Response to reviewers and summary of manuscript revisions

AC to Referee #1 (Antonia Longobardi):

We sincerely thank Referee #1 for the positive and encouraging feedback. We appreciate the recognition of the manuscript's structure, clarity, and thorough contextualization within the current literature, as well as the relevance of the analysis for understanding drought hazard in Sweden. We are pleased that the referee finds the manuscript suitable for publication without further revision.

AC to Referee #2:

We thank Referee #2 for the thoughtful and constructive review. We appreciate the positive assessment of the manuscript's insights, particularly regarding the regional patterns in soil moisture anomalies and the trend analysis of drought indicators. We also acknowledge the reviewer's concerns regarding the methodology for identifying droughts based on individual indicators, which we plan to fully address in the revised manuscript. We also plan to provide a more cautious interpretation and clearer terminology to improve the clarity and robustness of the analysis. Below, we address each of the specific comments in detail.

Responses to major comments:

1. We thank the referee for raising this important point regarding the interpretation and use of Soil Moisture Anomaly (SMA) as a drought indicator. As defined in the manuscript "drought is a natural hazard characterized by periods of drier-than-normal conditions with wide-ranging and cascading impacts across societies, ecosystems and economies." In line with this, we identified drier-than-normal periods using a suite of drought indicators, including SPI, SPEI, SSMI, SSI, and also including SMA, which provides valuable insights into long-term soil moisture variability.
   However, we acknowledge the reviewer's concern that SMA minima may, in some cases, reflect seasonal variability rather than drought conditions with societal or ecological impacts. We agree that using SMA alone to identify droughts is not yet a standardized approach and requires further validation, as the reviewer rightly points out. Please refer to response to the 2nd major comment for a detailed explanation.

2. In response to the 2nd major comment, we followed the reviewer's suggestion and revised the manuscript to clarify that the identification of droughts based solely on negative SMA values should be interpreted with caution. Specifically, we adjusted the terminology throughout the text to refer to "dry periods" rather than labelling them as "drought events" unless supported by historical validation.
   We highlighted that many of these low-SMA periods show good agreement with known historical droughts (as noted in Figure 2). As suggested by the referee, we have carried out a systematic comparison between the identified low-SMA periods and documented historical drought events in Sweden. This is presented in the table below which was introduced in Section 3.1. This comparison includes an expanded discussion of the temporal correspondence and agreement between severe/extreme dry periods and droughts events, providing a more rigorous assessment of SMA's potential for drought detection in the Swedish context.

Table 1. Drought events and drought impacts in Sweden.

Year	Documented drought events	Assessed socio-economic impact
1975-1976	Low precipitation rates in most parts of the country SMHI (2025a).	Agriculture was affected due to the dry summers. Low water flows in large parts of the country, especially in southern Sweden. Low water level in lakes, mainly in Vättern and Hjälmaren, causing boat traffic disruptions. Low groundwater levels during 1976-1977 (SGU, 2025).
1983	Low precipitation during summer in southern Sweden (SMHI, 1986).	Bean growers and livestock owners were affected from the water shortages (SVT, 2018).
1992	Low precipitation and high temperatures in southern Sweden. The most drought-affected areas were Skåne, Blekinge, Småland, Öland, Gotland, and Östergötland.	Agriculture and forestry were affected. Wildfires burned meadows, marshlands, and forests. Low water levels mainly in southern Sweden where several rivers dried up.
1994	Low precipitation from May to July, and high temperatures in July especially in central and southern Sweden (SMHI, 1994).	Soil moisture dropped to half of normal values in some regions across the country during summer (SMHI, 1994). Below-normal streamflow observed in parts of the country during summer months.
2002-2003	Low precipitation in some parts of the country since the end of 2002 to October 2003.	Low streamflow and lake levels disrupted boat traffic (during spring and fall 2003) and hydropower reservoirs filling throughout 2003 (SMHI, 2004). Low groundwater levels in 2002 and 2003.
2006	Low precipitation and high temperature rates in July (SMHI, 2006a).	Low stream water levels across the country (SMHI, 2006b). Low groundwater levels in southern Sweden.
2016-2018	Large deficit in precipitation with high temperatures in some parts of the country.	Major impact on natural ecosystems, agriculture and forests. Estimated total costs for Swedish agriculture ranged between 6 and 10 billion SEK (about 530-900 M Euro) in 2018. Some parts of the county experienced severe forest fires. Low stream and lake levels particularly during the summers of 2016 and 2018. Low groundwater levels affected the water supply in southern Sweden.

References: SMHI (2025a, 2006a, 2006b, 2004, 1994, 1986), SGU (2025), SVT (2018).

3. We fully acknowledge the concerns raised regarding the independent treatment of standardized drought indicators and the limitations of using each indicator in silo to define drought periods. In response, we revised the manuscript to clarify this methodological point and adjust the terminology accordingly. Specifically, we avoided referring the low-indicator-value periods as "droughts" unless supported by historical validation, instead we introduced the terminology “dry period”. Dry period was defined as the continuous period during which the standardized drought index values remain consistently equal or below -1, and a it concludes when the values exceed -1 (following the operational definition of drought).

4. We agree that the metrics “accumulated drought intensity”, “accumulated drought severity”, and “accumulated weighted drought severity” lack clear physical interpretation and are not sufficiently integrated into the core analysis. Given their dependence on record length and the absence of follow-up discussion in the manuscript, we removed these metrics from the study to

maintain focus and clarity. We appreciate the suggestion and believe this adjustment strengthened the overall coherence of the manuscript.

5. We agree that Section 4.2, while addressing an important and timely topic, extends beyond the direct scope of our study. To maintain clarity and focus in the Discussion, we shortened this section and limit it to aspects that are directly relevant to our findings. This revision helps ensure that the discussion remains aligned with the objectives and contributions of the present work. Section 4.2 was restructured as outlined below:

   Drought indicators based on precipitation are widely used for drought monitoring and early warnings, but there is a need for indicators representing drought propagation in different domains of the hydrological cycle and across various spatial and temporal scales (Bachmair et al., 2016). Addressing this need, the present study analyses historical drought patterns across Sweden using multiple standardized indicators, thereby contributing to improved drought risk assessment and informing long-term planning in sectors such as agriculture, water management, and energy. For example, understanding how soil moisture and streamflow deficits evolve across regions and seasons can help inform agricultural management or reservoir operations in the energy sector.

   Building on previous research that analysed drought effects on water, energy, food, and ecosystems (Teutschbein et al., 2023b; Aldea et al., 2023; Campana et al., 2018), this study enhances the understanding of spatial and temporal drought patterns. It provides valuable insights for reservoir management and hydropower production, especially in northern and western Sweden, where future climate projections suggest increased drought risk (Teutschbein et al., 2023b). Additionally, the study's insights into soil moisture trends provide important context for forest management, particularly regarding species like Norway spruce that are highly susceptible to drought damage in southern Sweden (Aldea et al., 2023). Overall, the integrated drought indicator approach offered by this study supports cross-sectoral planning and enhances resilience to current and future drought hazards.

   By evaluating the performance and limitations of multiple standardized drought indicators, this study identifies which indicators most accurately capture different dimensions of drought parametrization across various regions and timescales. This comprehensive assessment highlights the strengths and limitations of each metric in capturing the physical processes and impacts of drought. It enables decision-makers and practitioners to select the most relevant indicators tailored to their specific monitoring needs. Additionally, it supports early warning and forecasting systems that can benefit from integrating multiple data sources to better address the complexity of drought as a systemic risk. This approach aligns with the recommendations by Hagenlocher et al. (2023) and Van Loon et al. (2024), who emphasize that effective drought risk management requires moving beyond single-variable, event-based metrics toward multidisciplinary systems that consider hydrological, ecological, and socio-economic factors. The insights provided by this study therefore support the design of drought monitoring tools that are both scientifically robust and operationally practical, improving the ability to anticipate, communicate, and mitigate drought impacts across sectors.

6. The S-HYPE simulation data used in the study are available from SMHI, part of the national hydrological service. We cited the original source of the data in the revised manuscript and provided the following Data and Code Availability statement to support transparency and reproducibility. Please see the Response to the 5th minor comment for a detailed response.

7. Specifically, for each standardized drought indicator and selected timescale, we identified dry periods as periods during which the indicator value remains less than or equal to -1. The

duration of a dry period corresponds to the number of consecutive time steps (months) during which this condition is met.

The severity of a dry period was then calculated as the sum of the indicator values over this consecutive period—i.e., the cumulative sum of all values ≤ -1 during the event. This means that severity reflects both the intensity and length of a dry period: a longer or more intense event will result in a higher cumulative severity value. This calculation is performed separately for each standardized indicator and timescale used in the analysis.

We clarified this explanation in the revised manuscript to ensure it is clearly understood by the reader.

Minor comments:

1. In order to maintain the consistency of all the figure captions, Figure 3 expresses the range as "from -infinite to -30".
2. Considering that SPI, SPEI, SSMI, and SSI equations are standard, we included them in the Supplementary material SM1.
3. “Drought characteristics” was used instead of “drought parameters”, when referring to drought duration, severity, intensity, and frequency.
4. We agree that the study does not directly contribute to operational early warning systems, as it focuses exclusively on the characterization of historical drought conditions. However, we believe that the results can still provide indirect support for the development or refinement of early warning systems by improving the understanding of how different drought indicators behave across regions and timescales. In particular, the identification of spatial patterns, trends, and indicator thresholds may help inform which variables are most useful for early detection or risk mapping in future system design. We revised the manuscript to clarify this distinction and avoid overstating the study's relevance.
5. We added Acknowledgments and Data and Code Availability Statement in the revised manuscript, as outlined below:

   Acknowledgments:

   The study was supported by the Centre of Natural Hazards and Disaster Science (CNDS) and the Centre for Societal Risk Research (CSR) at Karlstad University. We gratefully acknowledge Swedish Meteorological and Hydrological Institute (SMHI) for providing the climatological and hydrological simulations utilized in this research.

   Data and Code Availability:

   The HYPE model code, which was used in the national S-HYPE model setup, is available from the HYPEweb portal (https://hypeweb.smhi.se/model-water/; (SMHI, 2025b)). The meteorological data used for driving the S-HYPE model can be obtained upon contact with SMHI, and the hydrological data used are available from the Vattenwebb portal (https://vattenwebb.smhi.se/; (SMHI, 2025c)).

   The R scripts used to compute the drought indicators, along with the resulting datasets, are openly available at a FAIR-aligned public repository via Zenodo: https://doi.org/10.5281/zenodo.16539104 (Canedo Rosso, 2025).

We thank the referee for the thoughtful and constructive suggestions, which we believe enhances the clarity, scientific rigor, and analytical depth of the manuscript, strengthening its relevance to ongoing discussions on drought monitoring and definitions.

References

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