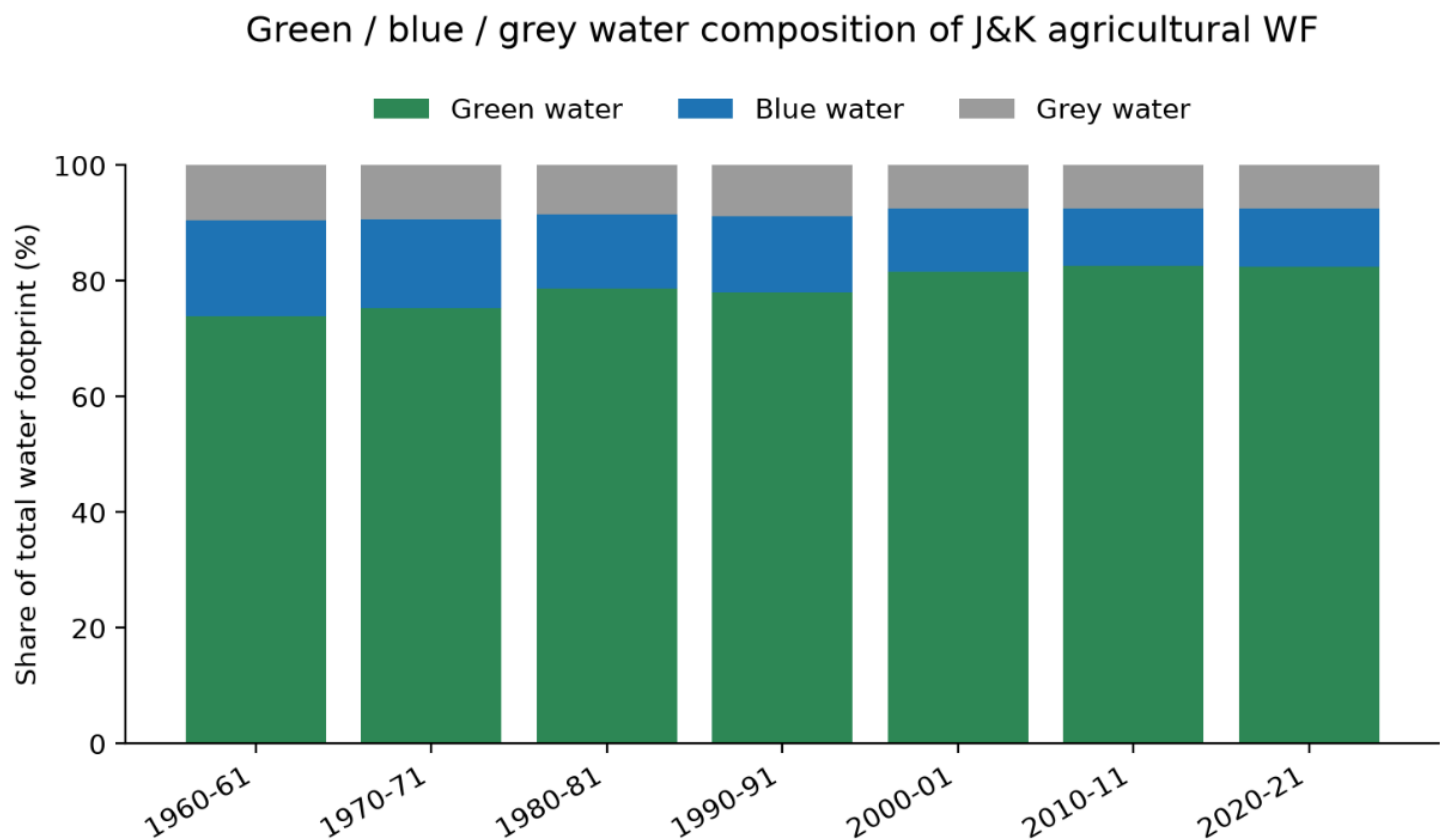


Figure 3

Green, blue and grey water composition of Jammu and Kashmir's agricultural water footprint, 1960–61 to 2020–21.

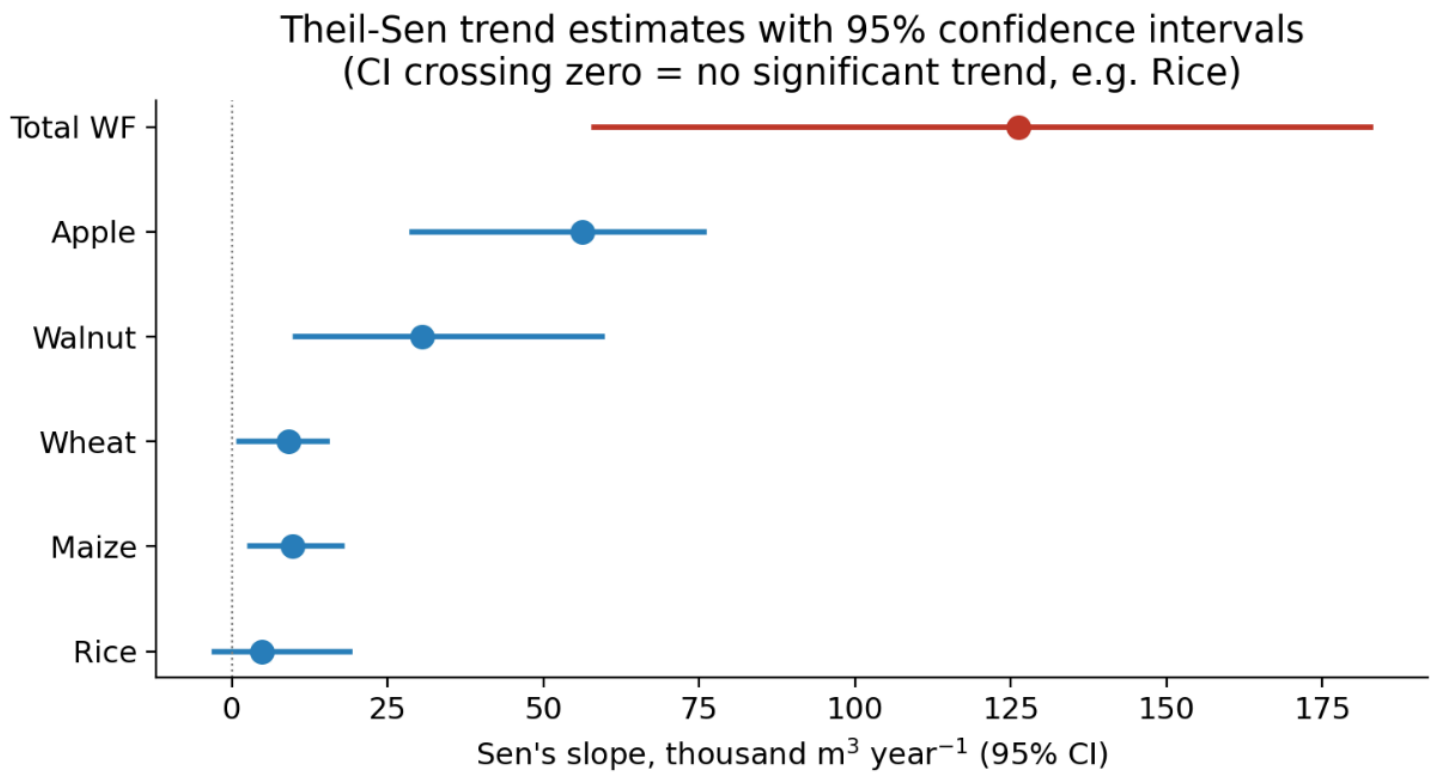


Figure 4

Theil-Sen slope estimates with 95% confidence intervals, total water footprint and top five contributing crops, 1960–61 to 2020–21.

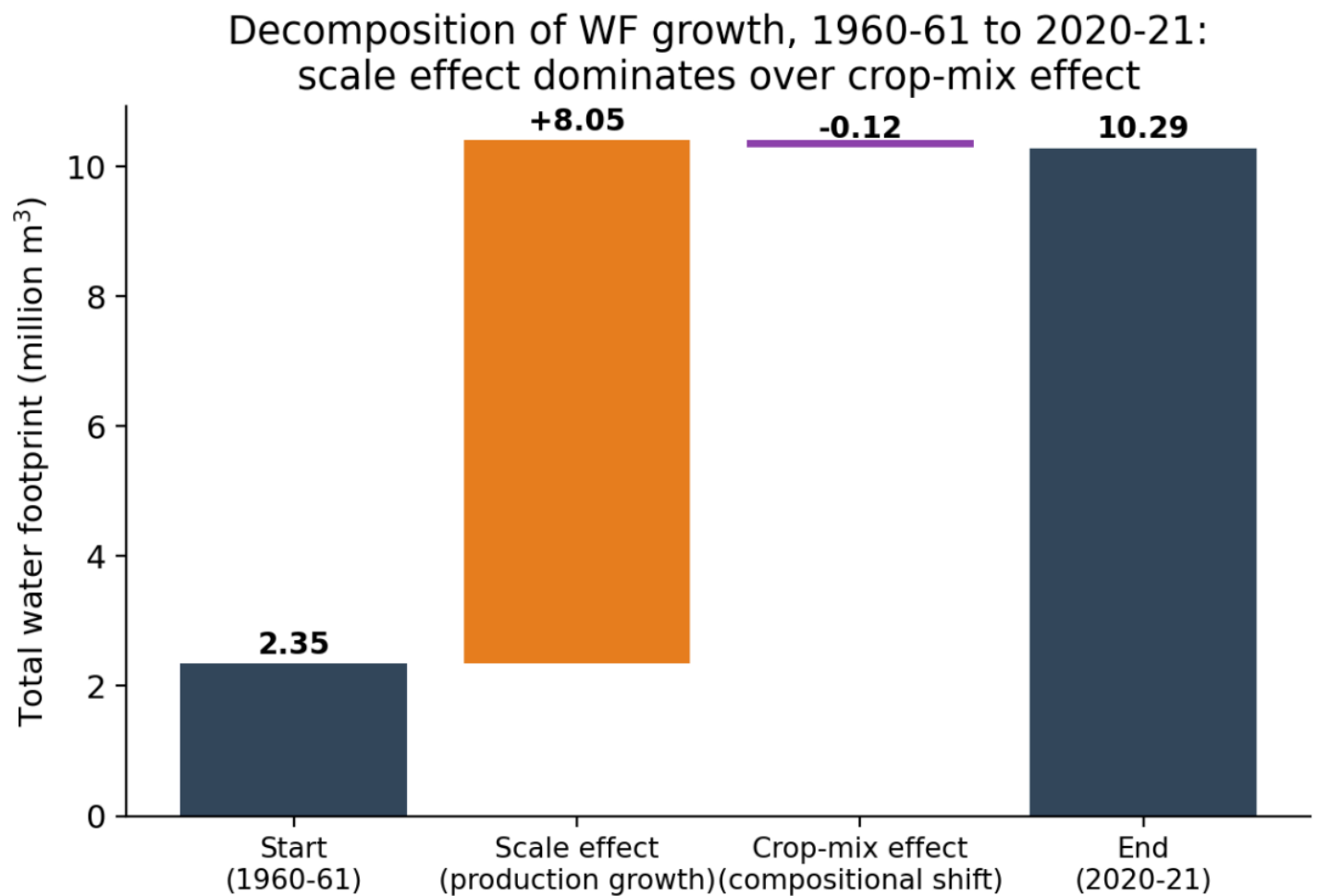


Figure 5

Decomposition of total water footprint growth, 1960–61 to 2020–21, into a production-scale effect and a crop-mix (compositional-shift) effect.

Water footprint trajectories of the eight largest-WF crops, 1960–61 to 2020–21

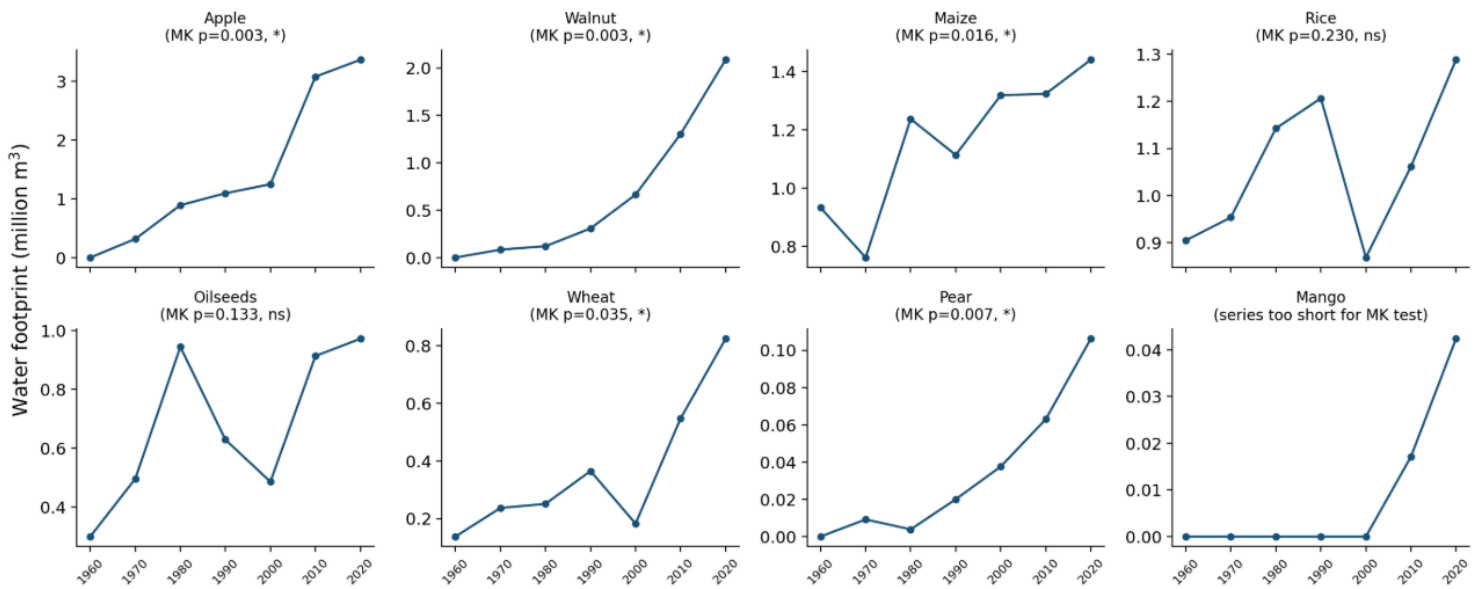


Figure 6

Water footprint trajectories of the eight largest-WF crops, 1960–61 to 2020–21, with Mann-Kendall significance annotated per panel.

Crop concentration of J&K's agricultural water footprint, 2020–21
(Gini coefficient = 0.79)

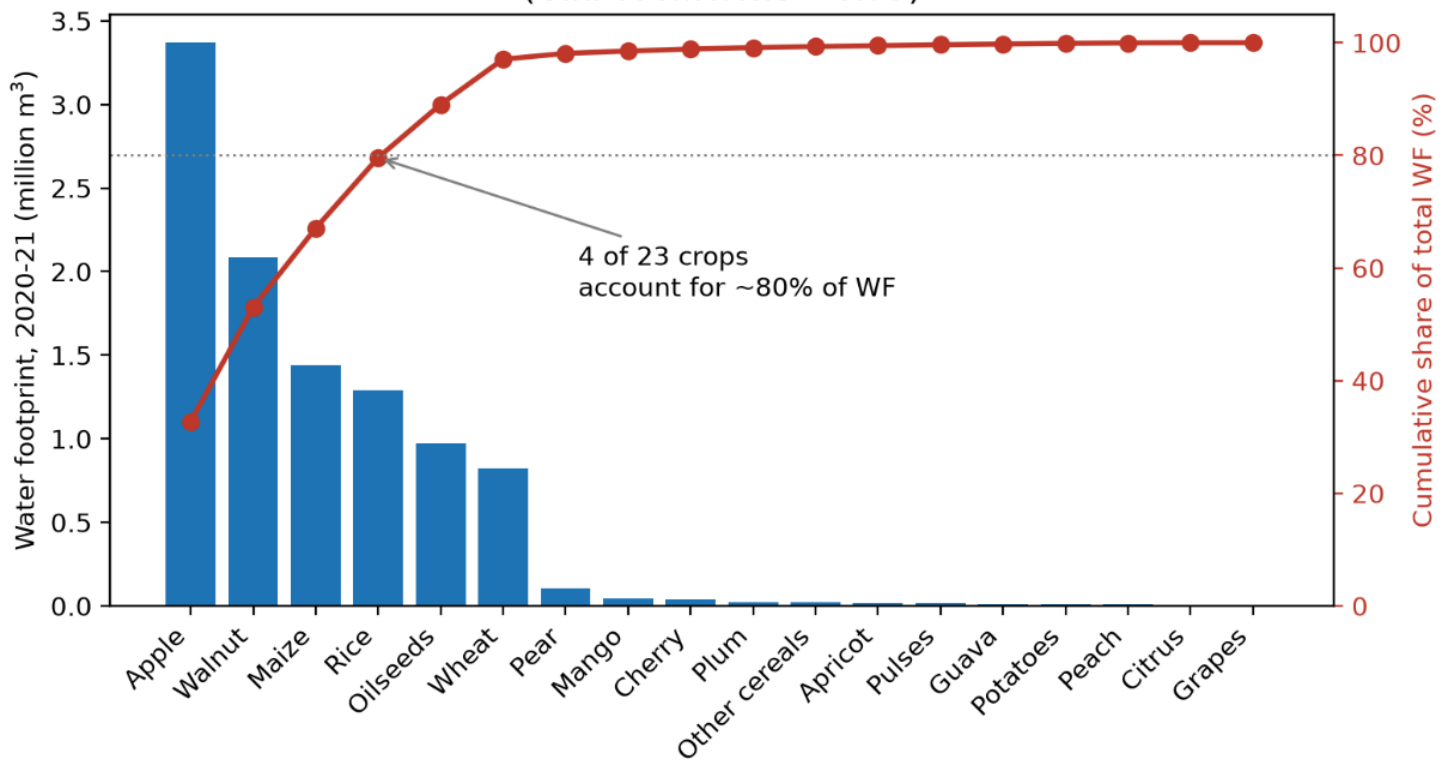


Figure 7

Pareto (concentration) chart of the 2020–21 crop-level water footprint, with cumulative share of total WF and the cross-crop Gini coefficient.

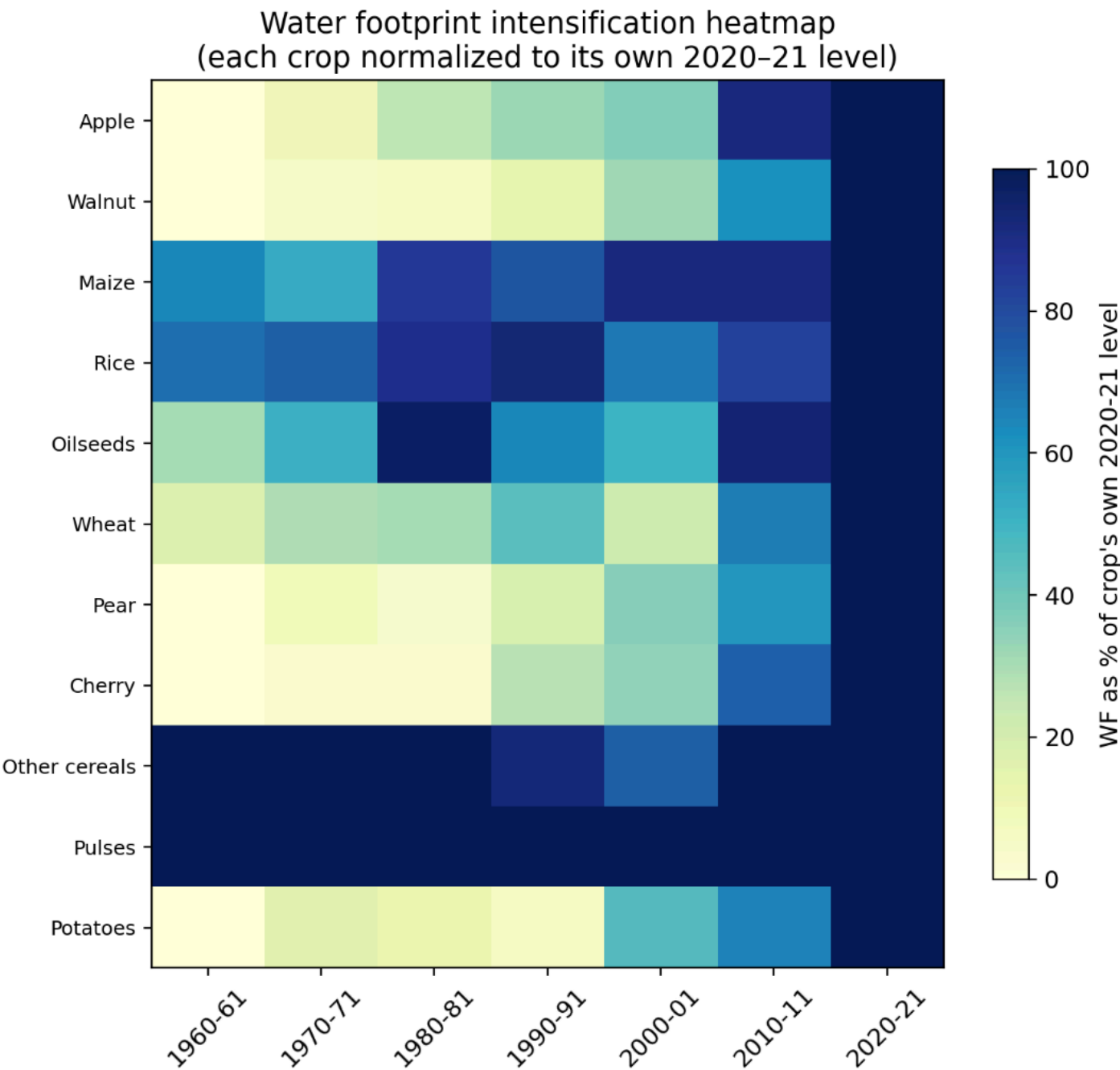


Figure 8

Water footprint intensification heatmap, 1960–61 to 2020–21, each crop normalised to its own 2020–21 level (crops with fewer than four non-zero decadal observations excluded).

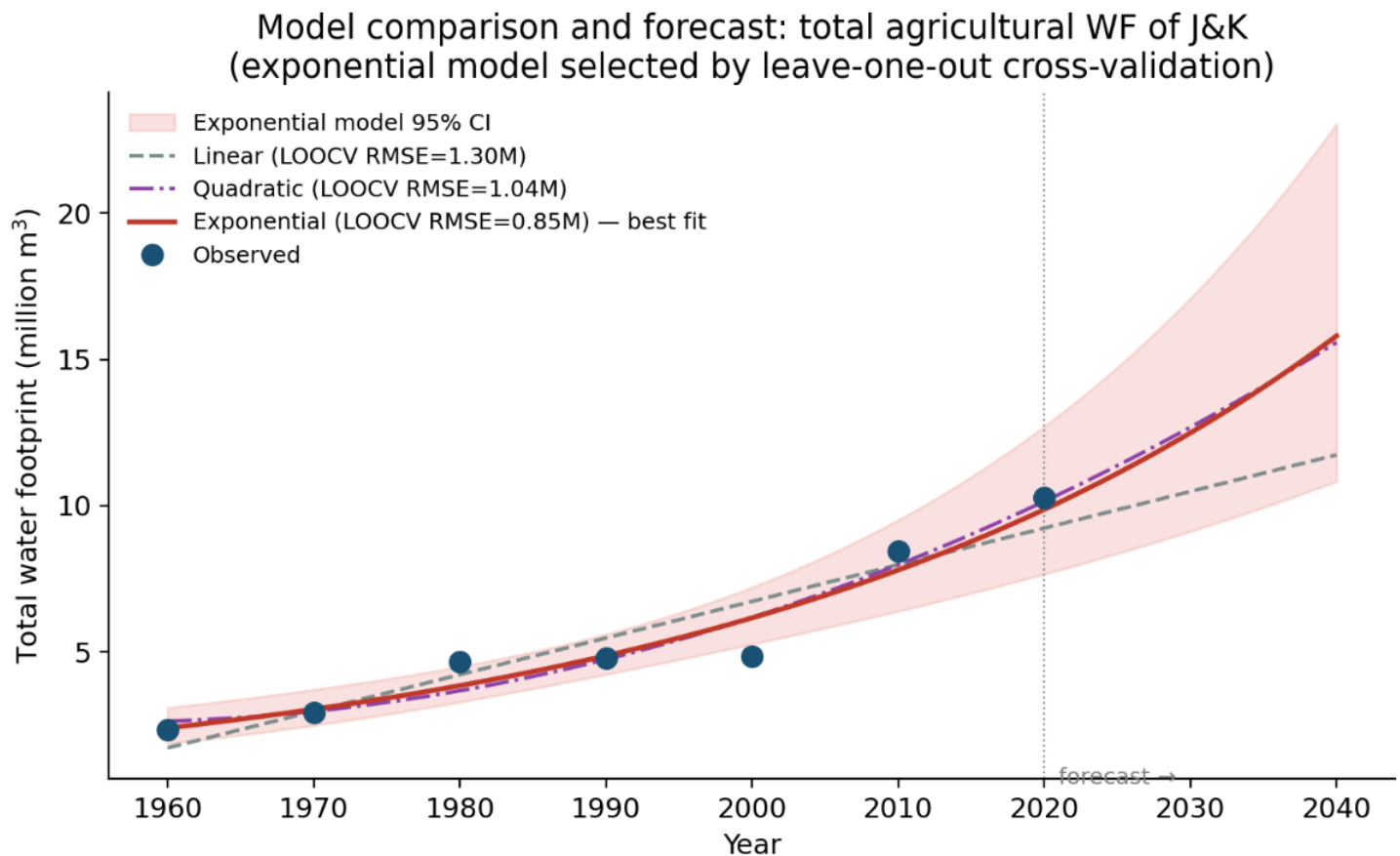


Figure 9

Observed total water footprint with linear, quadratic and exponential model fits, and exponential-model forecast to 2040 with 95% prediction interval.

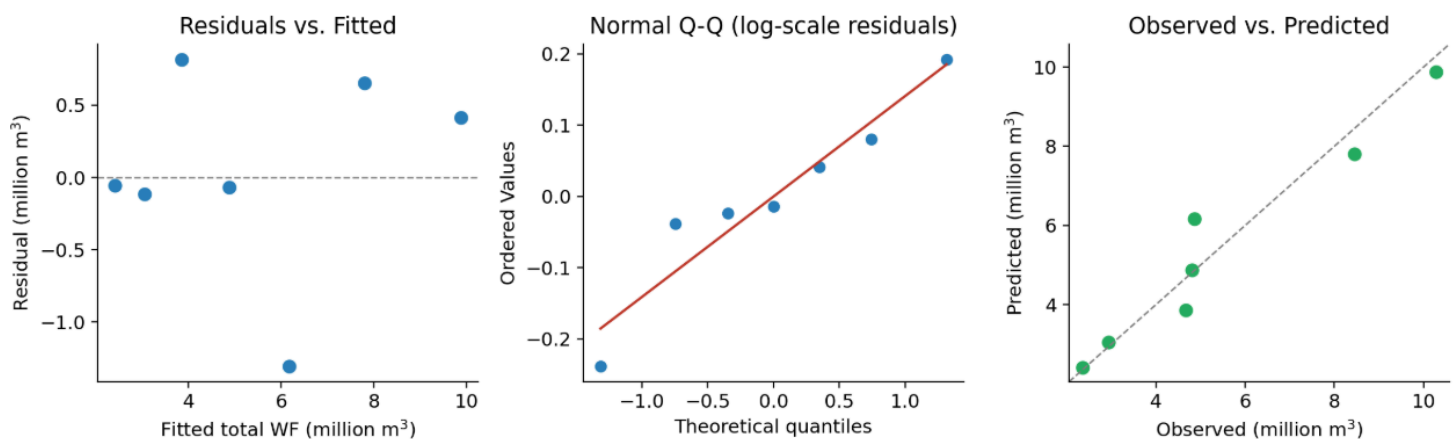


Figure 10

Residual diagnostics for the selected exponential trend model: residuals vs. fitted values, normal Q-Q plot of log-scale residuals, and observed vs. predicted total WF.

Supplementary Files

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- [floatimage1.png](#)