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Virtual-water bottlenecks expose Europe's supply chains to risks

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Virtual-water bottlenecks expose Europe's supply chains to risks

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Abstract

In Europe, water security is increasingly becoming both a supply chain issue and a local resource concern. We map blue-water use embodied in trade across 303 regions linked to EU demand by combining a NUTS-2 environmentally extended input-output framework with WaterGAP consumption estimates and Aqueduct water stress indicators. Approximately 90% of the water embodied in EU consumption originates outside the consuming region, and about half crosses NUTS-2 borders within Europe. Supply is highly concentrated: 12 regions account for roughly half of intra-EU virtual-water exports, with irrigated agriculture driving most flows. Overlaying export intensity with regional stress reveals 25 bottleneck regions, concentrated in Mediterranean Europe, that are both major suppliers and highly water stressed. These dependencies expose consumers across the Single Market to drought-sensitive production shocks. Current EU water, agricultural and market governance does not systematically manage this concentration-stress overlap.

Water crosses European regions less through pipes than through goods. This hidden movement of freshwater through production and trade, commonly termed virtual water[1,2], underpins food, manufacturing and energy supply chains across the European Single Market. Despite these substantial flows, policy and risk management of water flows remain largely territorial[3]. Water is regulated at source, whereas demand is organized through integrated markets spanning very different hydroclimatic zones. As climate extremes intensify, this gap between where water is used and where products are consumed is becoming increasingly important for structural resilience[4,5].

Europe is warming faster than any other continent, with recurrent droughts and declining renewable water availability in several southern basins[6–8]. At the same time, consumption in many regions depends on production in irrigation-intensive areas that already experience high competition for water. In principle, trade can reduce pressure by shifting water-intensive production to water-abundant regions[9,10]. In practice, specialization, subsidies, infrastructure lock-in and historical production networks can produce the opposite pattern, where water-intensive export production may concentrate in areas that already have become stressed[11].

We therefore ask three questions: First, how much of the water embodied in European consumption is locally sourced, imported from other European regions, or sourced from outside Europe? Second, how concentrated are intra-European virtual-water supplies at country and NUTS-2 levels? Third, to what extent do major supplier regions overlap with high baseline water stress? We answer these questions by combining environmentally extended multi-regional input-output (MRIO) analysis with spatially explicit blue-water consumption data and regional water stress indicators.

Our contribution is threefold. First, we provide a harmonized NUTS-2 map of virtual-water dependence linked to European final demand. Second, we identify concentration patterns that create supply-side vulnerability within the Single Market. Third, we quantify bottleneck regions where export concentration overlaps with high water stress. The results show that European water resilience cannot be secured by local efficiency measures alone[12–14]. It also requires supply chain governance that explicitly addresses geographic concentration and hydrological exposure[15].

The argument builds on a growing body of work showing that externalized water use has become a defining feature of modern consumption systems[16,17]. Classical virtual-water studies focused on national balances and bilateral trade asymmetries, showing how water-scarce economies import water-intensive goods while water-abundant economies export them. That evidence remains foundational, but it can hide concentration at finer spatial scales. A country that appears diversified in aggregate may rely heavily on only a few subnational production zones for key crops or inputs. For policy, this distinction is essential because droughts, water-allocation conflicts and infrastructure bottlenecks are spatially uneven, often below the national scale.

Like in many other parts of the world, a regional focus is also relevant for Europe. The EU has deep market integration but fragmented hydro-ecological and weather conditions. Rainfed and irrigation-intensive systems coexist within the same customs area, and supply chains connect them

through just-in-time logistics and common standards. As a result, water-related risk exposure can propagate across borders and sectors even when local water indicators in consuming regions appear stable. This can produce a false sense of resilience if monitoring remains bounded by administrative territory rather than by production networks.

A second motivation concerns the changing climate baseline that has been a dominant driver of freshwater anomalies[5,18,19]. Mediterranean and other regions have already experienced successive drought events that reduced yields, induced price increase, constrained irrigation allocations and shifted planting decisions[8,20]. These shocks are not isolated incidents. They occur in regions that are also central suppliers to broader European markets. If such regions are repeatedly stressed, the consequences include local welfare and ecosystem service losses, price volatility and supply shocks for downstream consumers and processors. Export concentration therefore converts climate hazard into systemic supply chain risks.

A third motivation is institutional. The EU has advanced frameworks for water status assessment, adaptation planning and corporate sustainability reporting. Yet these frameworks are not consistently integrated around a common metric of supply chain dependence on scarce water sources. Without that integration, policymakers can track water basin stress without knowing which stressed basins anchor continental supply chains, and firms can report aggregate risk exposure without identifying whether they rely on the same high-risk supplier nodes as their competitors. The result is fragmented risk visibility.

Our approach addresses this gap by combining three elements in one accounting frame: (1) production-network structure, (2) consumptive water concentration, and (3) water stress exposure at the same regional scale. This allows us to move from descriptive statements about high water use to a system-wide diagnosis of where dependency, concentration and scarcity can be evaluated jointly. Regions that are high exporters of virtual water but show low water stress levels represent manageable dependencies. Regions that are high virtual water exporters and experience high water stress represent strategic vulnerabilities.

We first report dependence and concentration in intra-European virtual-water trade. We then map the overlap between regional export concentration and water stress to identify bottlenecks. Finally, we discuss implications for transparency, diversification and adaptation, before detailing the methods.

Results

Most embodied water is imported across regions

The first result is the scale of cross-regional dependence[2,10]. Only about one tenth of the blue water embodied in EU27+2 (the 27 EU member states plus Norway and the United Kingdom) final

demand is sourced in the same NUTS-2 region where final consumption occurs (Fig. 1a). Around half is sourced from other European regions, while roughly two fifths originates outside the EU27+2 system.

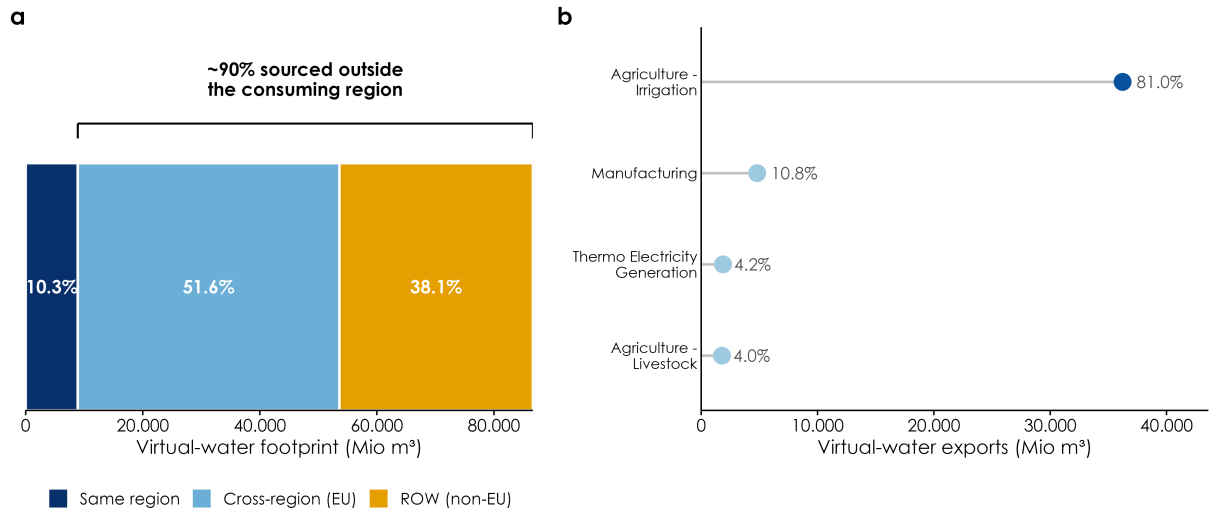


Figure 1: a) Composition of blue-water sources embodied in EU27+2 final demand: local same-region sources, inter-regional intra-European sources and extra-European sources. b) Sectoral composition of intra-European inter-regional virtual-water exports. Data: FIGARO + WaterGAP 2.2e.

This composition implies that most European consumers rely on freshwater sourced elsewhere[9,16]. The implication is not just that trade is important, but that regional water security cannot be inferred from local balances alone. Even regions with moderate local stress can be exposed if their embodied water originates from constrained supplier regions.

The result also clarifies why conventional water accounting can underestimate systemic exposure. Local status indicators are indispensable for basin governance, but they do not reveal whether critical consumption goods depend on remote stressed production zones. In other words, local adequacy does not guarantee supply chain resilience[15,17]. The structure in Fig. 1a indicates that a large share of effective water dependence is imported, meaning that resilience analysis must include upstream regions.

This imported dependence has distinct policy consequences. Interventions that only reduce household or municipal water demand may improve local water balances while leaving embodied import dependence unchanged. Conversely, changes in sourcing, contracts or product mix can alter system exposure without requiring large domestic infrastructure investments. The policy challenge is therefore not only to reduce total demand, but also to reduce dependence on highly stressed origins.

Intra-European virtual water supply is concentrated in few Mediterranean regions

Concentration is strong at both country and regional levels. Spain, Italy and Greece account for the largest shares of intra-European virtual water exports. At NUTS-2 resolution, concentration becomes even more pronounced: 12 regions account for approximately half of all inter-regional virtual-water exports inside Europe (Fig. 2; Table 1). Andalucia (NUTS2 ID: ES61) in Spain alone contributes about 11%.

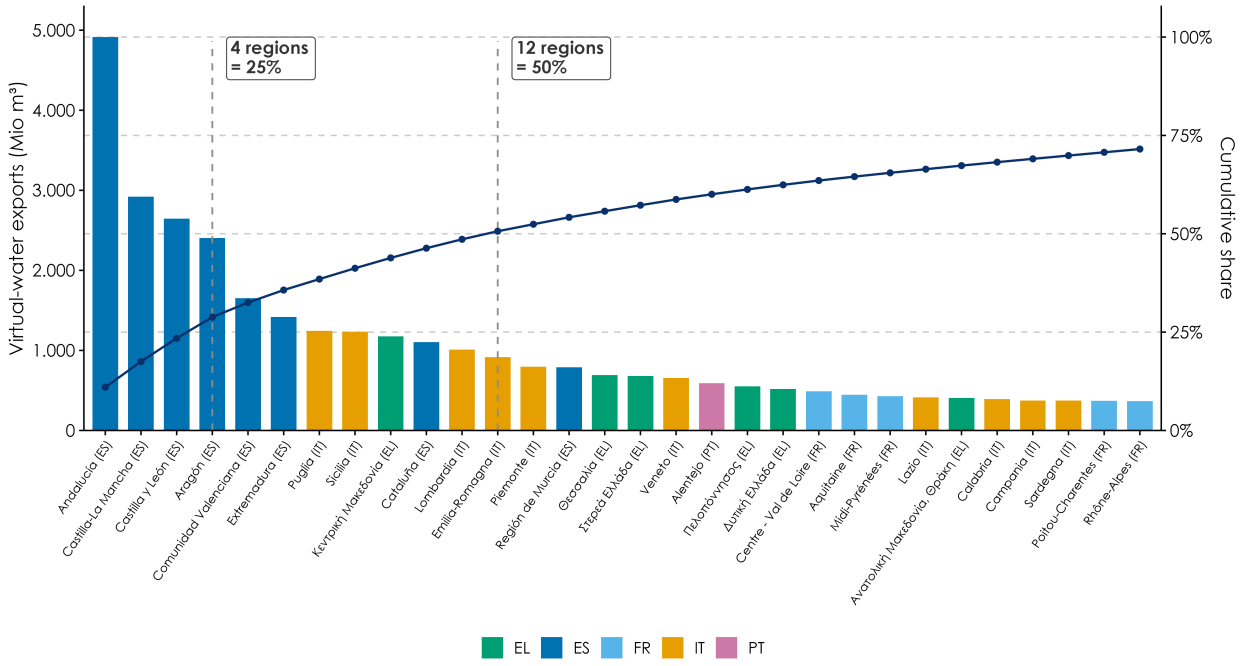


Figure 2: Concentration of intra-European inter-regional virtual-water exports across the top 30 NUTS-2 regions. Bars show regional export volumes (coloured by country); the line shows the cumulative share (right axis). Dashed horizontal lines mark 25/50/75/100%; vertical markers indicate that about 12 regions supply half of all exports (4 regions a quarter). Data: FIGARO + WaterGAP 2.2e.

Table 1: Top 20 NUTS-2 regions by inter-regional virtual water exports within the EU. Volumes in million m^3/year. Data: FIGARO + WaterGAP 2.2e.

Rank	NUTS-2	Region Name	Country	Exports (Mm^3)	Share (%)	Cum. (%)
1	ES61	Andalucia	ES	4,914	11.0	11.0
2	ES42	Castilla-La Mancha	ES	2,920	6.5	17.5
3	ES41	Castilla y Leon	ES	2,646	5.9	23.4
4	ES24	Aragon	ES	2,403	5.4	28.8
5	ES52	Comunidad Valenciana	ES	1,654	3.7	32.5
6	ES43	Extremadura	ES	1,419	3.2	35.7
7	ITF4	Puglia	IT	1,245	2.8	38.5
8	ITG1	Sicilia	IT	1,235	2.8	41.2
9	EL52	Kentriki Makedonia	EL	1,175	2.6	43.9
10	ES51	Cataluna	ES	1,103	2.5	46.3
11	ITC4	Lombardia	IT	1,010	2.3	48.6
12	ITH5	Emilia-Romagna	IT	915	2.0	50.6
13	ITC1	Piemonte	IT	795	1.8	52.4
14	ES62	Region de Murcia	ES	788	1.8	54.2
15	EL61	Thessalia	EL	693	1.5	55.7
16	EL64	Sterea Ellada	EL	681	1.5	57.3
17	ITH3	Veneto	IT	656	1.5	58.7
18	PT18	Alentejo	PT	589	1.3	60.0
19	EL65	Peloponnisos	EL	552	1.2	61.3
20	EL63	Dytiki Ellada	EL	519	1.2	62.4

The concentration profile is highly right-skewed. In a system of 288 NUTS-2 regions based on 2017 definitions, many regions export modest embodied-water volumes, while a small set carries disproportionate system importance. This topology matters for resilience: when a few nodes dominate supply, hazard events in those nodes have greater potential to cascade broadly through dependent value chains.

From a network perspective, this is a centrality problem[21,22]. Regions near the top of the distribution are not only large producers, they are key providers for multiple downstream chains simultaneously. Their disruption could therefore create correlated supply pressures across commodities and jurisdictions. Substitution may be possible over longer horizons, but near-term flexibility is constrained by seasonality, product standards, logistics infrastructure and processing capacity.

The geography of concentration also matters. The leading regions cluster in southern Europe, where high-value irrigated agriculture has long been integrated into continental food systems. This specialization has delivered welfare gains through stable supply and competitive prices, but it has also created path dependence. Investments in cold-chain logistics, contracts, crop varieties and processing capacity have reinforced these trade corridors, making rapid diversification difficult when hydrological conditions deteriorate.

Concentration further implies uneven adaptation burdens[7,12,23]. Regions that supply large embodied-water volumes effectively provide resilience services to the broader market, yet they often bear the

highest local costs of water scarcity management and investments in adaptive infrastructure upgrades. Without explicit recognition of this system role, financing and policy support may remain misaligned with where adaptation yields the largest continental benefit.

Irrigated agriculture dominates embodied-water flows

Sectoral decomposition shows that irrigated agriculture is the principal transmission channel of embodied-water risk exposure (Fig. 1b). It contributes around 81% of inter-regional virtual-water exports. Manufacturing adds the next-largest share (11%), while thermal power and livestock are minor (4% each).

The dominance of irrigation agriculture representing the highest embodied water flows is expected under a water consumption measure. In contrast, withdrawals in power generation and industry can be high, but substantial water volumes are often returned to freshwater systems. Irrigation consumption is more depletive because water is transpired, evaporated or incorporated into biomass. For supply chain resilience, this distinction is critical because consumptive use determines pressure on the water resource that can constrain future production.

This sectoral breakdown has practical implications for risk management. If most virtual water is concentrated in irrigated agri-food chains, water resilience strategies should prioritize crop-portfolio diversification, irrigation efficiency, drought contingency planning and contract structures that reduce simultaneous dependence on a narrow set of stressed territories. Generic economy-wide measures will be less effective than interventions targeted at these dominant channels.

The result also helps reconcile tensions between efficiency and resilience narratives. A region can appear efficient in trade terms while increasing systemic hydrological exposure, if output growth is concentrated in high-withdrawal sectors under stressed conditions. Efficiency and resilience are therefore not automatically aligned[24,25]. Policy must evaluate both production efficiency and stress-adjusted water dependency.

Finally, the sectoral distribution suggests that price volatility in selected food categories could serve as an early-warning indicator of virtual water stress transmission. Monitoring these categories alongside regional hydrological indicators could improve anticipatory governance and reduce reliance on ex-post emergency responses.

Bottleneck regions combine export centrality with high stress

To evaluate vulnerability, we overlay inter-regional export intensity with WRI Aqueduct baseline water stress indicators[26]. The resulting bivariate map (Fig. 3) identifies a high-exposure quadrant: regions that are both major virtual water exporters and highly water-stressed.

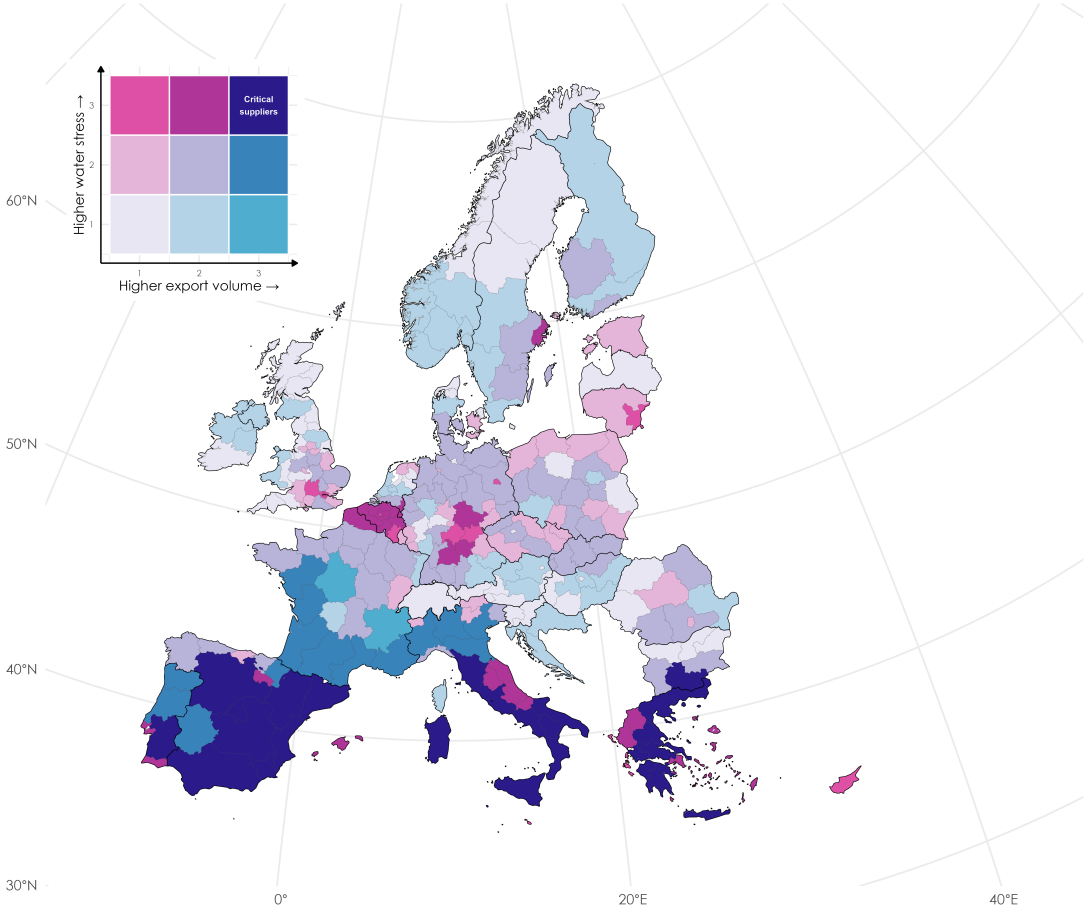


Figure 3: Bivariate classification of 288 European NUTS-2 regions by intra-European virtual-water export intensity (legend x-axis) and baseline water stress (legend y-axis; WRI Aqueduct 4.0). Inter-regional blue-water exports (Mm^3) are grouped into three classes using Jenks natural breaks on log-transformed values; water stress follows Aqueduct thresholds. The darkest class (top-right) marks bottleneck regions that are simultaneously major exporters and highly water-stressed (n = 25; see Table 2). Grey: no data. Year: 2017. Data: FIGARO + WaterGAP 2.2e + WRI Aqueduct 4.0.

Twenty-five regions fall into this bottleneck category. Most are in Mediterranean Europe, particularly Spain, Italy, Greece and Portugal, with one high-exposure case in Bulgaria. Among high-export regions, only a small minority are in low-stress classes.

Table 2: Bottleneck regions: NUTS-2 regions classified as high virtual water exporters with high or extremely high baseline water stress. Ranked by export volume. Data: FIGARO + WaterGAP 2.2e + WRI Aqueduct 4.0.

Rank	NUTS-2	Region Name	Exports (Mm^3)	BWS	Stress Level
1	ES61	Andalucia	4,914	4.43	Extr. High
2	ES42	Castilla-La Mancha	2,920	4.15	Extr. High
3	ES41	Castilla y Leon	2,646	3.61	High
4	ES24	Aragon	2,403	3.26	High
5	ES52	Comunidad Valenciana	1,654	4.00	Extr. High
6	ITF4	Puglia	1,245	4.90	Extr. High
7	ITG1	Sicilia	1,235	5.00	Extr. High
8	EL52	Kentriki Makedonia	1,175	3.86	High
9	ES51	Cataluna	1,103	3.27	High
10	ES62	Region de Murcia	788	5.00	Extr. High
11	EL61	Thessalia	693	4.87	Extr. High
12	EL64	Sterea Ellada	681	4.56	Extr. High
13	PT18	Alentejo	589	3.35	High
14	EL65	Peloponnisos	552	4.53	Extr. High
15	EL63	Dytiki Ellada	519	4.53	Extr. High
16	ITI4	Lazio	414	4.51	Extr. High
17	EL51	Anat. Makedonia, Thraki	407	3.26	High
18	ITF6	Calabria	393	5.00	Extr. High
19	ITF3	Campania	376	4.54	Extr. High
20	ITG2	Sardegna	374	4.12	Extr. High
21	EL43	Kriti	329	5.00	Extr. High
22	ITI1	Toscana	288	4.36	Extr. High
23	ITF5	Basilicata	267	5.00	Extr. High
24	ES30	Comunidad de Madrid	200	4.48	Extr. High
25	BG42	South Central Bulgaria	150	3.52	High

BWS = Baseline Water Stress (WRI Aqueduct 4.0). High: 40–80%; Extr. High: >80%.

These bottlenecks have two distinct implications. First, supplier regions face elevated production exposure from drought, water allocation conflicts and ecosystem constraints. Second, consuming regions may have limited substitution capacity at comparable scale in the short run because production networks and logistics are path-dependent. The combination creates continental exposure to localized hydrological shocks and supply chain vulnerabilities.

This exposure is likely to be strongest in product chains that combine seasonal perishability, irrigation dependence and limited short-run sourcing flexibility. Fresh produce, animal feed and water-intensive intermediate food inputs are especially vulnerable because substitution is constrained not only by price, but also by harvest calendars, supply contracts and processing capacity. A shortfall in one major supplier region can therefore cascade through multiple downstream channels at once, affecting direct food availability, input costs for processors and feed prices for livestock production. The practical implication is that systemic dependence does not require every consuming region to depend on every bottleneck. It is sufficient that a small number of stressed suppliers anchor key market segments for a large set of downstream users[27,28].

Understanding these bottlenecks also helps distinguish between scale and substitutability. Over time, some large exporters may be replaced by more resilient ones, if similar agro-climatic production zones and logistics networks exist elsewhere, or if new technological solutions emerge. Others are harder to replace because they occupy specialized niches built around irrigation infrastructure,

crop portfolios and long-established trade relationships. A policy-relevant reading of the map is therefore that some regions combine size, stress and low substitutability. These are the points where hydrological disruption is most likely to translate into European supply-chain instability.

The bottleneck map also reveals an asymmetry between risk ownership and risk impact. Although hydrological risk is physically concentrated in supplier regions, its economic impacts are geographically diffuse across consumer and processing regions. This asymmetry complicates governance because jurisdictions bearing the physical burden may not fully capture the downstream benefits of their adaptation investments[12,14,23]. Coordinated policy and co-financing mechanisms on the EU level are therefore necessary to align incentives with system-wide resilience goals.

Importantly, bottleneck status does not imply inevitable failure. It identifies where preventive action has the highest expected value. Regions in this class can remain reliable suppliers if adaptation trajectories outpace stress growth, governance institutions maintain credible allocation rules and demand-side pressures are moderated. The bottleneck classification should therefore be interpreted as a prioritization tool rather than a deterministic forecast.

A complementary insight is that not all high-stress regions are equally system-critical. Some regions face severe stress but export limited embodied-water volumes and therefore have lower transmission potential. Conversely, some high-export regions currently maintain moderate stress and may offer near-term diversification opportunities. Distinguishing these profiles is essential for targeted rather than uniform policy responses.

Bottleneck risk exposure is embedded in observed trade structures

As our accounting year is 2017, it represents an observed trade structure rather than a hypothetical future scenario. The concentration-stress overlap is thus already embedded in the measured architecture of European trade. Climate projections for Mediterranean regions indicate likely stress intensification, but even without scenario modeling, recent drought episodes show that water shocks can translate into supply disturbances. The central concern is therefore not only future climate change, but also the vulnerability already present in existing supply structures.

This temporal interpretation is important for decision-making. Scenario work is valuable for long-range planning, but observed trade structures already justify near-term action. Waiting for finer long-horizon certainty can lock in additional exposure through durable investments, crop choices, infrastructure and contracts. A prudent resilience strategy therefore combines immediate no-regret actions with iterative monitoring as climate and market conditions evolve.

Discussion

Our results show that European water security cannot be understood only in terms of local resource-management. Blue-water consumption embodied in European trade is largely non-local, concentrated in a small number of supplier regions and strongly linked to irrigated agriculture. Notably, about 64% of intra-European virtual-water exports originate in regions with high baseline water stress. This creates a form of supply chain risk exposure that is difficult to observe using conventional territorial water indicators alone.

The first implication is that water-risk governance needs to move from local status assessment toward supply chain visibility. Basin-level indicators remain essential for regional water allocation, ecological safeguarding and local adaptation. But they do not show which stressed basins or regions perform system-critical supply functions for distant consumers and processors. Likewise, consumption-based footprint indicators show externalized water use, but often at a scale too coarse to reveal subnational bottlenecks. Combining both perspectives allows policymakers and firms to identify where concentration and scarcity overlap.

The second implication concerns diversification. Trade is often treated as a mechanism that increases resilience by allowing consumers to source from multiple locations. This is true when suppliers are genuinely diversified across independent hydrological systems. It is less true when supply is concentrated in a small number of irrigated regions exposed to similar stress regimes. In such cases, market integration can amplify rather than dilute hydrological risk exposure. Resilience policy should therefore assess not only whether regions import embodied water, but whether they import it from a narrow set of stressed origins.

The third implication concerns adaptation finance. Supplier regions that are central to European virtual-water flows provide benefits beyond their own borders. Investments in irrigation efficiency, drought preparedness, soil-water retention, crop adjustment and governance of resource allocation can therefore generate resilience benefits for the entire Single Market. Yet the fiscal and political costs of these investments are often borne locally. This creates a governance mismatch: adaptation benefits are distributed across the Single Market, while adaptation burdens remain concentrated in supplier regions. European adaptation policy should recognize this asymmetry more explicitly.

These findings are directly relevant to current EU policy agendas. The Water Framework Directive and related water-governance instruments provide a foundation for basin-level management, but they do not systematically account for the role of stressed regions in cross-regional supply chains. The Common Agricultural Policy shapes production incentives in many of the regions identified here, yet support mechanisms are not consistently linked to the systemic water-risk of those regions. Corporate sustainability reporting can create additional visibility, but implementation would need to make supplier-region concentration and water-stress exposure more explicit.

The results also suggest a practical monitoring agenda for making supply chains more resilient.

Public agencies and firms could track three indicators jointly: the concentration of embodied-water supply, the baseline stress of supplier regions and the substitutability of products or inputs sourced from those regions. This would allow a distinction between ordinary import dependence and strategic bottleneck exposure. The latter requires targeted attention because disruption in a small number of regions can affect many downstream users simultaneously.

Policy responses should avoid simplistic conclusions. The results do not imply that stressed supplier regions should withdraw from European markets or that local self-sufficiency is desirable. In many cases, trade remains beneficial, and some stressed regions may sustain production through effective governance, efficiency gains and adaptation. The issue is not trade itself, but unmanaged concentration in water-stressed origins. A resilience-oriented strategy would combine transparency, selective diversification, demand moderation, and coordinated investment and finance for supplier-region adaptation.

Several limitations should guide interpretation. First, the analysis identifies structural risk exposure, not realized disruption. It shows where supply concentration and hydrological stress overlap, but not whether a particular drought will generate shortages or price effects in a given year. Second, the MRIO framework is static and does not model behavioral responses, substitution or dynamic re-optimization after shocks. Third, sectoral aggregation limits product-specific attribution, particularly within broad agri-food categories. Future work should connect this regional exposure map to firm-level sourcing data, commodity-specific trade flows, crop calendars and dynamic market responses.

Taken together, the evidence shows that Europe's hidden water dependencies are measurable, concentrated and policy-relevant. The analysis does not predict specific disruptions, but it identifies where supply-chain dependence and hydrological stress already overlap in observed trade structures. The relevant data systems, reporting mandates and adaptation agendas already exist, but they are not yet integrated around a shared diagnosis of concentration-stress exposure. Building that integration is the key step from descriptive awareness to practical resilience governance.

Methods

Analytical scope and unit of analysis

We quantify blue-water consumption embodied in final demand connected to EU27+2 by combining environmentally extended multi-regional input-output (EE-MRIO) analysis with regional hydrological indicators. EU27+2 refers to the 27 member states of the European Union plus Norway and the United Kingdom. The unit of analysis is the NUTS-2 region for European territories. The full MRIO system comprises 303 regions: 288 European NUTS-2 regions (the EU27 plus Norway and the United Kingdom) and 15 extra-European aggregates (14 major trading partners and a rest-of-

world region) included for trade closure (summary in Supplementary Table 4; the complete list of all 303 regions is given in Supplementary Table 6).

We focus on blue-water consumption rather than withdrawals. Consumption captures water that is not returned to local freshwater systems because it is evaporated, transpired or incorporated into products. It therefore better represents depletion pressure relevant for supply chain resilience. Throughout, "blue water" refers to freshwater abstracted from surface- and groundwater bodies; green water (soil moisture from precipitation, e.g. rain-fed crop growth) is outside the scope of this analysis.

MRIO construction and regionalization

The core economic structure combines two components of the FIGARO database[29,30]. The interregional trade architecture is taken from the FIGARO regional (NUTS-2) inter-regional input-output tables (reference year 2017), which resolve trade between European NUTS-2 regions at an aggregated sector level. The detailed sectoral structure used to disaggregate production into the 14 water-relevant sectors is derived from the FIGARO inter-country input-output tables (reference year 2015). We apply the country-level 2015 sectoral shares to the 2017 regional tables, yielding a balanced NUTS-2 matrix of intermediate and final demand across 303 regions (Supplementary Table 5). The headline accounting year of the regionalized system is therefore 2017, with sectoral detail anchored to the 2015 inter-country structure.

Regionalization assumes that sectoral technical shares within each country apply to constituent NUTS-2 regions where direct regional coefficients are unavailable. This assumption introduces smoothing but preserves accounting consistency and enables full-system decomposition of direct and indirect embodied-water flows.

The EE-MRIO model uses standard Leontief accounting. Let A denote the region-sector technical coefficient matrix and $L = (I - A)^{-1}$ the Leontief inverse. Let f denote a row vector of direct blue-water consumption intensities by region-sector, and let y denote a final-demand vector. Embodied-water requirements linked to final demand are computed as:

$$vw = fLy,$$

where vw records direct and indirect blue-water consumption throughout upstream production chains. For final demand in a specific consuming region or region group, the corresponding final-demand vector is used to trace embodied-water requirements to upstream producing regions and sectors.

Water data integration

Hydrological input data come from WaterGAP 2.2e at $0.5° \times 0.5°$ resolution[31,32]. Sectoral consumptive use is spatially intersected with NUTS-2 boundaries and aggregated to annual regional totals. Unit conversions are applied from model output units to million cubic meters per year.

Water intensities are assigned to the four sectors with material consumptive use in the system: irrigated agriculture, livestock, manufacturing and thermal electricity cooling. Remaining sectors are assigned negligible direct blue-water consumption in the baseline specification, while still carrying embodied water indirectly through intermediate inputs.

Stress overlay and bottleneck classification

Baseline water stress comes from WRI Aqueduct 4.0[26]. Baseline water stress measures total annual demand relative to available renewable supply after accounting for environmental flow requirements and upstream use. Higher values indicate stronger competition and lower buffer capacity.

For each NUTS-2 region, we combine two indicators: inter-regional virtual-water export volume and baseline water-stress class. Export volumes are classified using Jenks natural breaks on log-transformed values to represent the right-skewed distribution. Stress follows Aqueduct thresholds. Regions in the joint high-export and high-stress classes are labeled as bottlenecks.

Interpretation, uncertainty and robustness

Three caveats are central. First, modeled hydrology and allocation schemes imply measurement uncertainty, especially outside irrigation. Second, the static input-output structure does not capture dynamic re-optimization after shocks. Third, sectoral aggregation limits product-level attribution. The concentration result is computed directly from export volumes and therefore does not depend on any classification choice; ordinal export classes enter only the bivariate map (Jenks natural breaks on log-transformed values), and stress classes follow fixed WRI Aqueduct thresholds, so the identification of the high-export/high-stress bottleneck set is not sensitive to bin boundaries.

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Author contributions

I.M. and A.N. developed the conceptual framework. T.N. curated the data and implemented the empirical workflow. All authors interpreted the results and contributed to the manuscript.

Competing interests

The authors declare no competing interests.

Data availability

All data used are from publicly accessible sources: FIGARO, WaterGAP and WRI Aqueduct. Processed regional outputs and scripts sufficient to reproduce the reported tables and figures are available from the authors upon reasonable request.

Supplementary information

Supplementary Information accompanies this manuscript and includes additional robustness checks, extended regional rankings, and methodological details.

Table 3: Supplementary Table S1 | Verification values for key headline shares used in the manuscript.

Metric group	Metric	Value (%)
Virtual-water source composition	Same-region (local) share	10.0
Virtual-water source composition	Intra-EU inter-regional share	51.0
Virtual-water source composition	Extra-EU share	39.0
Sectoral composition of intra-EU exports	Irrigation agriculture share	81.0
Sectoral composition of intra-EU exports	Livestock share	4.0
Sectoral composition of intra-EU exports	Manufacturing share	11.0
Sectoral composition of intra-EU exports	Thermal electricity share	4.0

Notes: Values correspond to the baseline 2017 accounting used in the manuscript and are the exact percentages underlying the rounded claims reported in the Abstract and Results. For example, the table supports the statements "around 90% outside the consuming region" and "around 81% from irrigated agriculture." Source pipeline: FIGARO + WaterGAP 2.2e. Stress layer: WRI Aqueduct 4.0.

Table 4: Geographic coverage of the MRIO system. The full system comprises 303 regions: 288 European NUTS-2 regions (the EU27 plus Norway and the United Kingdom, "EU27+2") and 15 extra-European aggregates included for trade closure.

Bloc	Country	NUTS-2 / regions
EU27	Austria	9
	Belgium	11
	Bulgaria	6
	Croatia	2
	Cyprus	1
	Czechia	8
	Denmark	5
	Estonia	1
	Finland	5
	France	27
	Germany	38
	Greece	13
	Hungary	8
	Ireland	3
	Italy	21
	Latvia	1
	Lithuania	2
	Luxembourg	1
	Malta	1
	Netherlands	12
	Poland	17
	Portugal	7
	Romania	8
	Slovakia	4
	Slovenia	2
	Spain	19
	Sweden	8
EU27+2 (non-EU NUTS-2)	Norway	7
	United Kingdom	41
Extra-EU (trade closure)	Australia	1
	Brazil	1
	Canada	1
	China	1
	India	1
	Indonesia	1
	Japan	1
	Mexico	1
	Rest of World	1
	Russia	1
	South Africa	1
	South Korea	1
	Switzerland	1
	Turkey	1
	United States	1
EU27 NUTS-2		**240**
EU27+2 NUTS-2 total		**288**
Full system		**303**

Table 5: Sector classification and concordance. The NUTS-2 FIGARO-REG tables provide 10 aggregated sectors (NACE A*10). These are disaggregated into the 14 model sectors using country-level sectoral shares from FIGARO inter-country tables: the agriculture aggregate (A) is split into three sub-sectors and the industry aggregate (B–E) into three sub-sectors, while the remaining eight sectors map one-to-one. Direct blue-water consumption from WaterGAP 2.2e is available for four sectors; all others carry water only indirectly through intermediate inputs.

FIGARO-REG sector (NACE A*10)	Code	Model sector (14)	Direct WaterGAP data
A – Agriculture, forestry & fishing	Airr	Agriculture – irrigation	✓ irrigation
	Aliv	Agriculture – livestock	✓ livestock
	Arest	Agriculture – rest (forestry, fishing)	–
B–E – Industry (except construction)	Belec	Thermal electricity generation	✓ power-plant cooling
	Bmanu	Manufacturing	✓ manufacturing
	Bmining	Mining & quarrying	–
F – Construction	F	Construction	–
G–I – Trade, transport, accommodation & food	G	Wholesale & retail trade, transport, accomm. & food	–
J – Information & communication	J	Information & communication	–
K – Financial & insurance	K	Financial & insurance activities	–
L – Real estate	L	Real estate activities	–
M–N – Professional & admin. services	M	Professional, scientific, technical; admin. & support	–
O–Q – Public admin., education, health	O	Public administration, defence, education, health	–
R–U – Arts, other services, households	R	Arts, entertainment & recreation; other services; households	–

Notes: NACE Rev. 2 A*10 aggregation. The industry aggregate (B–E) nominally also contains water supply, sewerage and waste management (NACE E), which is subsumed within the industry split. WaterGAP additionally models domestic (household) water use, but this is a final-demand component handled separately at country level and is not one of the 14 production sectors. "–" denotes no direct blue-water consumption assigned (assumed negligible).

Table 6: Full list of the 303 regions in the MRIO system, by bloc.

Code	Region	Country	Bloc
AT11	Burgenland	Austria	EU27
AT12	Niederosterreich	Austria	EU27
AT13	Wien	Austria	EU27
AT21	Karnten	Austria	EU27
AT22	Steiermark	Austria	EU27
AT31	Oberosterreich	Austria	EU27
AT32	Salzburg	Austria	EU27
AT33	Tirol	Austria	EU27
AT34	Vorarlberg	Austria	EU27
BE10	Region de Bruxelles-Capitale/ Brussels Hoofdstedelijk Gewest	Belgium	EU27
BE21	Prov. Antwerpen	Belgium	EU27
BE22	Prov. Limburg (BE)	Belgium	EU27
BE23	Prov. Oost-Vlaanderen	Belgium	EU27
BE24	Prov. Vlaams-Brabant	Belgium	EU27
BE25	Prov. West-Vlaanderen	Belgium	EU27
BE31	Prov. Brabant Wallon	Belgium	EU27
BE32	Prov. Hainaut	Belgium	EU27
BE33	Prov. Liege	Belgium	EU27
BE34	Prov. Luxembourg (BE)	Belgium	EU27
BE35	Prov. Namur	Belgium	EU27

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Table 6 continued

Code	Region	Country	Bloc
BG31	Severozapaden	Bulgaria	EU27
BG32	Severen centralen	Bulgaria	EU27
BG33	Severoiztocen	Bulgaria	EU27
BG34	Ugoiztocen	Bulgaria	EU27
BG41	Ugozapaden	Bulgaria	EU27
BG42	Uzen centralen	Bulgaria	EU27
CY00	Kypros	Cyprus	EU27
CZ01	Praha	Czechia	EU27
CZ02	Stredni Cechy	Czechia	EU27
CZ03	Jihozapad	Czechia	EU27
CZ04	Severozapad	Czechia	EU27
CZ05	Severovychod	Czechia	EU27
CZ06	Jihovychod	Czechia	EU27
CZ07	Stredni Morava	Czechia	EU27
CZ08	Moravskoslezsko	Czechia	EU27
DE11	Stuttgart	Germany	EU27
DE12	Karlsruhe	Germany	EU27
DE13	Freiburg	Germany	EU27
DE14	Tubingen	Germany	EU27
DE21	Oberbayern	Germany	EU27
DE22	Niederbayern	Germany	EU27
DE23	Oberpfalz	Germany	EU27
DE24	Oberfranken	Germany	EU27
DE25	Mittelfranken	Germany	EU27
DE26	Unterfranken	Germany	EU27
DE27	Schwaben	Germany	EU27
DE30	Berlin	Germany	EU27
DE40	Brandenburg	Germany	EU27
DE50	Bremen	Germany	EU27
DE60	Hamburg	Germany	EU27
DE71	Darmstadt	Germany	EU27
DE72	Giessen	Germany	EU27
DE73	Kassel	Germany	EU27
DE80	Mecklenburg-Vorpommern	Germany	EU27
DE91	Braunschweig	Germany	EU27
DE92	Hannover	Germany	EU27
DE93	Luneburg	Germany	EU27
DE94	Weser-Ems	Germany	EU27
DEA1	Dusseldorf	Germany	EU27
DEA2	Koln	Germany	EU27
DEA3	Munster	Germany	EU27
DEA4	Detmold	Germany	EU27
DEA5	Arnsberg	Germany	EU27
DEB1	Koblenz	Germany	EU27
DEB2	Trier	Germany	EU27
DEB3	Rheinhessen-Pfalz	Germany	EU27
DEC0	Saarland	Germany	EU27
DED2	Dresden	Germany	EU27
DED4	Chemnitz	Germany	EU27
DED5	Leipzig	Germany	EU27
DEE0	Sachsen-Anhalt	Germany	EU27
DEF0	Schleswig-Holstein	Germany	EU27

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Table 6 continued

Code	Region	Country	Bloc
DEG0	Thuringen	Germany	EU27
DK01	Hovedstaden	Denmark	EU27
DK02	Sjaelland	Denmark	EU27
DK03	Syddanmark	Denmark	EU27
DK04	Midtjylland	Denmark	EU27
DK05	Nordjylland	Denmark	EU27
EE00	Eesti	Estonia	EU27
EL30	Attike	Greece	EU27
EL41	Boreio Aigaio	Greece	EU27
EL42	Notio Aigaio	Greece	EU27
EL43	Krete	Greece	EU27
EL51	Anatolike Makedonia, Thrake	Greece	EU27
EL52	Kentrike Makedonia	Greece	EU27
EL53	Dytike Makedonia	Greece	EU27
EL54	Epeiros	Greece	EU27
EL61	Thessalia	Greece	EU27
EL62	Ionia Nesia	Greece	EU27
EL63	Dytike Ellada	Greece	EU27
EL64	Sterea Ellada	Greece	EU27
EL65	Peloponnesos	Greece	EU27
ES11	Galicia	Spain	EU27
ES12	Principado de Asturias	Spain	EU27
ES13	Cantabria	Spain	EU27
ES21	Pais Vasco	Spain	EU27
ES22	Comunidad Foral de Navarra	Spain	EU27
ES23	La Rioja	Spain	EU27
ES24	Aragon	Spain	EU27
ES30	Comunidad de Madrid	Spain	EU27
ES41	Castilla y Leon	Spain	EU27
ES42	Castilla-La Mancha	Spain	EU27
ES43	Extremadura	Spain	EU27
ES51	Cataluna	Spain	EU27
ES52	Comunidad Valenciana	Spain	EU27
ES53	Illes Balears	Spain	EU27
ES61	Andalucia	Spain	EU27
ES62	Region de Murcia	Spain	EU27
ES63	Ciudad Autonoma de Ceuta	Spain	EU27
ES64	Ciudad Autonoma de Melilla	Spain	EU27
ES70	Canarias	Spain	EU27
FI19	Lansi-Suomi	Finland	EU27
FI1B	Helsinki-Uusimaa	Finland	EU27
FI1C	Etela-Suomi	Finland	EU27
FI1D	Pohjois- ja Ita-Suomi	Finland	EU27
FI20	Aland	Finland	EU27
FR10	Ile-de-France	France	EU27
FRB0	Centre - Val de Loire	France	EU27
FRC1	Bourgogne	France	EU27
FRC2	Franche-Comte	France	EU27
FRD1	Basse-Normandie	France	EU27
FRD2	Haute-Normandie	France	EU27
FRE1	Nord-Pas de Calais	France	EU27
FRE2	Picardie	France	EU27

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Table 6 continued

Code	Region	Country	Bloc
FRF1	Alsace	France	EU27
FRF2	Champagne-Ardenne	France	EU27
FRF3	Lorraine	France	EU27
FRG0	Pays de la Loire	France	EU27
FRH0	Bretagne	France	EU27
FRI1	Aquitaine	France	EU27
FRI2	Limousin	France	EU27
FRI3	Poitou-Charentes	France	EU27
FRJ1	Languedoc-Roussillon	France	EU27
FRJ2	Midi-Pyrenees	France	EU27
FRK1	Auvergne	France	EU27
FRK2	Rhone-Alpes	France	EU27
FRL0	Provence-Alpes-Cote d'Azur	France	EU27
FRM0	Corse	France	EU27
FRY1	Guadeloupe	France	EU27
FRY2	Martinique	France	EU27
FRY3	Guyane	France	EU27
FRY4	La Reunion	France	EU27
FRY5	Mayotte	France	EU27
HR03	Jadranska Hrvatska	Croatia	EU27
HR04	Kontinentalna Hrvatska	Croatia	EU27
HU11	Budapest	Hungary	EU27
HU12	Pest	Hungary	EU27
HU21	Kozep-Dunantul	Hungary	EU27
HU22	Nyugat-Dunantul	Hungary	EU27
HU23	Del-Dunantul	Hungary	EU27
HU31	Eszak-Magyarorszag	Hungary	EU27
HU32	Eszak-Alfold	Hungary	EU27
HU33	Del-Alfold	Hungary	EU27
IE04	Northern and Western	Ireland	EU27
IE05	Southern	Ireland	EU27
IE06	Eastern and Midland	Ireland	EU27
ITC1	Piemonte	Italy	EU27
ITC2	Valle d'Aosta/Vallee d'Aoste	Italy	EU27
ITC3	Liguria	Italy	EU27
ITC4	Lombardia	Italy	EU27
ITF1	Abruzzo	Italy	EU27
ITF2	Molise	Italy	EU27
ITF3	Campania	Italy	EU27
ITF4	Puglia	Italy	EU27
ITF5	Basilicata	Italy	EU27
ITF6	Calabria	Italy	EU27
ITG1	Sicilia	Italy	EU27
ITG2	Sardegna	Italy	EU27
ITH1	Provincia Autonoma di Bolzano/Bozen	Italy	EU27
ITH2	Provincia Autonoma di Trento	Italy	EU27
ITH3	Veneto	Italy	EU27
ITH4	Friuli-Venezia Giulia	Italy	EU27
ITH5	Emilia-Romagna	Italy	EU27
ITI1	Toscana	Italy	EU27
ITI2	Umbria	Italy	EU27
ITI3	Marche	Italy	EU27

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Table 6 continued

Code	Region	Country	Bloc
ITI4	Lazio	Italy	EU27
LT01	Sostines regionas	Lithuania	EU27
LT02	Vidurio ir vakaru Lietuvos regionas	Lithuania	EU27
LU00	Luxembourg	Luxembourg	EU27
LV00	Latvija	Latvia	EU27
MT00	Malta	Malta	EU27
NL11	Groningen	Netherlands	EU27
NL12	Friesland (NL)	Netherlands	EU27
NL13	Drenthe	Netherlands	EU27
NL21	Overijssel	Netherlands	EU27
NL22	Gelderland	Netherlands	EU27
NL23	Flevoland	Netherlands	EU27
NL31	Utrecht	Netherlands	EU27
NL32	Noord-Holland	Netherlands	EU27
NL33	Zuid-Holland	Netherlands	EU27
NL34	Zeeland	Netherlands	EU27
NL41	Noord-Brabant	Netherlands	EU27
NL42	Limburg (NL)	Netherlands	EU27
PL21	Malopolskie	Poland	EU27
PL22	Slaskie	Poland	EU27
PL41	Wielkopolskie	Poland	EU27
PL42	Zachodniopomorskie	Poland	EU27
PL43	Lubuskie	Poland	EU27
PL51	Dolnoslaskie	Poland	EU27
PL52	Opolskie	Poland	EU27
PL61	Kujawsko-pomorskie	Poland	EU27
PL62	Warminsko-mazurskie	Poland	EU27
PL63	Pomorskie	Poland	EU27
PL71	Lodzkie	Poland	EU27
PL72	Swietokrzyskie	Poland	EU27
PL81	Lubelskie	Poland	EU27
PL82	Podkarpackie	Poland	EU27
PL84	Podlaskie	Poland	EU27
PL91	Warszawski stoleczny	Poland	EU27
PL92	Mazowiecki regionalny	Poland	EU27
PT11	Norte	Portugal	EU27
PT15	Algarve	Portugal	EU27
PT16	Centro (PT)	Portugal	EU27
PT17	Area Metropolitana de Lisboa	Portugal	EU27
PT18	Alentejo	Portugal	EU27
PT20	Regiao Autonoma dos Acores	Portugal	EU27
PT30	Regiao Autonoma da Madeira	Portugal	EU27
RO11	Nord-Vest	Romania	EU27
RO12	Centru	Romania	EU27
RO21	Nord-Est	Romania	EU27
RO22	Sud-Est	Romania	EU27
RO31	Sud - Muntenia	Romania	EU27
RO32	Bucuresti - Ilfov	Romania	EU27
RO41	Sud-Vest Oltenia	Romania	EU27
RO42	Vest	Romania	EU27
SE11	Stockholm	Sweden	EU27
SE12	Ostra Mellansverige	Sweden	EU27

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Table 6 continued

Code	Region	Country	Bloc
SE21	Smaland med oarna	Sweden	EU27
SE22	Sydsverige	Sweden	EU27
SE23	Vastsverige	Sweden	EU27
SE31	Norra Mellansverige	Sweden	EU27
SE32	Mellersta Norrland	Sweden	EU27
SE33	Ovre Norrland	Sweden	EU27
SI03	Vzhodna Slovenija	Slovenia	EU27
SI04	Zahodna Slovenija	Slovenia	EU27
SK01	Bratislavsky kraj	Slovakia	EU27
SK02	Zapadne Slovensko	Slovakia	EU27
SK03	Stredne Slovensko	Slovakia	EU27
SK04	Vychodne Slovensko	Slovakia	EU27
NO01	Oslo og Akershus	Norway	EU27+2 (non-EU NUTS-2)
NO02	Hedmark og Oppland	Norway	EU27+2 (non-EU NUTS-2)
NO03	Sor-Ostlandet	Norway	EU27+2 (non-EU NUTS-2)
NO04	Agder og Rogaland	Norway	EU27+2 (non-EU NUTS-2)
NO05	Vestlandet	Norway	EU27+2 (non-EU NUTS-2)
NO06	Trondelag	Norway	EU27+2 (non-EU NUTS-2)
NO07	Nord-Norge	Norway	EU27+2 (non-EU NUTS-2)
UKC1	Tees Valley and Durham	United Kingdom	EU27+2 (non-EU NUTS-2)
UKC2	Northumberland and Tyne and Wear	United Kingdom	EU27+2 (non-EU NUTS-2)
UKD1	Cumbria	United Kingdom	EU27+2 (non-EU NUTS-2)
UKD3	Greater Manchester	United Kingdom	EU27+2 (non-EU NUTS-2)
UKD4	Lancashire	United Kingdom	EU27+2 (non-EU NUTS-2)
UKD6	Cheshire	United Kingdom	EU27+2 (non-EU NUTS-2)
UKD7	Merseyside	United Kingdom	EU27+2 (non-EU NUTS-2)
UKE1	East Yorkshire and Northern Lincolnshire	United Kingdom	EU27+2 (non-EU NUTS-2)
UKE2	North Yorkshire	United Kingdom	EU27+2 (non-EU NUTS-2)
UKE3	South Yorkshire	United Kingdom	EU27+2 (non-EU NUTS-2)
UKE4	West Yorkshire	United Kingdom	EU27+2 (non-EU NUTS-2)
UKF1	Derbyshire and Nottinghamshire	United Kingdom	EU27+2 (non-EU NUTS-2)
UKF2	Leicestershire, Rutland and Northamptonshire	United Kingdom	EU27+2 (non-EU NUTS-2)
UKF3	Lincolnshire	United Kingdom	EU27+2 (non-EU NUTS-2)
UKG1	Herefordshire, Worcestershire and Warwickshire	United Kingdom	EU27+2 (non-EU NUTS-2)
UKG2	Shropshire and Staffordshire	United Kingdom	EU27+2 (non-EU NUTS-2)
UKG3	West Midlands	United Kingdom	EU27+2 (non-EU NUTS-2)
UKH1	East Anglia	United Kingdom	EU27+2 (non-EU NUTS-2)
UKH2	Bedfordshire and Hertfordshire	United Kingdom	EU27+2 (non-EU NUTS-2)
UKH3	Essex	United Kingdom	EU27+2 (non-EU NUTS-2)
UKI3	Inner London - West	United Kingdom	EU27+2 (non-EU NUTS-2)
UKI4	Inner London - East	United Kingdom	EU27+2 (non-EU NUTS-2)
UKI5	Outer London - East and North East	United Kingdom	EU27+2 (non-EU NUTS-2)
UKI6	Outer London - South	United Kingdom	EU27+2 (non-EU NUTS-2)
UKI7	Outer London - West and North West	United Kingdom	EU27+2 (non-EU NUTS-2)
UKJ1	Berkshire, Buckinghamshire and Oxfordshire	United Kingdom	EU27+2 (non-EU NUTS-2)
UKJ2	Surrey, East and West Sussex	United Kingdom	EU27+2 (non-EU NUTS-2)
UKJ3	Hampshire and Isle of Wight	United Kingdom	EU27+2 (non-EU NUTS-2)
UKJ4	Kent	United Kingdom	EU27+2 (non-EU NUTS-2)
UKK1	Gloucestershire, Wiltshire and Bristol/Bath area	United Kingdom	EU27+2 (non-EU NUTS-2)
UKK2	Dorset and Somerset	United Kingdom	EU27+2 (non-EU NUTS-2)
UKK3	Cornwall and Isles of Scilly	United Kingdom	EU27+2 (non-EU NUTS-2)
UKK4	Devon	United Kingdom	EU27+2 (non-EU NUTS-2)

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Table 6 continued

Code	Region	Country	Bloc
UKL1	West Wales and The Valleys	United Kingdom	EU27+2 (non-EU NUTS-2)
UKL2	East Wales	United Kingdom	EU27+2 (non-EU NUTS-2)
UKM5	North Eastern Scotland	United Kingdom	EU27+2 (non-EU NUTS-2)
UKM6	Highlands and Islands	United Kingdom	EU27+2 (non-EU NUTS-2)
UKM7	Eastern Scotland	United Kingdom	EU27+2 (non-EU NUTS-2)
UKM8	West Central Scotland	United Kingdom	EU27+2 (non-EU NUTS-2)
UKM9	Southern Scotland	United Kingdom	EU27+2 (non-EU NUTS-2)
UKN0	Northern Ireland	United Kingdom	EU27+2 (non-EU NUTS-2)
AU	Australia	Australia	Extra-EU (trade closure)
BR	Brazil	Brazil	Extra-EU (trade closure)
CA	Canada	Canada	Extra-EU (trade closure)
CH	SCHWEIZ/SUISSE/SVIZZERA	Switzerland	Extra-EU (trade closure)
CN	China	China	Extra-EU (trade closure)
ID	Indonesia	Indonesia	Extra-EU (trade closure)
IN	India	India	Extra-EU (trade closure)
JP	Japan	Japan	Extra-EU (trade closure)
KR	South Korea	South Korea	Extra-EU (trade closure)
MX	Mexico	Mexico	Extra-EU (trade closure)
ROW	Rest_of_World	Rest of World	Extra-EU (trade closure)
RU	Russia	Russia	Extra-EU (trade closure)
TR	TURKIYE	Turkey	Extra-EU (trade closure)
US	United States	United States	Extra-EU (trade closure)
ZA	South Africa	South Africa	Extra-EU (trade closure)

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