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Executive Summary of the Thesis

A multi-sectoral drought vulnerability framework: Application for European basins

Laurea Magistrale in Master of Science in Civil Engineering for Risk Mitigation

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1. Research Aim, Concepts, and Literature Gap

Drought is a slow-onset hazard with impacts across water resources, food production, energy systems, transport, ecosystems, public services, and society. In drought-risk literature, risk is usually defined by the interaction of hazard, exposure, and vulnerability. This thesis focuses on vulnerability: the conditions that explain why similar water deficits can lead to different consequences across basins and sectors [1, 4, 12].

The research aim is to develop and demonstrate a transparent indicator-based framework for assessing *relative drought vulnerability* across European basins and sectors. The framework does not forecast drought events, estimate direct losses, or define universal thresholds. Its purpose is diagnostic: to compare where vulnerability is concentrated, which sectors are affected, and whether final patterns are mainly driven by shared territorial conditions or sector-specific drought-impact pathways.

Sectoral drought impacts are interpreted through hazard–impact pathways. A water deficit may reduce soil moisture, river discharge, reservoir storage, groundwater recharge, cooling-water availability, ecological flow conditions, or public-water reliability. These changes affect sectors differently: energy through generation and cooling constraints; inland waterway transport through low-flow navigation limits; human health through water-service and sanitation stress; irrigated crops through water demand and irrigation performance; and freshwater ecosystems through flow reduction, fragmentation, and ecological pressure [3, 10, 13].

A multi-sectoral assessment is needed because drought impacts rarely remain isolated within one sector. A sector-by-sector approach can identify specific hotspots, but it may miss *cross-sectoral* territorial conditions that affect several systems, such as poverty risk, economic capacity, water stress, infrastructure, storage and treatment capacity, and drought readiness. A single generic vulnerability index creates the opposite problem: it can over-simplify sectoral mechanisms and hide why energy, transport, health, agriculture, or ecosystems become vulnerable in different ways. This thesis addresses this challenge by separating the *cross-sectoral branch* from the *sector-specific branch* and combining them only at the final composite stage. The framework therefore shows both the shared

territorial background of drought vulnerability and the sector-specific pathways through which drought impacts emerge.

The literature review identifies four main gaps that motivate the framework. First, cross-sectoral conditions are often merged into a general vulnerability score instead of treated as shared territorial drivers. Second, sector-specific indicators are not always clearly linked to drought impact pathways. Third, many assessments focus on one sector or aggregate sectors too early, limiting comparison across systems. Fourth, normalization, weighting, aggregation, compensation, and missing-data assumptions are not always tested transparently, even though they can change final vulnerability maps [3, 6, 9].

2. Drought-Vulnerability Framework and Scoring

The framework has two connected branches (Cross-sectoral and Sector-Specific). The *cross-sectoral branch* represents shared territorial vulnerability conditions, and the *sector-specific branch* represents the impact logic of each sector. Both branches use the three vulnerability dimensions applied throughout the thesis: *sensitivity*, *susceptibility*, and *adaptive capacity* [4, 11].

In this thesis, these dimensions are adapted to drought as a general interpretation layer. *Sensitivity* describes how directly a system is affected by drought-related water deficits; for example, activities that depend strongly on water are more sensitive. *Susceptibility* describes the structural or functional conditions that make damage, disruption, or loss more likely once drought stress occurs; for example, a stressed water system can help drought impacts spread. *Adaptive capacity* describes the ability to prepare for, respond to, recover from, and adjust to drought impacts through institutional, financial, technical, and management resources; for example, stronger planning or infrastructure can reduce vulnerability. These dimensions classify indicators, guide weighting, and keep the vulnerability logic transparent in both branches; they are not separate final outputs.

The cross-sectoral branch includes social, economic, water-system, and readiness components. These components describe broader conditions that can amplify or buffer drought impacts across sectors. The sector-specific branch keeps the sectoral mechanism visible before the final composite is calculated. This distinction is central to the thesis: general territorial resilience matters, but it should not erase sector-specific dependence on water, infrastructure, production systems, or ecosystem condition.

Because of space constraints, Figure 1 shows only one energy-production hazard–impact pathway as an example; the full thesis includes all sector-specific pathways. The example distinguishes direct impacts, such as reduced water availability for a specific activity; indirect impacts, such as disruptions through infrastructure, production systems, or service networks; and systemic impacts, where drought stress affects several connected sectors at the same time. This shorter presentation explains the framework logic without listing all sector-specific vulnerability links in detail [13].

The scores are relative. A high value means high vulnerability compared with other basins in the same study area, dataset, and methodological setup; it does not mean a predicted loss, damage probability, or universal drought threshold. Each raw indicator is oriented so that higher normalized values always mean higher vulnerability. The S-curve normalization is expressed with increasing and decreasing forms:

$$\begin{aligned} N_{\mathrm{inc}}(x) &= \frac{1}{1 + e^{-k(x-x_0)}}, \\ N_{\mathrm{dec}}(x) &= 1 - N_{\mathrm{inc}}(x). \end{aligned} \tag{1}$$

The increasing S-curve is used when higher raw values mean higher vulnerability. The decreasing S-curve is used when higher raw values mean lower vulnerability or stronger protection. The midpoint x_0 defines the central transition of the curve, while k controls how quickly the score changes around that point.

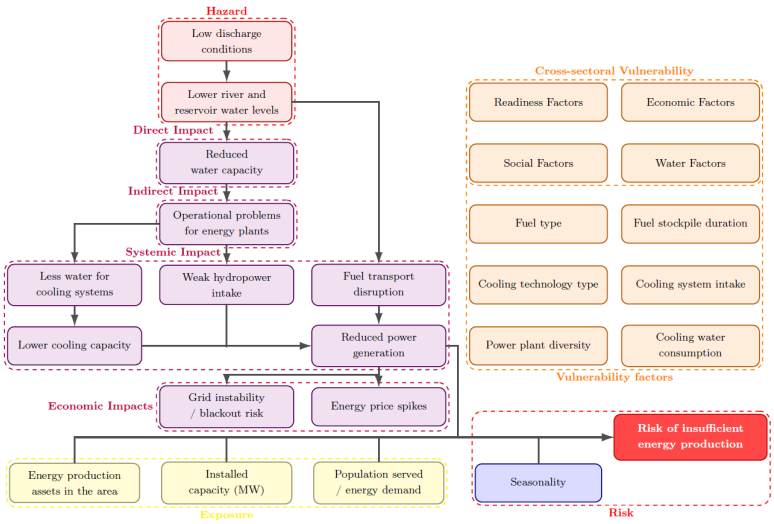


Figure 1: Direct, indirect, and systemic drought-impact pathways for energy production.

The final composite is calculated under both arithmetic and geometric formulations:

$$V_{final}^{arith} = w_{sector} V_{sector} + w_{cross} V_{cross}, \quad (2)$$

$$V_{final}^{geom} = V_{sector}^{w_{sector}} \cdot V_{cross}^{w_{cross}}. \quad (3)$$

The arithmetic formulation is used as a more compensatory benchmark, while the geometric formulation is kept as the reference because it limits full compensation between weak and strong branches. Using the cross-sectoral–sector-specific weight order, three branch-weighting scenarios are compared: balanced 50–50, cross-sector-dominant 80–20, and sector-dominant 20–80. Before geometric aggregation, valid normalized indicators are bounded below at 0.01 to avoid exact zero values.

Zero and missing-data handling is treated as a methodological step. After S-curve normalization, the 0.01 lower bound prevents zero-out effects in geometric aggregation. Expected missing values, where a sector or activity is absent, are assigned 0 because they mean non-applicability. Unexpected missing values are not replaced by 0; instead, the affected territorial unit is excluded from the relevant analysis to avoid artificially low vulnerability scores.

3. Framework Application

3.1. European Case Study

The framework is applied to a European basin-scale case study to test whether cross-sectoral territorial conditions and sector-specific drought-impact pathways can be represented with comparable data. The spatial units are HydroBASINS Level 06 sub-basins, derived from HydroSHEDS, which provide a consistent basin geometry for the assessment [5]. The study covers European basins, including the United Kingdom and Türkiye, and includes 660 basin units in total.

3.2. Indicator Selection

The indicators selected for this European case study are summarized in Figure 2. Indicator selection follows the impact-chain logic and is constrained by harmonized European data availability. In this Executive Summary, cross-sectoral components are described at group level, while sector-specific indicators are summarized separately below.

Social Factors. Social factors describe demographic and social conditions that can increase susceptibility to drought-related disruption.

Economic Factors. Economic factors describe financial and livelihood conditions that affect

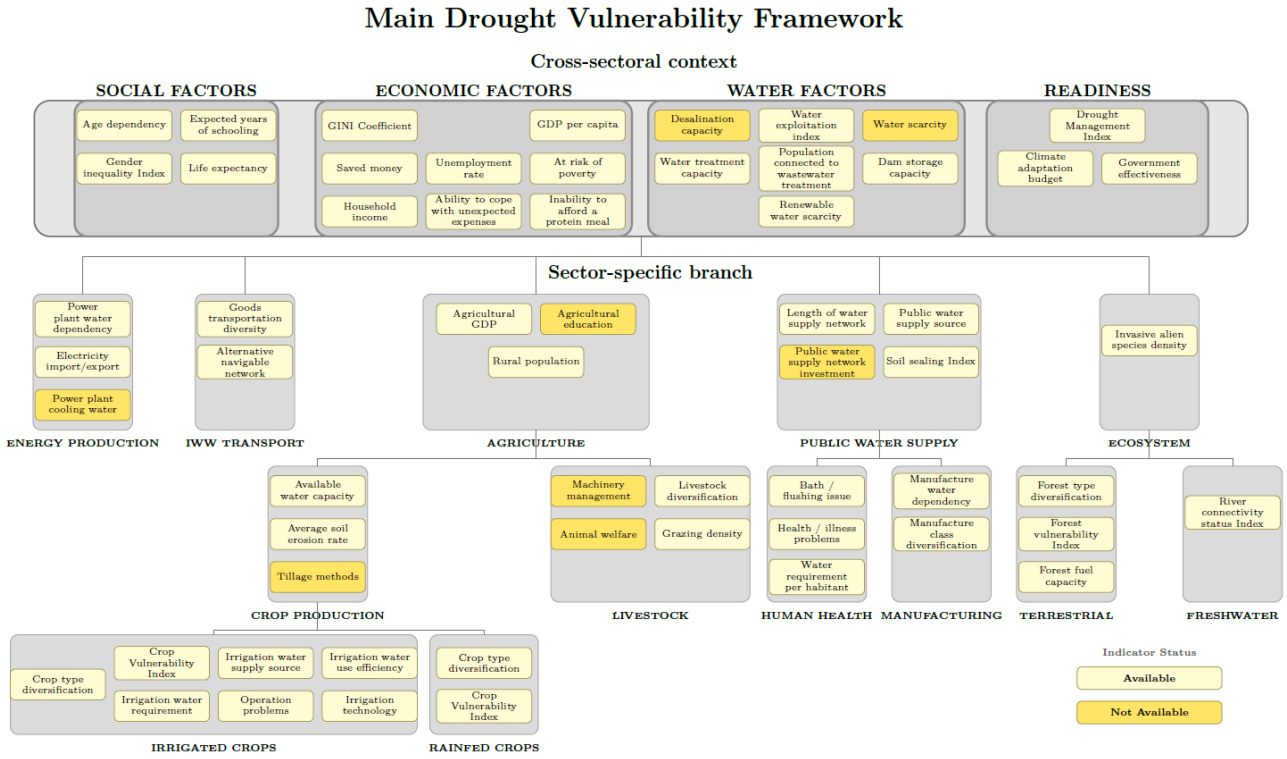


Figure 2: Operational indicator framework for the European application.

the capacity of households and regions to absorb drought impacts.

Water Factors. Water factors describe baseline pressure on water resources and infrastructure conditions that can amplify scarcity during drought.

Readiness Factors. Readiness factors describe institutional capacity to anticipate and manage drought; for example, the Drought Management Index (DMI) represents drought planning and monitoring capacity.

Energy Production. Energy-production factors describe how electricity generation depends on drought-sensitive water inputs; for example, Power Plant Water Dependency represents water-dependent fuel supply and cooling-water requirements.

Inland Waterway Transport. Inland-waterway factors describe the ability of river transport systems to remain functional under low-flow conditions; for example, Alternative Navigable Network represents potential rerouting options.

Human Health. Human-health factors describe population water demand and pressure on public water supply during drought.

Manufacturing. Manufacturing factors describe industrial dependence on water availability and the sensitivity of production processes to scarcity.

Irrigated Crops. Irrigated-crop factors describe the need for external water inputs to maintain crop production under drought conditions.

Rainfed Crops. Rainfed-crop factors describe crop drought sensitivity; for example, Crop Vulnerability represents crop-specific drought response using FAO-based crop properties.

Livestock. Livestock factors describe dependence on animal-production systems and the degree to which diversification can reduce drought sensitivity.

Terrestrial Ecosystems. Terrestrial-ecosystem factors describe wildfire-related sensitivity under dry conditions; for example, Forest Fuel Capacity represents combustible

biomass and potential fire-spread conditions.

Freshwater Ecosystems. Freshwater-ecosystem factors describe river-network condition under drought stress; for example, River Connectivity (CSI) represents how fragmentation can increase ecological susceptibility.

3.3. Spatial Data Harmonization

Before normalization, all indicators are converted to HydroBASINS Level 06 raw values. Administrative data are first split across basin–NUTS intersections with area-weighted shares, and the raw basin value is then calculated before applying the S-curve. Other datasets follow their own processing path: raster layers are summarized within basin boundaries, class-based rasters such as crop vulnerability or forest fuel capacity use class weights, and vector features such as dams or power plants are spatially assigned and aggregated as capacities, counts, densities, or weighted averages.

3.4. Case-Study S-Curve Implementation

In this thesis, basin-level raw indicators are oriented so that higher values always represent higher vulnerability and are then normalized with an S-curve. The risky anchor is defined as the mean of the worst-performing 25% of basins, the safe anchor as the best observed basin value, the midpoint x_0 as the median of valid values, and the steepness parameter as $k = 5$. Final normalized scores are rescaled to 0.01–1.00 to avoid exact zeros in geometric aggregation.

3.5. Score Aggregation and Sensitivity Analysis

Normalized indicators are organized in a basin-level scoring matrix and aggregated hierarchically from indicators to groups, branches, and final sectoral scores. Weights are redistributed only among valid and applicable components. After fixing the S-curve settings, the sensitivity analysis focuses on two methodological choices: the aggregation formulation and the branch weights. Arithmetic aggregation is used as a compensatory benchmark, while geometric aggregation is retained as the reference option because it limits compensation between weak and strong branches. In addition, seven cross-sectoral weight profiles and three geometric branch scenarios are tested. The final scenarios are labelled in cross-sectoral–sector-specific order: 50–50 as the balanced case, 80–20 as the cross-sectoral-dominant case, and 20–80 as the sector-dominant case. These outputs are then mapped at HydroBASINS Level 06 to compare final vulnerability patterns and their sensitivity to alternative assumptions.

4. Results and Discussion

4.1. Cross-Sectoral Component Maps

The results are first interpreted through the cross-sectoral component maps (Figure 3), which show the shared territorial conditions before sector-specific pathways are added. The social component shows a broad west–east gradient, with vulnerability generally increasing toward eastern European basins. The economic component follows a related but not identical pattern, with higher vulnerability in both eastern and southern basins. By contrast, the water-system component is more heterogeneous and produces localized hotspots, because water-related pressures are not fully aligned with social or economic vulnerability. The readiness component reflects management and budgetary capacity; in some Mediterranean basins, accumulated drought preparedness can partly offset broader economic constraints.

The cross-sectoral composite shows a clear regional gradient: Mediterranean and south-eastern basins are generally more vulnerable, with vulnerability decreasing toward northern and north-western Europe. Local contrasts reflect component effects, such as lower composite vulnerability in several Spanish basins due to favourable social conditions and higher vulnerability in basins in Türkiye due to economic constraints.

The sensitivity analysis compares the equal-weight baseline with six alternatives: four single-component dominant scenarios (economic, so-

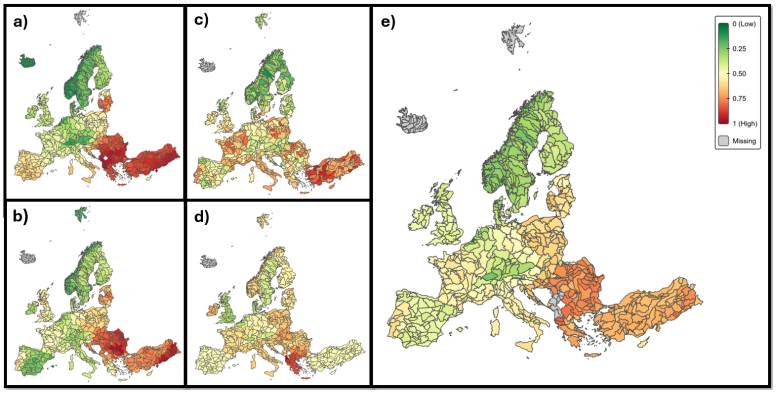


Figure 3: Cross-sectoral component maps: (a) economic factors, (b) social factors, (c) water factors, and (d) equal-weight cross-sectoral composite map.

cial, water-system, and readiness) and two trade-off scenarios emphasizing social–readiness or economic–water-system conditions. The maps remain highly correlated with the baseline ($r = 0.939$–0.980; Figure 4), so the main hotspot pattern is robust, although water-dominant and readiness-oriented assumptions still affect some basin scores. The equal-weight baseline is therefore retained as the balanced reference layer.

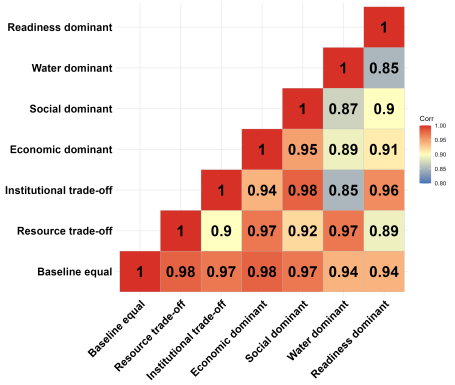


Figure 4: Triangular correlation matrix between alternative scenarios.

4.2. Sector-Specific Component Maps

The sector-specific component maps are interpreted before adding the cross-sectoral branch, so they show vulnerability driven by sectoral indicators (Figure 5). Energy production and inland waterway transport mainly reflect infrastructure dependence and activity presence. Energy scores are higher where electricity production relies strongly on dam-based hydropower, and lower where renewable-energy profiles are more diversified, such as Portugal and Italy. Inland waterway transport is highly presence-dependent: basins without relevant river-transport activity receive 0 under the expected-missing rule.

The public-water-system-related sectors show different spatial signals: human-health vulnerability remains very low across many northern basins, while manufacturing vulnerability is more pronounced in Mediterranean basins. In agriculture, irrigated and rainfed crops follow broadly similar regional structures, although cropland distribution still changes basin-level scores. Livestock differs, with comparatively lower vulnerability in Mediterranean basins than in many northern and central basins.

The ecosystem maps are more heterogeneous and localized, with several Portuguese basins standing out as hotspots. Overall, these sector-specific maps should be read as signals that may later be amplified or buffered by the cross-sectoral component, not as final vulnerability.

4.3. Final Sectoral Composite Vulnerability Maps

The final sectoral composite maps use the equal-weight cross-sectoral composite as the reference territorial layer and combine it with each sector-specific map through the geometric-mean approach. Their purpose is to show how broader socio-economic, water-system, and readiness conditions can buffer or amplify sector-specific drought vulnerability patterns across basins.

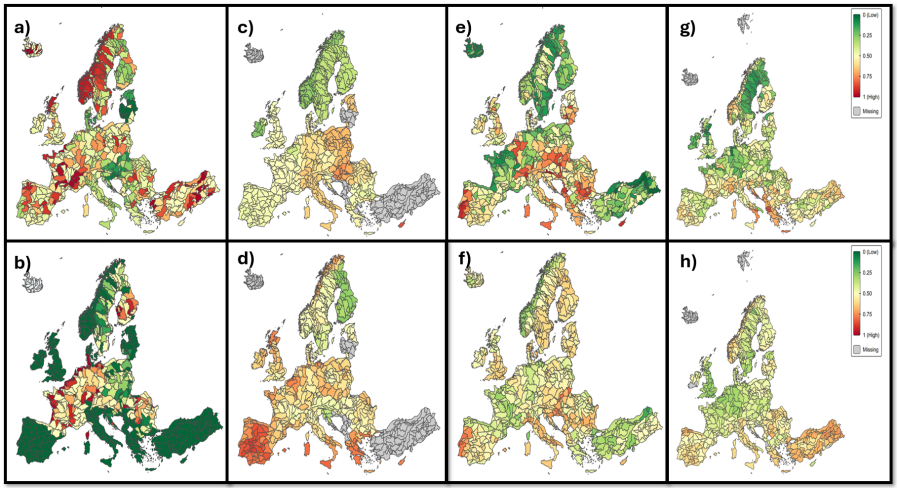


Figure 5: Sector-specific component maps: (a) Energy Production, (b) Inland Waterway Transport, (c) Human Health, (d) Manufacturing, (e) Freshwater Ecosystems, (f) Terrestrial Ecosystems, (g) Rainfed Crops, and (h) Irrigated Crops.

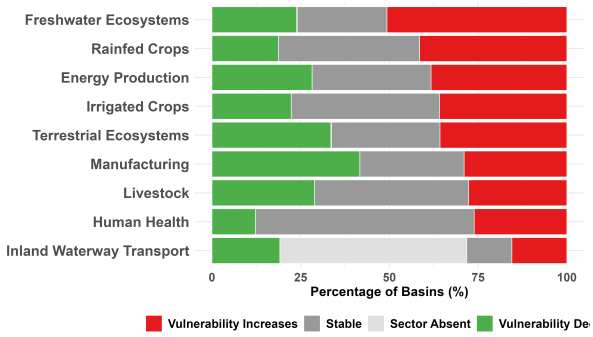


Figure 6: Sector-specific component maps versus 50–50 composite sector score comparison.

The 50–50 composites show that cross-sectoral capacity modifies sector-specific vulnerability unevenly across Europe (Figures 6 and 7). Manufacturing shows the clearest buffering, especially in northern and western basins where economic strength and readiness offset industrial exposure. By contrast, rainfed crops and freshwater ecosystems show stronger amplification when sector-specific sensitivity overlaps with weaker territorial capacity. Energy production remains more mixed, while human health is mostly stable and inland waterway transport is often structurally absent.

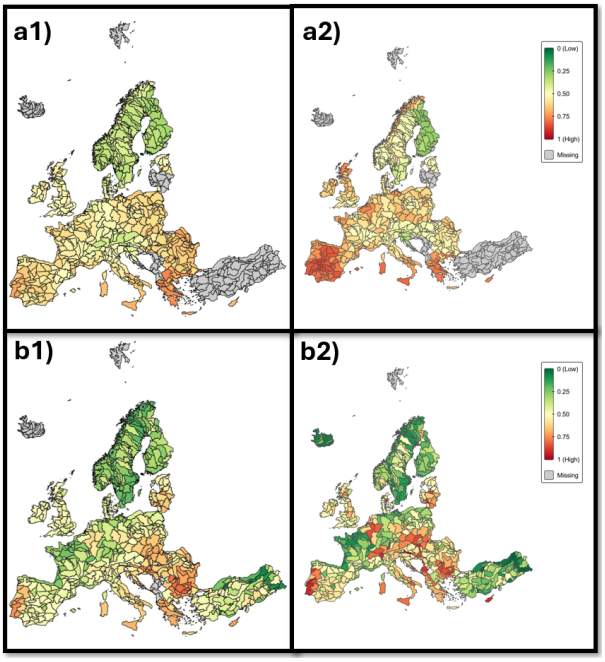


Figure 7: Comparison of 50–50 composite and sector-specific maps for manufacturing and freshwater ecosystems.

4.4. Aggregation Comparison

The aggregation-method comparison tests how final sectoral scores respond when branch weights are kept constant but arithmetic and weighted geometric rules are compared. Overall, both formulations give similar results for most sectors, especially agriculture- and public-water-related sectors, which remain close to the

one-to-one relationship. Inland waterway transport is the main exception: where activity is absent and the sector-specific branch is zero, the geometric formulation also returns zero, while the more compensatory arithmetic rule can still assign a low non-zero score through the cross-sectoral branch.

4.5. Branch-Weighting Scenario Comparison

This section tests how final sectoral scores change when the weights of the cross-sectoral and sector-specific branches are varied, while the weighted geometric aggregation rule is kept fixed. In each scenario label, the first number refers to the cross-sectoral branch and the second number refers to the sector-specific branch: 50–50 means 50% cross-sectoral and 50% sector-specific weighting, 80–20 means 80% cross-sectoral and 20% sector-specific weighting (cross-sector-dominant), and 20–80 means 20% cross-sectoral and 80% sector-specific weighting (sector-dominant).

4.5.1 Branch-Weighting Sensitivity

Overall, the comparison separates robust hotspots from patterns that depend on weighting assumptions. Livestock remains relatively stable, whereas energy production is more unstable. Sector-dominant (20–80) maps highlight sector-specific hazard–impact pathways, while cross-sector-dominant (80–20) maps can buffer sector-driven vulnerability where territorial conditions are favourable, especially in northern basins. Stability should therefore be interpreted as robustness to weighting assumptions, not as priority by itself; consistently high-vulnerability areas remain the main concern.

4.5.2 Basin-Level Stability Analysis

The basin-level stability analysis, summarized in Table 1, distinguishes robust sectors from weighting-sensitive ones. Human health and irrigated crops are the most stable, indicating strong alignment between sector-specific patterns and cross-sectoral territorial capacity. Inland waterway transportation, energy production, manufacturing, and freshwater ecosystems are more sensitive because of local hydrology, activity presence, and infrastructure can dominate broader socio-economic or institutional capacity. Rainfed crops, livestock, and terrestrial ecosystems remain intermediate; overall, sector-specific assessment is most important for water-dependent infrastructure and ecosystem sectors.

4.6. Evaluation against previous studies

The evaluation is used as a qualitative consistency check, not as a direct validation against observed drought losses or drought severity. The external layers are treated as reference maps rather than ground truth: they help assess whether the main spatial patterns of the thesis outputs are plausible when compared with independent vulnerability-oriented studies. The comparison focuses only on outputs for which a thematically comparable reference layer is avail-

Table 1: Distribution of basins across branch-weighting stability classes by sector. The stable column combines highly stable and stable basins.

Sector	Stable (%)	Moderate (%)	Unstable (%)
Human Health	75.4	24.6	0.0
Irrigated Crops	72.3	27.5	0.1
Rainfed Crops	62.3	35.3	2.4
Livestock	61.2	36.6	2.2
Terrestrial Ecosystems	52.6	45.0	2.4
Energy Production	45.8	36.7	17.5
Manufacturing	45.5	38.4	16.1
Freshwater Ecosystems	45.3	42.5	12.2
Inland Waterway Transportation	35.7	44.9	19.4

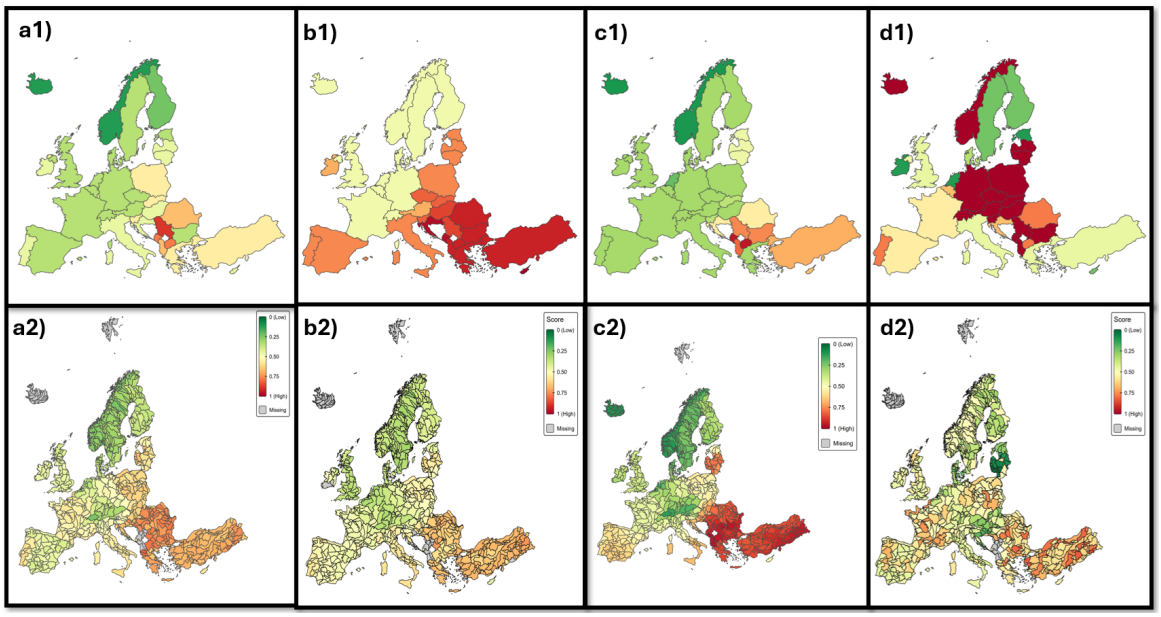


Figure 8: Evaluation against previous studies for cross-sectoral, irrigated crops, economic and energy production vulnerability maps. First line (a1)–(d1) show reference maps from literature, while second line (a2)–(d2) show multi-sectoral drought vulnerability application results. Panels (a): Cross-Sectoral Vulnerability, Panels (b): Irrigated Crops Vulnerability, Panels (c): Economic Factors Vulnerability, and Panels (d): Energy Production Vulnerability.

able, and the thesis maps are interpreted as the 50–50 branch-weighting results under the weighted geometric aggregation rule. The selected reference-map comparisons are summarized in Figure 8.

For economic vulnerability, the reference map from global drought-risk work provides a smoother European pattern because it is built for global comparison and relies on high-level economic factors [2]. The thesis map shows stronger within-Europe contrasts because it uses financial insecurity, inequality, and poverty-risk indicators, making west–east and south–north differences more visible. For cross-sectoral vulnerability, the comparison with an independent territorial drought-vulnerability layer shows a similar broad gradient, with lower vulnerability in northern and north-western Europe and higher vulnerability toward eastern and south-eastern basins [8]. The thesis composite is more detailed because it also includes water-system and drought-readiness information. For irrigated crops, the agricultural reference map is useful for checking broad plausibility, but it does not fully separate irrigated and rainfed systems. The thesis irrigated-crop map adds sector-specific detail through irrigation performance and operational constraints, so it reveals clearer system-specific and within-country contrasts, especially in Mediterranean agricultural areas [7].

5. Conclusions and Future Developments

This thesis developed and applied a multi-sectoral framework for assessing relative drought vulnerability across European basins. The main conclusion is that drought impacts cannot be explained by hydro-climatic deficits alone: vulnerability also depends on exposed activities, water dependence, infrastructure, socio-economic capacity, ecosystem sensitivity, and institutional readiness.

The main methodological contribution is the separation of the framework into two connected branches. The cross-sectoral branch represents shared territorial conditions, while the sector-specific branch preserves the drought-impact logic of each sector. This structure avoids reducing vulnerability to one generic score while still allowing comparison across sectors.

The European case study confirms the value of basin-scale and sector-specific assessment. Cross-sectoral maps identify broad regional gradients, whereas sector-specific maps show that vulnerable areas differ between systems. The sensitivity analysis also shows that aggregation and branch-weighting choices can affect final scores, especially for sectors with strong water or infrastructure dependence.

Several limitations remain. The framework depends on data availability, indicator quality, proxy selection, and spatial resolution, and the current model is static rather than event-based. Future work should compare the index with observed drought impacts, include time-varying indicators or climate scenarios, and refine the framework with local datasets or participatory weighting and link it with drought hazard and exposure to support a drought risk assessment.

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