From Complexity to Clarity: A Scalable Network Framework for Quantifying Anthropogenic Drought in Flanders

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Abstract. Anthropogenic drought increasingly threatens even temperate regions, yet policymakers lack concise, quantitative tools to visualise system interactions and assess intervention effectiveness. This study presents a streamlined network-based workflow that reconciles system complexity with operational clarity. Prior research has highlighted the value of multidimensional network models but produced unwieldy representations due to an abundance of connections and components. This was addressed by optimizing scalability, focusing on key actors and hydrological factors, refining the visualisation strategy, and treating policy measures as contextual modifiers rather than discrete nodes. The simplified network preserves flexibility, permitting higher-resolution detail when data is available, while improving interpretability and computational tractability. The resulting framework is immediately actionable: it empowers water managers to simulate targeted interventions by reweighting connections, and transparently communicate projected impacts to stakeholders. While acknowledging limits imposed by data resolution and the implicit representation of governance dynamics, the approach offers a practical bridge between conceptual complexity and policy application. By combining quantitative rigour, visual clarity and modular extensibility, the method delivers a decision-ready platform for enhancing drought resilience.

1 Introduction

Drought is an increasingly frequent natural hazard with significant consequences for various sectors, exacerbated by ongoing climate change. Unlike other natural disasters, typically triggered by acute, singular events, drought develops gradually. The accumulation of effects over an extended period, combined with widespread and often non-structural impacts, makes drought a complex phenomenon that is difficult to define unambiguously. This creeping nature also complicates the development of effective mitigation and adaptation measures. [1]

In addition to natural factors, human activities play a crucial role in the emergence and intensification of drought, further increasing its complexity. [1]

Given that drought is a complex and multidisciplinary phenomenon, it is prone to misinterpretation and can be viewed from various perspectives. Therefore, this research

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considers drought as a dynamic process rather than a static product. The definition used is "Anthropogenic drought", resulting from the interaction between human activities and/or natural processes, ultimately leading to water stress (both social and ecological). [2] Understanding drought thus requires a interdisciplinary approach. [3]

In response to these challenges, recent research by Vercruysse et al. (2024) proposed a structured theoretical approach for visualizing and understanding drought systems. They introduced a methodology that integrates the Water Resilience Assessment Framework (WRAF) with the Actor-Relational Approach (ARA), and network analysis. This interdisciplinary approach aims to dissect the complex relationships within drought systems, providing insights into key actors, environmental factors, institutional frameworks, and mediating organizations that influence drought resilience. However, this previous application faced two main challenges: (1) the network was overly large, which reduces clarity, and (2) the absence of quantitative weights limited its usefulness for policy evaluation.

To support policymakers, there is a need for clear, accessible tools that illustrate interactions within drought systems and help assess the impact of potential measures. Therefore, this research contributes to existing knowledge by addressing the complexity and interdisciplinary nature of drought, refining the way networks are visualized, and simplifying them to include only primary nodes. The approach is applied to the Flemish region in northern Belgium, selected for its increasing drought risk and the availability of open-source data. This allows for a clearer visual representation of the system's complexity and supports deeper insights at various scales.

2 Materials & Methods

This study builds on the operational framework for visualizing drought systems proposed by Vercruysse et al. (2024), which includes the following steps: (1) defining the system boundary, (2) identifying the system components, (3) conducting a network analysis, and (4) assessing trends and system status.

The current research refines this framework by improving the second and third steps. In step two, the system components were adapted to enhance scalability, while in step three, the network analysis was made quantitative. For completeness and clarity, all steps are briefly outlined in this publication.

2.1 Defining the System Boundary

The system boundary is essential for managing the complexity while still acknowledging external influences. In this study, the drought system boundary is defined by prioritizing hydrological and functional criteria, ensuring that most relevant elements are included, while adjacent subsystems are treated as input or outputs of the system.

2.2 Defining the System Components

The Actor-Relational Approach (ARA), **Fig. 1**, offers a framework for unpacking the complexity of drought systems by organizing key system components into four interconnected categories:

- Actors are those entities capable of taking action. These actors possess agency and can join or leave the system in response to evolving conditions. [4]
- Factors refer to the broader environmental and socio-economic conditions that influence or limit actor's behaviour. [4]

- Institutions encompass both formal and informal rules, policies, or agreements that govern behaviour and coordination among actors. [4]

- Mediators or Intermediaries are mechanisms or platforms that shape communication and interpretation of information. These mediators play a crucial role in aligning various system elements toward collective outcomes. [4]

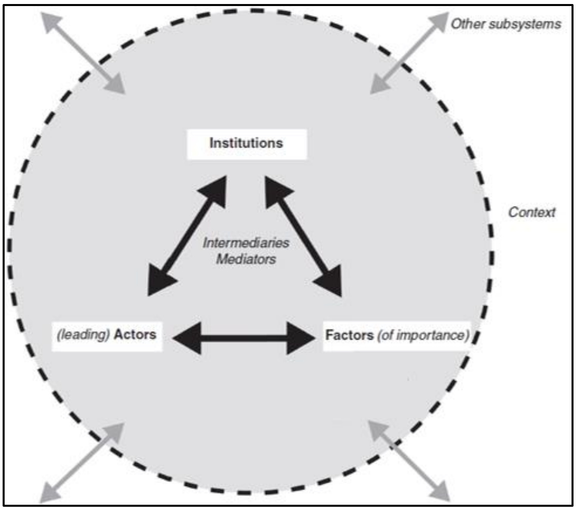

Fig. 1. The actor-relational approach – scheme [4]

The drought system is seen as dynamic and co-evolving. Actors may modify environmental factors or influence institutional frameworks, while mediators help reinterpret and channel information in ways that shape behaviour. This can lead to either increased vulnerability or resilience to drought. This paper suggests improvements to this approach in order to seek for more resilient solutions. Resilience is here defined as interactions between human and natural subsystems that can co-evolve, allowing both "bounce back" and "bounce forward" responses.

The previous study, [3], has introduced greater flexibility in visualizing drought systems by allowing the inclusion of additional nodes in the network, thereby capturing increased complexity. However, expanding the number of nodes and connections does not inherently improve the system's interpretability or practical utility. To maintain clarity and operational feasibility, it is important to constrain the overall size of the network. Accordingly, this study employs a carefully selected subset of components that offers a coherent and representative overview of the drought system.

The selection was grounded in the key actors and factors for which data - primarily from intermediaries - is available for the Flanders study area. This subset was further refined using insights from prior research conducted in the region, providing a solid foundation and confidence that a simplified model could still adequately represent the broader drought system.

Although the model can be expanded to incorporate more detailed components when higher-resolution data are available, such extensions should be critically assessed. Specifically, the increased complexity must clearly contribute to improving the system's capacity to evaluate the effectiveness of drought mitigation or adaptation measures.

2.3 Network Analysis

Once the components of the drought system have been identified, a network analysis is employed to visualize and interpret the relationships among them, within Gephi. Previous applications of the Actor-Relational Approach (ARA) described in Vercruysse et al. (2024) represented all component types, actors, factors, institutions, and mediators, as individual nodes, resulting in highly complex networks with numerous connections. This study proposes a more streamlined approach by representing only the essential actors and factors as nodes, thereby enhancing clarity and interpretability.

This simplification is supported by a revised visualization strategy. In the proposed model, relationships (edges) between actors and factors are context-dependent, reflecting the dynamics of specific situations. For instance, institutional elements - understood as measures within the ARA framework - are not depicted as nodes. Instead, they are embedded within the edges, as they shape the interactions between actors and factors. These measures can influence or constrain actor behaviour, ultimately affecting water use and related environmental factors. As a result, the nature and number of edges vary depending on the type and scope of institutional interventions present in a given scenario.

Intermediaries or mediators, though not directly represented as nodes, retain a critical function in this network structure. Their role is to facilitate the flow of information between actors, factors, and institutions. In the ARA perspective, mediators may either transmit data unchanged or reinterpret it to promote system resilience. [4] Accordingly, the quantification of edges in the network captures the informational exchanges facilitated by these mediators. When all relevant information flows are represented, the network is considered fully connected.

2.3.1 Fruchterman–Reingold Layout

The network's preliminary arrangement is generated using the Fruchterman–Reingold force-directed algorithm. In this model, edges behave like springs that draw connected nodes together, while each node exerts a repulsive force on its neighbours. Through iterative minimization, the algorithm converges on a configuration in which densely connected nodes form tight clusters, and more weakly connected nodes are spatially separated [5]. This initial layout reveals the network's overarching structure, highlighting broad groupings without yet distinguishing finer community boundaries.

2.3.2 ForceAtlas2 Layout

To enhance cluster separation and improve visual clarity, the ForceAtlas2 algorithm is subsequently applied. Like Fruchterman–Reingold, ForceAtlas2 simulates spring-like attraction along edges and charge-based repulsion among nodes, but it introduces tuned forces that expand space around highly connected vertices and spread out loosely associated clusters [5]. Because node positions in ForceAtlas2 depend exclusively on the network's topology: proximity indicates stronger structural ties, whereas isolation reflects weaker or non-existent connections.

2.3.3 Network Metrics

To pinpoint structurally pivotal elements within the drought system, the following centrality measures were computed in Gephi:

- Degree Centrality: The total number of edges incident to a node, serving as an indicator of its activity level or prominence in undirected networks.
- Betweenness Centrality: The proportion of shortest paths between all node pairs that traverse a given node. Nodes with high betweenness act as bridges, controlling or facilitating information flow.
- Eigenvector Centrality and PageRank: Eigenvector centrality assigns greater weight to nodes connected to other high-scoring nodes, thereby capturing the influence of one's neighbours. For directed networks, PageRank adapts this concept by incorporating edge directionality and damping factors.

By combining these metrics, actors and factors are identified which occupy critical positions in terms of connectivity, brokerage, and influence, providing a basis for targeted resilience strategies [3].

2.4 Trends and Status

After the network model is established, the framework proceeds to evaluate both the system's baseline condition and its prospective trajectory. The status assessment characterizes the drought system's recent or current state, while trend analysis projects how key components may evolve over time [3]. In jurisdictions where comprehensive observational datasets exist, these records form the empirical basis for both status and trend evaluations [3].

This paper presents a methodology that remains within the network approach by utilizing the network created in Gephi to analyse status and trends. The NESEV software module is recommended for the visualization of the status and trends. Although NESEV, similar to Gephi, is a network-based software, it incorporates improvements that enable a clearer and more comprehensive overview of the quantified network.

By overlaying metrics and observed or anticipated changes onto the ARA-derived network, practitioners may identify which actors or factors warrant prioritized monitoring within the simulated institution. Periodic re-examination of network topology and associated component metrics enables the detection of resilience-enhancing co-evolutionary patterns or, conversely, emerging vulnerabilities. This information is essential for effective resilient management. [3]

3 Results

3.1 Defining system boundary

Many regions are challenged by the emergence of droughts. Flanders, the northern region of Belgium (**Fig. 2**), seems to be new to this problem, although the annual renewable water availability per capita in Flanders is lower than those reported for traditionally drought-prone European areas [6]. Furthermore, in 2019, the World Resources Institute ranked Belgium 18th in terms of drought risk .

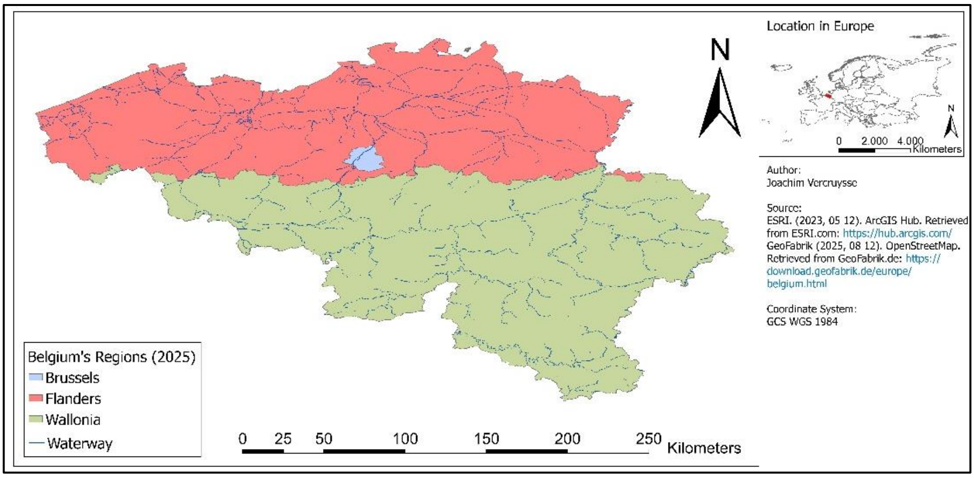

Fig. 2. Location of the study area Flanders

Flanders' struggles to fulfil the objectives of the European Water Framework Directive especially through droughts [7]. Several interrelated factors exacerbate this vulnerability. First, a high population density, 492 inhabitants per km^2, resulting in 15.8% impervious surface cover, limits precipitation infiltration and reduces groundwater recharge [6]. Second, historical flood-control policies prioritized rapid drainage of precipitation to the North Sea via engineered canal networks and sewer systems, fostering a reactive, short-term approach to water management that offers counterproductive resilience to drought episodes, especially since Flanders is highly dependent on rainwater. [6]

Moreover, Flanders' predominantly anthropogenic water regime introduces additional drought risks, as human management decisions exert direct control over hydrological flows [6]. On the other hand, the region benefits from extensive open-source hydrological and meteorological datasets, enabling comprehensive evaluation of drought-relevant components. Consequently, this study adopts the administrative boundaries of Flanders as the system boundary for network modelling and resilience assessment.

3.2 Defining system components

In their investigation of drought complexity, Vercruysse et al. (2024) initially identified 142 distinct system components and 1,575 interconnections within the drought-affected region (see **Fig. 3**). Quantifying such a vast network proved unfeasible due to its structural complexity, the limited availability of comprehensive datasets, and the fact that not all relationships can be meaningfully represented by scalar values. Consequently, an appropriate level of abstraction was sought, one that would preserve the system's core dynamics while rendering quantitative analysis practicable and intelligible.

Building on existing Flemish studies [8, 9] and guided by data availability, the original network was distilled into eleven principal nodes. These nodes align with the Actor–Relational Approach (ARA) framework, comprising five actor categories (households, agriculture, industry, commerce and services, and other stakeholders), and six hydrological factors. The actor groups correspond to those routinely employed in contemporary water-management assessments, including the reactive assessment framework, the impact-tool methodology, and the Flemish Environment Agency (VMM) dashboard. The factors capture the principal water flows that define system balance: rainwater, surface water, groundwater, wastewater, drinking water, and evapotranspiration. By this simplification, a clear representation of essential drought dynamics was maintained, while enabling a quantitative evaluation.

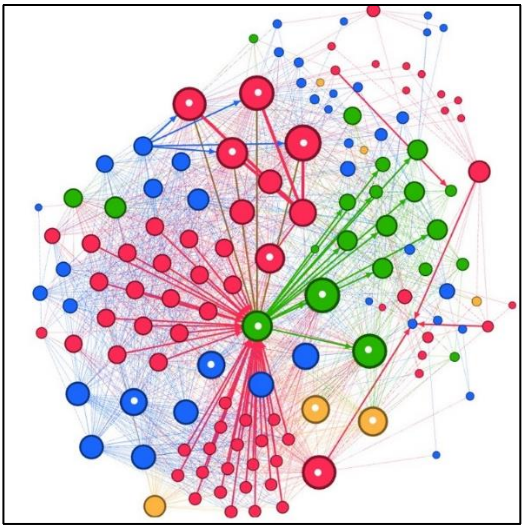

Fig. 3. Representation Gephi network analysis [3]

In this study, rather than implementing and testing specific drought-mitigation measures and different institutions, the current state of the system was simulated to establish a baseline against which future interventions may be evaluated.

To capture the mediating and intermediary processes that shape water dynamics, a series of data layers were incorporated, each representing a distinct type of sectoral or environmental information:

- Sectoral water consumption: Actual water use by households, agriculture, industry, and commerce and services was extracted from the VMM's interactive dashboard. [9]
- Precipitation records: Total available water input was estimated using daily rainfall data obtained from the Waterinfo platform. [10]
- Evapotranspiration: Data on evapotranspiration were derived from previous research executed in Flanders as part of the development of the 'Reactive assessment framework'. [8]
- Soil type: Information on soil types across Flanders was sourced from the Digital Soil Map and relevant research literature. [11]
- Infiltration: Infiltration coefficients per soil type were based on data from a study employing the WetSpass model. [11]
- Surface impermeability (WOK map): The percentage of impermeable surface per pixel of 5 meter resolution, indicating areas where artificial surfaces inhibit infiltration, was sourced from the Water-Impedance (WOK) dataset. [12]
- Land-use classification: Actual land-use categories, reflecting observed land use rather than legal zoning, were identified using the Flemish Land-Use Map. [13]
- Topographic reference (GRB): Detailed spatial data on buildings, parcels, roads, watercourses, and railways were obtained from the Large-Scale Reference Base (GRB) to quantify impervious surfaces of roads and surface-water coverage. [14]
- Building registry (GRAR): Roof-area estimates, essential for runoff calculations, were derived from the Flemish Building Registry (GRAR), which provides unique identifiers and lifecycle information for every building unit. [15]

By integrating these datasets, a comprehensive representation of the current hydrological and anthropogenic context was established. Future adaptive measures can then be overlaid onto this framework to assess their potential impacts on water resilience without introducing unwarranted complexity.

3.3 Network Analysis

The initial data preparation was performed in Excel before importing the network into Gephi for visualization and further analysis.

At the core of the quantification procedure is the construction of a water-balance matrix for the 11 principal nodes and their 45 connecting edges, with each link assigned a volumetric flow (m^3) corresponding to the chosen temporal resolution. Although annual aggregates may obscure the onset and duration of drought episodes, monthly simulations permit the observation of water-balance dynamics and the identification of drought periods. Therefore, all subsequent calculations were performed on a monthly basis.

Precipitation allocation: Monthly rainfall totals were obtained from the Waterinfo-platform and spatially averaged to derive a uniform precipitation depth (mm) across the study area. This depth was then converted to volume by multiplying it by the total surface area.

Actor-specific precipitation: Using the GRB-layers to delineate roads and water bodies, the GRAR building registry to extract roof surfaces, and the land-use classification map to identify residential, agricultural, industrial, commercial, and natural covers, precipitation volume was apportioned to each actor class.

Surface classification: The WOK dataset provided per-pixel impermeability percentages, enabling a detailed breakdown of each actor's area into impervious, pervious, roof, and open-water categories.

Evapotranspiration estimation: Evapotranspiration (ET) was computed following the methodology of the reactive assessment framework, which had previously established ET coefficients for the Flemish region. Monthly precipitation inputs and surface classifications served as inputs to this calculation.

Runoff and infiltration: Maximum potential infiltration was estimated using the WetSpass-Flanders model, which calculates groundwater recharge rates based on soil type. A weighted average was derived according to the relative proportions of each soil class present in the study area. Runoff was inferred as the residual of incoming precipitation after subtracting the sum of ET and infiltration values. Following the quantification of all flows - precipitation allocation, evapotranspiration, infiltration, and runoff - were quantified for each link, the resulting matrix was exported to Gephi. This enabled the visualization of volumetric interactions among actors and factors, providing a foundation for future scenario testing of drought-mitigation measures.

To illustrate the evolution of the model, **Fig. 3** reproduces the network visualization from Vercruysse et al. (2024), while **Fig. 4** presents a simulated current state and measure for the updated network developed in this study. In the new visualizations, see **Fig. 4**, the structure of the system is rendered more transparently, illustrating the origins, directions, and institutional roles of water flows. This improvement is attributed to the use of essential nodes, edges based on the type of institution, and the incorporation of mediators and intermediaries that provide quantitative depth to the model. Moreover, node colour encodes network degree (red = low, green = high), node size reflects PageRank centrality (small = low, large = high), and edge hue represents the volume of water flow (red = low, blue = high), thereby facilitating simultaneous interpretation of multiple relational and flow-based metrics in the same diagram.

The simulated measure in **Fig. 4**, enforces maximal utilisation of available rainwater by households relative to their consumption. In the network, households shift from using rainwater, groundwater and drinking water (**Fig. 4a**) to relying primarily on rainwater and, to a lesser extent, on drinking water (**Fig. 4b**). This eliminates groundwater abstraction and reduces demand on potable supplies. As a result, household water-use efficiency increases and discharge to surface waters declines proportionally. These changes are reflected in network metrics: households' degree (node colour shifts from orange to red) and PageRank (node size decreases) signal reduced connectivity and relative influence within the system. The household node also moves closer to the rainwater node, consistent with its increased dependence on rainwater.

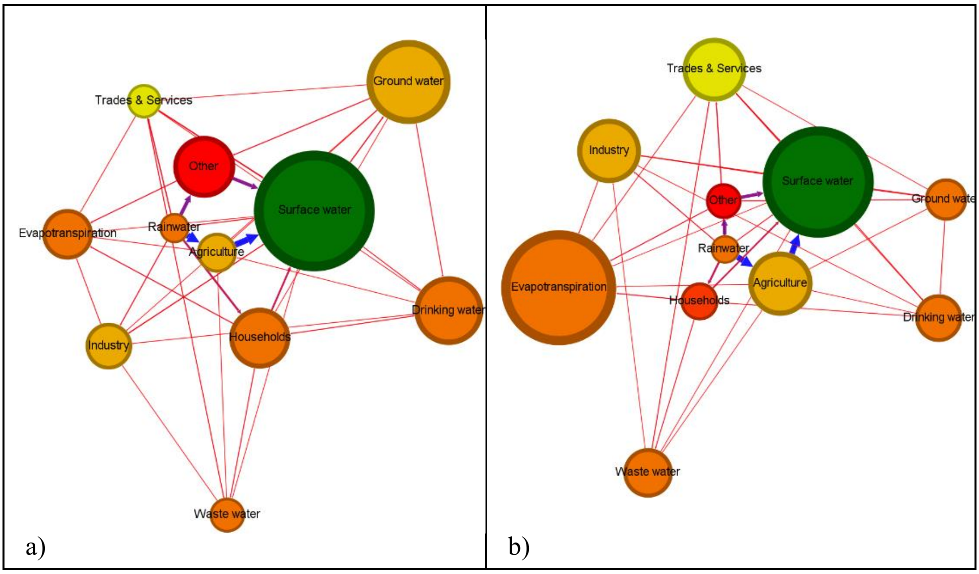

Fig. 4. Updated network analysis in Gephi with **a)** the simulated current state and **b)** the simulated measure. The colour of node represents the degree (red = low, green = high), the size of the node represents the PageRank (small = low, large = high), the thickness and colour of the edges represent the amount of water flowing through the system (narrow and red = low, thick and blue = high).

3.4 Trends and Status

NESEV produces a clear, quantitative overview of water fluxes within the network (**Fig. 5**) and supports time-step simulations, thereby enabling users to assess hypothetical measurements and scenarios at multiple temporal resolutions.

Because NESEV operates in a manner analogous to Gephi, the requisite Excel data can be readily reformatted for import into the software. For each system status, NESEV generates a comprehensive overview that elucidates prevailing trends; alternatively, individual graphs may be inspected and analysed in isolation. At the network-node level, the tool computes the net inflow or outflow volume, providing an immediate visual summary of water movement and highlighting nodes with significant gain or loss.

Should users wish to examine temporal trends, data from discrete intervals can be exported to Excel and subsequently aggregated to construct a continuous trajectory of network dynamics (**Fig. 6**).

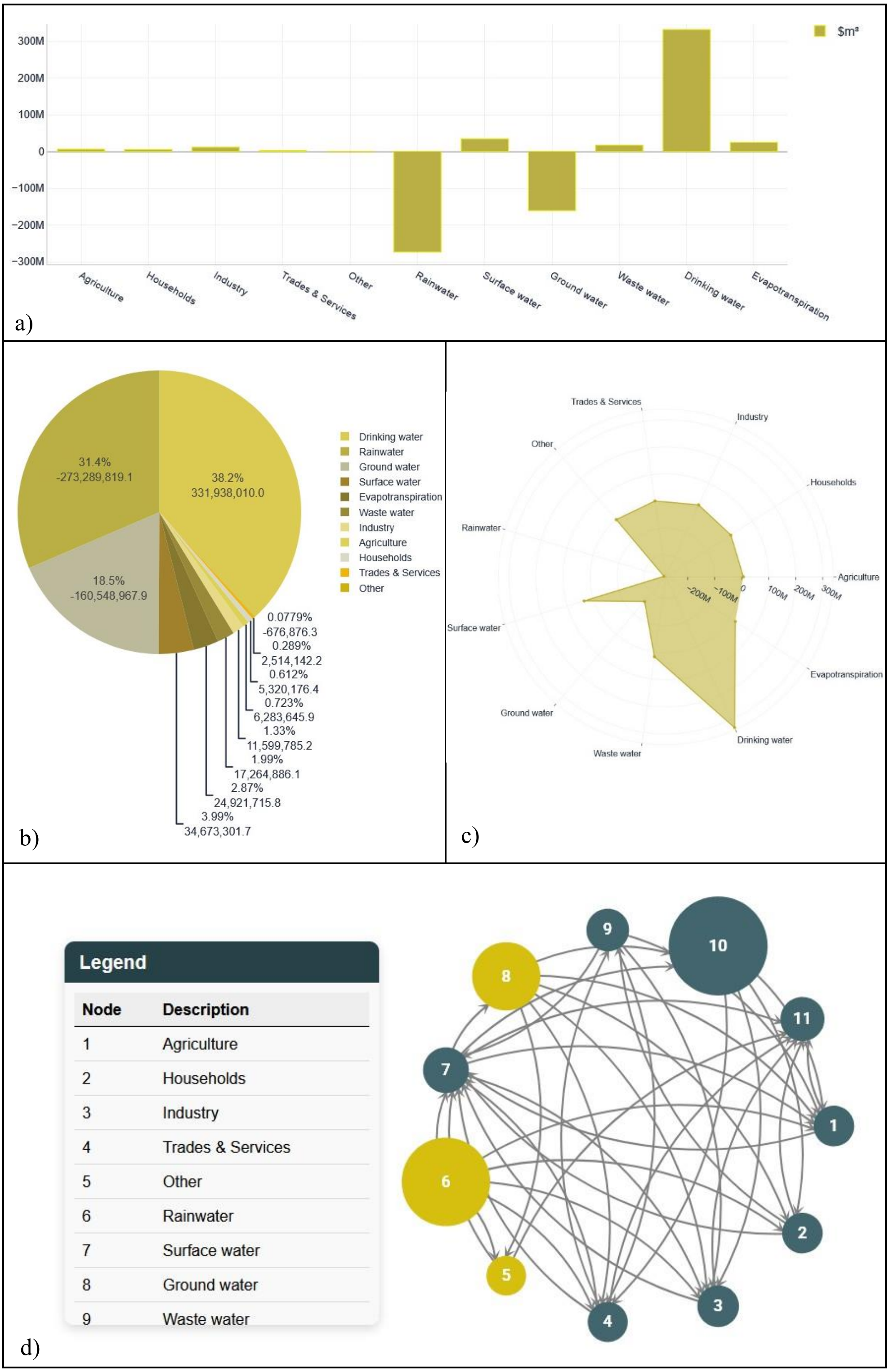

Fig. 5. Overview NESEV: **a)** Columns Chart (m³), **b)** Pie Chart of nodes (%) based on m³, **c)** Radar Chart (m³), **d)** Network representation

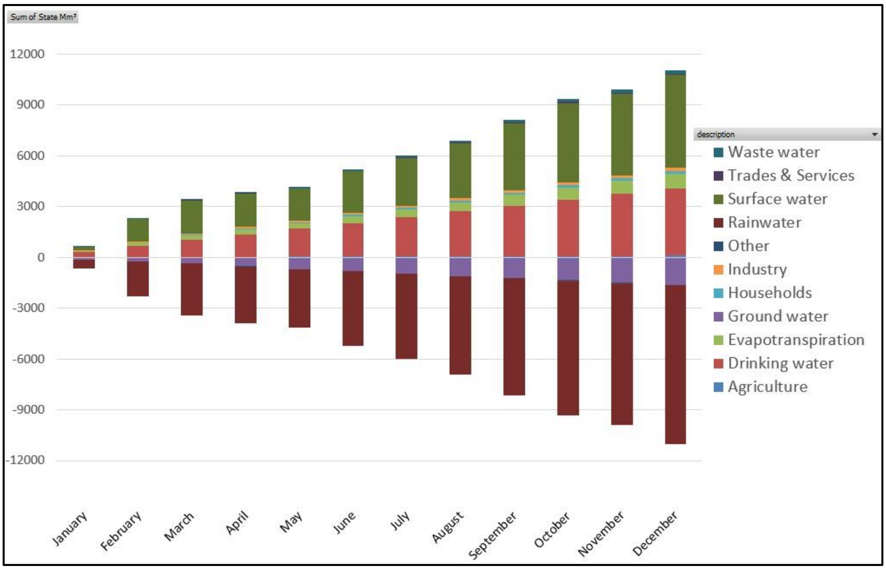

Fig. 6. Representation of a trend for the region Flanders in 2020

By superimposing performance metrics and observed or projected perturbations upon the network, practitioners can pinpoint the actors or processes that merit prioritized monitoring within the simulated framework. Regular re-evaluation of network topology and associated component metrics facilitates the identification of resilience-enhancing co-evolutionary patterns, or vulnerabilities, thereby furnishing critical insights for adaptive and resilient water-resource management.

4 Discussion

The present study demonstrates that this updated network-analysis framework allows an effective capture of the core dynamics of anthropogenic drought systems, balancing clarity and quantitative rigor. By reducing the original 142-node network to eleven principal nodes and embedding institutional measures within edge attributes rather than as separate nodes, a model that is both interpretable and amenable to quantification was achieved. The updated Gephi visualization clearly distinguishes high-influenced nodes, identified via PageRank, and key water-flux pathways, delineated by edge-weight colour gradients, thus facilitating rapid identification of resilience leverage points. This contrasts with the earlier, more expansive application of the network analysis, which suffered from visual clutter and inability to incorporate scalar weights into network edges.

The integration of sectoral water-use data, precipitation records, evapotranspiration estimates, and infiltration/runoff computations into a unified water-balance matrix represents an advance over prior qualitative or semi-quantitative approaches. Monthly time-step simulations preserve the temporal resolution necessary to detect drought onset and persistence, unlike annual aggregates that can obscure critical drought-development phases. The framework’s capacity for time-step scenarios testing further empowers practitioners to evaluate hypothetical measures, by reweighting edge flows and observing shifts within the nodes.

Nevertheless, several limitations should be acknowledged. While the inclusion of eleven nodes captures the principal water-mass exchanges within Flanders’ drought system, finer model resolution may be required to support localized management decisions. Such refinement, however, would entail increased complexity and demand for more detailed data. Moreover, the reliance on open-source datasets introduces uncertainties related to spatial aggregation and temporal discontinuities. Future work could address these issues by incorporating high-frequency remote-sensing products to refine precipitation-allocation and evapotranspiration estimates. Although the current model cannot achieve perfect accuracy given the current data constraints, this does not compromise its intended purpose. Rather than serving as a high-resolution forecasting tool, the model is designed to provide policymakers with a comprehensive overview and conceptual framework for the exploration and development of resilient drought-management strategies.

Finally, while embedding institutional measures within edges preserves model parsimony, it limits the capacity for explicit analysis of how governance structures evolve over time. Coupling this approach with a complementary qualitative policy-network analysis may yield richer insights into governance dynamics.

Despite these limitations, the findings presented here have clear practical relevance. First, water-resource managers in Flanders and similar temperate regions can employ the presented workflow to establish baseline resilience assessments and to prioritize monitoring efforts toward the most influential nodes. Second, the model's modularity allows for the rapid evaluation of targeted measures, by adjusting the edge weight, immediately revealing impacts on water demand. Third, the use of open-source software (Gephi) and publicly available data democratizes access to network-based drought assessment, fostering cross-sectoral collaboration among practitioners, researchers, and policymakers. At the moment, NESEV is still in development, hence not yet publicly available.

Moreover, this paper serves as a critical stepping stone for future research aimed at systematically assessing the impact of specific mitigation and adaptation measures on drought resilience. By providing a flexible modelling framework, it facilitates the quantification of how interventions alter network flows and resilience thresholds. Equally important, the reduced-node framework sets the stage for in-depth analysis of actor interdependencies, facilitating exploration of how shifts in governance influence both resource allocation and institutional authority within drought-affected regions.

5 Conclusion

This research advances the application of the network analysis - based on the Water Resilience Assessment Framework and the Actor–Relational Approach - to drought systems. This is achieved by demonstrating that a reduced-node network, enriched with volumetric edge weights, provides a clear and scalable framework for resilience assessment. Institutional measures are subsequently embedded within edge attributes to preserve model simplicity without compromising policy-relevance.

Focusing on the Flemish region, a complex, 142-component network was distilled into an eleven-node model that retains critical hydrological and anthropogenic interactions. Monthly water-balance quantification, combined with force-directed layouts and centrality metrics, reveals the most influential actors and fluxes, thereby guiding strategic monitoring and intervention. Additionally, integration of the NESEV platform facilitates scenario testing and trend analysis on monthly basis, preserving drought-development dynamics.

While refinements remain a subject for future research, the proposed workflow offers an immediately applicable tool for water-resource managers confronting drought risks. Furthermore, it enables a deeper exploration of how individual and collective measures influence the network. Future studies can leverage the presented approach to perform impact assessments and potentially capture shifts of institutional power from actors, thereby fostering a more comprehensive understanding of governance dynamics in drought management.

In sum, by reconciling complexity with clarity, this study offers a replicable methodology for systematizing drought-resilience assessments across diverse contexts, supporting adaptation and mitigation strategies.

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