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A basin-month freshwater atlas for regional absolute environmental sustainability assessment

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A basin-month freshwater atlas for regional absolute environmental sustainability assessment

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Abstract

Global freshwater abundance can hide monthly deficits in individual basins. We developed an atlas to test whether renewable surface water can meet stated human needs after reserving flows for ecosystems. We combined monthly runoff, population and demand estimates across 190,675 basins, then followed surplus water downstream without counting it twice. Our main benchmark estimates the water needed to provide decent living standards efficiently. In 1991-2024, water remaining after ecological reservation exceeded this demand 7.44-fold globally, yet natural routing covered only 58.5%. In a separate 2025 analysis, 127 of 194 countries had sufficient annual water generation within their borders but retained routed shortfalls of at least 1%. Global maps and an Austrian case reveal spatial and seasonal gaps hidden by national totals. Sensitivity tests and indicator comparisons qualify these estimates. The atlas supports regional sustainability screening; site-specific assessments require validated flows, measured consumption and justified allocation.

1. Introduction

Renewable freshwater supplies households, food production and industry, while rivers also need flow to sustain ecosystems. Whether these needs can be met depends on where and when water is available. Planetary boundaries define a safe operating space for Earth-system processes, including freshwater . Freshwater links climate, land and the biosphere through runoff, soil moisture, evaporation, precipitation and storage . A global boundary can signal Earth-system change, but it does not tell us how much water remains for human use in a particular river basin and month. A river basin is the land area draining towards a common outlet; this is the regional unit needed to connect water availability with demand.

Water scarcity arises when supply and demand do not coincide in space or time. Runoff within a country's borders may exceed its annual demand even though people live in other basins or need water in other months. Rivers carry some upstream surplus downstream; supplying disconnected basins requires infrastructure and allocation decisions . We therefore reserve environmental-flow requirements (EFR), the water retained to support aquatic ecosystems, before calculating availability for human use. Previous studies document seasonal scarcity, downstream effects and sensitivity to indicator definitions . Annual basin balances have also been used to test whether local surface water can meet minimum human needs within safe and just Earth system boundaries. We extend this sufficiency question to individual months and track the origin of upstream support.

These distinctions lead to three empirical questions. First, how much of a stated human demand can a basin meet from locally generated water after ecological flows are reserved? Second, how much additional demand can be met by unallocated surplus arriving through the natural river network, without assigning the same upstream water twice? Third, do the inferred deficits remain similar when demand assumptions, hydrological inputs and basin delineation change? Answering these questions at monthly resolution makes the source and timing of a capacity estimate explicit. It does not establish whether modelled water is accessible through existing infrastructure or whether a population currently lacks water.

Aqueduct baseline water stress, the Water Exploitation Index plus (WEI+) and Available Water Remaining (AWARE) describe water-use pressure or scarcity impacts for defined areas and periods . Our question is complementary: after reserving ecological flows, can the water available in each basin and month meet an explicitly stated human need? To answer it, the atlas distinguishes water generated by runoff within the basin from surplus arriving from upstream. We call the latter calculation routing: following water downstream through connected rivers. Each unit of water is assigned only once, and its source remains identifiable. The output is a capacity estimate for screening, not an allocated entitlement. This information is needed for absolute environmental sustainability assessment (AESA), which compares the pressure caused by an activity with a justified share of environmental capacity . For water, an assessment must first establish the relevant basin's capacity and then determine how much may be assigned to a facility, city or population. The atlas addresses the first step by estimating monthly water availability after ecological reservation and testing a specified human demand. It does not itself

allocate a fair share to individual users. Such a comparison requires validated flows, a sharing rule and measured consumptive use, meaning water used without returning to the same relevant water system, together with return flows.

Human demand must be defined before sufficiency can be tested. Decent living standards (DLS) describe the material conditions needed for basic wellbeing, such as nutrition, housing and essential services. Our main demand benchmark uses country-specific estimates of the water needed to provide these conditions efficiently. It therefore covers a wider bundle than household water alone. We assign this demand to the basin where the modelled population lives, so the atlas tests a declared demand against local and upstream capacity; it does not trace actual water use at the production locations of traded goods.

Two direct-use benchmarks place the wider DLS demand in context: 50 L person^{-1} day^{-1} for basic needs and a selected 150 L high-domestic comparison . The upper end of the 120–150 L household-use range discussed for Austria provides context for the latter choice . We also apply that study's 4,377 L person^{-1} day^{-1} total-footprint estimate as a broad stress test. It includes water embodied in agricultural and industrial goods, including use abroad, and combines blue water with green water (rainwater used by vegetation) and grey water (a dilution-volume indicator). It is therefore not a local blue-water withdrawal requirement.

We first assess the global pattern, then examine Austria to show how a water-rich country's annual balance can conceal differences between individual basins and months. Nested Austrian basins also let us test whether finer boundaries change the result when the climate inputs remain the same. We compare demand assumptions, local and routed coverage, hydrological sources and basin scales, and relate the country results to established indicators.

2. Results

2.1 Defining regional freshwater sufficiency

Each calculation assesses one basin in one calendar month. We subtract EFR from runoff generated within the basin and use the remaining water to meet its stated demand. Local sufficiency means full coverage. Routing adds surplus from connected upstream basins after their own claims have been met; routed sufficiency also means full coverage. Annual or national surplus cannot resolve a deficient basin-month unless water reaches it when needed. The 100% threshold tests fulfilment of a stated human need. The demand level is normative, rather than an ecological tipping point or a numerical downscaling of the planetary freshwater boundary.

We report the share of demand covered, the remaining deficit volume and the number of deficit months. Tracking each source distinguishes local hydrological self-sufficiency from dependence on upstream water.

These metrics answer different questions. Deficit months measure frequency: a month with 1% unmet demand and one with 90% each count once. Coverage measures the fraction of demand served, while deficit volume measures the amount left unmet. Frequency maps should therefore be read alongside coverage and volume when choosing locations for further investigation.

2.2 Global abundance and historical basin-month deficits

Across 190,675 global HydroBASINS level-8 basins, ERA5-Land runoff yielded 45,068 $km^3\ yr^{-1}$ of locally generated blue water in the 1991-2024 climatology, the average seasonal pattern over that period. After EFR reservation, 11,989 $km^3\ yr^{-1}$ remained, compared with efficient DLS demand of 1,610 $km^3\ yr^{-1}$. This global ratio of 7.44 does not show whether supply and demand coincide. Matching them by basin and month served 816 $km^3\ yr^{-1}$ locally (50.7%) and 943 $km^3\ yr^{-1}$ after downstream routing (58.5%), leaving 668 $km^3\ yr^{-1}$ unmet. Surplus in other basins or months cannot simply offset this deficit. Among 195 reporting countries, 58 retained routed DLS coverage below 50%; India and China contributed 48.2% of the global modelled DLS deficit by volume. These are scenario shortfalls, not counts of households without water.

Deficit volume and relative coverage describe different aspects of scarcity. A large population can contribute substantially to the global deficit while having a smaller percentage shortfall than another country. A small country can contribute little globally while leaving a large share of its own demand unmet. Reporting both separates demand size from shortfall intensity.

Figure 1 shows the mean annual number of deficient months over 1950-2025. Efficient DLS appears first, followed by the 50 and 150 L direct-use comparisons and the 4,377 L footprint stress test. Higher demand generally expands deficits. The last case includes green and grey water equivalents and cannot represent blue-water withdrawals. Counts use a fixed 2025 population proxy, describing people living in the mapped classes today rather than historical exposure.

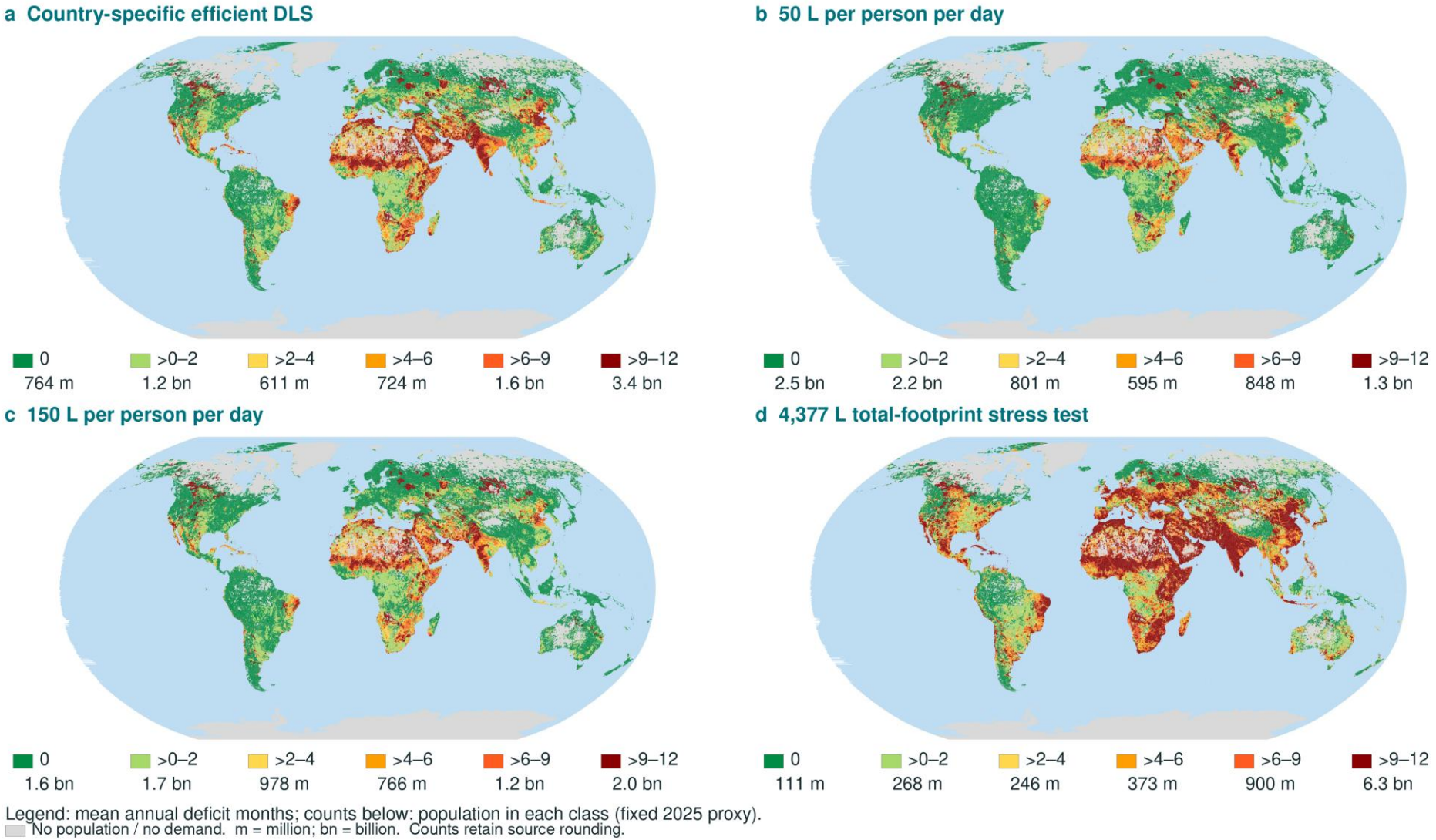

Figure 1: Mean annual deficit months in global HydroBASINS level-8 basins, 1950–2025. a) Country-specific efficient DLS, the main benchmark; b) 50 L; c) 150 L person^{-1} day^{-1}; d) 4,377 L person^{-1} day^{-1} total-footprint stress test. Colors show months yr^{-1} with unmet demand after natural downstream routing, including transboundary links. Counts beneath each panel give the fixed 2025 proxy population in the corresponding colour class, retaining source rounding. Grey denotes no population or no demand. The footprint stress test includes non-blue-water equivalents.

Applying the same test to smaller Austrian level-12 basins reveals recurring shortfalls concentrated in the east (Figure 2). Most mapped basins have few deficient months under 50 L; higher demand exposes more persistent hotspots. In the efficient-DLS panel, about two million people in the fixed 2025 population proxy live in basins with more than nine mean deficit months per year. This is exposure to a modelled scenario class, not observed supply failure. For this historical map, routing is restricted to the Austrian study network and excludes support from cross-border inflows. It therefore illustrates internal spatial differences rather than all water potentially arriving in Austria. The smaller polygons do not improve the resolution of the underlying climate data.

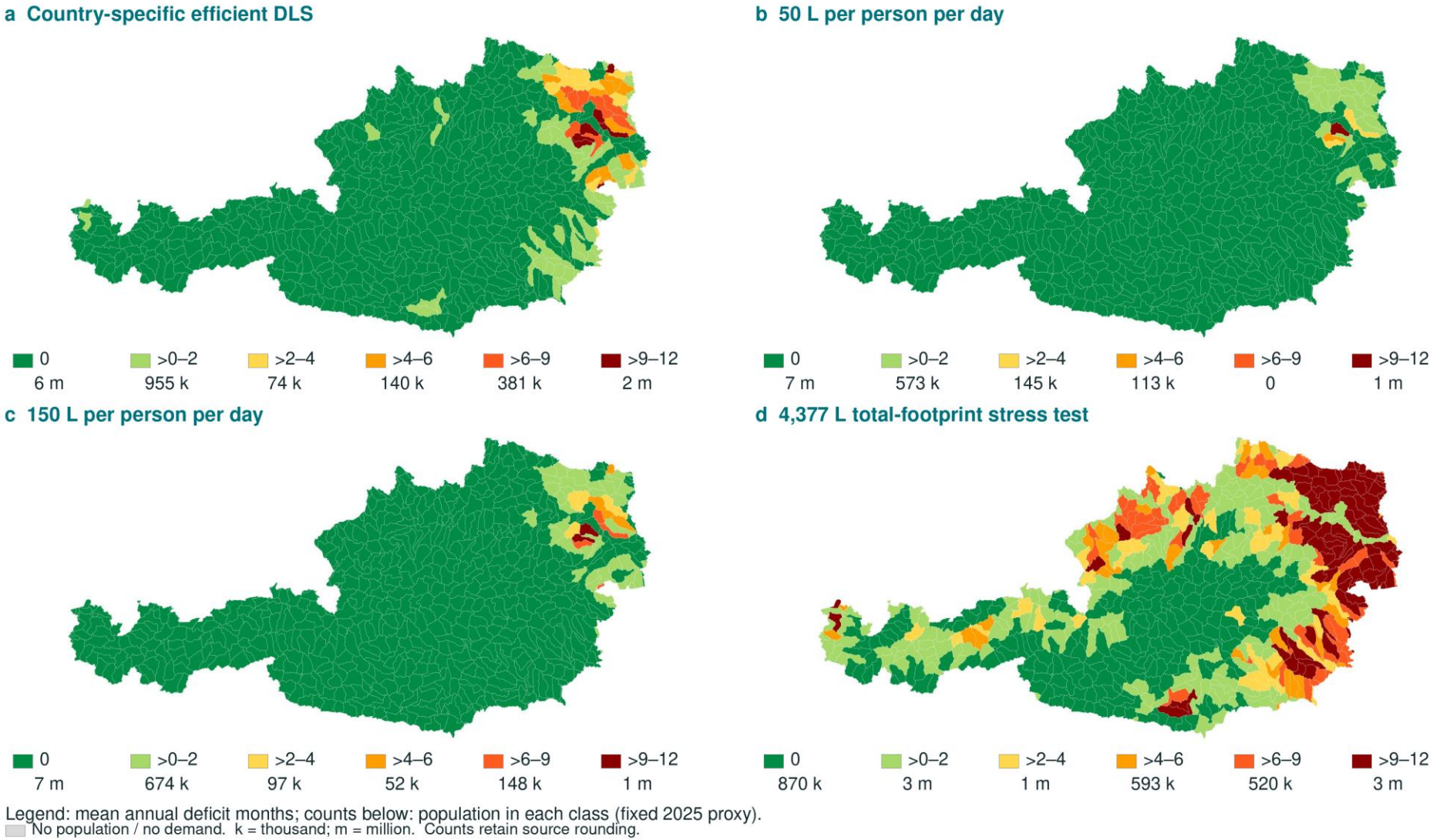

Figure 2: Mean annual deficit months in Austrian HydroBASINS level-12 study basins, 1950-2025. a) Efficient DLS; b) 50 L; c) 150 L person^{-1} day^{-1}; d) 4,377 L person^{-1} day^{-1} footprint stress test. Classes and the fixed 2025 population summary match Figure 1. Routing is restricted to the Austrian study network, excluding cross-border inflows. These historical map results should not be equated with the separate 2025 country calculation using the full global river network.

2.3 Demand assumptions change the 2025 sufficiency result

The separate calendar-year 2025 analysis estimated 12,084.326 km^3 of post-EFR water. Under efficient DLS, natural routing covered 54.7% of demand (Table 1). Coverage was 79.1% at 50 L and 69.4% at 150 L, falling to 24.8% in the footprint stress test. For DLS, 729.126 km^3 remained unmet even though 11,202.937 km^3 of source water remained unallocated at terminal outlets. The deficit and surplus occur in different basins or months and cannot be netted globally. These 2025 values also refer to a different analysis window from the 1991-2024 coverage of 58.5%. The direct-use benchmarks, wider DLS bundle and total-footprint stress test represent different demand assumptions, rather than interchangeable measures of observed consumption.

Table 1: Global calendar-year 2025 demand scenarios and natural routing. Panel a) reports annual demand, local and routed deficits and coverage; panel b) reports the reduction in deficit due to routing, unallocated source water and country medians. Coverage = (demand - deficit)/demand. The 4,377 L test includes non-blue-water equivalents; none of the scenarios represent observed withdrawal.

a) Annual demand and coverage

Scenario	Demand assumption	Demand $km^3\ yr^{-1}$	Local deficit $km^3\ yr^{-1}$	Local coverage %	Routed deficit $km^3 yr^{-1}$	Routed coverage %
Efficient DLS	Vélez-Henao country-specific	1,610.5	861.8	46.5	729.1	54.7
Basic needs	50 L/person/day	149.4	41.0	72.6	31.3	79.1
High domestic	150 L/person/day	448.3	173.2	61.4	137.4	69.4
Consumption stress test	4,377 L/person/day	13,080.6	10,515.2	19.6	9,836.2	24.8

b) Routing and remaining source water

Scenario	Deficit reduction by routing %	Unallocated source water $km^3\ yr^{-1}$	Median country routed coverage %	Median transboundary dependency %
Efficient DLS	15.4	11,202.9	63.1	5.8
Basic needs	23.7	11,966.2	91.8	4.3
High domestic	20.7	11,773.4	80.7	5.0
Consumption stress test	6.5	8,839.9	25.4	7.0

2.4 Annual national surplus can hide monthly shortfalls

In 2025, post-EFR runoff generated within national borders met or exceeded annual DLS demand in 127 of the 194 countries with positive modelled demand, yet these countries still had routed shortfalls of at least 1% of annual demand. Figure 3 shows the 30 most populous of them. An annual generation-to-demand ratio above one only compares national totals; it does not show whether water is available in the basin and month where demand is assigned. Across all 194 countries, demand-weighted unmet DLS demand fell from 53.5% locally to 45.3% after routing. The heatmap shows the monthly gaps underlying this difference.

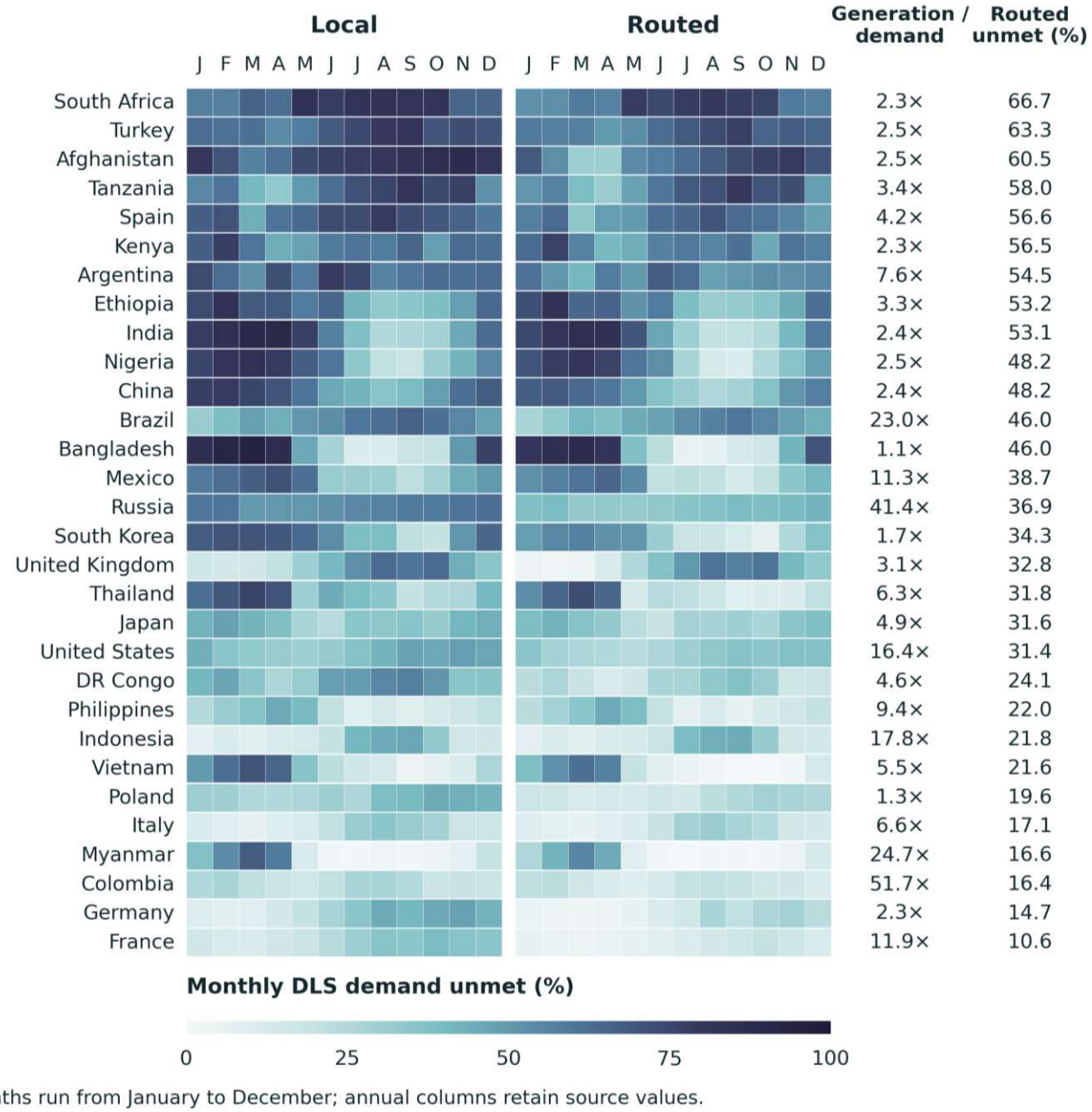

Figure 3: Annual national water generation and monthly efficient-DLS shortfalls in 2025. The 30 most populous countries among the 127 with annual post-EFR generation ≥ DLS demand and annual routed shortfall ≥1% are ordered by routed unmet share. Cells show monthly demand-weighted local and routed unmet demand, from January to December; the upper strip covers all 194 positive-demand countries. Right-hand columns give annual generation/demand and routed unmet share. Calendar months are modelled directly, without imposing wet/dry or four-season categories. Natural routing excludes engineered transfers and storage.

Brazil illustrates the mismatch: post-EFR runoff within its borders equalled 23.0 times annual DLS demand, yet 46.0% remained unmet after routing. Russia's values were 41.4 and 36.9%. Brazil's shortfall varies visibly by month, while Russia retains unmet demand throughout the year. The model uses calendar months without imposing wet/dry seasons for Brazil or four seasons for Russia. Water seasonality and demand location can both shape these patterns; the country heatmap cannot separate their effects. These scenario deficits do not describe observed household access.

2.5 Routing increases service and exposes upstream dependence

In the climatological DLS calculation, routing served an additional 126.1 km^3 yr^{-1}, increasing global coverage by 7.83 percentage points. Of this support, 92.1 km^3 yr^{-1} originated in domestic and 34.0 km^3 yr^{-1} in foreign upstream basins. Across the 1991-2024 country aggregation, 140 countries received some of their served demand from a foreign upstream source. Egypt illustrates this dependence: local generation met 0.08% of DLS demand, rising to 42.3% after routing; 99.8% of the demand served was attributed to foreign upstream sources. This modelled support is not an observed transfer or a guaranteed entitlement. Upstream dependence raises governance questions .

2.6 Austria links the maps to location-specific screening

The 2025 Austrian country calculation uses the global river network and therefore permits cross-border upstream support. With ERA5-Land input, post-EFR generation within Austria equalled 11.33 times national annual DLS demand. Nevertheless, 26.19% remained unmet locally and 3.02% after routing; December's routed unmet share was 5.66%. Figure 2 instead averages 1950-2025 and restricts routing to Austria. The map and the 2025 result both show why national abundance cannot establish local sufficiency, but their percentages are not directly interchangeable.

The European Environment Agency does not identify Austria among countries with seasonal WEI+ stress in 2023; Aqueduct 4.0 offers a similar national risk summary. These indicators describe water-use pressure, whereas the atlas tests specified demand in each basin and month. Its Austrian shortfalls therefore establish neither errors in those indicators nor observed supply failures. Eastern hotspots indicate locations for investigation. A facility assessment needs measured monthly consumption and returns, intake and discharge locations, upstream inflows and downstream claims.

2.7 Hydrological-product and basin-scale sensitivity

ERA5-Land estimates locally generated runoff; WaterGAP 2.2e discharge includes upstream water passing through rivers (Figure 4 and Figure 5). Their global analyses yielded 45,068 and 44,212 km^3 yr^{-1} before EFR, and 11,989 and 12,650 km^3 yr^{-1} after EFR. Routed DLS coverage was 58.5% in the ERA5-Land climatology and 66.7% in the WaterGAP source run, an 8.2 percentage-point difference. The paired maps cover 1991-2014; totals and coverage retain their respective periods. Because variables and windows differ, this is a sensitivity test, rather than like-for-like validation or an error range.

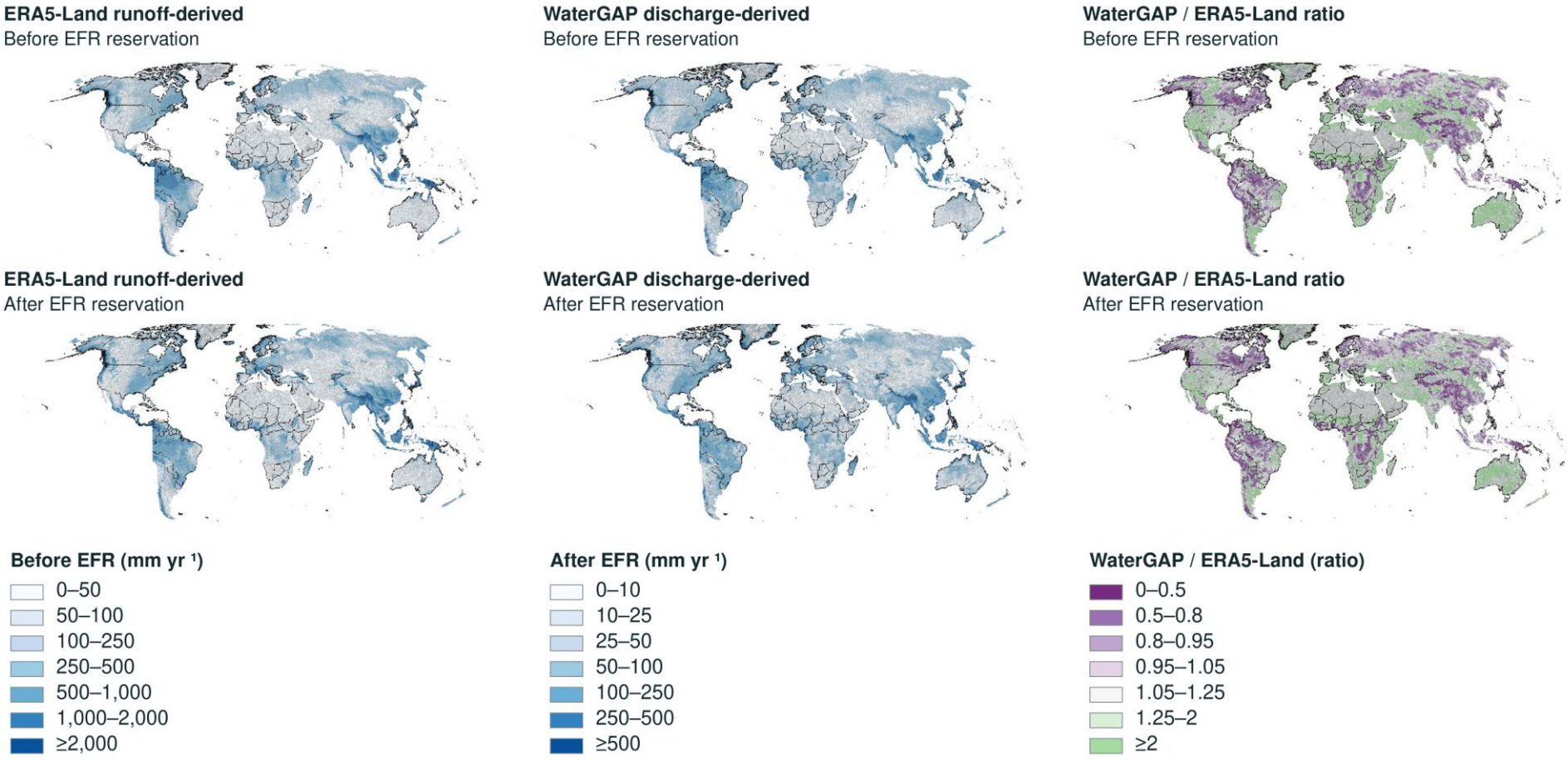

Figure 4: Hydrological-source sensitivity in global level-8 basins, 1991-2014. Columns show ERA5-Land runoff-derived resources, WaterGAP 2.2e discharge-derived resources and the WaterGAP/ERA5-Land ratio. Top and bottom rows show resources before and after EFR reservation. The enlarged common legends retain the original classes; ratios are masked where ERA5-Land is below 1 mm yr^{-1}. Runoff-derived generation and discharge-derived capacity represent different hydrological quantities.

The two sources also differed in seasonality. Across global basins, the median Pearson correlation between their seasonal patterns was 0.814, and the median shift in the month of peak water availability was one month. In a separate Austrian geometry test, subdividing the study area from level 10 to level 12 changed ERA5-Land post-EFR capacity from 36.88 to 36.60 km^3 yr^{-1}, a 0.8% difference. Associated DLS coverage was 93.72% and 93.59%; WaterGAP gave 93.91% and 93.76%. This tests sensitivity to basin delineation rather than reproducing the 2025 country balance. Similar aggregate values do not guarantee stable estimates for individual small basins.

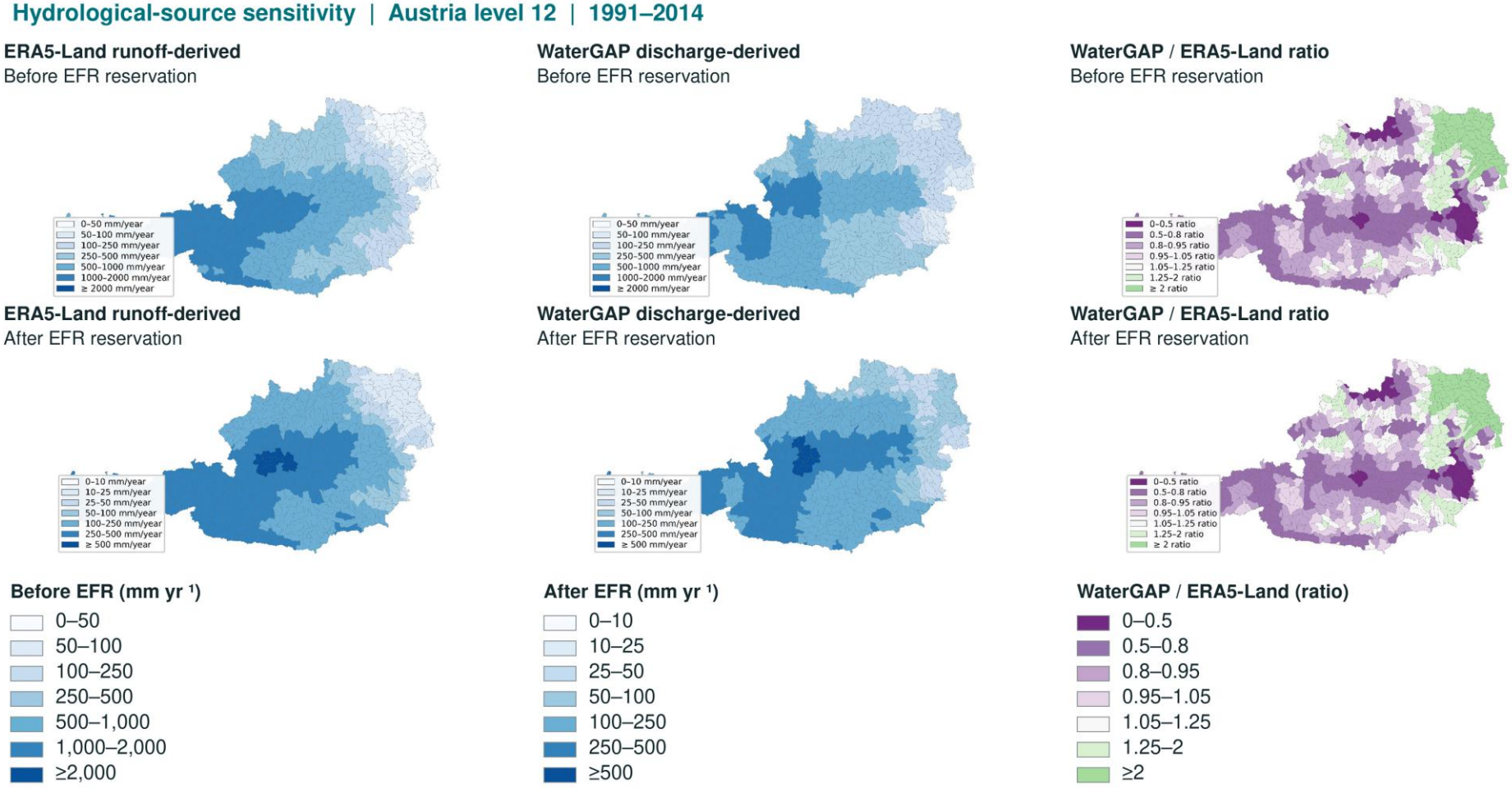

Figure 5: Hydrological-source sensitivity in Austrian level-12 basins, 1991-2014. Columns show ERA5-Land runoff-derived resources, WaterGAP discharge-derived resources and their ratio, before (top) and after (bottom) EFR reservation. Common legends retain the original classes. Ratios omit locations where ERA5-Land is below 1 mm yr^{-1}. Smaller basin polygons do not add independent hydrological detail to either input product.

The source and geometry tests address different uncertainties. Changing the hydrological input materially alters coverage; subdividing Austrian basins changes aggregate capacity only slightly. Neither validates individual catchment capacity. Local estimates need comparison with measured flows and equivalent hydrological inputs.

Figure 5 shows why a single national correction factor is inadequate. In some Austrian basins, WaterGAP-derived post-EFR capacity is less than half the ERA5-Land value; elsewhere it exceeds twice that value. These ratios compare different hydrological quantities, not error. A basin near full coverage may change class with the input. Source-equivalent data and observed flows are needed to establish the size and direction of that change.

2.8 Concordance with established water indicators

Figure 6 compares country rankings by atlas deficit with five external water indicators. Spearman's rank correlation (ρ) describes how similarly two lists order countries: +1 means identical order, while 0 means no consistent association. A value of 0.6 is therefore not a 60% match. We compared local and routed deficits. All ten correlations were positive (ρ = 0.52–0.67), so countries with larger deficits generally ranked as more stressed under the other indicators, although individual positions differed.

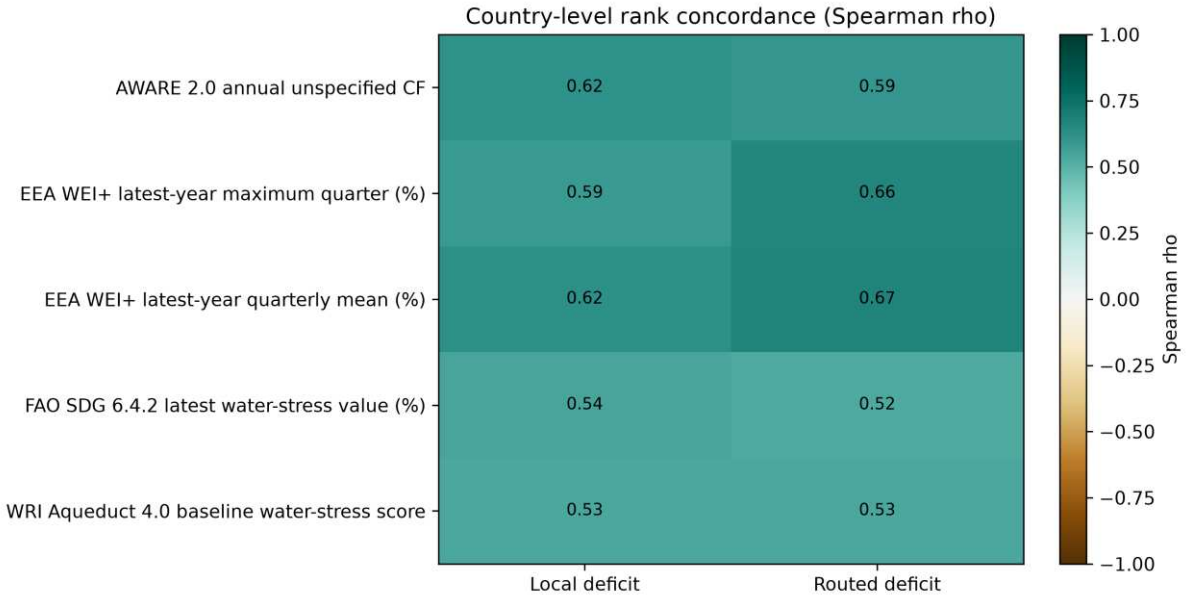

Figure 6: Agreement in country ranking between Water Atlas deficits and five external water indicators. Cells show Spearman's rank correlation (ρ) for local and routed deficits against Aqueduct 4.0 baseline water stress, FAO SDG 6.4.2, mean and maximum quarterly WEI+, and AWARE 2.0. Higher positive values indicate more similar country rankings. Definitions, periods and spatial aggregation differ, so concordance is not validation against observed shortages or Austrian basin-level flows.

Agreement was strongest with mean quarterly WEI+: ρ was 0.62 for local and 0.67 for routed deficits. Aqueduct gave 0.53 for both, while AWARE agreed more strongly with local deficits (0.62 versus 0.59 routed). The indicators differ in demand definitions, environmental-flow treatment and periods. The atlas tests a specified human need against basin water availability; the others measure water stress or scarcity impacts. These correlations are a country-level plausibility check and cannot show improved routing accuracy or validate observed shortages.

3. Discussion

The atlas links the planetary freshwater concern to a regional question about meeting human needs. Planetary boundaries address Earth-system; safe and just Earth system boundaries also consider surface-water flow alteration at subglobal scales stability . Calls for indicators that describe water scarcity more directly highlight the need for regional information. Our 100% coverage threshold tests whether modelled water remaining after EFR can meet a stated demand in one basin and month. It does not numerically downscale the planetary boundary. The output identifies where and when a capacity gap remains under declared ecological and human claims, with uncertainties in runoff, EFR, demand, routing and spatial or temporal aggregation.

The global result exposes the practical importance of matching supply to demand: post-EFR water exceeded efficient DLS demand sevenfold, but natural routing met 58.5% in the climatological ledger. The 2025 heatmap sharpens the same point at country scale. If renewable water arises in one catchment, it does not necessarily supply another without a connected flow path, engineered transfer or legal and institutional arrangements; seasonal surplus likewise cannot automatically supply another month. Routing therefore distinguishes local hydrological self-sufficiency from conditional upstream support. A high routed share with low local coverage also implies sensitivity to upstream change, even though the ledger does not predict rights, infrastructure or political choices.

The local and routed outputs support three distinct screening interpretations. Where local post-EFR generation covers all stated demand, the basin-month is locally sufficient under the modelled scenario. Where a local deficit closes after routing, sufficiency depends on upstream surplus remaining after upstream claims are met; the source ledger shows whether that dependence crosses a border. Where a deficit persists after routing, the modelled natural network cannot meet the stated demand that month. These cases direct different follow-up questions about local flows, upstream reliability and possible managed supplies. None establishes actual water access, legal rights or a share available to a facility.

The sufficiency result depends on the need being tested. The basic direct-use benchmark and efficient DLS cover different bundles; the 4,377 L footprint case also includes green and grey water and cannot define a blue-water withdrawal limit . For regional AESA, the atlas supplies an initial estimate of capacity. Comparing a company, city or population with a justified share still requires hydrological validation, measured monthly consumption and returns, ecological and downstream claims, and a rule for sharing capacity. This additional evidence is also needed before the result can inform an entity-specific European Sustainability Reporting Standard E3 materiality assessment .

For a facility, the atlas identifies the basin and months requiring closer examination; it cannot assign a usable water budget on its own. A basin marked as sufficient may still face competing abstractions or depend on storage outside this ledger. Conversely, a mapped deficit may be offset in practice by managed transfers or groundwater. A site-level AESA must therefore establish the facility's intake and return locations and timing, its consumptive use, and the claims of other users. Only after validating the basin capacity and specifying an allocation rule can that use be compared with a defensible share of remaining water.

Hydrological sensitivity remains central to this interpretation. ERA5-Land and WaterGAP differ materially in estimated coverage, while similar Austrian totals at basin levels 10 and 12 say little about error in an individual catchment. External indicators also measure different constructs: FAO SDG 6.4.2 is a withdrawal-based stress ratio ; WEI+ measures water-use pressure; Aqueduct provides water-risk indicators; and AWARE characterises scarcity impacts of water consumption . Figure 6's positive rank correlations ($\rho = 0.52–0.67$) are a country-level plausibility check. They cannot validate monthly basin capacity, establish that routing improves accuracy, or verify the Austrian hotspots against measured flows or shortages.

The main limitations are modelled runoff and discharge, approximate global EFR, assumed human demand and natural routing without reservoirs, engineered transfers or interannual storage. Groundwater, water quality, return-flow timing, rights, affordability and access are incompletely represented. Demand assigned to residents does not reconstruct supply-chain withdrawal locations. Historical-map population summaries use a 2025 proxy, and level-12 polygons do not provide level-12 meteorological detail. Austria's historical maps also exclude cross-border inflows, unlike the 2025 global-network calculation. Independent validation against gauged flows and a source-equivalent WaterGAP runoff calculation are needed before assigning capacity to particular users. A deficit denotes a modelled scenario gap, not observed deprivation.

4. Conclusion

Global freshwater abundance does not guarantee that water is available where and when it is needed. The atlas tests this at monthly basin scale by reserving environmental flows, matching local runoff to stated human demand and following remaining surplus downstream without double counting. It distinguishes local sufficiency, dependence on upstream water and deficits that persist after routing. In the climatological analysis, post-EFR water exceeded efficient DLS demand more than sevenfold, yet natural routing covered only 58.5%. Global maps, the 2025 heatmap and the Austrian case reveal gaps hidden by national annual balances. Sensitivity tests qualify the capacity estimates, and external indicators provide a country-level plausibility check. The atlas can therefore guide regional AESA towards the basins and months needing closer investigation. A site-specific assessment still requires validated flows, measured consumptive use and a defensible allocation among users.

5. Material & Methods

5.1 Accounting units, periods and input datasets

We calculated monthly renewable surface-water sufficiency across 190,675 global HydroBASINS level-8 basins, with nested Austrian level-10 and level-12 basins. HydroBASINS supplies the basin boundaries and NEXT_DOWN links, which identify each basin's downstream neighbour . We aggregated ERA5-Land monthly runoff to these polygons using area-weighted raster overlap . Runoff depth and basin area provide locally generated water volumes. GHS-POP R2023A population grids were normalised to a 2025 country proxy and used to assign demand spatially . Ecological reservation drew on the International Water Management Institute's Global Environmental Flows Information System (GEFIS) . For hydrological-source sensitivity, we used WaterGAP 2.2e discharge from the Inter-Sectoral Impact Model Intercomparison Project . The WaterGAP 2.2d model description documents the related lineage, rather than the exact 2.2e dataset. WaterGAP's 0.5° grid supplies no additional hydrological detail when subdivided into smaller basin polygons.

The primary ERA5-Land climatology spans 1991-2024. We separately calculated calendar-year 2025 and the mean annual number of deficit months over 1950-2025, with fixed 2025 population proxy only for historical-map summaries. Spatial product ratios use the 1991-2014 period shared by ERA5-Land and WaterGAP; the global totals and DLS coverages reported here retain their respective analysis windows. Negative numerical runoff artefacts were set to zero and flagged. A diagnosed attenuation in archived ERA5 precipitation and runoff from September 2022 to February 2024 was corrected from a renewed ERA5-Land monthly-averaged-by-hour-of-day 00:00 source before basin caches were regenerated; evaporation was not subtracted from runoff twice.

5.2 Ecological reservation and human demand

EFR were reserved before any human demand was served. GEFIS fractions were bounded between zero and one and aggregated to basins. Where fractions were absent, the variable monthly flow method reserved 60%, 45% or 30% of monthly flow under low-, intermediate- and high-flow conditions, respectively . These are screening estimates rather than locally agreed ecological standards. The main scenario used country-specific efficient DLS water-use intensities . We compared it with 50 L person^{-1} day^{-1} for basic direct needs and a selected 150 L high-domestic benchmark . The latter is a scenario choice, consistent with the upper end of the 120-150 L household-use range discussed in the Austrian footprint study . That study also reports the 4,377 L person^{-1} day^{-1} total footprint used for the final stress test. Because it combines blue, green and grey water equivalents, this case is a broad sensitivity comparison rather than physically withdrawable blue-water demand. None of the scenarios describes observed water use in the assessed basin.

Country-specific DLS water-use intensities were assigned to the residential basin of the modelled population. This consumer-basin rule asks what locally available water would be needed to support the stated living-standard bundle of those residents. It does not locate the farms or factories producing their goods, or trace virtual-water trade. Accordingly, each deficit compares resident-assigned scenario

demand with modelled post-EFR blue-water availability under the chosen routing rule; it is not a reconstruction of supply-chain withdrawals.

5.3 Exclusive routing and sufficiency metrics

NEXT_DOWN links defined a directed river-network graph. We removed invalid links and self-loops and processed basins from upstream to downstream. In each month, post-EFR local runoff first served the basin's own demand. Still unallocated incoming water then served any remaining demand. Only surplus left after these claims moved to the next downstream basin. Each assigned unit retained its source basin and country in a source-destination ledger, preventing the same water from serving more than one claim. Water merely passing through a basin was not counted again as new local generation. Global historical maps permit natural transboundary routing; Austrian historical maps restrict links to the Austrian study network. The separate 2025 national calculation uses the global network.

Demand-weighted coverage equals served demand divided by stated demand; deficit volume is the remaining unmet amount. A basin-month is deficient if local or routed coverage, according to the calculation being reported, is below 100%. Annual coverage aggregates monthly served demand and demand, rather than offsetting monthly deficits against unrelated surpluses. Historical maps average annual deficit-month counts over 1950-2025. For Figure 3, we selected 2025 countries with annual post-EFR national generation ≥ annual DLS demand and a routed deficit ≥1% of that demand. Of 194 positive-demand countries, 127 qualified, and the 30 most populous are shown. The climatological aggregation reports 195 country units, a different reporting set from the 2025 positive-demand subset. Monthly source data and the scenario workbook provide the Figure 3 and Table 1 values.

5.4 Sensitivities and interpretation for absolute assessment

The source comparison distinguishes ERA5-Land runoff-derived generation from WaterGAP 2.2e discharge-derived capacity. We compared aggregate post-EFR water and DLS coverage, correlations between basin seasonal patterns, peak-month offsets and pre- and post-EFR map ratios over the shared 1991-2014 period. Global totals and coverage retain the analysis windows stated above. The Austrian geometry test compares full-basin estimates at levels 10 and 12, separately from the country-assigned 2025 balance. WEI+ and Aqueduct provide complementary comparisons with different periods, use definitions and spatial summaries . WaterGAP discharge includes upstream flow and cannot be counted as new local generation in every downstream basin. A source-equivalent test would aggregate WaterGAP total runoff (qtot) to the same polygons and apply the same EFR and exclusive routing rules. The present comparison is a sensitivity analysis, not validation against gauged flows.

For facility-level AESA, water remaining in a basin and month after EFR, prioritised human demand and preceding upstream allocation is a candidate capacity estimate. An absolute assessment additionally requires observed facility consumption and returns, claims by other users, and a defensible sharing rule, with groundwater, storage, water quality and applicable rights considered. The atlas alone assigns neither a corporate fair share nor a legal or reporting verdict. Workflow quality controls check units, topology, joins, EFR bounds and mass conservation. Figure 7 separates the basin-capacity screening

step from the subsequent facility assessment; it does not imply numerical downscaling of the planetary boundary.

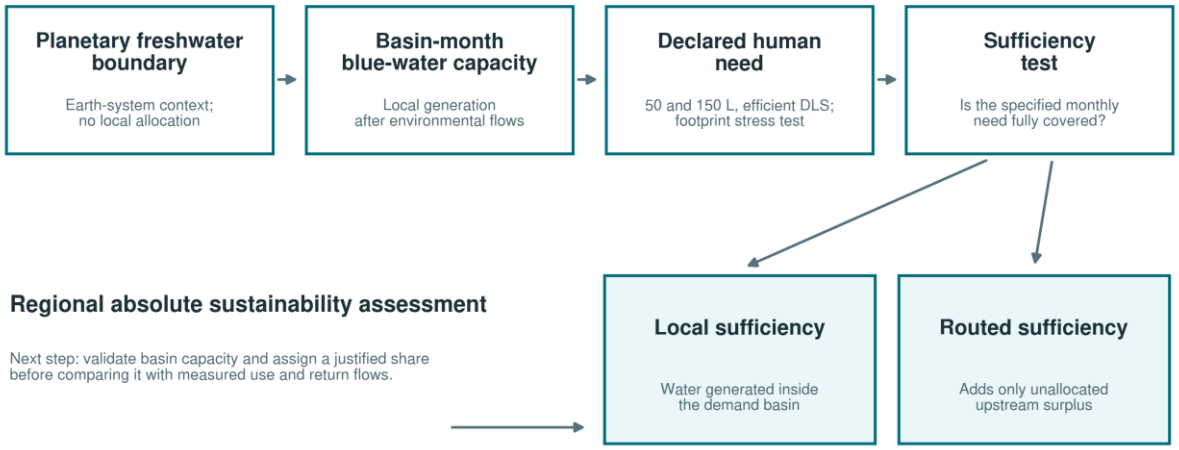

Figure 7: Assessment sequence from the planetary freshwater context to basin-month screening for regional AESA. Environmental flows are reserved before stated human need is compared with local runoff and, separately, uniquely allocated upstream surplus. A facility-level absolute assessment additionally needs validated basin capacity, measured consumptive use and a justified allocation. The arrows do not represent numerical downscaling of a planetary boundary.

5.5 Country-rank comparison with external indicators

For Figure 6, we compared country ranks of local and routed atlas deficits with Aqueduct 4.0 baseline water stress , FAO SDG 6.4.2 water stress , WEI+ latest-year quarterly mean and maximum, and AWARE 2.0 annual unspecified characterization factors. Spearman correlations describe the ordering of countries available to each pair; country coverage, periods, weighting, use definitions and spatial units differ. These are not estimates of predictive accuracy or comparisons aligned to one common demand scenario. In particular, national concordance cannot validate the Austrian level-12 maps or identify the ecological and infrastructure causes of their hotspots. Austria requires separate basin-level checks against observed flows and supply conditions.

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- WaterAtlaspaperandsupplementtables2025monthlylocalandrouted.xlsx