Navigating Crises: Exploring Collaborative Decision Making in Data-Driven Natural Hazard Risk Management

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Abstract

This research investigates the collaborative decision-making processes of Natural Hazard Risk Management (NHRM) teams during the early stages of crises, particularly as natural disasters become more frequent due to climate change. It addresses a research gap by focussing on risk-monitoring teams, while existing literature is primarily concentrated on operational response teams. Utilising a multiple case-study approach, this research examines three supra-regional NHRM teams in the Netherlands, drawing on concepts of situation awareness, team sensemaking, and the Data-Information-Knowledge-Wisdom (DIKW) hierarchy. The developed framework, built on literature and expert insights, enriched by observations, and validated in its application to decision making in real crises, illustrates the dynamic interactions among the domains Data Management, Knowledge Management, and Adaptive Leadership. It underlines Data Management's critical role in ensuring data quality, analysis and decision support, Knowledge Management's importance in transforming data into strategic actions through multidisciplinary collaboration, and Adaptive Leadership's ability to ethically navigate through uncertainties. The research highlights the collaborative decision-making process as an iterative, dynamic process, with ongoing data reassessment to refine decisions and observes role fluidity within the NHRM teams. It reveals the interdependence among the domains, with the functioning of one influencing the others. Recommendations include regular domain reviews, specialised training in data interpretation and its communication, use of tools and platforms, protocol adaptability, and implementing strategies to reduce cognitive load.

Keywords: Natural Hazard Risk Management, Collaborative Decision Making, Data-Driven Decision Making, Situation Awareness, Team Sensemaking, DIKW Hierarchy, Multiple Case-Study Research

Introduction

The escalating impact of climate change has heightened the frequency and intensity of natural disasters, posing serious threats to society (Coronese et al., 2019; UNDRR, 2020b; Zhou et al., 2018). In the Assessment Report of 2023, the Intergovernmental Panel on Climate Change (IPCC; 2023) outlines the expectation of increased climate-related challenges worldwide. These challenges include extreme weather events, such as heatwaves, heavy rain, drought, as well as associated wildfires and floods. Crisis-response teams face challenges due to their reliance on experience and knowledge, yet applying these insights is constrained by limited exposure to large-scale incidents (Schraagen & Van 2008; Zhou et al., 2018).

Recognising the necessity to enhance natural disaster preparedness, global initiatives are directed towards the integration of modern technologies, such as refining early warning systems, and enhancing disaster detection setups (Barnes et al., 2019; Munawar et al., 2022). Moreover, big data introduces opportunities to mitigate crisis impact by providing access to critical real-time information (Tin et al., 2013). The integration of diverse datasets, such as geological, meteorological data, and social statistical data, further enhances informed decision making in natural disasters (Zhou et al., 2018).

As modern technologies and big data transform risk and crisis management, bringing enhancements in visualisation, analysis, and prediction, it also introduces the challenges associated with effectively managing large volumes of data (Akter & Wamba, 2017). Endsley (2000) notes a disparity between the large amount of data generated and people's ability to sort through it, gather relevant pieces, and extract the specific information necessary for decision making. According to Huberty (2015), the primary challenge extends beyond data availability; it lies in extracting meaningful insights and using them purposefully.

At the core of effective crisis response is the critical exchange of information among key stakeholders, enabling informed decision making (Moe & Pathranarakul, 2006). However, the dynamic nature of crises introduces rapidly changing situations with data and information coming in from a variety of sources, presented in various formats, and at different reliability levels. Factors like time pressure can affect the evaluation, processing, and dissemination of information (Schraagen & Van de Ven, 2008). Decisions during a crisis largely depend on the available information, yet inaccuracies in data, its integration, or its communication can compromise these decisions (Fisher & Kingma, 2001).

Navigating Crises in Natural Hazard Risk Management

In response to the growing need for crisis teams to effectively manage data during crises, a multiple case-study was conducted. This research investigated how teams that operate in a

data-driven context, manage data during demanding circumstances. This research, with a specific focus on Natural Hazard Risk Management (NHRM) teams, seeks to uncover valuable insights into effective data-driven approaches, but also identify and understand the challenges associated that arise in such approaches. The reason for focussing on NHRM teams arises from the increasing occurrence of natural hazards, primarily attributed to climate change. Natural hazards, as defined by the United Nations Office for Disaster Risk Reduction (UNDRR; 2020a), are “natural processes or phenomena that may cause loss of life, injury, or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage" (p. 20). The term ‘natural’ in this context does not indicate that these crises solely result from hydrometeorological events beyond human influence. Rather, it is used to exclude other situations, such as industrial accidents, political instability, or cyber threats.

While literature predominantly focusses on the response phase and operational teams in natural disasters, there is limited attention to the critical decisions made just before and in the initial phase of a crisis by risk-monitoring teams. These teams, having access to substantial data, play a critical role in hazard identification, issuing warnings and providing advice to operational teams. As stated by Kowalski-Trakofler et al. (2003), the decisions made in the initial crisis phase are critical for successful mitigation, damage control, harm prevention, financial resource management and the eventual resolution of the disaster. Despite their critical role, a research gap exists in the exploration of collaborative decision making among data-driven NHRM teams. By delving into the collaborative decision-making processes of these teams, this research aims to bridge this gap and enhance understanding of how they navigate high-stakes scenarios while managing data and information.

Collaborative Decision Making

Collaborative decision making entails individuals from different entities working together through joint efforts and resource sharing to achieve a common goal (Kapucu & Garayev, 2011). The process of collaborative decision making involves collective problem-solving, combining diverse perspectives, knowledge, and resources, leading to shared sense of ownership of the outcome. In this research, the concept applies to multidisciplinary teams engaged in the domain of data-driven NHRM. Teams are characterised as “a distinguishable set of two or more people who interact dynamically, interdependently and adaptively toward a common valued goal/object/mission, who have each been assigned specific roles or functions to perform and who have a limited life span of membership” (Salas et al., 1992, p. 4). Unlike general groups, teams involve members with diverse roles and tasks, leading them to focus on different pieces of information during the decision-making process (Artman, 2000).

Team Situation Awareness

In the challenging context of crises characterised by time constraints, complexity, and uncertainty, response teams are confronted with the challenge of acquiring situation awareness (Van de Walle et al., 2016). Situation awareness, as defined by Endsley (1988, p. 97) is "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future". This definition breaks down into three ascending levels: first, the perception of elements in the current situation; second, the comprehension of current situation and third; the projection of future status.

Acquiring situation awareness leads to increased knowledge, a shift in expectations, and engagement in subsequent information gathering (Salas et al., 1995). However, maintaining this situation awareness is challenging for decision makers due to the dynamic and ever-changing nature of information flows (Endsley, 2000; Salas et al., 1995). While possessing situation awareness alone does not guarantee effective decision making, it aids in reducing decision errors and improving overall performance (Artman, 2000; Endsley, 2000; Patrick et al., 2006).

Despite being an individual cognitive asset, situation awareness holds significant value in teams' contexts, where common goals are pursued, emphasised by Endsley and Jones (2001). They identify two critical factors that shape a team's overall situation awareness: 1) the presence of high individual situation awareness among team members regarding their respective roles, and 2) shared situation awareness among team members, resulting in an accurate shared understanding of aspects relevant to each member's specific needs.

Team Sensemaking

Sensemaking is closely linked to situation awareness, where situation awareness is often perceived as a state of knowledge acquired from current data, inferences, and predictions. In contrast, sensemaking represents the active process towards achieving this state, including the strategies employed and barriers encountered (Klein et al., 2006). In teams, sensemaking is a collaborative effort to understand the current situation and anticipate future scenarios, typically in uncertain conditions. This includes various processes, such as data collection, data quality monitoring, data synthesis, resolving disputes, and information dissemination (Klein et al., 2010). These processes align with the crisis response stages of observation, interpretation, choice, and dissemination identified by Hale et al. (2005).

The observation stage focusses on data collection and organisation, addressing gaps and balancing search criteria to avoid overlooking critical events or wasting time (Klein et al., 2010). Decision makers must navigate the tension between immediate action and gathering

more information for event verification and decision-making quality (Hale et al., 2005). During the interpretation stage, teams assign meaning to observations, validate data credibility, identify inconsistencies, and merge new information with previous understanding to form an overall picture (Hale et al., 2005). Interpretation challenges may emerge from unfamiliarity with data collectors or collection methods, potentially leading to misunderstandings (Klein et al., 2010). Additionally, conflicting interpretations might require dispute resolution strategies, such as hierarchical decision making or consensus-building, as suggested by Klein et al. (2010).

In the choice stage the team collaboratively evaluates the overall picture, considers alternative scenarios, and makes decisions (Hale et al., 2005). Effective communication is key, requiring a balance between adequate detail sharing and filtering to focus discussions on critical issues. This stage also requires an environment where concerns can be expressed to challenge the collective perspective and interpretation of events (Klein et al., 2010). The dissemination stage focusses on what information to distribute and when. Poorly designed message formats can hinder recipient understanding, as Hale et al. (2005) observed. Thus, considerations such as timing, level of detail, and recipient understanding are essential (Klein et al., 2010).

Data-Driven Decision Making

To gain a clearer insight into how teams manage data during collaborative sensemaking to evolve from collecting raw data to making informed decisions, the Data-Information-Knowledge-Wisdom (DIKW) by Ackoff (1989) hierarchy provides a systematic framework.

DIKW Hierarchy

The DIKW hierarchy outlines four levels of meaning and utility in handling data, with each level building upon the one below. Starting at the base, data refers to raw, unprocessed facts without context. Data on its own lacks practical use until it is transformed into a usable form. Moving up to the next level, information refers to organised, structured, and contextualised data and provides answers to who, what, where and when (Ackoff, 1989).

Following this, knowledge emerges by applying data and information, involving uncovering patterns and relationships to transform information into practical know-how (Ackoff, 1989). However, this definition of knowledge has faced criticism for overlooking its dual nature, consisting of both practical, explicit know-how and more implicit forms of knowledge, referred to as know-what (Frické, 2008). This research recognises the multifaceted nature of knowledge, addressing its diverse dimensions. At the top of the hierarchy, wisdom comes into play as a distinctly human element that surpasses the capabilities of machines. As defined by Rowley (2007), wisdom involves the ability to execute the optimal behaviour based on what is known, integrating knowledge with ethical and social considerations for the greater

good. While the DIKW hierarchy offers a clear linear perspective, Klein et al. (2006) argue that it oversimplifies real-world decision making, particularly within the dynamic process of sensemaking, which often lack clear starting and ending points.

Challenges in Data-Driven Decision Making

Navigating decision making in data-driven contexts comes with challenges. Decisions are highly dependent on the available information, but can be compromised by inaccuracies in data, poor data integration or communication issues. Fisher and Kingma (2001) identified three factors that affect data-driven decision making: information overload, experience level, and time constraints. Information overload arises when an excessive amount of information must be processed in limited time, leading to challenges in data quality due to filtering, inadequate responses, and reliance on outdated data. The related problem of data overload, as noted by Endsley (2012), results from the vast amounts of rapidly changing data across various systems. It involves a constant flow of information that goes beyond individuals' capacity to effectively collect and process data, resulting in reduced situation awareness as human cognitive processing abilities are stretched to their limits (Darioshi & Lahav, 2020; Endsley, 2012).

Experience, the second factor, plays a dual role in decision making. While it can enhance error sensitivity and intuition, there is a risk of overreliance on perception, potentially compromising accuracy. Lastly, time constraints may lead to rushed decision making or selective information processing, impairing situation awareness and hindering efficient information gathering (Endsley, 2012). Stressors like mental workload and uncertainty can further reduce situation awareness, leading to attentional tunnelling and premature closure in decision making (Bolstad et al., 2006; Endsley, 2012).

Present Studies

Drawing on concepts of team situation awareness, sensemaking, and the DIKW hierarchy, this study explores the collaborative decision-making processes among NHRM teams operating in a data-driven environment. Unlike previous literature, which predominantly focusses on operational teams during the response phase of natural disasters, this research zooms in on the critical decisions made just before and in the initial phase of crises by risk monitoring teams. Specifically centred on the NHRM context in the Netherlands, it utilises a multiple case-study approach. Aligned with Schoch's (2020) perspective on case-study research, it takes an exploratory approach to investigate a specific phenomenon in its real-life context. This approach seeks to provide a profound understanding of the cases being studied, extracting valuable insights with the potential for transferability – the application of the principles and lessons learnt to other cases. In doing so, the study aims to contribute not only

to the understanding of collaborative decision making in data-driven NHRM, but also to offer insights applicable to similar contexts. The central research question guiding this research is: “How do natural hazard risk management teams manage a data-driven approach in their collaborative decision-making processes while navigating high-stakes situations?”

Considering the unexplored nature of NHRM teams, this multiple case-study design adopts an exploratory approach due to its suitability for collecting data on relatively unknown subjects (Hammond & Wellington, 2012). Following Swedberg’s (2020) recommendation for exploratory research, a multi-method approach was employed, integrating various primary and secondary research methods. Three distinct yet interconnected studies were conducted: Study 1 involved expert interviews, Study 2 included observations of training sessions, and Study 3 entailed an analysis of crisis evaluation and meeting reports, alongside an actual crisis meeting observation. Each study’s method was chosen to provide distinct insights into NHRM teams’ collaborative decision making. Interviews yielded in-depth perspectives, training sessions observations captured real-time dynamics, and analyses of actual crises added contextual depth.

Study 1: Expert Insights into Collaborative Decision Making in Natural Hazard Risk Management

Method

To gain a deeper understanding of collaborative decision making in the NHRM domain, interviews were conducted with experts. These interviews were conducted in a semi-structured format, providing a balance between predefined questions and the opportunity for experts to openly share their perspectives and experiences. The predetermined questions used in these interviews were crafted based on existing literature, exploring professionals' roles, insights, challenges, and strategies in data-driven collaborative decision making during high-stakes situations. This approach allowed for the integration of follow-up questions, enhancing the depth of insights obtained.

Participants

Three supra-regional entities in the Netherlands – the Weather Impact Team (WIT), the National Coordination Committee for Flood Threat (LCO), and the National Fire Brigade Centre (LACB) – were selected for their shared characteristics, including team composition and access to substantial data resources. To provide context, the WIT advises the Royal Netherlands Meteorological Institute (KNMI) on issuing 'code-red' weather warnings, the LCO issues early warnings for increased flood risks and provides information about threatened areas, and the LACB monitors wildfire risks and offers advice to other entities. Professionals from these three

entities were identified through purposive sampling, resulting in the participation of three experts, each representing a distinct entity, in the study.

Procedure

The experts were informed about the research through phone or email communication. They received an information sheet and consent form via email, detailing data-collection procedures, confidentiality, and the voluntary nature of participation. Their right to withdraw or decline specific questions was also emphasised. After obtaining written consent, face-to-face interviews, approximately one hour each, were conducted in their work environment. Each interview was audio-recorded to ensure the precise capture of insights. Ethical approval for this research was obtained from the Ethics Committee of the Faculty of Behavioural, Management, and Social Sciences (domain Humanities and Social Sciences) of the University of Twente.

Data Analysis

Following the interviews, transcripts were generated using Amberscript software. Then, the transcripts were refined to achieve a word-for-word accuracy. An extra layer of filtering was then applied to correct mistakes, edit grammar, and remove repetitions in the transcript, which is termed ‘intelligent verbatim’ (McMullin, 2021). This editing process aimed to improve the qualitative coding process. Participants had the opportunity to review the interview transcripts for accuracy. Subsequently, transcripts were translated to English for further analysis.

A hybrid qualitative data analysis, known as abduction, was conducted using the ATLAS.ti 23 software. This approach balances between inductive and deductive methods, seeking to derive the most logical and useful explanation of phenomena (Thompson, 2022). It involves setting theoretical parameters to guide data exploration, with themes partly derived from existing theory and partly emerging from the data (Fereday & Muir-Cochrane, 2006). The coding process started by crafting detailed initial codes, which were then organised into categories, forming the main codes. Table 1 presents examples of main codes, specifying whether they were derived deductively or inductively and their source codes. Additionally, each code is supported by a transcript snippet illustrating its application. The main codes served as the building blocks for developing overarching themes.

Table 1

Coding Analysis Overview: Arriving at Main Codes

Main Codes	Coding Approach	Initial Codes	Example

Multidisciplinary Collaboration	Inductive	Inter-Organisational Collaboration, Multi-disciplinary Teams, Stakeholder Involvement	*"We do external consultation with (...), so we ask how they see the chances and take that into account."*
Information Dissemination	Deductive	Data Visualisation, Message Framing/ Customisation	*"We are refining the layout to ensure they see the critical information first."*
Impact-Based Decision Making	Inductive	Consequential Decision Making, Impact Assessment, Decision Evaluation	*"We not only try to reach an impact estimate in the conversation, but also have a tool here, an impact tool."*

Results

In the analysis of interview data, three principal themes were identified that delineate the collaborative decision-making dynamics within the studied NHRM teams: 1) Data Management, 2) Knowledge Management, and 3) Adaptive Leadership. These themes were developed by applying the DIKW hierarchy as conceptualised by Ackoff (1989), which facilitated a systematic organisation of the coded data. Specifically, Data Management aligns with the 'Data' level of the DIKW hierarchy, Knowledge Management is linked to the 'Knowledge' level, and Adaptive Leadership connects to the 'Wisdom' level. The application of the DIKW hierarchy, while instrumental in structuring the data, does not imply a strictly linear, sequential process. Table 2 provides an overview of the identified themes, sub-themes, and main codes, with the themes representing distinct domains, the sub-themes capturing the associated responsibilities, and the main codes reflecting the corresponding activities.

Table 2

Overview of Collaborative Decision Making Themes in NHRM Teams

Themes	Sub-themes	Main Codes
Data Management	Data Quality Management, Data Analytics, Decision Support	Data Collection, Data Qualification, Data Organisation, Data Storage, Data Analysis, Data Synthesis

Knowledge Management	Collaborative Knowledge-Building, Strategic Decision Making	Data Interpretation, Multidisciplinary Collaboration, Use of Tools/Platforms, Consensus-Building, Dispute Resolution, Information Dissemination
Adaptive Leadership	Managing Uncertainty, Ethical Leadership	Protocol Implementation, External Stressor Management, Workload Balancing, Impact-Based Decision Making, Timely Communication

Data Management

The teams involved in NHRM operate in a data-driven environment, where they rely on data to inform their collaborative efforts. This is reflected in their alignment of actions with established protocols that are tied to certain threshold criteria, such as wind speed in extreme weather scenarios. When thresholds are likely to be exceeded, as indicated by model outcomes, or estimates from monitoring specialists, team collaboration is initiated.

Throughout this process, NHRM team members collect data related to the event. When the team comes together, they collaboratively synthesise and interpret these observations, aiming to construct an overall picture of the situation. However, this task can be difficult, as one expert highlighted: “What emerges is the challenge of interpreting data in a practical context. We easily rely on data, yet understanding its real-world implications is complex.” Some teams share physical proximity with these specialists by being located in the same building, while others involve these experts directly in meetings. In the interviews, the experts unanimously stressed the critical role of data specialists in the interpretation of data, particularly given the uncertainties in these models. One expert expressed:

> The model can forecast upcoming events, yet there are always uncertainties. Those uncertainties are what it is all about, as unexpected events may unfold. This is why it is not fully automated; it necessitates highly intelligent individuals who are trained to comprehend these models to provide expert judgment and explain those uncertainties.

However, the uncertainty inherent in models also pose difficulties for data specialists, as noted by the experts, particularly in the initial phases of an event when variability is highest.

A notable example is the variability in weather models, as noted by an expert: "You have to know that with weather forecasts, the first week can be reliable, but the uncertainty increases by the second week, and by four weeks, the predictions really hold no weight." This complicates flood or wildfire risk management that heavily depend on these forecasts. The LCO expert stated:

> We base our actions on the best knowledge and data available at any given time, and we also depend on weather forecasts. If these forecasts change, or if a rain shower shifts slightly in one direction or another, it can result in considerable variation.

Additionally, data specialists may encounter model outliers that, while often insignificant, can serve as subtle indicators of potential future events. As noted by one of the experts interviewed, individuals who have experienced a specific crisis might exhibit heightened sensitivity to anomalies. In guiding their decision making, NHRM teams adhere to established protocols, using colour-coded alerts – yellow for caution, orange for significant preparation, and red for critical conditions – based on predefined thresholds. However, the WIT team, utilising these colour warnings for extreme weather, issues code-red alerts based on potential societal impact, rather than meteorological threshold criteria.

Knowledge Management

The NHRM teams are composed of individuals with varied expertise from multiple entities, allowing for a broad range of perspectives in meetings. This diversity, as highlighted in the interviews, is important for merging specific knowledge with data to uncover new insights. An example within the context of wildfire risk management illustrates this dynamic, where the LACB expert detailed how multidisciplinary collaboration facilitated the identification of interconnected risk factors:

> At one stage, we evaluated risk factors, focussing on mowing grass along roadside verges. The risk is that a car veering off the road into tall grass might ignite a wildfire. At some point, the nature conservation organisations indicated that the breeding season is over, which signals the time they typically resume using heavy machinery like tractors again, which can also serve as potential ignition sources.

While certain roles in these teams are fixed, additional participants may be invited to these meetings based on the crisis' nature. When asked about the challenges of collaborating with unfamiliar parties and their approaches, one expert remarked:

> Most stakeholders are familiar with the decision-making structure involving *picture compilation, situation assessment* and *decision making.* This familiarity promotes a

> shared understanding of the process: knowing what to expect, when to anticipate input from others, and when to express their perspectives.

The systematic application of the decision-making structure involving *picture compilation, situation assessment* and *decision making* within team meetings was consistently mentioned in the expert interviews. One expert outlined key questions that guide this process. Initially, clarifying the scenario: 'What is the overall picture?' Next, determining the focus: 'What do we need a decision on?' Then, evaluating the preparedness: 'Are we able to make a decision now?' and identifying potential information gaps: 'If not, what information do we still need to acquire in order to make informed decisions?'

This structured decision-making approach aims at clarity and focus, reducing prolonged debates while all team members can contribute their insights. This requires an environment that encourages critical thinking within time constraints, as noted by an expert, achieving a balance between adherence to facts and considering uncertainties and worst-case scenarios. To enhance meeting efficiency, while also addressing technical gaps for an upcoming weather scenario, the WIT team introduced an impact tool. The WIT expert explained:

> In our meetings, we not only try to reach an impact estimate through discussion, but also to utilise an impact tool. This tool, crafted with questions tailored to the specific responsibilities of each entity, helps them understand the context of the situation. Thus, [*entity*] receives different questions compared to those managing the roads. Then they make their own impact assessments, which is generated in a dashboard and then used as input for the meeting.

The interviews revealed the collaborative nature of decision making within the NHRM teams, with the absence of unilateral choices by individuals. Instead, decisions are reached through a consensus-building process, which can be complex, particularly in case of conflicting interpretations. The interviewed experts highlighted various strategies that NHRM employ to solve such problems. One such strategy involves seeking input from external experts or entities, thereby broadening the range of perspectives considered and enriching decision insight. Additionally, NHRM teams adopt a hierarchical approach, often guided by the chair. Besides ensuring inclusive participation and adherence to roles, the chair has an influential role in guiding the decision-making process, leading to what one expert described as 'democratically supported decisions with guidance.' During the interviews, the experts were hesitant about

labelling it as a decision. Instead, they perceived it more as guidance for other entities, with the actual decision-making process unfolding in that context.

Upon reaching a conclusion, the NHRM teams communicate it to other entities through various channels like websites, phone communications, and the National Crisis Management System (LCMS) – a tool designed for facilitating information exchange among crisis partners (NIPV, 2023). Acknowledging the challenges in information dissemination, especially to non-experts, NHRM teams are working on initiatives, as mentioned by an expert:

> We are actively seeking ways to enhance their understanding. This includes providing clearer explanations and training them to interpret the reports more effectively, ensuring they do not overlook crucial information that may not be on the first page. Additionally, we are updating the layout to prioritise the visibility of key information. In the future, albeit a bit further away, we aim to transform our data presentation methods.

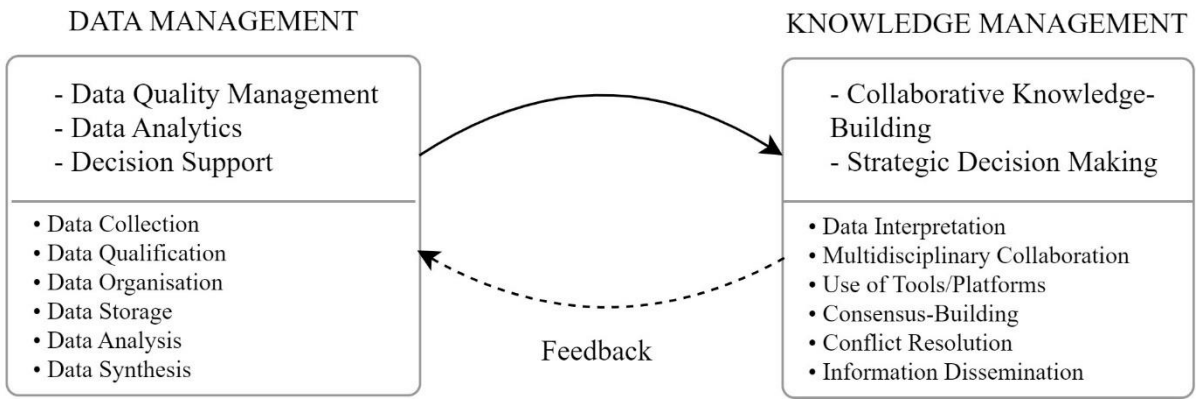
Highlighting the importance of clear communication with both partners and the public, an expert mentioned, "We work closely with communication experts to carefully craft our messages. Our goal is not just to issue warnings, but also to ensure that they lead to actionable outcomes, thereby minimising the impact as much as possible."

Data Management and Knowledge Management

Data Management and Knowledge Management are closely connected, as illustrated in Figure 1. The process starts with data specialists collecting and analysing data, transforming data into practical insights. Once certain thresholds are exceeded, it activates the NHRM teams to engage in Knowledge Management activities. This transition from data handling to collective response activation is captured in the framework with an arrow linking Data Management to Knowledge Management.

Figure 1

The Interconnectedness between Data Management and Knowledge Management



Through collaborative meetings, the teams engage in a structured decision-making process that is informed by the data collected. This process involves the systematic assessment of the situation and the identification of information gaps. When these meetings uncover a need for additional information, the process loops back to the Data Management domain, potentially involving additional data collection and analysis to obtain the necessary clarity for making informed decisions. This cyclical and iterative process is captured by the feedback loop in Figure 1.

Adaptive Leadership

Leadership in the NHRM context, as revealed in the interviews, consists of a balance of anticipatory and responsive strategies. Decision makers face the complex task of initiating measures that may carry significant societal implications, balanced against the potential harm of absent or delayed responses. Among the interviewed experts, there was a tendency to favour assertive responses, even when faced with limited or incomplete data, to mitigate potential damage. One expert expressed this anticipatory stance: “It is generally better to gather the team too early, perhaps unnecessarily, rather than too late.” Such measures might require deviating from established protocols, for instance to protect vulnerable populations. This was illustrated by an expert referring to an event where a code red alert was issued despite uncertainties about the severity of the natural hazard, an anticipatory decision driven by ethical considerations. The expert described the nuanced emotions associated with such decisions:

> In terms of the human aspect, when making a critical decision, it may seem odd, but you hope for some impact, not excessive, but enough to validate the decision, so that people acknowledge, “It was indeed necessary to issue a code red.”

The challenge of forecasting natural hazards lies in the persistent uncertainty until shortly before an event, often leading to criticism for relying on potentially outdated forecasts. An expert pointed out, “We attempt to incorporate this uncertainty into our assessments, yet such uncertainty is seldom apparent in general weather forecasts.” When signs of a hazard are evident but not yet definitive enough to exceed threshold criteria, formal response protocols may temporarily pause. However, this does not link to inaction for these teams. Termed by an expert as the ‘grey area', this intermediary phase between inaction and full-scale crisis response, is crucial for alerting and preparing stakeholders through informal communication. The LCO expert illustrated this leadership approach during the ‘grey area’:

> Coastal storms, with their uncertainty and influence from low-pressure zones, remain unpredictable until two or three days before. Despite this, we foresaw the approaching

> storms and the risk of high water. It was also spring tide and that is the moment to really pay attention. Initially, we saw a code-yellow situation, leading to us informally making calls, making inquiries, and sharing information, rather than issuing formal warnings.

In the supra-regional NHRM teams, which operate at a distance from immediate crises, decision making is more distributed. An expert emphasised the contrast with regional structures, stating: “Unlike the decision-making processes in the regions that prioritise speed, our system is designed for thoroughness. However, it is not designed for making decisions within half an hour, presenting a challenge in translating this approach into acute situations.” Nevertheless, NHRM teams are also equipped with emergency measures for acute scenarios such as circumstances where multiple hazards emerge simultaneously. These measures include seeking emergency advice from external sources, expedited upscaling, and utilising an ‘emergency brake’ to issue a code-red warning without convening the entire team. An expert underscored the necessity of clear, predefined guidelines to facilitate swift action during crises, suggesting the documentation of key priorities such as valuing human life and delineating the importance of nature versus cultural heritage.

> This way, decision makers have a straightforward approach guiding their actions from a governance standpoint, allowing them to operationalise their tasks more efficiently. Ideally, this system would enable the delegation of decisions that would typically require a bureaucratic review, streamlining the process.

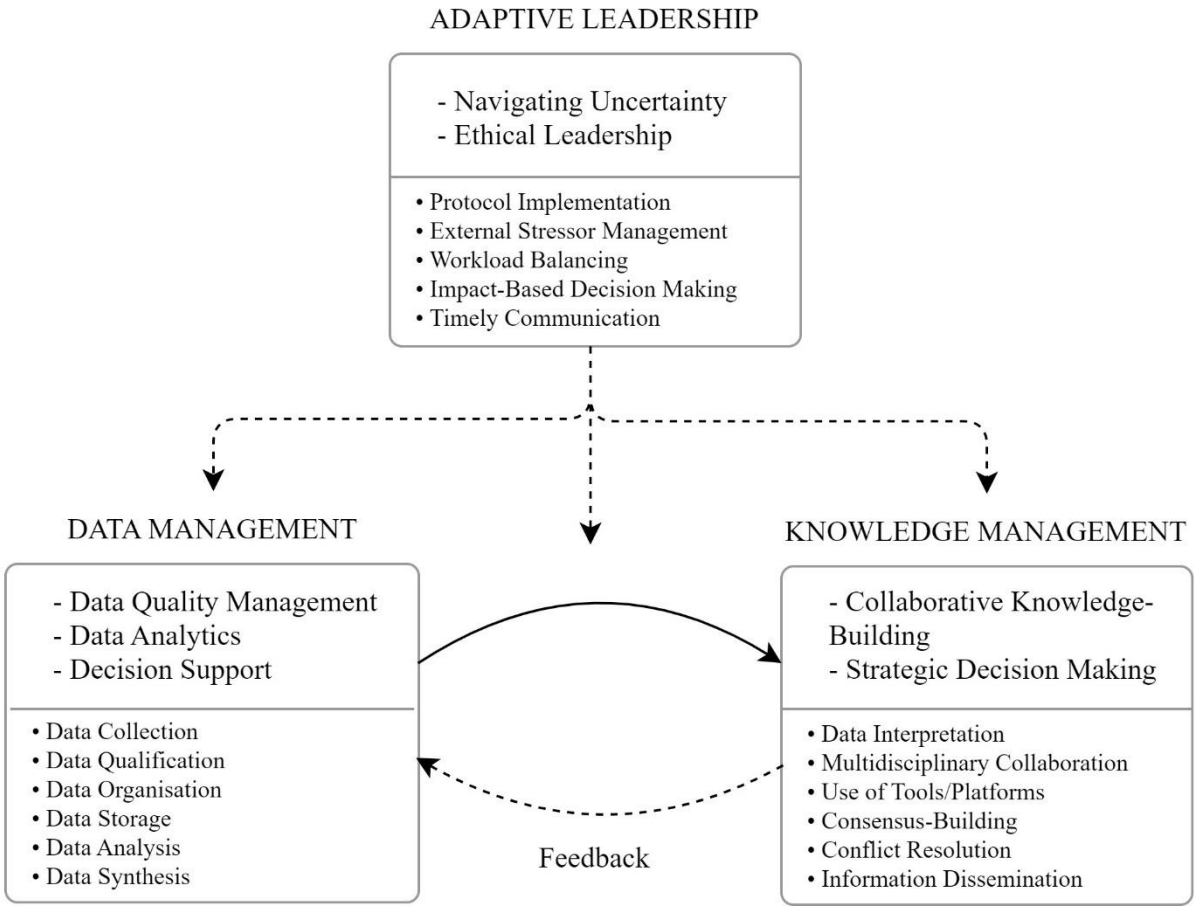
Another expert also expressed a desire for moving away from bureaucratic towards a more adaptable approach, allowing the issuance of more tailored warnings. The expert stressed that every situation is unique and cannot be fully addressed by strict protocols or predetermined thresholds. Yet, the expert also acknowledged the complexity of responsibility when something goes wrong, particularly in cases where the issued warnings are lower than what standard protocols would suggest. The interviews also revealed the demanding nature of crisis management, which may require a continuous 24-hour commitment, placing considerable strain on team members. To mitigate this, NHRM teams have adopted supportive practices, including peer check-ins, in particular for those with personal ties to affected areas, and shift rotations to prevent fatigue.

In the context of the other domains of Data Management and Knowledge Management, Adaptive Leadership introduces a dynamic component to the decision-making process,

adapting responsively to changes and guiding decisions grounded in ethical principles. Figure 2 illustrates the connection between these domains.

Figure 2

A Framework for Collaborative Decision Making in NHRM Teams



Together these domains form a holistic system that supports the collaborative decision-making process. Data Management ensures data accuracy and analytical processing of data, forming the basis of the process. Knowledge Management builds on this foundation, using the team's expertise to derive actionable insights from the data. Adaptive Leadership plays a more dynamic role, involved when circumstances require it, leading through change and uncertainty with ethical considerations. It informs and shapes both Data Management and Knowledge Management and has a bridging role for smooth transitions and adaptability in protocol execution and crisis response. This includes facilitating timely stakeholder communication and implementing workload mitigation strategies, such as shift-based work patterns.

Discussion

In examining how NHRM teams manage a data-driven approach in their collaborative decision making during high-stakes situations, the research framework provides insight into how the domains Data Management, Knowledge Management and Adaptive Leadership are connected. Data Management is foundational in the framework, handling data quality, analytics, and decision support. By incorporating threshold criteria into protocols, teams transform raw data into information, aligning with what Ackoff (1989) describes as the transformative process from raw data to practical utility. To mitigate challenges related to unfamiliarity with data sources, a concern identified by Klein et al. (2010), NHRM teams involve data specialists in their operational structure to ensure data accuracy.

Knowledge Management builds upon the foundation of Data Management. This domain involves collaborative knowledge-building, based on available data and information, aligning with the third step of the DIKW hierarchy (Ackoff, 1989), and strategic decision making. The decision-making structure, involving the phases of *picture compilation, situation assessment* and *decision making* closely correspond to Endsley's (1988) three levels of situation awareness, from initial perception to comprehension and projection of future status. The feedback loop to Data Management, as illustrated in the framework, allows teams to identify information gaps. This indicates a dependence on Data Management to fill in these gaps by enhancing data inputs, thereby supporting informed decision making.

Adaptive Leadership introduces a dynamic element to the framework, focussing on responsiveness and ethical considerations in managing uncertain, high-stakes scenarios. Interviews provide nuanced insight into the decisions made, revealing the dilemma of balancing swift action with its societal implications against the risks of procrastination. This dilemma reflects the tension identified by Hale et al. (2005) between acting immediately and awaiting further information to ensure verification and decision quality. Moreover, decision makers must weigh these decisions against the implications of both immediate and long-term public trust and perception. This balance aligns with the DIKW hierarchy's highest level where wisdom – the ethically informed application of knowledge (Rowley, 2006) – is crucial. The framework also illustrates the strategic use of informal communication to prepare stakeholders before threshold criteria are exceeded and the NHRM teams come together. This is indicated by the dotted line pointing to the arrow from Data Management to Knowledge Management, signalling the need for timely communication before the initiation of the formal scaling-up processes.

Limitations

The study has several limitations that should be considered. The use of purposive sampling to select participants from these specific entities could introduce sampling bias, which

may limit generalisability of findings. Additionally, the reliance on self-reporting introduces the possibility of participants providing socially desirable responses or inaccuracies due to memory errors or misinterpretation of questions. This reliance potentially compromises the reliability of the data collected. Considering these limitations, Study 2 adopts an alternate approach by directly observing collaborative decision making during training sessions. This method aims to provide a more objective exploration of collaborative dynamics, mitigating potential subjectivity associated with self-reporting. The objective of Study 2 is to enhance, clarify, and expand upon the findings from Study 1.

Study 2: Dynamics of Collaborative Decision Making in Natural Hazard Risk Management Teams during Training Sessions

Method

To further explore the collaborative decision making in NHRM teams, this study primarily concentrated on the Knowledge Management aspect of the framework from Study 1, which involves collaborative knowledge-building and strategic decision making. Within this study, observational research is conducted during training sessions. In contrast to experimental studies, this method refrains from influencing participants or the surrounding environment (Johnson, 2012). This method aimed to provide a non-intrusive view of team dynamics during crisis scenarios, enriching the interview data from Study 1. To achieve this, attendance at two LCO training sessions was arranged, during which teams collaboratively addressed a crisis scenario through an online Microsoft Teams meeting. This attendance provided a direct observation of behaviours, interactions, and the subsequent outcomes.

Participants

Prior to the training sessions, participants were grouped into teams. Each team consisted of a chair, an information coordinator, and three advisors with distinct expertise. Notably, unlike a real crisis scenario, a representative from the Union of Waterboards and a communication specialist were not included in this team composition. An internal contact informed the training participants about the study, sharing research objectives via email, accompanied by an information sheet and consent form provided by the researcher.

Procedure

To ensure a comprehensive understanding, overt non-participant observations were conducted, with participants' consent. However, it was recognised that this method could lead to the Hawthorne effect, in which participants might alter their behaviour due to the awareness of being observed (McCambridge et al., 2014). To mitigate this effect, precautions were taken

such as remaining muted and not activating the camera during the discussion part. Participants received scenario details in advance, allowing for preparation. However, participation without prior preparation was also an option.

The scenario entailed a high-water situation on the river Rhine, in which a waterboard – a regional water authority – sought advice from the LCO, after receiving a warning about water levels from the Water Management Centre. Dealing with multiple vulnerable points along a dyke[1] section, the waterboard is considering the early deployment of a measure, deviating from standard protocol. They sought advice from the LCO regarding the appropriateness of this proposed action.

The training structure was designed to progress through the decision-making structure, involving *picture compilation, situation assessment* and *decision making.* However, teams were permitted to deviate from this structure if the situation would demand it. The training session, lasting approximately 1.5 hours, allocated a maximum of 45 minutes to discussions and coming to decisions, followed by an evaluation. During these sessions, notes were taken to document key insights and observations. To mitigate potential observer bias, sessions were recorded through video or audio to accurately capture insights. One recording captured only the discussion component, while the recording from the other session included both the discussion and evaluation components.

Data Analysis

Recorded data underwent transcription using Amberscript software and subsequently refined in line with the intelligent verbatim principles (McMullin, 2021). Within the transcripts, the distinct phases (*picture compilation, situation assessment, decision making*) served as anchor points for analysis. Subsequently, the transcripts were translated to English for further analysis. The data analysis was conducted using ATLAS.ti 23, employing an abductive approach to coding with a primary focus on deductive coding. The codes, initially derived from Study 1 played a key role in guiding the coding process to validate and extend interview findings. This method also remained open to uncovering new insights emerging from empirical data, allowing for the development of new codes.

Results

The focus on Knowledge Management within the visual framework provided a targeted focus on how NHRM teams manage the collaborative knowledge-building and strategic decision making during crisis scenarios.

[1] In this context, a dyke refers to an artificial embankment constructed to protect the land behind it from high water levels and wave surges (Rijkswaterstaat, 2023)

Data Management and Knowledge Management

This study, while centred on Knowledge Management, also highlighted the role of Data Management within the collaborative decision-making process. Team members prepared for the sessions by engaging in Data Management activities, as demonstrated by aligning scenario-specific data with established protocols. For example, they would state, "According to our protocol, this situation qualifies as a code red, which indicates effects like (…) can be expected." Additionally, the team members checked against stakeholders' protocols, as reflected in statements like, "In alignment with the waterboard's protocols, dyke surveillance will be initiated." During the synthesis phase, a standardised approach to data handling was observed. Team members used numeric benchmarks to quantify the rarity of events based on model outcomes, often referring to events as 'once in 50 years' occurrences. This standardisation extended to determine the frequency of measure deployment. However, the training scenario revealed that the protocol's prescribed decisions were influenced by more than just technical criteria; factors such as regional support also played a role in shaping these protocols.

The structured training progressed through *picture compilation, situation assessment,* and *decision making* to collaboratively interpret the situation and formulate decisions. Although the training sessions offered the option to deviate from this structure, the teams remained committed to its steps, as reflected in comments such as "Your comment marks a crucial step towards *situation assessment*, so we will park it for now; if it is not addressed later, please bring it up again." The meetings followed a structured sequence, starting with the chair's introduction and moving to the information coordinator who formed the initial picture, setting the stage for collaborative knowledge-building. Advisors then contributed, utilising their individual data collection and specific expertise to expand on the initial picture, utilising tools like maps to pinpoint critical points along the dyke.

Moving into the *situation assessment* phase, the teams collaboratively analysed and critically evaluated the available information to form a comprehensive understanding of the scenario. They adopted a careful approach to data interpretation, as expressed in statements like, "This is our first time using this measure. We are not entirely sure of its effects; it is based on models." Historical data served as a reference for evaluating the dyke's resilience. However, a team members raised a critical point about the reliability of historical data, questioning, "Have there been changes to the dyke since then? If it has been modified, past performance might not be a reliable indicator." The discussion extended to include factors beyond model-generated data, like dyke enhancements and environmental conditions. A member highlighted the dynamic nature of dyke conditions, noting:

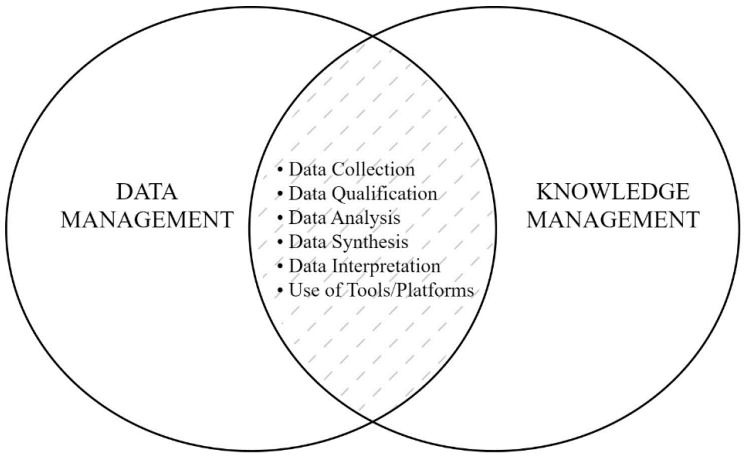
> Considering the broader context, numerous dykes have undergone enhancements, yet the day-to-day conditions vary significantly from past conditions. Factors such as prolonged dry periods or animal disturbances can lead to local vulnerabilities. Since we do not have direct oversight of these details, it is important for local waterboards to monitor and communicate these specific risks.

The *situation assessment* phase featured discussions and critical questioning among team members. In this process, discrepancies arose, particularly regarding the effectiveness of proposed measures. During one discussion, it became evident that there were contrasting interpretations when a members remarked, "Your comment made me rethink my understanding of the deployment thresholds; I believed it was at [*water level*] at [*town*]. From my perspective, earlier deployment can be truly effective, as indicated in the study (…)" To resolve this, the decision was made to temporarily set the difference aside and let the members do some individual research in the protocols post-meeting.

Figure 3 captures the dynamic relationship between Data Management and Knowledge Management within NHRM teams, illustrated as two overlapping circles in a Venn diagram. This represents the idea that while each domain has its own distinct responsibilities, there is an area of overlap where their activities intersect and are performed collaboratively.

Figure 3

Intersecting Domains of Data Management and Knowledge Management in NHRM teams



Knowledge Management and Adaptive Leadership

Throughout the *decision making* phase, NHRM teams demonstrated an interplay of Knowledge Management and Adaptive Leadership. The chair played a prominent role in synthesising input and formulating decisions accordingly, embodying a leadership role during the meetings. Decisions were typically reached through consent, indicating a lack of active

opposition rather than unanimous agreements. While the teams swiftly decided on the deployment of the measure, debates emerged about how to communicate advice, including whether to recommend specific actions and consider factors like evacuation. These discussions, occurring in both training sessions, triggered a broader debate regarding LCO's role in relation to other crisis partners. Team members emphasised the importance of adhering to their specific roles and should refrain from considering factors like evacuation, as expressed by a member:

> Our expertise lies in conducting national assessments and ensure that the measure they propose has no adverse effects and are feasible for deployment. Besides, the local waterboards have their own protocols, and given their direct involvement with the levels; possess a more detailed understanding of the local conditions than we do.

Despite facing time limitations during the training, the impact of such constraints on their decision making was not visible. However, they did encounter challenges in navigating through uncertainties, particularly regarding the measure's effectiveness, which was solely based on model predictions. To navigate uncertainties, the teams adopted an impact-based approach, weighing a range of factors from technical and environmental aspects to social concerns, including potential public resistance. This impact-based approach was captured was reflected in this statement:

> It is crucial for us to zoom out and recognise that the significance of this decision extends beyond this specific area. We must also consider the other dyke along the [*river*]. While there might not be an immediate request from other waterboards, we need to contextualise our actions within the broader context.

When the teams considered deviating from the protocol, they acknowledged the necessity for coordination with managing entities, as highlighted in the discussions: "If we are considering a deviation from the protocol, then [*entity*], as the managing body, needs to be involved." The teams' advisory role, while not directly responsible for the final decision, carried considerable weight, as indicated by the concern: "We will offer advice, but should there be any adverse outcomes, it could be argued that they followed LCO's advice." This underscores the teams' sense of accountability and the perception that others might hold them accountable. Leadership was also evident in the discussions about communicating the effectiveness of the measure and managing expectations of crisis partners. In one training session, a member raised the question:

> Should our advice also caution that, despite the measure's positive impact, it does not eliminate flood risk and that it is crucial that everyone still follows their normal procedures?

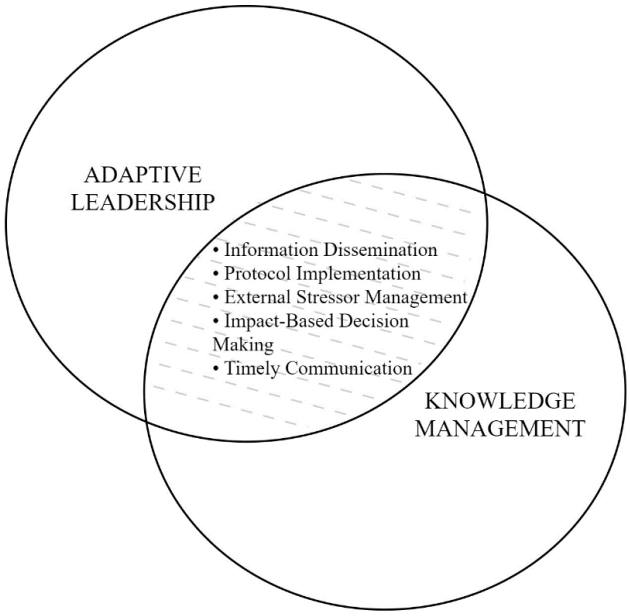
Ultimately, the teams chose to adhere to the established protocols, taking a measured approach to mitigate risk misinterpretations, while also communicating to the waterboard that, despite the deployment of the measure, the situation remained a code-red situation. This was intended to encourage crisis partners to still consult their own protocols. Moreover, the teams considered worst-case scenarios, assessing potential consequences for both human lives and financial resources. They exercised caution in disseminating specific figures externally to avoid misinterpretation of those figures as indicative of the current situation and shared further. Instead, these figures were intended to illustrate potential outcomes under the worst conditions.

One team proposed setting up a scenario team to explore various alternative scenarios, involving other colleagues to bring in new perspectives. In contrast, the other team refrained from alternate scenarios, as they were confident the proposed measures would be effective regardless. As the discussions concluded, the decision was made to use LCMS for widespread information sharing and to initiate direct communications with specific stakeholders for timely communication and ensure the accuracy and verify information.

Figure 4 captures the relationship between the domains of Knowledge Management and Adaptive Leadership, illustrating their overlapping activities in a Venn diagram. The activities in the shaded area where both circles overlap represents activities that are common to both domains. These activities are not isolated within one domain but are vital to both domains.

Figure 4

Intersecting Domains of Knowledge Management and Adaptive Leadership in NHRM teams



Discussion

This study provides a detailed look of how Data Management, Knowledge Management, and Adaptive Leadership intertwine within the decision-making framework of NHRM teams, as presented in Figure 2 in Study 1. Whereas Study 1 may have implied that the domains are distinct, non-overlapping domains, this study shows their integration, as indicated by overlaps in Figure 3 and 4, which reflect that activities are not exclusive to one domain.

Data Management's key role involves standardising data communication, which converts raw data into usable information, a process that aligns with Ackoff's (1989) DIKW hierarchy and facilitates NHRM teams' ability to organise and interpret data. The reliance on both quantitative data and qualitative insights, such as comparing historical data with current dyke conditions, illustrates the practical application of data and information. Using tools like maps for context, supported by expert insights, transforms this into practical knowledge, reflecting the next step in the DIKW hierarchy (Ackoff, 1989). The decision-making dynamics observed in the training sessions align with Klein et al. (2010)'s concept of team sensemaking, incorporating essential elements, such as critical questioning and dissent. The resolution of divergent views through undertaking further data analysis illustrates the iterative feedback between Data Management and Knowledge Management.

Additionally, the teams' impact-based approach and nuanced approach to advising, adherence to protocols and consideration of worst-case scenarios, demonstrate Adaptive Leadership's role in ethical decision making and managing uncertainty. Moreover, the establishment of tailored protocols that consider factors beyond mere benchmarks for decision

making, reflects Adaptive Leadership's influence on Data Management. This validates the dynamic that is captured in Study 1's framework by a dotted line between these domains.

Extending Study 1's findings, this study reveals a more complex, intertwined relationship between the three domains. It aligns with Klein et al.'s (2006) observation of sensemaking's non-linear dynamics in crises. Furthermore, the findings reveal role fluidity within NHRM teams, with members simultaneously involved in Data Management, Knowledge Management, and Adaptive Leadership. They shift from organising data to collaboratively interpreting it and critically reassessing protocols to make ethical sound decisions, reflecting the multifaceted nature of crisis management.

Limitations

While this study provides insights into collaborative decision-making dynamics in crisis scenarios, it has limitations. The use of overt non-participant observation may have influenced participant behaviour due to the Hawthorne effect, despite the efforts made to mitigate this effect. Additionally, the absence of representation of two key roles typically present in such teams, might have skewed discussions, potentially leading to an overemphasis on certain elements while others. Another limitation is the absence of time pressure in training sessions due to its simulated nature, which may have resulted in responses that diverge from authentic crisis decision-making dynamics. Moreover, the study's focus on the specific context of LCO training sessions may not fully cover the diverse contexts of other NHRM teams, affecting the broader applicability of these insights. Study 3, which examines NHRM teams in actual crisis scenarios, is crucial for providing a more accurate understanding of collaborative decision making under real time constraints. This study serves to validate and enhance the insights from Study 1 and Study 2.

Study 3: Analysing Collaborative Decision Making in Natural Hazard Risk Management Teams during Real Crisis Scenarios

Method

To investigate collaborative decision-making dynamics within NHRM teams during high-stakes situations, this study involved analysing internal reports and attending a real crisis meeting. The internal reports detailed meeting reports and evaluation reports from actual crisis scenarios. Additionally, attendance to a real crisis meeting of the WIT team added depth to this investigation. This study aimed to validate and expand upon the framework established in Study 1, enriched by insights from Study 2. It focussed on examining the framework's application in

real crisis scenarios, identifying both its practical implications and any challenges or limitations that emerged during its application.

Procedure

Various experts from the selected NHRM teams were asked to share relevant reports, adhering to specified inclusion criteria. These criteria required reports covering cases from the past five years involving decision making under time constraints. A total of twelve reports were obtained, with nine reports acquired from the WIT, which included evaluations of code-red warnings, as well as three meeting reports on a storm with a code-orange warning. Notably, one of the WIT's evaluation reports included questionnaire outcomes in which team members assessed the process leading to a code-red warning. In addition, three LCO meeting reports were acquired, all related to a single crisis event, complemented by technical documents. Due to the recent establishment of the LACB, no reports from this team were available for analysis.

Arrangements for attending a WIT meeting included email communications, inclusion in weather update lists, and a preparatory Teams meeting with an expert. An hour prior to the scheduled meeting, a notification was received for a meeting to determine whether a code orange or red should be issued for the upcoming weather scenario. This short notice underscored the high-stakes nature of the collaborative decision-making process, aligning with the central focus of this study. During this meeting, a brief introduction was given on the research, followed by obtaining consent for recording. The meeting lasted for 15 minutes and was audio recorded.

Data Analysis

The data analysis followed the same approach as Study 2. Unique elements included the anonymisation and translation of internal reports. Transcription refinement and coding in ATLAS.23 proceeded as before, using the same anchor points. The primary focus in this study was on deductive coding with the codes from the previous studies guiding the process to validate and enhance these findings.

Results

By applying the framework developed in Study 1, enriched by the figures from Study 2, this study offered a deeper understanding of the challenges encountered by NHRM teams in actual crisis situations. These case examples reveal the dynamic nature and some of the complexities encountered by NHRM teams in their collaborative decision-making processes in real-world contexts.

Data Management

During the meetings examined in this study, Data Management was evident in the initial technical data presentations, which were subsequently enriched with information, as expressed

in comments such as: “The current water levels occur multiple times a year.” A similar approach was applied in converting technical meteorological details into an impact matrix, thereby translating into potential societal disruption. However, during a WIT meeting, an expert tried to clarify a weather situation by classifying it as a code-red scenario based on meteorological data, causing confusion among the other members. With this approach, the expert deviated from standard protocol, which do not set explicit threshold criteria for code red but rather rely on impact assessments.

This study highlighted the unpredictability of events and the uncertainty within predictive models. One report described the seasonally variable impact of storms, pointing out, “While summer storms are less frequent than those in autumn and winter, their impact is often more substantial. Their rapid development present challenges, particularly to traffic and recreation.” Faced with such unpredictability in a scenario, a NHRM team adopted a cautious approach in their decision making. Reflecting on their approach, members expressed that the uncertainties within the models might have led to an overly conservative approach. During a meeting, a weather expert noted efforts to enhance decision making through the automation and continuous generation of probability estimates, aiming to refine the process of issuing warnings.

Knowledge Management

The crisis meetings under examination shared several procedural consistencies. Each meeting was conducted in either a virtual or hybrid setting and strictly followed the decision-making structure, involving *picture compilation, situation assessment* and *decision making.* Additionally, prior to these meetings, external consultations took place to inform discussions and assess alignment expectations. Notably, participation in the meetings examined, extended beyond the fixed participants, actively involving additional stakeholders depending on the crisis’ nature. For instance, during LCO meetings, a weather expert provided weather-related insights. Similarly, during a WIT meeting, water management entities, including the LCO, participated because a weather event coincided with a high-water scenario.

During the NHRM team meetings, a variety of factors were considered in the decision-making process, drawing insights from expert insights and the evaluation of measures. In one meeting, the information exchange on measures that had already been deployed, influenced the group’s inclination towards issuing a code-orange alert rather than escalating to code red. Reflecting on this, team members recognised that the discussion of active measures had influenced their judgment, reducing the perceived need for a code-red warning. However, during this meeting the WIT impact tool was not used due to time constraints. This was viewed

as a missed opportunity for a more nuanced impact assessment. Yet, despite the availability of tools, a member pointed out the complexity in weighing and comparing distinct types of impact.

An evaluation report highlighted that it should also be considered by members during a discussion that alerts do not need to be nationwide; instead, partial code-red alerts for specific provinces can be issued. In the attended WIT session, the chair emphasised this targeted approach to weather alarms:

> Concluding the *picture compilation* phase, we now move on the subsequent phase, *situation assessment.* This step entails assessing safety risks, specifically the necessity of a weather alert, whether it should be a code red or a regional alert? And if so, which specific region and time should be targeted, and based on what criteria should we determine whether such an alert is necessary or not?

The analysis highlighted the use of LCMS by NHRM teams as a key tool for sharing information with crisis partners. In the first meeting concerning an upcoming hazard, an image was initiated, that was continuously updated with the latest data. To further enhance system functionality and streamline information exchange, it was proposed to form agreements during non-crisis periods detailing the use and integration of images to ensure the inclusion of relevant situational images. After each meeting, the advisory message to partners was refined to reflect the most up-to-date and accurate insights. Additionally, the teams paid close attention to the clarity of their communications, recognising areas where further explanation was necessary, reflected in statements such as “We may need to provide more clarification about the implications of the anticipated increase in water levels in this region.” This led to a collaboration between the chair and the communication team to develop a clearer and more effective message for dissemination.

Adaptive Leadership

The diverse scenarios under study required an adaptable approach from the NHRM teams. For example, an urgent meeting was initiated just one hour ahead of an approaching natural hazard to determine whether a code-red alert was necessary. Similarly, a situation that initially received an orange alert quickly escalated to the worst-case scenario, triggering the emergency brake, and capturing significant media attention. Media interest, however, varied due to external influences, such as a high-water scenario that coincided with elections, resulting in limited media coverage.

Reflecting on the deployment of the emergency brake, it was noted that even with a lower likelihood of a code-orange scenario, additional considerations like peak traffic times

were crucial. Consequently, it was suggested in the report that bringing the team together should be based on more than only threshold criteria for a code orange. Factors such as specific timing of weather events and the capacity to timely alert the public or stakeholders should also be considered to minimise dependence on emergency measures. The report also highlights the need for timely assessment of the likelihood of a code red to ensure timely communication with crisis partners to enhance their preparedness and response effectiveness. Nonetheless, the question is raised in the report about whether a different strategy could have facilitated an earlier issuance of code red, particularly considering the storm's rapid development in the final stage.

The studied NHRM employ a range of strategies to improve preparedness and reduce uncertainty among their partners, the public, and team members. A key practice involves the LCO's use of LCMS to share both the most likely and worst-case scenarios, generated by scenario teams. In matters of public awareness and preparedness, the WIT opted not to issue a code orange alert for an approaching storm to emphasise the severity of an expected more severe weather event later in the week, for which a code orange had already been issued. To enhance internal preparedness, the WIT implemented extra weather briefings to ensure team members had a better understanding of potential weather conditions. Nonetheless, the explanation of a model's expert on technical aspects of the weather models led to confusion during one of these briefings. The report suggested that comparisons to historical weather events could be used to enhance clarity and accessibility of the information.

Discussion

In applying the established framework from Study 1 to real crisis scenarios, this study enriches the understanding of collaborative decision making within NHRM teams. The complexities revealed through the application demonstrate the interdependence between Data Management, Knowledge Management, and Adaptive Leadership. An issue in Data Management was observed when an expert deviated from standard protocol, causing confusion. It illustrates the tension between following strict protocols and adapting to the unique needs of each crisis. Additionally, the uncertainties inherent in predictive models can result in overly cautious decision-making approaches within the Knowledge Management domain, reflecting the interconnectedness between Data Management and Knowledge Management.

In Knowledge Management, the study reveals that consulting with external experts and including input from a wide range of stakeholders in the meeting can enrich the decision-making process. Nonetheless, it also poses challenges in achieving a unified understanding, further complicated by the complexity in assessing various impacts. The study illustrates the potential for selective data presentation to skew collective decision making, supporting

Endsley's (2012) observation on decision making under pressure, where time constraints can lead to rushed judgments and impair situation awareness. The dissemination component of Knowledge Management reflected the critical role of Adaptive Leadership, aligning with the framework's overlap of these domains as identified in Study 2. Adjusting communication messages after meetings to suit changing circumstances demonstrates the team's leadership role in managing dynamic information flows, a key challenge in maintaining situation awareness as outlined by Endsley (2000) and Salas et al. (1995).

Additionally, the study reveals the challenges associated with the use of emergency measures, particularly in stakeholder communication and media attention. It underscores the need for impact assessments and the consideration of various scenarios, including worst-case outcomes. Moreover, the study points to the importance of effective communication, which serves not just to inform and prepare stakeholders and the public, but also to ensure that team members have a clear understanding of the situation. This requires consideration of the timing, specificity, and the understandability of information, as suggested by Klein et al. (2010), particularly when communicating complex technical data.

Limitations

This study is subject to several limitations that should be considered. The reports that were analysed primarily focussed on technical details, providing limited insight into the team dynamics and interactions crucial for understanding the role fluidity observed in Study 2. A lack of in-depth information on the decision-making process hindered the verification and identification of factors influencing NHRM teams' decision making. Additionally, the retrospective nature of the reports could result in a less accurate portrayal of the situational context, potentially leading to recall bias or omission of context-specific details. Lastly, the observational aspect of this study was restricted to a single 15-minute crisis meeting. This brief observation period provided merely a glimpse of the NHRM teams' operational dynamics and might not fully reflect the depth and complexities of decision making in high-stakes contexts.

General Discussion

In addressing the identified research gap concerning the collaborative decision-making processes within data-driven NHRM teams during high-stakes environment, this research has developed a comprehensive framework. This framework, established in Study 1, further enriched by insights from Study 2, and validated in real-world contexts through Study 3, reveals the complex interplay between Data Management, Knowledge Management, and Adaptive Leadership. Data Management forms the decision-making framework's base, focussing on data quality management, analytics, and decision support. It transforms raw data into structured,

interpretable information through threshold criteria, protocols, and standardisation, reflecting Ackoff's (1989) DIKW hierarchy's data-to-information stage, and laying the foundation for informed decision making.

Knowledge Management builds upon this foundation, converting data and information into strategic insights through collaborative knowledge-building, consistent with Ackoff's (1989) DIKW hierarchy, where data and knowledge are converted into practical knowledge. The decision-making structure, involving *picture compilation, situation assessment* and *decision making* closely aligns with Endsley's (1988) levels of situation awareness, facilitating a comprehensive understanding and anticipation of future states. Tools like LCMS and the WIT team's impact tool play a crucial role in improving role-specific understanding and shared situation awareness among involved parties, essential for team situation awareness as noted by Endsley and Jones (2001). The dynamic feedback loop between Data Management and Knowledge Management underscores the iterative nature of crisis management, with ongoing data reassessments to address information gaps and refine decision making.

Adaptive Leadership entails a flexible and ethical approach to navigating uncertainties and making critical decisions. It requires balancing immediate action and its potential societal implications against the risks of delaying decisions for more information, a tension highlighted by Hale et al. (2005). Wisdom, the last level of the DIKW hierarchy, has a central role in this domain, guiding the ethical application of knowledge for the greater good, as noted by Rowley (2006). Leadership's critical role in strategic communication, bridges Data Management and Knowledge Management, emphasising the importance of clear, timely and audience-tailored messaging, as outlined by Klein et al. (2010). Moreover, leadership shapes Data Management and Knowledge Management through the development of tailored protocols and workload management strategies, such as employing shift-based scheduling, to mitigate cognitive overload in high-pressure scenarios that may compromise situation awareness, as noted by Endsley (2012). While this shift-based approach may support the maintenance of situation awareness, it requires effective coordination to ensure continuous and coherent shared situation awareness among team members, irrespective of shift rotations.

The findings reveal an iterative process without a clear beginning and end point, in line with Klein et al.'s (2006) observations on sensemaking in crisis dynamics. Additionally, NHRM teams demonstrate role fluidity, as members simultaneously engage in Data Management, Knowledge Management, and Adaptive Leadership. This underscores the significance of individual contributions across various decision-making areas. However, this fluidity can lead to role ambiguity or overlap, potentially compromising the effectiveness of crisis response

efforts. The research also recognises the potential vulnerabilities within the interconnected Data Management, Knowledge Management, and Adaptive Leadership in NHRM teams. The overall effectiveness is dependent on each domain's performance. For instance, Knowledge Management relies on Data Management to inform its decision-making process and fill information gaps. However, challenges may arise when individual experiences influence the interpretation of data. While such personal insights can enhance intuition and the detection of anomalies, it can undermine objectivity and lead to overreliance on personal insights, risking skewed analyses, as Fisher and Kingma (2001) caution. Furthermore, inadequate data filtering may lead to data overload and cascade into information overload within the Knowledge Management domain, impairing judgment, and situation awareness (Darioshi & Lahav, 2020; Endsley, 2012). This may lead to hasty or narrow-focussed decisions (Bolstad et al., 2006).

While adaptable leadership is crucial in crisis, it can have drawbacks. Excessive adaptability and frequent deviations from established protocols might lead to confusion and inconsistency in responses that could compromise the reliability of response efforts. Hence, it is important to maintain a balanced approach that respects established protocols yet remains flexible to the demands of the crisis. Moreover, this research emphasises the importance of clear and timely communication. Effective information exchange, both internally among team members and externally with stakeholders, is critical for alignment and informed decision making, aligning with Moe and Pathranarakul's (2006) view of communication as fundamental component in crisis management.

Ultimately, this research underlines the integral roles of Data Management, Knowledge Management, and Adaptive Leadership in NHRM teams' decision making. It highlights the need to balance intuition with factual analysis, flexibility with strict protocol adherence, and underlines the importance of clear communication in navigating crises. These insights contribute strategies for enhancing crisis management in data-driven contexts to academic research and real-world practice.

Practical Implications

Drawing from the findings on the examined NHRM teams, this research suggests several strategies refine crisis management practices within teams managing large volumes of data. Given the interconnectedness of Data Management, Knowledge Management, and Adaptive Leadership, where the effectiveness of one domain can influence the others, regular evaluations in these specific areas are recommended. Recognising the key role of Data Management in informed decision making, entities should ensure that the data foundation is reliable and actionable through protocols and standardisation processes. This approach not only

converts raw data into structured and interpretable information, but also integrates data filters to tackle the challenge of data overload and its potential cascading effect into information overload. Additionally, targeted training programs are advised to refine team members' skills in data interpretation and sharing data insights.

For Knowledge Management, it is recommended to invest in the development and use of tools and platforms that promote shared understanding and multidisciplinary collaboration, such as the WIT impact tool and LCMS. Such resources can support role-specific insights and shared situation awareness, enabling a more cohesive crisis response. To align the data with the information needs, maintaining a strong connection with Data Management is crucial, facilitated through a feedback loop. Moreover, including at least one data specialist in the meetings is essential to ensure data comprehension for everyone involved.

Leadership should strive for a balanced approach that respects protocols yet remains flexible to unforeseen circumstances. This involves the implementation of adaptable protocols and emergency measures. To manage uncertainty, timely communication is crucial for preparing stakeholders. It is recommended to present both the most likely and worst-case scenario to equip them for various outcomes. Additionally, employing strategies like shift-based scheduling can mitigate cognitive strain and preserve situation awareness throughout the team.

Limitations and Future Directions

The findings of the studies should be interpreted with the consideration of their limitations, as detailed in the discussion sections of each specific study. Additionally, there are some broader limitations to consider. Focussing on three supra-regional entities within the NHRM domain, which share common characteristics, narrows the representation of varied roles, dynamics, or contexts. This, along with limited participants that participated in the research, restricts the generalisability of findings. Therefore, it is recommended for future research to expand its scope beyond the NHRM domain. Examining a larger number of teams across a wider variety of high-stakes, data-driven environments can enhance the understanding of collaborative decision making in critical situations and assess the framework's applicability across diverse contexts.

Furthermore, the qualitative research design, with its reliance on self-reports, observations, and retrospective accounts, inherently introduces subjectivity. This could affect the study's reliability and its ability to draw causal inferences. Despite these limitations, employing a multi-method approach may have mitigated some methodological biases, thereby enhancing the validity of the findings. Additionally, the research's strength lies in its ability for a detailed exploration of real-life contexts, revealing insights that might remain hidden in more

controlled research settings. Future research can enrich these findings by employing mixed-method or quantitative approaches. This would enable the identification of causal relationships and a more precise assessment of aspects related to collaborative decision making. For instance, future studies could explore whether similar teams make consistent decisions when presented with the same information or examine the influence of role fluidity on team performance and crisis adaptability. Such insights could inform the development of targeted interventions.

Moreover, the translation of Dutch transcripts into English carried the risk of losing specific linguistic nuances, potentially affecting the depth and accuracy of data interpretation. However, the researchers' proficiency in both languages likely minimised these translation biases. Looking forward, the increasing role of automation in NHRM collaborative decision making presents an important area for future research. Future studies could explore how automation might enhance or hinder the decision-making process and investigate how teams weigh algorithmic input against human expertise.

Conclusion

This research investigated the collaborative decision-making processes within NHRM teams. It emphasises the critical integration of Data Management, Knowledge Management, and Adaptive Leadership in navigating high-stakes scenarios. The developed framework demonstrates how these domains dynamically interact, offering an adaptable yet systematic strategy for crisis management. Data Management ensures data integrity and transforms raw data into interpretable information, forming the basis for Knowledge Management to generate strategic insights through multidisciplinary collaboration. Adaptive Leadership adds the flexibility needed for ethical decision making and crisis responsiveness. The research's framework illustrates an iterative decision-making process with ongoing data reassessment to address information gaps and refine decisions, guided by the Adaptive Leadership's principles. Role fluidity within NHRM teams highlights the complexity of crisis management and carries the risk of potential role overlap or ambiguity. The domains' interplay supports a unified and comprehensive approach, although their interdependence poses risks, as dysfunction in one domain can affect the overall crisis response effectiveness. Consequently, regular domain reviews and refinements are recommended. This study addresses a gap in literature by providing insights into NHRM teams' strategic navigation of high-stakes scenarios with a data-driven approach, contributing to both academic research and practical crisis management practices.

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