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The role of decision support tools in drought management: Insights from the Netherlands

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ABSTRACT

Droughts have an increasing impact on the entire European continent. As the frequency and intensity of droughts rise in many parts of Europe, the implementation of effective drought adaptation and mitigation strategies becomes increasingly important. However, it is not known how diverse tools are used in drought management with increasing drought severity. This study explores the role of Decision Support Tools (DSTs) in strategic and operational drought management in the Netherlands. Through a survey among national and regional water authorities, this study shows the increasing reliance of water managers on field measurements, Data Information Systems (DISs), stakeholder consultation, and legislation with increasing drought severity. Weather forecasts and expert knowledge remain important throughout all drought management phases. Despite the increased use of DISs with drought severity, the use of hydrological models does not follow the same trend. DISs, which often incorporate hydrological models, reveal a 'hidden' use of these models. Rather than serving as 'key artifacts' for modelers, they become active 'participants' in broader data systems during advanced phases of drought management. All these aspects influence key responsibilities in model use including appropriateness and transferability, reproducibility, and transparency. These factors are critical to consider when aiming to bridge the gap between science and policy in the application and development of DSTs.

1. Introduction

Droughts are becoming more frequent and severe across Europe, a trend worsened by climate change (Hagenlocher et al., 2023). A recent Joint Research Center (JRC) study underscores this intensifying pattern (Rossi et al., 2023). The 2018–2020 European drought, described by Rakovec et al. (2022) as unprecedented, affected an average of 35.6 % of the continent and was accompanied by a near-surface air temperature anomaly of + 2.8 K. Their study emphasizes the need for Europe to prepare for future droughts of similar intensity but with even longer durations than any recorded in the past 250 years. Additionally, Alencar and Paton (2024) report that return periods for extreme droughts are

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decreasing, indicating that such events are becoming more frequent. Economically, annual drought-related damages in the European Union and the UK average around 9 billion euros, although this is likely an underestimation due to difficulties in fully quantifying all impacts (Blauhut et al., 2022; Cammalleri et al., 2020).

Drought management decisions, with the aim to prepare for drought and to mitigate its impacts, often encompass social, economic, technical, and environmental considerations amid numerous alternatives and various uncertainties (Liu et al., 2008). In this context, Decision Support Tools (DSTs) are indispensable, as they provide insights into complex issues, enhance decision-making transparency, and promote learning (O'Brien, 2011; Walling and Vaneeckhaute, 2020). A distinction can be made between evidence-based information (data driven, like field measurements combined with numerical modeling) and experiential-based information (like expert knowledge). The extent to which both types are used provides insights into the approaches of water managers in addressing drought (Boogerd et al., 1997; Pullin et al., 2004; Pezij et al., 2019). However, as indicated by Raymond et al. (2010), the classification of information is not rigid, as knowledge integration involves diverse methods shaped by different perspectives, values, and approaches.

DSTs support decision-makers in both strategic planning and the implementation of operational measures. While operational settings often impose time constraints, requiring quick decisions based on

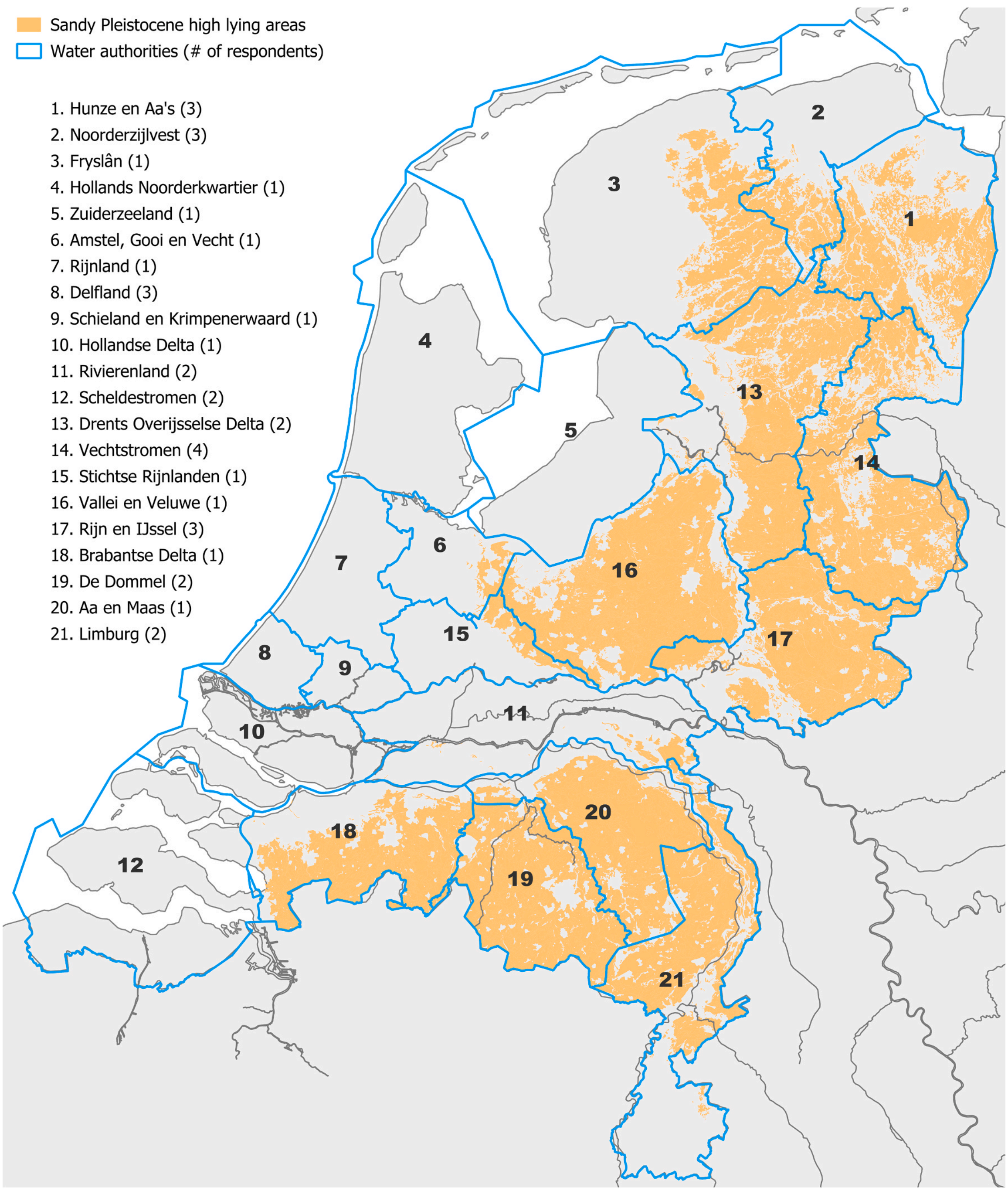

Fig. 1. Map of the Netherlands with the sandy Pleistocene high-lying areas (orange) (± 0–100m+MSL) based on the soil physical unit map of the Netherlands (Heinen et al., 2022). The regional water authorities are indicated with numbers. The number of respondents to the questionnaire per authority are given in the legend between brackets.

multiple criteria such as water availability and navigation (Tian, 2015; Pezij et al., 2019), strategic processes allow for a more deliberate, long-term approach. Strategic planning encompasses activities such as analyzing potential future developments, developing strategies to advance in a particular direction, and assessing progress (O'Brien, 2011).

The aim of this study is to investigate the diversity of DSTs used by water managers in drought management, and how their use changes across different phases of drought severity. The importance of studying the use of DSTs in drought management is underscored by the need to bridge the science-policy gap (Rakovec et al., 2022). While scientific literature focuses heavily on the continuous improvement of model processes and representations, water management emphasizes usability (Landström, 2023). Understanding the current use of DSTs in drought management not only supports their ongoing development, but also ensures that they are aligned with user needs. Furthermore, this contributes to the transparency of the tools underling decisions (Remmers et al., 2023). A baseline understanding of the use of DSTs could be helpful to discover best practices, establish expectations, and ensure consistency across different contexts. To address our aim, we will use the Netherlands as a case study.

2. Study area

Like much of Europe, the Netherlands faced significant impacts from the recent droughts of 2018–2020 and 2022, particularly in the southern and eastern regions (Buitink et al., 2020). Economic losses in 2018 alone are estimated between 450 and 2080 million euros (Philip et al., 2020). While these recent prolonged drought events have reinforced the urgency of addressing water scarcity, the Netherlands has faced significant other droughts in the past, including those in 1911, 1921, 1959, and 1976 (Sluijter et al., 2018). Historically, the Netherlands has focused on managing water abundance, optimizing systems to prevent flooding and manage excess water. However, with severe drought events expected to become more frequent, there is an urgent need to adapt these systems to also address water scarcity (Bartholomeus et al., 2023; van den Eertwegh et al., 2021). A key challenge lies in balancing the intense competition between land and water use (Bartholomeus et al., 2023), creating a landscape of complex, often conflicting stakeholder interests.

The Netherlands consists of peat and clay soils in the West (hereafter referred to as the low-lying areas) and relatively higher sandy soil areas in the East and South (hereafter referred to as the high-lying areas), as shown in Fig. 1. The country's freshwater supply mainly relies on two major trans-boundary rivers (the Rhine and the Meuse), a big freshwater reservoir in the north (Lake IJssel), and groundwater reserves located on higher grounds, including the coastal dunes. Low-lying and high-lying areas in the Netherlands face distinct water management challenges. In low-lying areas, clayey and peat-based soils are vulnerable to salinization due to seepage when water levels drop, leading to soil subsidence and saltwater intrusion that threaten agriculture and freshwater supplies. Drought measures here focus on maintaining water levels through controlled surface water management and freshwater flushing. High-lying areas, more dependent on precipitation (Philip et al., 2020), rely heavily on groundwater, which has declined over the past century due to intensified drainage, agriculture, groundwater abstraction, and urbanization (Witte et al., 2019). Drought measures in these areas emphasize water retention, groundwater recharge, efficient water use, and irrigation restrictions during prolonged dry periods.

The national water authority in the Netherlands (Rijkswaterstaat) manages water allocation and flood safety at the national level, while 21 regional water authorities oversee local water regulations. The regional water authorities are governmental institutions, and members of their boards are elected through democratic processes every four years (Rijkswaterstaat and the Association of Dutch Water Authorities, 2019). Whereas the National Water Model (NWM) is widely accepted as Decision Support Tool (DST) at the national level (Mens et al., 2021), regional water authorities rely on their own diverse toolkits to address hydrological extremes, including droughts. Yet, which DSTs are used and how they are applied is largely unknown. The variation in land use, soil types, and the shift in water governance from managing water abundance to addressing drought — alongside regional differences among water authorities — makes the Netherlands an interesting case study to investigate how DSTs are applied and adapted across different phases of drought management.

3. Methodology

To investigate the diversity of Decision Support Tools (DSTs) used by water managers in drought management, and how their use changes across different phases of drought severity, a survey was conducted among drought management experts from water authorities in the Netherlands. The following subsections outline the survey design and the resulting dataset.

3.1. Questionnaire

Given the study's aim to capture the diversity of DST usage in drought management, a questionnaire was chosen as the most suitable method, allowing for both quantitative and qualitative insights while maximizing participant reach.

The first step in the design of the questionnaire was the identification of DSTs commonly used in the Netherlands. This study identified eight distinct information types used by water managers, including subcategories listed in Table 1. Those categories were defined based on exploratory interviews with water managers and, in comparison with Pezij et al. (2019), two additional categories — stakeholder consultation and satellite data — were included. Satellite data, although often integrated with models, was treated as a separate category. Examples of data and model-based tools include the Dutch drought monitor, regional groundwater models (e.g., AMIGO, AZURE, MORIA), and the "Waterinfo" platform of Dutch and Belgian water authorities. A Decision Support System (DSS) is an interactive computer system that helps water managers evaluate various options and strategies (Kuypers et al., 1999) and is often tailored to the management area of water authorities (e.g., VIDENTE, Bernisse-Brielse Meer). A Data Information System (DIS) primarily focuses on storing, organizing, and providing access to data; examples include HydroNET and smart water management information screens. We classified most of the DSTs in this study as evidence-based - implying that they are based on data - except for expert knowledge, stakeholder consultation, and legislation, which are categorized as

Table 1
Identified information types, related subcategories, and Decision Support Tool type.

Information type	Subcategory	DST type
Field measurements		Evidence-based
Weather forecasts		Evidence-based
Satellite data		Evidence-based
Models	Hydrological models	Evidence-based
	Economical models	Evidence-based
Decision Support Systems (DSSs)		Evidence-based
Data Information Systems (DISs)	National data information systems	Evidence-based
	Regional data information systems	Evidence-based
	Local data information systems	Evidence-based
Expert knowledge		Experiential-based
Stakeholder consultation		Experiential-based
Legislation		Experiential-based

experiential information types.

The second step in the design of the questionnaire was the formulation of questions. The questionnaire consisted of open and closed questions covering three key themes: (1) drought measures, (2) DSTs, and (3) perspectives on model use and uncertainties. Some questions used Likert scale responses (1 = "fully disagree" to 7 = "fully agree"), and conditional logic was applied to tailor questions to respondents' expertise. The questionnaire was refined based on exploratory interviews with representatives from national and regional water authorities and was reviewed for clarity. The final questionnaire is provided in Appendix A. The survey took approximately 30–45 min to complete.

The last stage was the distribution. The questionnaire was developed and distributed via Qualtrics. Survey participation requests were distributed via email (including snowball sampling), LinkedIn, and direct outreach to water authorities. The data was collected between April and June 2024.

The questionnaire started with an explanation of drought management phases (Fig. 2), which were derived from crisis management plans of several Dutch water authorities (Waterschap Vechtstromen, Waterschap Rivierenland, and Wetterskip Fryslân) and the Dutch water allocation and drought script (WMCN-LCW, 2021):

- **Phase 0:** Regular management situation: Sufficient water is available, regular tasks are performed, and preparations are made for potential water shortages.
- **Phase 1:** Impending water shortage: Local problems with water supply due to declining river water levels and increased demand.
- **Phase 2:** Actual water shortage: Water demand exceeds supply, local-level decisions are not being adhered to, and not all functions in the management area can be fully served.
- **Phase 3:** (Impending) area-wide crisis: Multiple functions and sectors are affected, leading to national water distribution.

After introducing the drought management phases, the initial questions aimed to gain a first understanding of drought management practices. The first questions focused on the drought measures considered by water authorities in each phase, where we distinguished between measures to decrease demand, enhance prioritization and efficiency, and increase supply and infrastructure, in line with the EC Blueprint to Safeguard Europe's Water Resources of, (2012) (2012).

3.2. Dataset

A total of 75 questionnaires were collected, of which 48 were mostly completed (≥ 20 columns answered). Most respondents were affiliated with regional water authorities ($N = 38$), followed by Rijkswaterstaat (the Dutch national water authority) ($N = 6$), and other organizations ($N = 4$). To ensure geographical coverage, each of the 21 Dutch regional water authorities was represented in the dataset with one to four responses (Fig. 1). Since each water authority typically involves one to four individuals in drought management, our sample represents a substantial share of Dutch drought experts, enhancing the findings' representativeness. To aid our analysis on regional differences, we classified water authorities as either low-lying or high-lying areas of the Netherlands, based on the presence of sandy Pleistocene highlands (Fig. 1).

The number of responses varied per question, and analyses were conducted based on the responses provided for each specific question. Fourteen out of 34 questions in the questionnaire were selected to address the research question, with details on question selection provided in Appendix A. The other 20 questions provided background information or provided additional information for further research. Data analysis was performed using Python scripts and Excel.

4. Results

Among the respondents, 28 have worked at their organization for more than 10 years, and the majority identify as advisors (N = 31). Most respondents ($N = 31$) are currently or were previously involved in drought management. Additionally, 37 respondents recognized the drought management phases outlined in the survey. However, some water authorities indicated that they do not scale up their response during drought management phases, treating drought as business as usual. For example, in the high-lying Dommel region, where free-draining sandy soils lack external water supply, restrictions on groundwater and surface water usage are standard practice, integrated into regular operational water management.

4.1. Use of drought measures in high-lying versus low-lying areas of the Netherlands

Fig. 3 categorizes drought measures into three types - Decrease Demand, Prioritization and Efficiency, and Increase Supply and Infrastructure - as defined by the EC Blueprint to Safeguard Europe's Water Resources of, (2012) (2012). It compares these measures across high- and low-lying areas of the Netherlands in relation to regional water authorities. The number of measures increased with the drought phases. Once a measure was initiated, it remained effective for all subsequent drought phases.

A key observation is that Increase Supply and Infrastructure is the earliest and most widely considered drought adaptation strategy during Phase 0. This category accounts for 54 % of drought measures in high-lying regions and 64 % in low-lying regions. This suggests that in the early stages of drought management, efforts are focused primarily on ensuring water availability, rather than decreasing water demand or optimizing distribution.

However, Decrease Demand and Prioritization and Efficiency measures, although initially less emphasized (both <30 % in Phase 0), gain importance in Phase 1, 2, and 3. In high-lying regions, these measures are already more prominent in Phase 0 compared to low-lying regions (19 % vs. 10 % for Decrease Demand, 27 % vs. 25 % for Prioritization and Efficiency, respectively). This suggests that high-lying areas begin diversifying their approach earlier in response to water scarcity risks than low-lying areas.

Open-ended responses further highlight regional differences in adaptation strategies. High-lying water authorities often focus on structural adjustments in groundwater management, such as raising groundwater and surface water levels. In contrast, low-lying regions prioritize optimizing freshwater delivery and minimizing salt intrusion. Despite these differences, several common themes emerged. These include monitoring and improving information provision to enhance situational awareness, as well as increasing awareness and collaboration with stakeholders. Measures also focus on enhancing water buffers and storage for long-term resilience, along with adapting policies and management practices, such as changes in spatial planning, drainage,

Phase 0 *Normal situation (adaptation)*	Phase 1 *Impending water shortage*	Phase 2 *Actual water shortage*	Phase 3 *(Impending) area-wide crisis*
Strategy process	*Operational drought management*		

Fig. 2. In the survey, respondents were provided with defined drought management phases: Phase 0, considered the 'strategy process,' and Phases 1 through 3, regarded as phases of operational drought management.

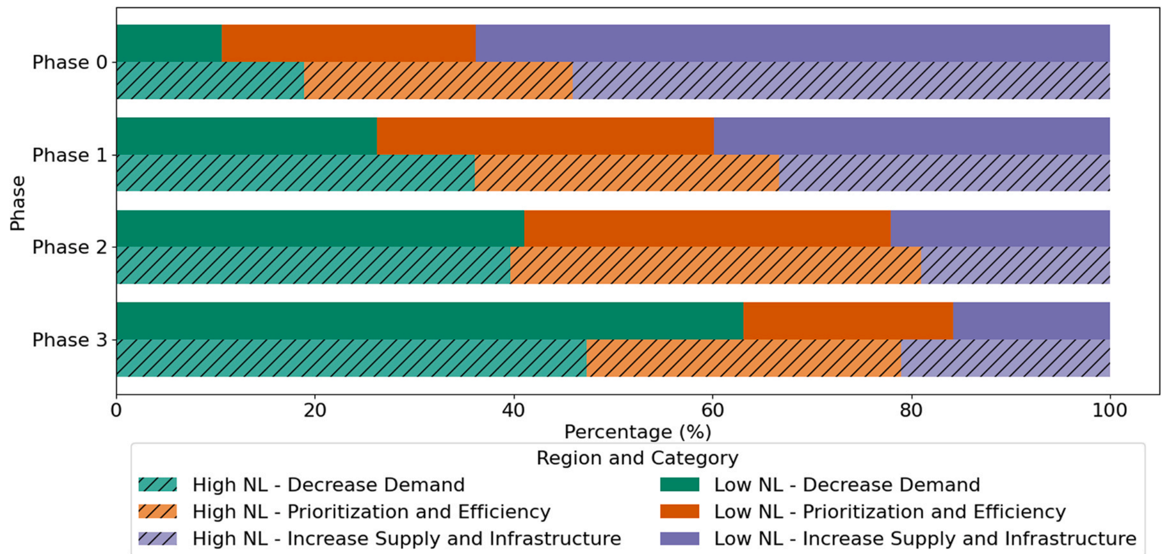

Fig. 3. The considered drought measures for both the high and low-lying areas of the Netherlands. It shows when water authorities consider the implementation of certain drought measures according to the drought management phases. The measures are categorized into three groups: 'Decrease Demand,' 'Prioritization and Efficiency,' and 'Increase Supply and Infrastructure'.

and irrigation policies. Additionally, there is a growing acceptance of recurring drought conditions, prompting a shift toward self-sufficiency in water management. A water manager from a high-lying water authority described their approach to drought management as follows:

"*In operational situations, we continuously monitor the situation and scale up if necessary to take timely additional measures. For the long term, the strategy is: saving, supplying, and accepting.*"

4.2. *Use of Decision Support Tools (DSTs) during various drought management phases*

The survey asked respondents to indicate how frequently they use various DSTs across different drought management phases. For each DST, they could choose from response options ranging from *"Never used"* to *"Always used"* and *"We do not use this instrument"*. Fig. 4 shows that DST usage slightly increases in higher drought management phases, but with notable differences across tool types.

Field measurements are frequently used as a DST and show an

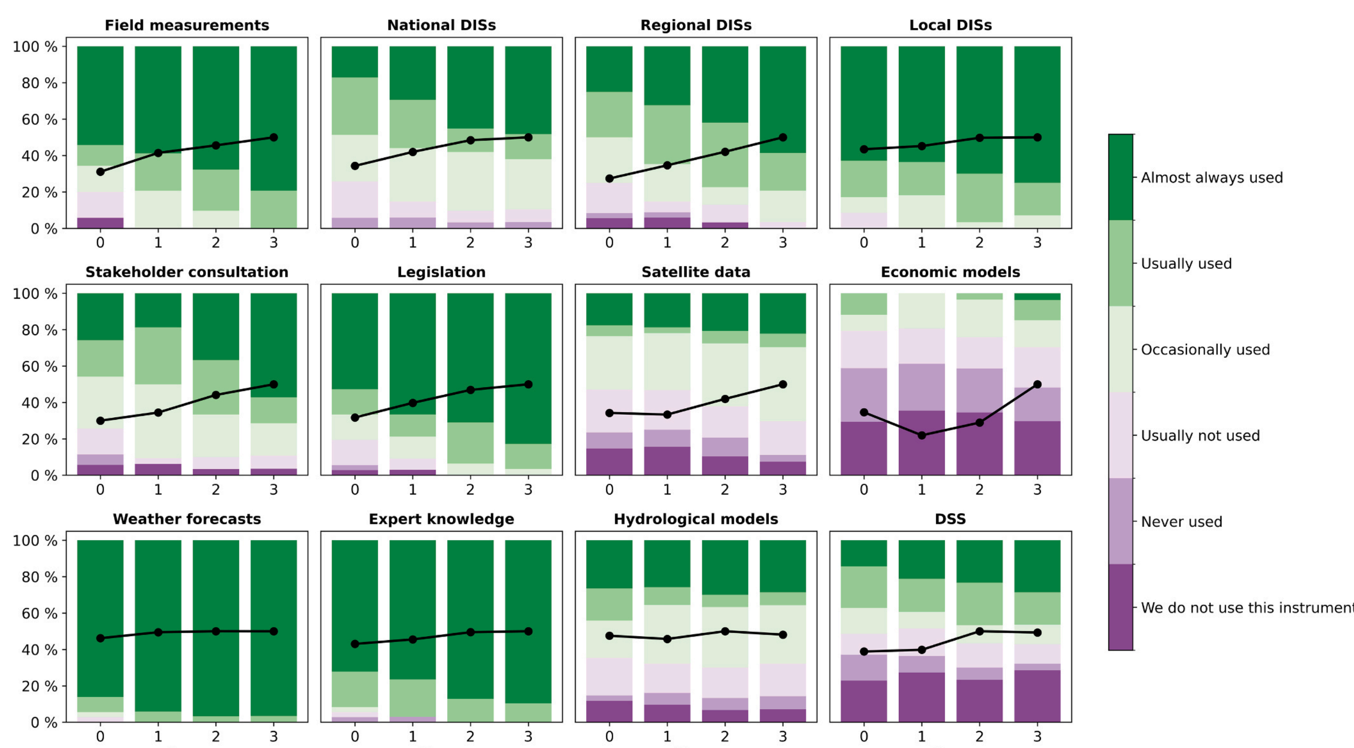

Fig. 4. Change in DST use over different drought phases in Dutch water management practices aggregated for all water authorities. The black line shows the weighted trend in DST use.

increase in use during higher drought management phases. Similarly, Data Information Systems (DISs) show an increasing trend across all spatial scales (local, regional, and national) with the largest observed trend for national and regional DISs. Stakeholder consultation and legislation both become more prominent in higher drought management phases, with legislation gaining particular relevance in high-lying areas (note: differences between high- and low-lying areas are not shown separately here, but can be found in Appendix B: Figs. B.1 and B.2).

In contrast, satellite data are used far less frequently, often only occasionally or not at all. Similarly, economic models are rarely used - only to some extent in the highest phase - suggesting that economic factors have a limited influence on drought-decision making. Weather forecasts and expert knowledge are consistently used across all phases, whereas hydrological models and Decision Support Systems (DSSs) show a polarized usage pattern: Some water authorities rely on them consistently, while others do not use them at all. Their usage hardly changes across the drought management phases.

Respondents were also directly asked whether their use of models changes across drought management phases. The responses were almost evenly split: 14 reported a change in model use, 13 indicated no change, and 6 were uncertain. No clear differences emerged between high- and low-lying areas. Among those who reported increased model use, the main reason was a greater need for evidence-based decisions as drought intensifies (11 out of 14). Models assist in predicting system behavior, coordinating water demand, and informing stakeholders. Respondents highlighted:

"*When drought management phases intensify there is an increasing need for incorporation of prognoses in decision making for which models are necessary tools.*"

"*There is an increasing need for objective information to facilitate water managers in coordinating their water demand.*"

"*With intensifying drought, more questions are asked. To be able to answer these questions well, it is necessary to develop expectational patterns and scenarios for which models are necessary tools.*"

One respondent mentioned that models can provide the necessary information in case expert knowledge falls short in situations one has never experienced before. However, this presents a challenge, as models are generally not validated for extreme drought conditions. While process-based models are designed to be broadly applicable, their reliability under unprecedented droughts remains uncertain.

Lastly, a multiple-choice question was used to assess the respondents' perceptions of which type of DST should receive more attention or require further development. The majority (85 %) prioritized evidence-based information types, highlighting a perceived need for a stronger role for evidence-based DSTs.

4.3. Model Use within Decision Support Tools (DSTs)

While the respondents indicated that the use of hydrological models remains consistent across drought management phases, the use of Data Information Systems (DISs, at local, regional, and national level) increases. Respondents provided the names and/or descriptions of the hydrological models, DSSs, and DISs used in their organization, revealing a wide diversity in the origin of the data (measured, modeled, or both) on which these systems are based.

Fig. 5 shows the various (model) components embedded within these systems in the low-lying and high-lying areas. More than half of the DISs - 68 % in low-lying areas and 59 % high-lying areas - are model-based or incorporate models, including surface water, groundwater, unsaturated zone simulations, statistical models, and weather forecasts.

One might expect low-lying areas to focus more on surface water management and high-lying areas to prioritize assessing available water resources, given differences in land use, soil types and management strategies. However, the data do not fully support this distinction. Respondents from low-lying areas reported using Data Information Systems (DISs) that include both measurement and model processed data, with a slight emphasis on surface water (28 %) over groundwater (21 %). Similarly, in high-lying areas, the DISs also leaned slightly towards surface water (24 %) over groundwater (18 %). This pattern is, however, not entirely surprising, as groundwater levels in high-lying areas are mainly managed indirectly through the surface water system.

In addition to model-based systems, 13 % of the DISs in the low-lying areas and 21 % in high-lying areas are solely based on measurements and do not include data processed by models (e.g. CAW = Central Automated Water-management system (Actemium, 2025), and the "Landelijk Meetnet Water" (National Measurement network Water) (Informatiepunt Leefomgeving (IPLO), 2025)). A small portion of DISs, 4 % in low-lying areas and 3 % in high-lying areas, consists of telemetric systems used for remote control of water structures, such as automatic weirs.

Although models are integrated into various DSTs, they are not recognized as having a leading role in the decision-making processes for

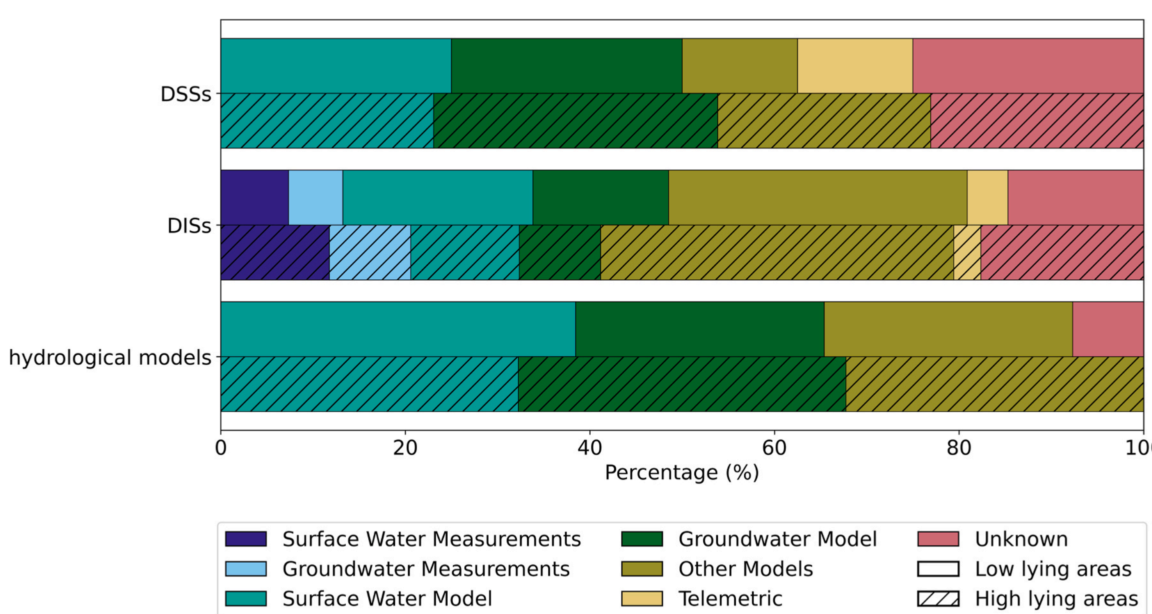

Fig. 5. Overview of the type of models applied in DISs used by the respondents, split for low-lying and high-lying areas. "sw" = surface water, "gw" = groundwater.

implementing drought measures. Table 2 shows that around half of the respondents indicated that models do not play a leading role in decision-making, while 22 % remained neutral. Among those who acknowledged a leading role for models (25 %), location appears to be a factor, with respondents from high-lying areas relying more on models compared to those from low-lying areas (38 % versus 15 %).

5. Discussion

This study investigated the use of Decision Support Tools (DSTs) by water authorities in the Netherlands across different drought management phases. A distinction was made between the adaptation/strategy phase (Phase 0) and the operational phases of managing drought (Phases 1, 2, and 3). While previous studies (e.g., Mens et al. 2021) have explored stand-alone drought Decision Support Tools (DSTs), there is a lack of understanding regarding the specific needs and usage of different DSTs used by water managers to prepare for and handle drought situations. Recently, the Dutch Ministry of Infrastructure and Water indicated their need for better embedding of existing knowledge, instruments and models for water availability on the science-policy interface which underlines the need for an overview and a better understanding of the currently available tools (Nationaal Deltaprogramma Zoetwater, 2025).

5.1. DSTs and drought

The results of this study indicate that water authorities use various types of evidence-based information, although the use of hydrological models remains limited and does not show an increasing trend during the higher phases of drought management. Pezij et al. (2019) also found that hydrological models were rarely applied in operational water management in the Netherlands. They were considered inaccurate for use at the required spatial scales, and water managers faced difficulties interpreting the outputs effectively (Pezij et al., 2019). In addition, hydrological models developed for the Netherlands are generally calibrated for multi-year average water levels and flood/wet scenarios, making them less suitable for simulating drought conditions (Van Kempen et al., 2021; Van Loon et al., 2012). This was mentioned in the exploratory phase, where some interviewees expressed concerns about the models' accuracy in low-flow and dry conditions, potentially limiting their uptake. The results of this study also indicate that economic models are not widely used across the different drought management phases. Although the National Water Model incorporates economic aspects (Mens et al., 2021), economic models do not appear to be part of the decision-making processes by the regional water authorities during drought events. Instead, economic considerations are implicitly included in the "Verdringingsreeks", a prioritization list that places the preservation of critical infrastructure and ecological integrity - such as water level and quality control (flushing) - above the extraction of water for drinking and industrial use, which is prioritized over agricultural irrigation.

Despite the limited use of hydrological and economic models as such, the overall use of Decision Support Tools (DSTs) increases for higher drought management phases. This increase is primarily driven by the need for more specific information to support focused stakeholder communication, especially as competing interests and stakes grow. This aligns with the finding that stakeholder consultation and legislation gain importance in higher drought management phases. This may seem contradictory, as crisis management often brings more legislation to enable swift decisions, which may shift stakeholder engagement from consultation to primarily information-sharing, potentially limiting their influence on decision-making. This expands the role of water managers, who must justify decisions to superiors and the public - and potentially in a court of law - while managing resources within legal constraints and opportunities, including stakeholder consultation (Borowski and Hare, 2007).

As drought phases progress and decision-making becomes more urgent, the demand for evidence-based information grows to justify and legitimize decisions made under high-pressure. This is particularly noticeable in the growing use of national and regional Data Information Systems (DISs), reflecting a shift toward greater standardization of data sources and modeling approaches. By providing a common baseline and fostering mutual understanding among water managers, standardization enhances cross-boundary and interdependent decision making, an essential factor in the coordination of effective responses during drought calamities (Remmers et al., 2023,2024).

5.2. Data Information Systems (DISs) and their respective roles concerning hydrological models

Monitoring dashboards - including national, regional, and local data information systems (DISs) - are increasingly used across drought management phases, whereas the use of hydrological models remains relatively stable. This preference for monitoring dashboards aligns with findings by Hanger et al. (2013), who suggest that decision-makers are not typically constrained by a lack of information, but rather by the need for better filtered, more accessible information. DISs meet this need by integrating multiple data streams and incorporating machine learning techniques (Hauswirth et al., 2021), allowing decision-makers to synthesize large amounts of data (Krishna Prabhakar, 2022; Wilhite and Svoboda, 2000). While hydrological models, or economic models, alone may not be sufficient for decision-making during severe drought conditions, within a DISs, they become just one component of a broader data flow, where their performance is less critical and more supporting rather than leading (Remmers et al., 2023). This shift underscores the transition from standalone models to multi-source decision support systems in higher drought management phases, where usability and data integration become key priorities.

As DISs incorporate various data streams - including measurements and model generated outputs - they influence key responsibilities related to model use, namely appropriateness and transferability, reproducibility, and transparency (Crout et al., 2008; Remmers et al., 2023). More than half of the DISs that were mentioned by the respondents include numerical simulation models, making it difficult at times to distinguish between raw data, model-generated input data and model results. This challenge aligns with the argument of Leonelli (2019), who critically addresses the notion that data and models are fundamentally different. In practice, data are often processed, curated, and idealized before being used in models, creating what they refers to as "data models". These data models blur the line between empirical observations and theoretical frameworks. Within DISs, this blurred distinction could impact reproducibility and transparency, particularly when models are developed by external consultancy agencies, limiting insight

Table 2
Respondents' opinions (values are given in %) on whether models have a leading role in the decision-making processes for implementing drought measures by their organisation (regional water authorities only, high- versus low-lying areas). The proposition: "*In general, models play a leading role in the decision-making processes for taking drought measures in my organisation.*".

	Strongly disagree (%)	Disagree (%)	Partially disagree (%)	Neutral (%)	Partially agree (%)	Agree (%)	Strongly agree (%)
High-lying areas	13	19	19	13	25	13	0
Low-lying areas	5	25	25	30	10	5	0
All areas	8	22	22	22	17	8	0

into model assumptions and methodologies. Moreover, modeling choices directly affect the simulation of hydrological extremes (Melsen et al., 2019), making transparency even more important.

The results of this study show that models are often “hidden” within DISs, which are primarily relied upon in higher drought management phases. While the use of hydrological models remains consistent across phases, model use increases indirectly through DISs. This raises the question of whether drought managers are fully aware of these embedded models. While some respondents indicated a change in model use across the drought management phases, others did not when asked directly about this topic, suggesting no clear or unanimous answer. When models operate in the background without direct user interaction, water managers may underestimate their reliance on them in decision-making. In higher drought management phases, models passively influence decision-making through DISs, whereas in the strategy phase, they are treated more as key artifacts used primarily by modelers. This shift underscores the evolving role of models, transitioning from standalone tools to integrated components within broader data flows.

6. Conclusions

Strategic and operational drought management depends on Decision Support Tools (DSTs), which encompass both experiential and evidence-based information. Through surveys, this study explored the use of DSTs by the national and regional water authorities in the Netherlands for four drought management phases. The results indicate that operational drought management increasingly depends on field measurements, Data Information Systems (DISs) across various spatial scales, stakeholder consultation, and legislation with increasing drought severity. Weather forecasts and expert knowledge consistently remain important across the drought management phases. The use of hydrological models and Decision Support Systems (DSSs) varies among the organizations, with no clear trend observed across the different drought management phases. Economic models and satellite data are not frequently used by the water authorities for drought management. In general, there is a perceived need to focus on the development of evidence-based DSTs rather than experiential-based DSTs for drought management.

The increased use of Data Information Systems (DISs) during higher drought management phases suggests a trend toward the standardization of methods that facilitate effective cross-boundary and interdependent decision-making. Interestingly, most DISs mentioned by the respondents are centered around or include a model ($\geq$63 %). While not all respondents report increased use of hydrological models during these phases, our results suggest a general rise in model usage through the integration of hydrological models within DISs. It is possible that there is unawareness of model usage within these systems, as the line between data and models is often unclear.

We interpret this as a shift: from models being used as key artifacts by modelers themselves, to models functioning as passive participants within the broader data flow of DISs. This suggests a transition in the role of models, from primary tools to integrated elements of decision-making systems during higher phases of drought management. Given that many hydrological models in the Netherlands were originally designed for high-water, flood situations and wet conditions, this shift — along with the changing role of models within DISs — affects key responsibilities in model use, including appropriateness, transferability, reproducibility, and transparency. Overall, these aspects underscore the need for careful consideration of how models are integrated and relied upon in decision-making. This study serves as a baseline for examining the role of DSTs in drought management, aiming to bridge the science-policy gap, while critically reflecting on the responsibilities that come with it.

Author contribution

MRL and LMTBB designed the study, conducted the research and analysis, created the visualizations, and wrote the manuscript under the supervision of PRvO, AMJCG, and PJGJH. LAM, AJT, and RPB contributed to the conceptualization, methodology, and provided review and editing.

CRediT authorship contribution statement

Marleen R. Lam: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Liduin M.T. Bos-Burgering:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Miriam (A.M.J.) Coenders-Gerrits:** Writing – review & editing, Supervision, Conceptualization. **Ruud P. Bartholomeus:** Writing – review & editing, Conceptualization. **Petra J.G.J. Hellegers:** Writing – review & editing, Supervision, Conceptualization. **Lieke A. Melsen:** Writing – review & editing, Conceptualization. **Adriaan J. Teuling:** Writing – review & editing. **Pieter R. van Oel:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The dataset used in this study was collected during the course of this research. It has been anonymized and is publicly available on the 4TU. ResearchData repository via DOI.

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Appendix A. Questionnaire

The questionnaire that was sent to the respondents contained the questions listed in Table A.1. Out of these questions the following questions where selected for this study:

- Question 2–6: the answers to these questions provide background information about the respondent, e.g., organization type and name of the specific water authority. *Used for results described in Section 3.1–3.4.*
- Question 7: the answers to this question provide insight in the extent to which the drought management phases are recognized within the organization of the respondent. *Used for results described in Section 3.1.*

- Question 8: the answers to this question provide insight in the (type of) drought measures applied under the distinct drought management phases. *Used for results described in Section 3.2.*
- Question 11–14: the answers to these questions provide insight in the DSTs used under the distinct drought management phases. *Used for results described in Section 3.3.*
- Question 15: the answers to this question provide insight in the potential hidden model use. *Used for results described in Section 3.4.*
- Question 16: the answers to this question provide insight in the respondents' opinion on whether models have a leading role in the decision-making processes for implementing drought measures by their organization. *Used for results described in Section 3.4.*
- Question 22: the answer to this question provide insight in the respondents' opinion which DSTs should receive more attention in shaping perceptions and making decisions regarding drought management in their organization. *Used for results described in Section 3.3.*

Table A.1
An overview of the questions incorporated in the questionnaire, including category (0. general, 1. drought measures, 3. DSTs, 4. perspectives on model use and associated uncertainties, 5. closing) and type of question.

Question number	Question description	Category	type of question
Q2	What is your current workplace?	0	multiple choice - listed options
Q3	At which water authority are you employed?	0	multiple choice - drop down menu
Q4	At which province are you employed?	0	multiple choice - drop down menu
Q5	What best describes your role within this organization?	0	multiple choice - check boxes
Q6	How long have you been employed here?	0	multiple choice - listed options
Q7	For our research study, we are interested in the use of tools for decision making during distinct drought management phases in your mangament area. Does your organization apply similar coordination phases?	0	multiple choice - listed options
Q8	Below a number of (potential) drought measures are listed. We would like to know from which drought-mangement phase onward does your organization consider implementing certain measures. Identify below.	1	multiple choice - listed options
Q9	My organization is heavily engaged in drought adaptation (long-term measures) in phase 0 (normal situation) and/or phase 1 (impending water shortage)	1	likert scale
Q10	What type of measures are considered or taken as well for long-term drought management strategies?	1	open
Q11	During phase 0 (normal situation), please indicate to which extent the provided tool or instruments are used for taking drought management decisions.	2	multiple choice - listed options
Q12	During phase 1 (impending water shortage), please indicate to which extent the provided tool or instruments are used for taking drought management decisions.	2	multiple choice - listed options
Q13	During phase 2 (actual water shortage), please indicate to which extent the provided tool or instruments are used for taking drought management decisions.	2	multiple choice - listed options
Q14	During phase 3 ((impending) area-wide crisis), please indicate to which extent the provided tool or instruments are used for taking drought management decisions.	2	multiple choice - listed options
Q15	Please list for the given systems/models which are used to support drought management decisions. You can use the full name or an abbrevation.	2	open
Q16	In general, models play a leading role in the decision-making processes for taking drought measures in my organisation.	2	likert scale
Q17	On the basis of which criteria is a tool selected to support decision-making processes within your organization?	2	multiple choice - check boxes
Q18	How would you describe your personal model knowledge in relation to the use and development of models?	3	multiple choice - check boxes
Q19	Does, in your opinion, the use of models change during the different drought management phases within your organization?	3	multiple choice - listed options
Q20	Do you have an idea why and how model use changes during the different drought management phases?	3	open
Q21	In my opinion, models are properly applied to support decision making processes within the different drought management phases.	3	likert scale
Q22	Which type(s) of information should receive more attention in shaping perceptions and making decisions regarding drought management in your organization?	3	multiple choice - check boxes
Q23	I have more confidence in the models used within my own organization than those from external parties.	3	likert scale
Q24	National data information systems (like the "drought portal") are often/sometimes/not used for shaping perceptions and are currently often/sometimes/not helpfull with regards to drought issues in our management area.	3	multiple choice - drop down menu
Q25	Why are national data information systems used often in relation to drought within your management area?	3	open
Q26	Why are national data information systems not used in relation to drought within your management area?	3	open
Q27	Are you a member of a drought team, within or outside your own organisation? If yes, what is your role within the team?	3	multiple choice - check boxes
Q28	Briefly describe your role within the team	3	open
Q29	Do you communicate model results during drought meetings?	3	multiple choice - listed options
Q30	Are model uncertainties communicated during these meetings?	3	multiple choice - listed options
Q31	Why are model uncertainties communicated during these meetings?	3	open
Q32	Why are model uncertainties not communicated during these meetings?	3	open
Q33	Is feedback provided on the information exchanged between the expert/modeller and the decision-maker after a drought period?	3	multiple choice - listed options
Q34	Would you be interested to receive updates about our research and/or may we contact you for a follow-up interview? If yes, would you please provide your e-mail address?	4	multiple choice - listed options/open
Q35	If you have any additional information that could support our research, please feel free to share it below. Thank you in advance!	4	open

Appendix B. Use of Decision Support Tools (DST) during various drought management phases

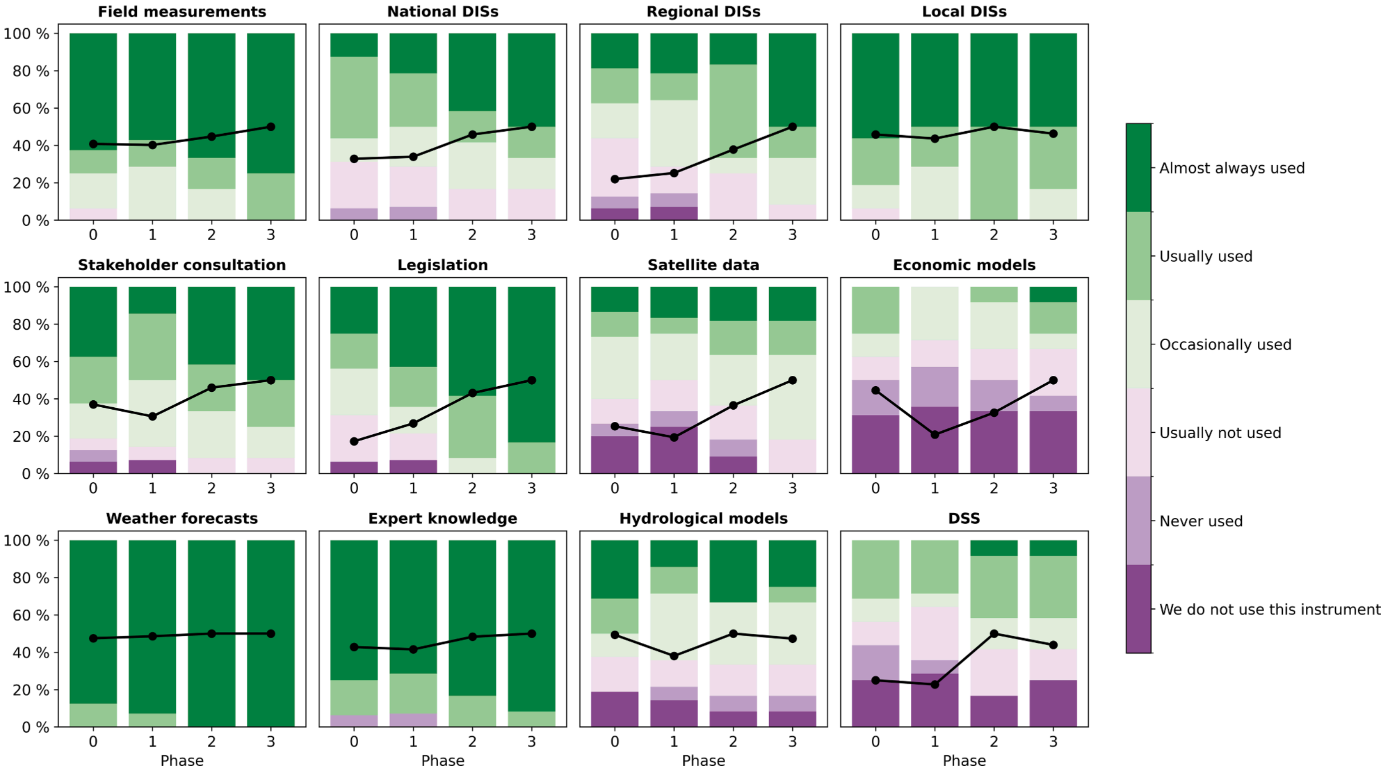

Fig. B.1. Change in DST use over different drought phases in Dutch water management practices aggregated for water authorities in low-lying areas. The black line shows the weighted trend in DST use.

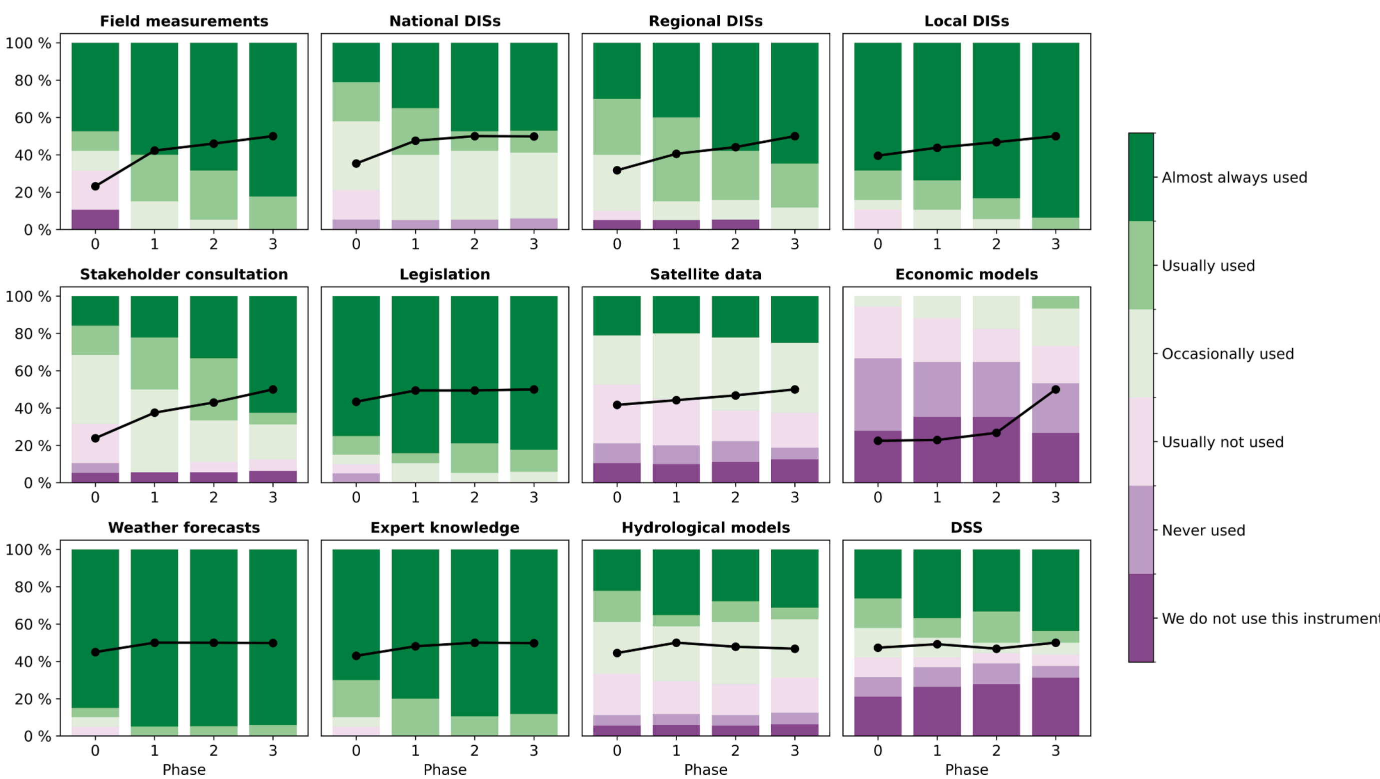

Fig. B.2. Change in DST use over different drought phases in Dutch water management practices aggregated for water authorities in high-lying areas. The black line shows the weighted trend in DST use.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envsci.2025.104065.

References

Actemium, 2025.Centrale automatisering waterbeheer (caw). Online.⟨https://actemium.nl/solutions-services/watermanagement/oplossingen/centrale-automatisering-waterbeheer-caw/⟩.accessed: 2025-03-13.

Alencar, P.H., Paton, E.N., 2024. Which droughts are becoming more frequent? a copula entropy analysis on the return period of droughts in Europe. Nat. Hazards 1–23. https://doi.org/10.1007/s11069-024-06848-y.

Bartholomeus, R.P., van der Wiel, K., van Loon, A.F., van Huijgevoort, M.H., van Vliet, M.T.H., Mens, M., Muurling-van Geffen, S., Wanders, N., Pot, W., 2023. Managing water across the flood-drought spectrum - experiences from and challenges for the Netherlands. Camb. Prism.: Water 1–22. https://doi.org/10.1017/wat.2023.4.

Blauhut, V., Stoelzle, M., Ahopelto, L., Brunner, M.I., Teutschbein, C., Wendt, D.E., Akstinas, V., Bakke, S.J., Barker, L.J., Bartošová, L., Briede, A., Cammalleri, C., Kalin, K.C., De Stefano, L., Fendeková, M., Finger, D.C., Huysmans, M., Ivanov, M., Jaagus, J., Jakubínský, J., Krakovska, S., Laaha, G., Lakatos, M., Manevski, K., Neumann Andersen, M., Nikolova, N., Osuch, M., Van Oel, P., Radeva, K., Romanowicz, R.J., Toth, E., Trnka, M., Urošev, M., Urquijo Reguera, J., Sauquet, E., Stevkov, A., Tallaksen, L.M., Trofimova, I., Van Loon, A.F., Van Vliet, M.T., Vidal, J. P., Wanders, N., Werner, M., Willems, P., Zivković, N., 2022. Lessons from the 2018-2019 European droughts: a collective need for unifying drought risk management. Nat. Hazards Earth Syst. Sci. 22, 2201–2217. https://doi.org/10.5194/nhess-22-2201-2022.

Boogerd, A., Groenewegen, P., Hisschemöller, M., 1997. Knowledge utilization in water management in the Netherlands related to desiccation. J. Am. Water Resour. Assoc. 33, 731–740. https://doi.org/10.1111/j.1752-1688.1997.tb04100.x.

Borowski, I., Hare, M., 2007. Exploring the gap between water managers and researchers: Difficulties of model-based tools to support practical water management. Water Resour. Manag. 21, 1049–1074. https://doi.org/10.1007/s11269-006-9098-z.

Buitink, J., Swank, A.M., Van Der Ploeg, M., Smith, N.E., Benninga, H.J.F., Van Der Bolt, F., Carranza, C.D., Koren, G., Van Der Velde, R., Teuling, A.J., 2020. Anatomy of the 2018 agricultural drought in the Netherlands using in situ soil moisture and satellite vegetation indices. Hydrol. Earth Syst. Sci. 24, 6021–6031. https://doi.org/10.5194/hess-24-6021-2020.

Cammalleri, C., Naumann, G., Mentaschi, L., Formetta, G., Forzieri, G., Gosling, S., Bisselink, B., Roo, A.D., Feyen, L., 2020. Global warming and drought impacts in the EU. Number JRC118585 in EUR 29956 EN. Publications Office of the European Union, Luxembourg. https://doi.org/10.2760/597045.

Crout, N., Kokkonen, T., Jakeman, A.J., Norton, J.P., Newham, L.T., Anderson, R., Assaf, H., Croke, B.F., Gaber, N., Gibbons, J., Holzworth, D., Mysiak, J., Reichl, J., Seppelt, R., Wagener, T., Whitfield, P., 2008. Chapter Two Good Modelling Practice. Dev. Integr. Environ. Assess. 3, 15–31. https://doi.org/10.1016/S1574-101X(08)00602-9.

EC Blueprint to Safeguard Europe's Water Resources of 2012, 2012.A blueprint to safeguard europe's water resources — european environment agency.⟨https://www.eea.europa.eu/policy-documents/a-blueprint-to-safeguard-europes⟩.

Hagenlocher, M., Naumann, G., Meza, I., Blauhut, V., Cotti, D., Döll, P., Ehlert, K., Gaupp, F., Van Loon, A.F., Marengo, J.A., Rossi, L., SabinoSiemons, A.S., Siebert, S., Tsehayu, A.T., Toreti, A., Tsegai, D., Vera, C., Vogt, J., Wens, M., 2023. Tackling growing drought risks—the need for a systemic perspective. Earth'S. Future 11, e2023EF003857. https://doi.org/10.1029/2023EF003857.

Hanger, S., Pfenninger, S., Dreyfus, M., Patt, A., 2013. Knowledge and information needs of adaptation policy-makers: a European study. Reg. Environ. Change 13, 91–101. https://doi.org/10.1007/s10113-012-0317-2.

Hauswirth, S.M., Bierkens, M.F., Beijk, V., Wanders, N., 2021. The potential of data driven approaches for quantifying hydrological extremes. Adv. Water Resour. 155, 104017. https://doi.org/10.1016/j.advwatres.2021.104017.

Heinen, M., Mulder, H.M., Bakker, G., Wösten, J.H., Brouwer, F., Teuling, K., Walvoort, D.J., 2022. The Dutch soil physical units map: BOFEK. Geoderma 427. https://doi.org/10.1016/j.geoderma.2022.116123.

Informatiepunt Leefomgeving (IPLO), 2025.Landelijk meetnet water (lmw).⟨https://iplo.nl/thema/water/monitoring-water/monitoring-waterkwantiteit/landelijk-meetnet-water/⟩.Accessed: 2025-03-13.

Krishna Prabhakar, S.V.R., 2022. Implications of regional droughts and transboundary drought risks on drought monitoring and early warning: a review. Climate 10, 124. https://doi.org/10.3390/cli10090124. ⟨https://www.mdpi.com/2225-1154/10/9/124⟩.

Kuypers, A., Lobbrecht, A., Wentholt, L., 1999.Beslissen in de dagelijkse waterbeheersing. Technical Report 13. Stichting Toegepast Onderzoek Waterbeheer (STOWA). Utrecht, Nederland.⟨https://www.stowa.nl/publicaties/beslissen-de-dagelijkse-waterbeheersing⟩.

Landström, C., 2023. Why won't water managers use new scientific computer models?: The co-production of a perceived science-practice gap. Z. F. üR. Tech. ätzung Theor. und Prax. / J. Technol. Assess. Theory Pract. 32, 36–42. https://doi.org/10.14512/tatup.32.1.36.

Leonelli, S., 2019. What distinguishes data from models? Eur. J. Philos. Sci. 9, 22. https://doi.org/10.1007/s13194-018-0246-0.

Liu, Y., Gupta, H., Springer, E., Wagener, T., 2008. Linking science with environmental decision making: Experiences from an integrated modeling approach to supporting sustainable water resources management. Environ. Model. Softw. 23, 846–858. https://doi.org/10.1016/J.ENVSOFT.2007.10.007.

Melsen, L.A., Teuling, A.J., Torfs, P.J., Zappa, M., Mizukami, N., Mendoza, P.A., Clark, M.P., Uijlenhoet, R., 2019. Subjective modeling decisions can significantly impact the simulation of flood and drought events. J. Hydrol. 568, 1093–1104. https://doi.org/10.1016/j.jhydrol.2018.11.046. ⟨https://www.sciencedirect.com/science/article/pii/S0022169418309016⟩.

Mens, M., Minnema, B., Overmars, K., van den Hurk, B., 2021. Dilemmas in developing models for long-term drought risk management: the case of the National Water Model of the Netherlands. Environ. Model. Softw. 143, 105100. https://doi.org/10.1016/j.envsoft.2021.105100.

Nationaal Deltaprogramma Zoetwater, 2025.Kennisagenda waterbeschikbaarheid - 5 februari 2025.⟨https://www.deltaprogramma.nl/documenten/publicaties/2025/02/kennisagenda-waterbeschikbaarheid/kennisagenda-waterbeschikbaarheid⟩. accessed: 2025-03-13.

O'Brien, F., 2011. Supporting the strategy process: a survey of UK OR/MS practitioners. J. Oper. Res. Soc. 62, 900–920. https://doi.org/10.1057/jors.2011.2.

Pezij, M., Augustijn, D.C., Hendriks, D.M., Hulscher, S.J., 2019. The role of evidence-based information in regional operational water management in the netherlands. Environ. Sci. Policy 93, 75–82. https://doi.org/10.1016/j.envsci.2018.12.025.

Philip, S.Y., Kew, S.F., Van Der Wiel, K., Wanders, N., Jan Van Oldenborgh, G., Philip, S. Y., 2020. Regional differentiation in climate change induced drought trends in the Netherlands. Environ. Res. Lett. 15. https://doi.org/10.1088/1748-9326/ab97ca.

Pullin, A.S., Knight, T.M., Stone, D.A., Charman, K., 2004. Do conservation managers use scientific evidence to support their decision-making? Biol. Conserv. 119, 245–252. https://doi.org/10.1016/j.biocon.2003.11.007.

Rakovec, O., Samaniego, L., Hari, V., Markonis, Y., Moravec, V., Thober, S., Kumar, R., 2022. The 2018–2020 multi-year drought sets a new benchmark in europe. Earth'S. Future 10, e2021EF002394. https://doi.org/10.1029/2021EF002394.

Raymond, C.M., Fazey, I., Reed, M.S., Stringer, L.C., Robinson, G.M., Evely, A.C., 2010. Integrating local and scientific knowledge for environmental management. J. Environ. Manag. 91, 1766–1777.

Remmers, J.O., Teuling, A.J., Melsen, L.A., 2024. A modeller's fingerprint on hydrodynamic decision support modelling. Environ. Model. Softw. 181, 106167. https://doi.org/10.1016/j.envsoft.2024.106167.

Remmers, J., Teuling, A., Dahm, R., van Dam, A., Melsen, L., 2023. Power to the programmer: Modeller's perspective on automating the setup of hydraulic models for Dutch water authorities (Manuscript). Socio-Environ. Syst. Model. 6. https://doi.org/10.18174/sesmo.18657.

Rijkswaterstaat and the Association of Dutch Water Authorities, 2019.Water management in the Netherlands. Technical Report. Rijkswaterstaat and the Association of Dutch Water Authorities.⟨https://www.helpdeskwater.nl/publish/pages/165190/rij_8475_watermanagement_en_dv_1.pdf⟩, 10.1201/9781439833834.ch17.

Rossi, L., Wens, M., De Moel, H., Cotti, D., SabinoSiemons, A., Toreti, A., Maetens, W., Masante, D., Van Loon, A., Hagenlocher, M., Rudari, R., Naumann, G., Meroni, M., Avanzi, F., Isabellon, M., Barbosa, P., 2023. European Drought Risk Atlas. JRC. https://doi.org/10.2760/33211.

Sluijter, R., Plieger, M., van Oldenborgh, G.J., et al., 2018.De droogte van 2018: een analyse op basis van het potentiële neerslagtekort. Technical Report. Royal Netherlands Meteorological Institute (KNMI). De Bilt, Netherlands.⟨https://klimaatadaptatienederland.nl/@204145/de-droogte-van-2018/⟩.

Tian, X., 2015.Model Predictive Control for Operational Water Management: A Case Study of the Dutch Water System. Ph.D. thesis. TU Delft.⟨http://repository.tudelft.nl/view/ir/uuid:aded9b65-677d-42bc-af93-969199aa1f77/⟩, 10.4233/uuid:aded9b65-677d-42bc-af93-969199aa1f77.

van den Eertwegh, G., de Louw, P.G.B., Witte, J.P., van Huijgevoort, M.H. J. Bartholomeus, R.P., van Deijl, D., van Dam, J.C., Hunink, J., America, I., Pouwels, J., Hoefsloot, P., de Wit, J.A., 2021.Droogte in de zandgebieden van Nederland: Effecten op en oplossingsrichtingen voor natuur, landbouw en het bodem- en watersysteem. Technical Report. knowH2O.

Van Kempen, G., Van Der Wiel, K., AnnaMelsen, L., 2021. The impact of hydrological model structure on the simulation of extreme runoff events. Nat. Hazards Earth Syst. Sci. 21, 961–976. https://doi.org/10.5194/nhess-21-961-2021.

Van Loon, A.F., Van Huijgevoort, M.H., Van Lanen, H.A., 2012. Evaluation of drought propagation in an ensemble mean of large-scale hydrological models. Hydrol. Earth Syst. Sci. 16, 4057–4078. https://doi.org/10.5194/hess-16-4057-2012.

Walling, E., Vaneeckhaute, C., 2020. Developing successful environmental decision support systems: Challenges and best practices. J. Environ. Manag. 264. https://doi.org/10.1016/j.jenvman.2020.110513.

Wilhite, D.A., Svoboda, M.D., 2000. Drought early warning systems in the context of drought preparedness and mitigation. Proc. Expert Group Meet. held Sept. 5-7, 13–17.
Witte, J.P.M., Zaadnoordijk, W.J., Buyse, J.J., 2019. Forensic hydrology reveals why groundwater tables in the province of noord brabant (the netherlands) dropped more than expected. Water 11, 478.
WMCN-LCW, 2021.Landelijk draaiboek waterverdeling en droogte; Informatie-uitwisseling en afstemming van maatregelen en communicatie. Technical Report.〈www.helpdeskwater.nl〉.

DSTs: Decision Support Tools
DISs: Data Information Systems
DSSs: Decision Support Systems
NWM: National Water Model