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The Precautionary Principles of the Potential Risks of Compound Events in Danish Municipalities

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The risk of compound events describes potential weather and climate events in which the combination of multiple drivers and hazards consolidate, resulting in extreme socio-economic impacts. Compound events affecting exposed societies can therefore be deemed a crucial security risk. Designing appropriate preparation proves difficult, as compound events are rarely documented. This paper explores the understanding and practices of climate risk management related to compound events in specific Danish municipalities vulnerable to flood hazards (i.e., Odense, Hvidovre, and Vejle). These practices illuminate that different understandings of compound events steer risk attitudes and consequently decisions regarding the use of different policy instruments. Through expert interviews supported by policy documents, we found that the municipalities understand compound events as either a condition or situation and develop precautionary strategies to some extent. Depending on their respective geographical surroundings, they observe compound events either as no clear trend (Odense), a trend to be critically watched (Hvidovre), or already as a partial reality (Vejle). They perceive flood drivers and their combinations as major physical risks to which they adopt different tailor-made solutions. By choosing a bottom-up approach focusing on local governance structures, it demonstrated that the mismatch between responsibility and capacity and the ongoing separation of services related to climatic risks in the Danish municipality context need to be critically considered. The findings highlight that the complex challenge of compound events cannot be solved by one (scientific) discipline alone. Thus, the study advocates a broader inclusion of scientific practices and increased emphasis on local focus within compound event research to foster creative thinking, better preparation, and subsequently more effective management of their risks.

Keywords: compound events, precautionary principles, climate change, risk management, vulnerability, Denmark

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1. INTRODUCTION

On 11 October 2019, the Danish municipality of Vejle was hit hard by an extreme rainfall event (the third extreme rainfall event in Vejle in 2019 according to Butts, 2021). This extreme event (55 mm / day) flooded numerous homes and shops in Vejle city. In addition, Vejle had experienced particularly wet weather conditions in that particular autumn before the event. This had led to a high degree of saturated soil that the rainwater on that day in October could not run off properly and the rivers running through Vejle were flowing over their banks rapidly. As the

weather forecast did not predict such extreme rainfall, Vejle municipality and its affected citizens were overwhelmed by the situation. The rapidity of the rainfall and the already high water levels from the surrounding fjord led to a challenging situation where the authorities were unable to prevent damage by using their existing water-pump systems (Cherry, 2019; Mørk, 2019; Sahl, 2019; Vejle Kommune, 2019). Such a situation can be an example for a compound event. The risk of a compound event consequently describes the likelihood of multiple interacting climatic drivers or hazards, such as heavy rain storm combined with saturated soil, which occurs in a vulnerable environment. They are often resulting in high to extreme socio-economic impacts (Leonard et al., 2014). The conceptual idea of 'compound events' is not a particularly new phenomenon in disaster research and crisis management, as extreme events do rarely happen in isolation. In climate science, however, conventional research approaches were predominantly focused on single drivers or univariate hazards, to narrow research outputs and to reduce the complexity of climate dynamics, overseeing the potential risks stemming from dependent multiple climatic drivers (Zscheischler et al., 2018; Bevacqua et al., 2021).

Due to the very likely rise in sea level towards the end of this century as a result of climate change (Oppenheimer et al., 2019), imposing higher levels of pressure on the overall risk management system, coastal areas can be argued to be especially prone to increased risk of compound events. Designing appropriate precautionary strategies that effectively address compound events is thus of crucial importance for coastal areas. However, it often proves difficult. This can be explained by several factors. First, compound events are rarely documented. That can be explained by the lack of awareness of their mere existence, which leads to both observations and knowledge about future dependencies being incomplete. Second, climate and weather extremes are traditionally modelled as an impact analysis from a top-down reasoning. Different greenhouse gas (GHG) emission scenarios are explored through earth system models, thus following a global to local research approach. Since the hydro-climatic factors in those models are down-scaled to spaciotemporal process scales, the focus of analysis lies on the impact these analysed hazards evoke (Leonard et al., 2014). Because risk assessments within climate science have focused on single drivers that generate multiple impacts, ignoring the possibility of multiple dependent drivers or hazards inducing severe outcomes (Zscheischler et al., 2018, 2020) and often resulting in cost-benefit estimations. The implication of this is that we potentially miss the complex and interacting links between climate drivers and gives rise to the argument that compound events constitute an "underestimated" risk in that down-scaling procedure needs to be closely assessed within climate science (Zscheischler et al., 2018, 2020; de Ruiter et al., 2020; Hao and Singh, 2020).

Risk management is essential to provide guidance for decision making to reduce expected losses and to seize opportunities (Travis and Bates, 2014; Harjanne et al., 2017). The complexity of the interaction of multiple factors in compound events implies that focus should increasingly be on multiple drivers or hazards leading to single outcome extreme events from a bottom-up perspective, instead of tracing single drivers to many outcomes through top-down techniques (Zscheischler et al., 2018). The "precautionary principle" and "benefit-cost analysis" are types of risk management strategies which are frequently discussed in the literature on climate change adaptation and disaster risk management (Mandel and Gathii, 2006; Randall, 2011; Farber, 2015). When there is a potential risk, but there is significant scientific uncertainty, the precautionary principle is applied (Weiss, 1992). The precautionary principle allows for risks to be labelled unacceptable because the consequences if they occur are extreme or irreversible. The "benefit-cost" criterion weights the expected benefits and costs of a proposed action. The benefit-cost criterion does not adequately account for future consequences, which are frequently discounted by economic convention (Reguero et al., 2018). The "present value" of climate change is small if discounted, in particular if the compound event is already happening. Instead, it is important to act upon risks like compound events in an ex-ante manner, to prevent them from escalating to even greater devastating outcomes. However, this precautionary approach proves to be a challenging one, as it aims to justify preventive measures for events that are not clearly substantiated. This is the case for compound events, and it is hard to measure a particular reward for precautionary actions and 'successful' adaption.

This study is centred on empirical case studies, focusing on how precautionary strategies are used within climate risk management approaches by Danish municipalities regarding their perception and application of particular organisational tools to the matter of compound events. As studies regarding adaptation practices to compound events in longer term planning approaches have not been found in recent research, it is puzzling to analyse how and to what extent municipalities practice precautionary strategies and tools for compound events already.

Denmark provides an interesting context to explore how compound events are managed. First, because Denmark is particularly exposed to multiple climate hazard due to its extremely long and complex coastlines (Sørensen et al., 2016). About 80 percent of the population lives in urban areas around the coast, which is particularly exposed to weather and climate related hazards, such as storms and floods (Madsen et al., 2019; Su et al., 2021). Second, Danish municipalities have a great degree of authority to create local climate adaptation plans from a municipal perspective (Hoff and Strobel, 2013). Since 2014, Danish municipalities ("kommuner"), are required to create climate adaptation plans by law (Danish Nature Agency [DNA], 2011, 2012). Consequently, it has a wide application of climate adaptation strategies across its 98 municipalities, where each one has developed its own climate adaptation plans (Jensen et al., 2016). Additionally, the EU Floods Directive (2007/60/EC) required that specific municipalities at high risk must actively engage in and contribute to reducing the risk of floods by 2015. This development largely transferred the responsibilities of climate adaptation and flood risks to the municipality level (Lund, 2018; European Commission [EC], 2019). Yet, the question of to what extent the preparation of the population for such an occurrence of compound events poses a complex management problem to the present day is so far an

under-researched topic within the current Danish adaptation and risk management strategies.

In the area of compound flooding events, many scholars have focused on the relationship of compound drivers on flood risk, especially looking at the colliding variables of storm surge, precipitation, and sea and/or river water (van den Hurk et al., 2015; Bevacqua et al., 2017, 2019; Zscheischler and Seneviratne, 2017; Ward et al., 2018; Ganguli and Merz, 2019; Couasnon et al., 2020; Poschlod et al., 2020; Raymond et al., 2020; Ridder et al., 2020). The complexity of the interaction of multiple factors in compound events implies that research should increasingly focus on multiple drivers or hazards leading to single outcome extreme events from a bottom-up perspective, instead of tracing single drivers to many outcomes through top-down techniques (Zscheischler et al., 2018). This implicates the affected stakeholders and their role before, throughout and after a compound event become a focal point of analysis. Thus, this study concentrates on the long-term planning of risk management approaches and thus focuses on governing bodies which handle climate change adaptation strategies in particular. Through expert interviews of civil servants of the selected municipalities supplemented with document analysis, this study aims to explore the dynamics of current climate risk management tools. As the topic of compound events comprises a wide complexity, this study focuses on the aspect of physical processes related to natural risk factors within compound events, such as rain, storm, or sea level rise (SLR), solely regarding societal risk factors, such as, e.g., the current Covid-19 pandemic, to a limited extent. Thus, its objective is to provide qualitative and empirical insights into a complex and theoretical debate, to contribute to future robust climate change adaptation planning.

2. RISK MANAGEMENT TOOLS

2.1. Climate Risk Management Theory and Tools

The risk lens allows compound event research to focus on the perception and practices of decision-makers whose aim it is to ensure security for their citizens. The aim of risk management in general is to reduce potential loss or to develop opportunities through a forward-thinking technique. This management strategy can provide a precautionary stance towards potential dangers and surprises in a complex world. In respect to compound events and their impact on society, climate risk management can be seen as an approach to find solutions to that challenge by decreasing the risk. Here, climate risk management is defined as "a process for incorporating knowledge and information about climate-related events, trends, forecasts, and projections into decision making to increase or maintain benefits and reduce potential harm or losses" (Travis and Bates, 2014). Therefore, this lens on the practice and decisions within this approach rationalises the focus of this study on central decision-makers at local management level in this study and their decisions regarding their risk management strategies of compound events.

In general, risk can be approached as risk avoidance (not doing anything), risk acceptance (knowingly not doing anything), risk transfer (transferring risk to another entity, e.g., through insurance), and risk minimisation (reducing the risk) (Blyth, 2008). Within climate risk management, the latter is often applied through a 'no regret principle,' meaning to adopt measures no matter whether the natural hazards actually manifest themselves (Hellmuth et al., 2007). This approach is closely connected to the idea of the precautionary principle as well as to adaptive planning for challenges associated with global warming. In particular, climate change adaptation strategies tend to focus on decision-making approaches which provide relevant knowledge, management capacities, monitoring, evaluation, and learning procedures that provide the necessary means to anticipate and adapt to long-term climate risk (Thomalla et al., 2006). Yet, it also includes reactionary aspects based on past events and current events, touching upon the practices of disaster management.

This research on compound events positions itself between both climate change adaptation and disaster management, as it is defined as an extreme event with high impact which leads to the handling of a crisis. It primarily describes a natural hazard impacted by climate change and has elements to treat it as a forward-looking risk, as it has limited historical data. On a theoretical level, this classification does not provide a particular challenge as compound events can be seen from the climate risk management perspective. On practical levels, however, looking at an applied case of Danish society, the classical services of univariate hazards are still present in the related agencies. Due to the emphasis of this study towards more long-term planning of uncertain future developments, compound events, and their risk management are placed on climate change adaptation planning and its relevant stakeholders within the chosen Danish municipalities.

In the context of climate risk management, the handling of risks can be ideally visualised through a "planning circle" of risk management practices, such as shown in **Figure 1** (Vincent and O'Mahoney, 2021). The Danish municipalities' handling of the risk of compound events display a process which is not steered into a direction of how exactly it needs to be managed on a formal level. Although their application of risk management is context specific, it can be seen as a process which builds upon and enhances the risk management planning circle. Thus, the overall practice of risk management needs a push factor to start the process. In the analysed Danish municipalities, for instance, it has commenced through either a critical event, which showed compound indicators, or a legislative need [e.g., the EU Floods Directive (2007/60/EC)].

First, the process starts with the identification of climatic risk factors, for example, mapping what the major and minor risks are and considering temporary and spatially overlaps of these risk factors. In this step, decision making criteria can be mapped and other non-climatic risk factors (e.g., dense urbanisation) can be included. Secondly, this is followed by the step of assessing the risk through monitoring, analysis and estimation and setting them into the context of the vulnerability of the analysed area, considering the set vulnerability threshold and incorporating recent climate science. Thirdly, this is followed by evaluating

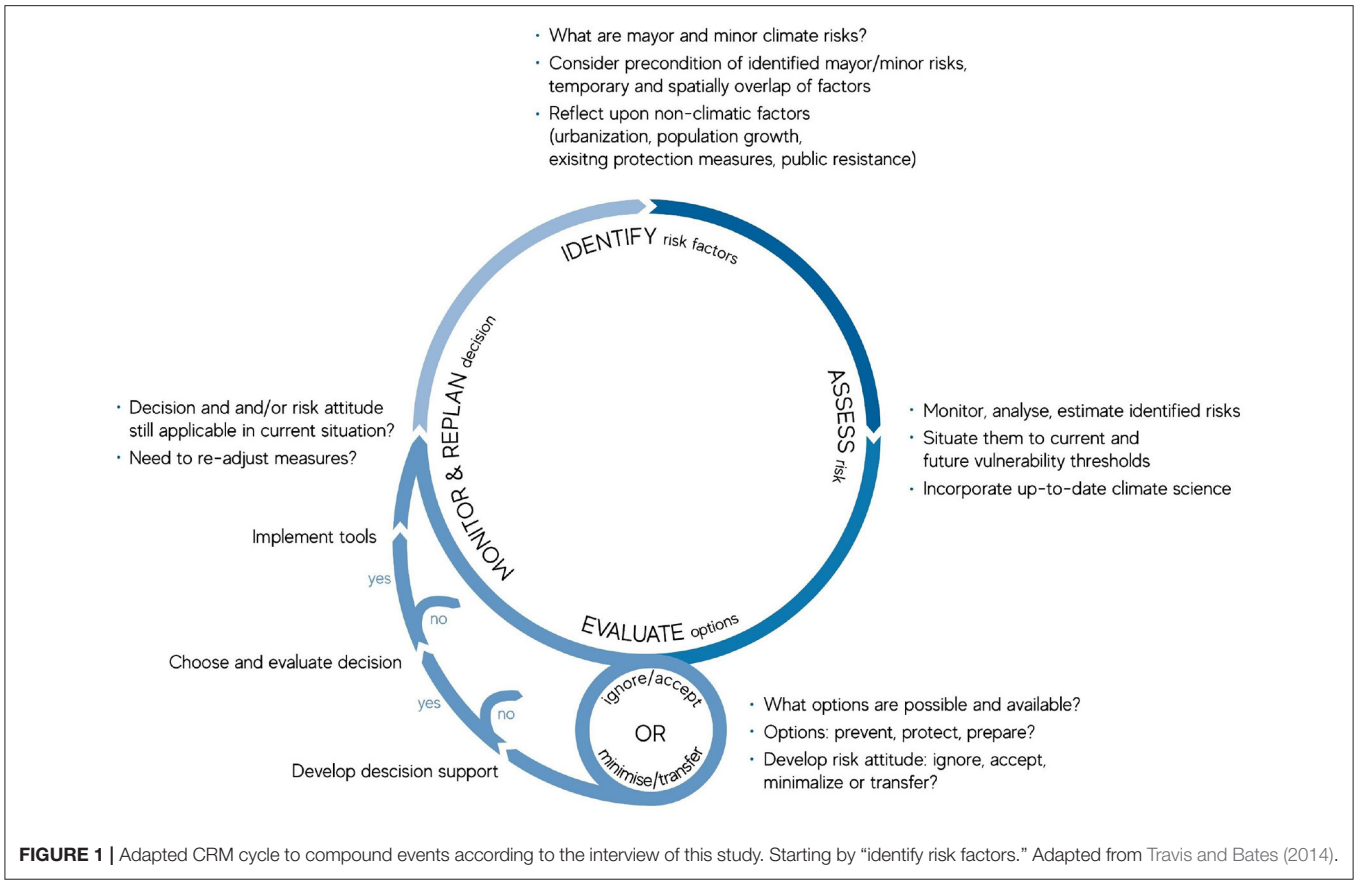

FIGURE 1 | Adapted CRM cycle to compound events according to the interview of this study. Starting by "identify risk factors." Adapted from Travis and Bates (2014).

the options which are possible and available. These can include strategies to prevent, protect or prepare society for the identified risk. As a conclusion of this step, a risk attitude has evolved which either leans towards stances of ignoring and/or accepting the risk or minimising the risk and/or transferring the impact to other entities. If the former stance of risk acceptance and ignorance is chosen, the cycle continues to the last general step, labelled monitoring and re-planning. This last step displays the action of continuously assessing the risk factors and initiating a re-organisation of measures if needed. Yet, if the option has been chosen to minimise the risk or transfer it, the overall climate risk management circle has been added with another layer within the side-circle which leads to a step of developing decision support. After a positive response, the decision path is followed by choosing and evaluating the decision. Further, the appropriate tools are implemented which can be related to measures of information, authority, finance and/or organisation. This second layer leads back to the last step in the circle, which is monitoring and re-planning. Conclusively, the cycle implies constant communication around the risk between the managing entities and impacted stakeholders.

2.2. NATO Approach

Zooming in to one of the last steps of the "planning cycle" described above, and to the general level of organisational practice, the focus on organisational tools guides the study to detect the instruments informing a risk management strategy within local management practices regarding compound events. Fundamentally, each organisation manages its objectives through certain measures, such as instruments or tools. Bemelmans-Videc et al. (1998) examine various (policy) instruments in different contexts and categorise them in a broad scheme. Policy instruments, also referred to as government tools, can be understood as the application of techniques to how public authorities exercise their power to achieve their goals and to initiate social change. These instruments are thus linked to a power-dynamic, as specific tools have particular effects ranging from coercive to soft assertiveness (Ali, 2013).

Overall four general categories of organisational instruments can be identified within the literature. Hood et al. (2007) developed the so called NATO-approach of instruments, on which Bemelmans-Videc et al. (1998) based their scheme. It describes measures of nodality (N), authority (A), treasury (T), and organisation (O) as way of describing how governing bodies affect society. Nodality is primarily understood as the way objectives are translated through information sharing and receiving, such as research and surveys. Authority is translated as legal controls through, e.g., regulation, laws, and official monitoring. Treasury relates to instruments of financial character, like loans and grants. Organisation explains the creation of an organisational entity which builds decision capacity, providing a specific service or task (Hood et al., 2007).

These categorisations of tools are generally used to capture dynamics of power by central actors and evaluate good practices to specific policy or risk situations (Collins et al., 2003; Bax, 2011; Filatova, 2014).

For this research, the above NATO-approach is used to uncover the climate risk management practices in the chosen municipalities, such as Hvidovre, Odense, and Vejle. In particular, it aims to uncover the extent to which the precautionary principle is practiced in the context of compound events in specific Danish settings. The precautionary principle highlights the opportunity to act within uncertain situation with potential risks. Compared to scientific decision making strategies, or cost-benefit approaches, precautionary climate risk management aims to anticipate uncertain risks which are not situated in an environment where risk factors can be determined and of which probabilities can be created (Stirling, 2007). Essentially, the precautionary principle can be a way of governance which includes uncertain and ambiguous future risks (Diprose et al., 2008). By revealing the applied strategies and tools, practices can become visible of how local governance structures in specific municipalities in Denmark reduce highly complex and uncertain situations to tangible action, such as in the example of compound events.

3. EXPERT INTERVIEW AND DOCUMENT ANALYSIS

This study comprises a case study of three Danish municipalities by means of semi-structured expert interviews and document analysis. A bottom-up approach is suggested for compound event research as it has the advantage of taking related factors from the perspective of each specific system into account, while paying due diligence to all potential factors which might be significant to the particular community (Leonard et al., 2014; Wahl et al., 2018; Zscheischler et al., 2018). This approach is translated to risk management at the municipal level, to increase the understanding of the development of precautionary strategies to compound events by civil servants in the local government. Civil servants are pointed out as central stakeholders on a sub-level, as they can be seen as local experts for the specific environment, substantiated by their responsibilities for assessing those risks.

3.1. Case Selection

Aiming to entangle the practices involved in climate risk management, a qualitative and in-depth study approach was chosen in the three Danish municipalities, Hvidovre, Odense, and Vejle. Out of 98 municipalities, they were chosen on the basis of "paradigmatic" sampling (Flyvbjerg, 2006). Paradigmatic sampling is described as pointing out general features and indicators of the specific society of the research focus (Flyvbjerg, 2006). This means that the cases are assumed to be a prototype for both the occurrence and management of compound events in a specific geographical context. Selecting these kinds of "prototypes" aims to increase the understanding of the emerging processes. However, it is not particularly easy to find predetermined selection criteria for paradigmatic case studies, as the case "transcends any sort of rule-based criteria" (Flyvbjerg, 2006). Paradigmatic sampling is thus not oriented towards a random selection of cases but follows an information-oriented selection process.

The overall criteria for choosing the cases needs to be based upon the expectation that the selected municipality is actively engaged in preparation for climate and weather related hazards. As each municipality in Denmark has to provide its own climate change adaptation plan by law since 2014 (Jensen et al., 2016), the legislative basis for having an appropriate plan can be ensured. In addition, the connected risk assessments to the EU Floods Directive (2007/60/EC) required ten risk areas in Denmark to prepare more concrete risk management plans in connection with flooding (Jebens et al., 2016). This has been updated in 2018, extending the old and adding new flood risk areas. These zones can be assumed to have particular experience and knowledge of risk management planning for natural hazards, focused on flooding. Additionally, the classification through the EU Floods Directive (2007/60/EC) also suggested that the appointed areas are particularly vulnerable to natural hazards, so that the stakeholders have particular reason to care about the risk of compound events (Jebens et al., 2016). Moreover, the precondition that these municipalities were not otherwise interdependent nor close to each other should be met. Here, an attempt was made to choose municipalities who are not particularly close to each other in neither an administrative nor geographical sense. Additionally, a couple of practical considerations played a decisive role. The municipalities were chosen who had previously expressed their need for more information related to compound events in past projects operationalised by the Danish Meteorological Institute (DMI), such as in the COHERENT (https://www.coherent-project.dk, Halsnæs and Kaspersen, 2018), CoDeC project (Madsen et al., 2019), and ClimateAtlas project (Su et al., 2021). This particular need was considered a motive for the willingness of municipalities to be interviewed. This was supported by pre-research studies at the DMI (Madsen et al., 2019), which identified meteorological dynamics in Denmark, suggesting that longer heavy rain periods followed by storm surges (Madsen et al., 2015) and the sea water level in connection with sustained rain during flood events (Madsen et al., 2018) are crucial trends to be further observed in future research.

3.2. Data Collection and Analytical Strategy

During the months of October and November 2020, 9 single interviews and 1 group interview were conducted via online video-call conferences. The interview participants were selected on the basis of seniority and relevance within and to the municipality, to receive a well-informed opinion about the current local practices. All interviewees, having multiple years of experience in climate adaptation and (flood) risk management, participated on a voluntary basis. In particular, the interviews were held with appointed civil servants in the fields of flood risk planning and climate adaptation of each municipality. In addition, other representatives were interviewed, such as from the Kommuners Landsforening (KL), which is an interest organisation of Danish municipalities, and from the

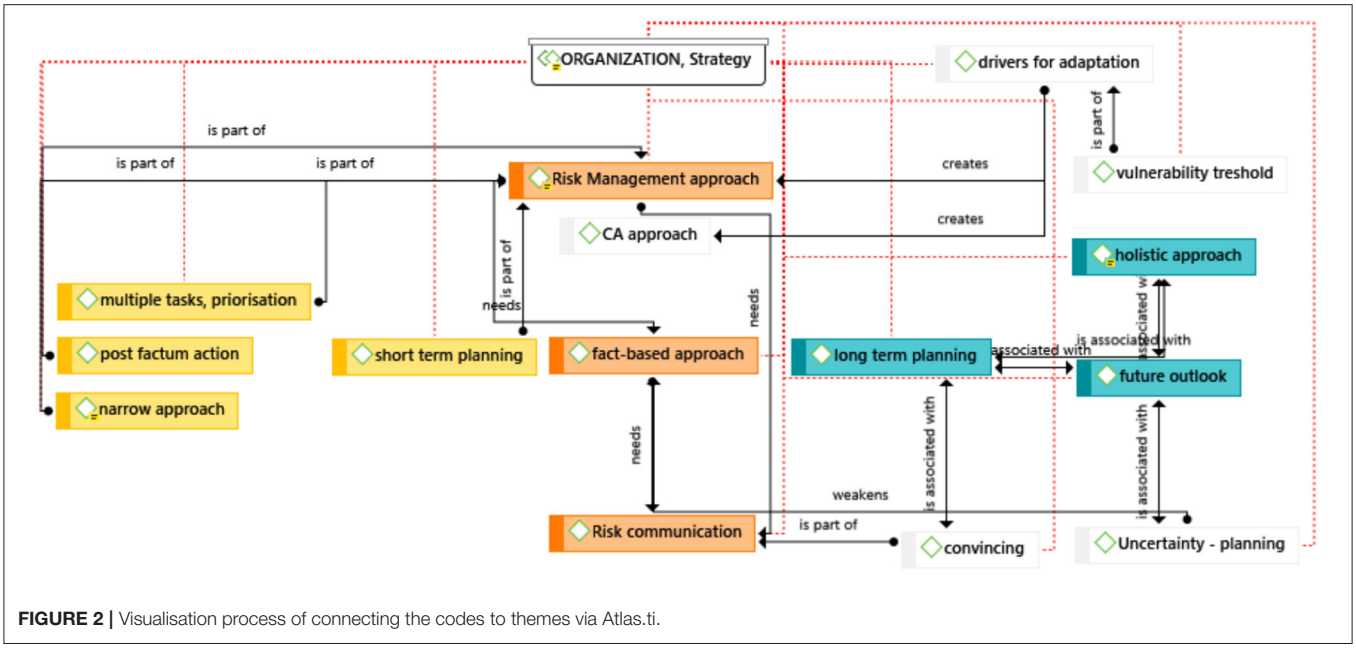

FIGURE 2 | Visualisation process of connecting the codes to themes via Atlas.ti.

Kystdirektoratet (KDI), the Danish Coastal authority, which is in close cooperation with the municipalities, where both institutions play a vital mentoring role for the municipalities. A sample of the interview guide can be reviewed in **Supplementary Material**. This has been supported by a document analysis of related primary sources published by the municipality, centred on reviews of climate adaptation plans, policy action reports and flood risk assessments which were available and in use in autumn 2020. After conducting the interviews, they were transcribed, open-coded and labelled (supported by ATLAS.ti), which has been backed by the supplementary primary sources of the municipalities. Through a visualising procedure (**Figure 2**), themes have been established, which are used as categories to guide the analysis.

4. RESULTS

The context and practices of the analysed municipalities of Hvidovre, Odense, and Vejle are described from a general standpoint, followed by linking it (if mentioned) to the specific handling of compound events.

4.1. Municipality of Hvidovre

The municipality of Hvidovre is located by the Køge bay in the south of Denmark's capital city Copenhagen (**Figure 3**). With its total area of around 23 square kilometres, it is home to a little more than fifty thousand people and a population which doubled in the last 70 years (Danish Statistikbanken, 2020a,b). Its citizens live in close proximity to water, such as from the Køge Bay, leading to the Baltic sea, the waters of Kalveboderne, and the river "Harrestrup Å" (**Figure 4**, upperleft panel).

The greatest physical risks in Hvidovre are perceived to be coming from inland flooding, originating from heavy rainfall such as cloudbursts which can also lead to overflow of the river Harrestrup Å, and storm surges, coming predominately from the Kalveboderne area. Additionally, the SLR is seen as another risk factor in the long run which can potentially amplify storm surges. Hvidovre is regarded as vulnerable because of the increased urbanisation of the municipality which does not leave much room for natural draining in the case of flooding. This means that the water is coming faster down the stream, as a lot of area around the river is paved. Since houses and infrastructure are close to the water, one of the interviewees explains: "We have basement floors in houses, 2 m from the stream. That is 2 m below the sea level, and it is absurd to build those places, but no one thought it out fifty years ago" (**Table 1** Interview HK I). This reflects the fast pace of urbanisation which created the high alertness in that area where floods occur on a regular basis. The most important impact seems to be the flooding of houses and infrastructure. Recent flood incidents forced people to leave their homes and move away to other municipalities (**Table 1** Interview HK I; Interview HK II).

Hvidovre's experience with compound events is described as being linked to a combination of heavy precipitation, which fills up the river Harrestrup, and increased sea level or a storm surge. Such a compound event was described as "nearly" happening at the end of September 2020, when around 70 mm of rain was forecasted with a simultaneous half metre higher sea level than usual (**Table 1** Interview HK I). Yet, the amount of rain turned out to be less than predicted and the water levels from the river did not peak at the same time as the sea level was at its highest point, leaving a time lag of about 1 h. The risk of a compound event in Hvidovre is understood as a compound flood from rain and storm surge, or saturated soil and rain, overflowing the river and pressing water from the sea and ground. Thus, this event has left the impression on the municipality to feel the urgent need to be prepared for an eventual realisation of such a compound event (**Table 1** Interview HK I; Interview HK II).

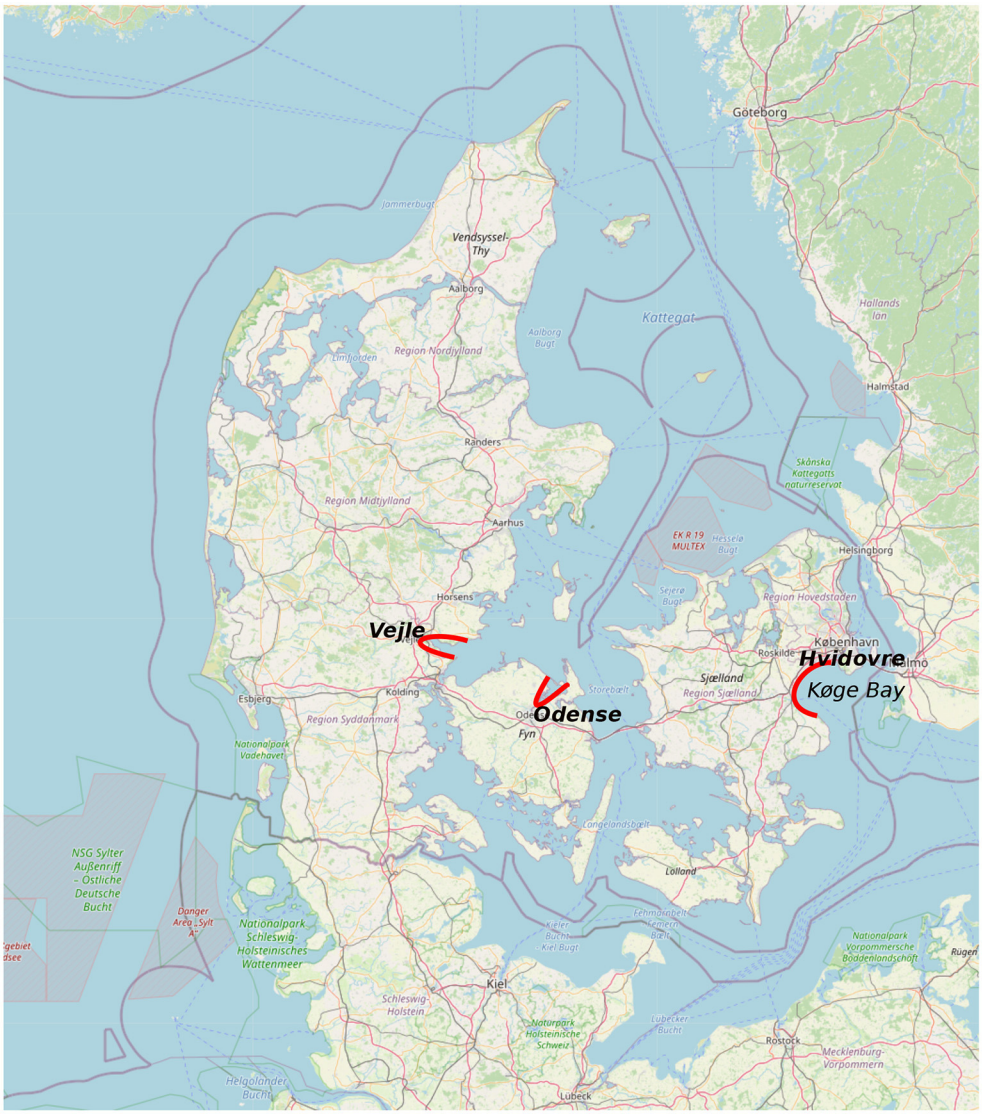

FIGURE 3 | Map of Denmark with the three risk areas (red) appointed by the EU Floods Directive (2007/60/EC) in Jebens et al. (2016). The locations of three interviewed municipalities were shown in bold text. Base map and data from OpenStreetMap and OpenStreetMap Foundation under the Open Database License.

4.1.1. Strategical Approach: Thematic Planning Approach

The translation of the strategic orientation towards more concrete actions is made via specific tools, the NATO-framework of organisational tools (see section 2.2). Starting with the use of nodality instruments, Hvidovre's approach to risk management has been connected strongly to the strategy of convincing others to initiate climate adaptive measures. This points towards the direction that information gathering, and dissemination are tools often used. In cooperation with other surrounding municipalities, increased awareness of risks has been established through the modelling of the stream and data collection at certain points along the river Harrestrup Å (https://harrestrupaa.dk/). Hvidovre is also part of the knowledge sharing and mainstreaming initiative DK2020 (Realdania, 2020a). This initiative promotes the development and upgrade of climate adaptation plans of some Danish municipalities to be in line with the Paris Agreement of 1.5°C and to adjust their plans nationwide to the same standards (Realdania, 2020a). Internally, information about physical risks is shared by aiming to inform other departments besides the environment section, to include climate adaption strategies in their daily work. Also, externally, information is shared through brochures and reports with the citizens, although they could be increased in scope, according to an interviewee (**Table 1** Interview HK II).

With regards to measures taken related to authority, Hvidovre has only restricted capacity to limit the risk of water overflow via technical solutions, as space is rare to build higher walls than 1 m due to SLR. The municipality employs most of its tools related to authority in emergency situations, when it decides to put pumps

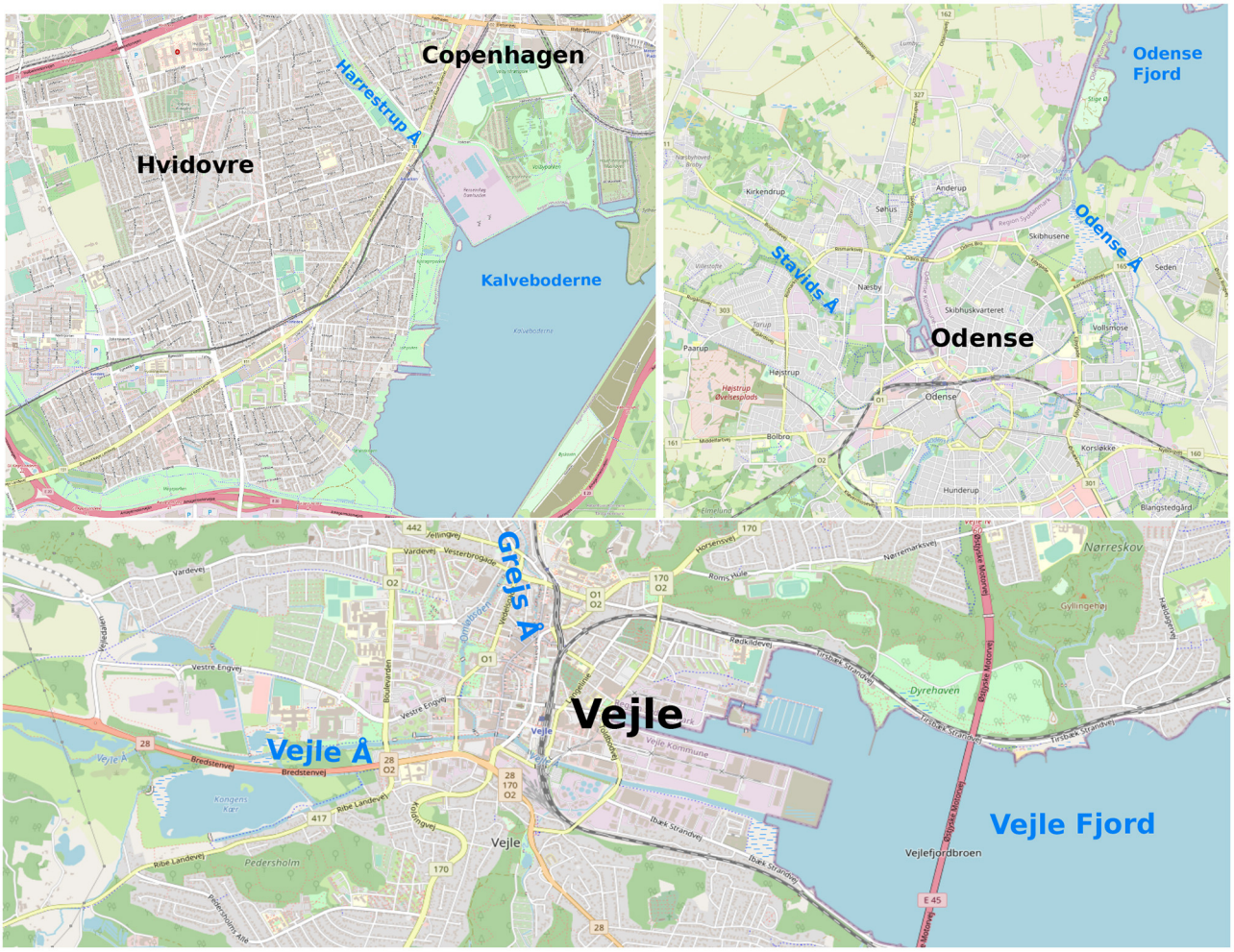

FIGURE 4 | Map of three interviewed municipalities in Denmark. Upperleft panel: Municipality of Hvidovre; expected compound events of inland flooding from Harrestrup Å and storm surge from Kalveborderne. Upperright panel: Municipality of Odense; expected compound events while inland flooding from Stavids Å and Odense Å meeting with storm surge from Odense Fjord. Bottom panel: Municipality of Vejle; expected compound events while inland flooding from Vejle Å and Grejs Å meeting with storm surge from Vejle Fjord. Base map and data from OpenStreetMap and OpenStreetMap Foundation under the Open Database License.

into the river and limit the movements of people. It has the control to react upon forecasts and initiate preventive measures. In a more long-term perspective, Hvidovre Municipality uses the risk management plan and the climate change adaptation plan to set binding measures to handle risks. However, compound risks are not yet particularly mentioned in the overall guidelines but put into the revision of the flood risk management plan for 2021 which concludes that the topic has not reached the priority of putting it into official plans at the current date (Hvidovre Kommune, 2014, 2020).

The use of treasury tools which represent the financial capacity of Hvidovre to be spent on risk management measures can be described as limited as "there is not really some government financing for anything" (**Table 1** Interview HK II). The financing of climate adaptation projects is closely linked to the willingness of individual politicians to invest into certain projects, external funding from foundations or the EU, and subject to HOFOR, which is a supply company partially owned by the municipality around Copenhagen, or the landowners themselves. Therefore, financial tools closely related to the handling of compound events have not been found while analysing the handling of compound events.

Within the realm of the instrument of "organisation", which describes a specific task force to deal with risks, Hvidovre's environmental department organises itself internally into 2 sections. One section designs the overall plans and the other makes the concrete projects which closely work with each other. Additionally, Hvidovre outsources its organisational capacity to consultants and sewage companies which can be partially explained by its small size. Also, locals are included into the decision process of risk management, such as in the creation of local plans, like for example the cloudburst plan (Hvidovre Kommune, 2020). Furthermore, Hvidovre seems to work within the department silos, when it comes to climate

TABLE 1 | Participants of interview.

Role	Organisation	Date	Reference
Special consultant, Plan & Environment Department	Hvidovre Kommune	Oct.2020	Interview HK I
Head of Department, Plan & Environment Department	Hvidovre Kommune	Oct.2020	Interview HK II
Environmental and Climate consultant, Water management	Odense Kommune	Nov.2020	Interview OK I
Environmental project manager	Odense Kommune	Nov.2020	Interview OK II
Leading consultant, Technology & Environment Department	Vejle Kommune	Oct.2020	Interview VK I
Consultant, Technology & Environment Department	Vejle Kommune	Oct.2020	Interview VK I
Climate coordinator	Vejle Kommune	Nov.2020	Interview VK II
Coastal Technical Manager	KDI	Nov.2020	Interview KDI I
Coastal Technician	KDI	Nov.2020	Interview KDI II
Chief consultant, Centre for Climate and Business	KL	Nov.2020	Interview KL

adaptation and related risk management, as the emphasis on convincing other departments of their flood preparedness shows. Externally, Hvidovre works with various cooperation projects in the surrounding municipality, such as the "maturing project" planned together with Copenhagen which aims to secure the southern area of both municipalities' against storm surges (Realdania, 2020b).

Generally, Hvidovre's strategical approach to climate risk management is to stick to thematic planning of specific origins of flooding, such as management plans for cloudburst or storm surges. Hvidovre Municipality follows a strategy of risk minimisation to protect its citizens from the risk of SLR up to 1 m higher than today (**Table 1** Interview HK I). Due to the size of the municipality, the team dealing with the issues of the environment is relatively small. That requires setting priorities and a lot of their daily work involves explaining and convincing the risks and consequences to other departments or politicians. It is pointed out that the problem is not informing people about the issues related to compound events, but rather making their concerns heard in the pool of other risks (e.g., the current COVID-19 pandemic). One interviewee explained that they feel like being "party crashers" in the municipality context, as their work on environmental risks does make them feel like crashing the plans of their colleagues by reminding them of the possible dangers (**Table 1** Interview HK I). Hvidovre pushes for a fact-based policy, meaning that their strategy is based on data and facts to push for solutions, because they "don't act unless they are sure that there is a problem" (**Table 1** Interview HK I). One interviewee mentioned: "we need some smaller flooding, like every 5 years or something like that, to not forget what the problem is" (**Table 1** Interview HK I). This 'refreshed memory' is proposed to create more long-term thinking among the population and to increase financial support for concrete projects. However, this need is titled as "absurd" as this is actually what is trying to be avoided (**Table 1** Interview HK I). Much action and support has been reported by the interviewees to happen after major events, such as floods in 2011 and 2017, or the intense cloudburst in Copenhagen in 2011, which initiated concrete actions after severe impacts happened (**Table 1** Interview HK I; Interview HK II). There is a high demand to solve issues as fast as possible, which puts the Hvidovre Municipality in a limited position to plan its action in a more holistic and long-term strategic approach. A forward-looking and precautionary approach to managing potential climatic risks like compound events is, however, desired to be established, to be better prepared for uncertain future developments (**Table 1** Interview HK I).

4.2. Municipality of Odense

The Municipality of Odense is located in central Denmark, on the third largest island of Funen. It has an area of around 305 square kilometres and around 205 thousand inhabitants (Danish Statistikbanken, 2020a,b). Its biggest city Odense is the third largest city in Denmark. It is positioned close to the Odense Fjord which adjoins the Kattegat sea area in the north. The river Odense Å and Stavids Å flow through the municipality, ending in the Odense Fjord (**Figure 4**, upperright panel).

Odense Municipality is primarily exposed to cloudbursts and storm surges from the fjord, which are currently perceived and managed as separate hazards. Odense has been hit by occasional floods, of which the last one happened in 2006. The storm "Bodil", which seriously hit the North Zealand of Denmark (where Copenhagen located) in 2013, was mentioned repeatedly as an event that had an important effect on Odense as well. As it was only closely spared, the wind direction "only" initiated a 60-year flood event (Odense Kommune, 2021c). Compared to the other selected municipalities in this study, the vulnerability of the discussed area is perceived as relatively low, as the surroundings of Odense Å and the Fjord are not densely populated. Therefore, the major risk related to physical hazards is estimated as floods originating from either rain or storm surges, but their likelihood is perceived as low since it is "Sometimes [. . .] getting very wet, but it doesn't really do damage" (**Table 1** Interview OK II). Yet, the municipality has established high protection arrangements as vulnerability thresholds. For example, water coming from the fjord, from which all buildings and infrastructure need to be protected against 2,5 m, and from rain, where 90 mm of rainwater within 4 h must be handled.

Regarding the matter of compound events, no concrete experience has been linked by the interviewees to a compound event in the past in Odense. But the potential for high-water levels in the river through rain and simultaneous matching high-water levels from the fjord is acknowledged to have the potential for

such a compound event (Odense Kommune, 2021c). The lack of concrete facts and predictions is perceived to limit action and financial support. Additionally, the rarity of particular extreme events in recent memory is seen as challenging, as Odense is described as "in a lack of grand giving events" (**Table 1** Interview OK I) to create immediate action. Therefore, the risk attitude can be described to be one of risk acceptance. As Odense Municipality is aware of existing developments of combined effects but so far has not experienced them, it has the attitude that there is only a limited need for immediate action. However, a precautionary stance should be applied as one of the interviewees described the situation of the municipality as: "We are actually lucky" (**Table 1** Interview OK I) to not have been hit by any particularly severe events (**Table 1** Interview OK I; Interview OK II). This precautionary stance is also applied in the project targeting climate neutral 2030 (Odense Kommune, 2021a).

4.2.1. Strategical Approach: Cooperative Approach

To translate their overall risk management approach, the Municipality of Odense uses different practices to transform their strategies into action. A major driver for focusing on physical hazards, particularly floods, has been the appointment through the EU Floods Directive (2007/60/EC) of Odense Municipality as a risk area and another EU funded project on sustainable urban development (**Table 1** Interview OK II). Starting with the tool of nodality of the NATO-framework of instruments, the municipality initiated research on modelling the nature, particularly started to monitor the real-time developments of the water in the fjord and rivers. Furthermore, it uses information sharing techniques to notify residents about certain flood risks to create awareness among landowners. Also, through public hearings on specific problems, information is received to include local knowledge in the decision-making process. For this purpose, Odense created its own website which actively encourages its inhabitants to report and get information on flood preparation (**Table 1** Interview OK I; Interview OK II).

Regarding the use of authority tools such as legal controls or technical solutions initiated through the power of the municipality, Odense has established sluices and special water corridors where protection measures are applied to prevent high impact events. Additionally, in the case of an emergency, it has the authority to decide when to start evacuating, use tubes or put sandbags into crucial infrastructure. Consequently, authority measures are used in more concrete situations of emergency or in technical and engineering solutions, which leaves the room open for the potential occurrence of compound events (**Table 1** Interview OK I; Interview OK II).

The financial capacity of the municipality of Odense and its use of treasury tools for risk management strategies is relatively limited. It was described that the EU funded project mentioned above pushed for the possibility to create appropriate climate adaptation projects and to create an internal awareness of their importance (Interview OK II, 2020). Furthermore, the willingness of public spending on climate adaptation is seen as lacking. Frustration over this was expressed by one interviewee that while for the COVID-19 pandemic, around "500 billion Danish kroners [were found] to help them out" (**Table 1** Interview OK II), no money has been granted to their plan related to climate adaptation projects.

Lastly, Odense practices, particularly tools of organisation, which describe a governing body that can actively interfere in the decision-making process. Internally, Odense Municipality just recently created a group called 'climate ready' (translation by the interviewee) which consists of one person from each department (**Table 1** Interview OK I). Still in the silos of the departments, but consciously chosen due to the strength of knowledge and task distribution within the silo-structures, the group discusses important water and climate management strategies on a regular basis. This approach is seen as an important step, as it makes "people who normally don't think they are involved in climate adaptation just say, okay, maybe it looks fascinating" (**Table 1** Interview OK I). Odense Municipality can therefore be regarded as following a holistic approach towards risk management that links various aspects of daily life and themes into one coordination, which can be an advantage in cases of complex events such as compound events with high impact.

The overall strategical approach by Odense Municipality is to employ a cooperative approach. They function as a facilitator of initiating and involving all landowners, either with private property or for commercial purposes, "to do the right thing" (**Table 1** Interview OK II) together. However, this process is hard to manage due to the limited intense experience with physical hazards in the recent past (**Table 1** Interview OK II). Politicians seem to prioritise other pressing problems, such as schools or nurseries, rather than climate related issues. It is argued that it would actually be cheaper to implement certain projects now as costs might be much higher later with no action, indicating the need for more precautionary actions (Odense Kommune, 2021b).

4.3. Municipality of Vejle

Vejle municipality is located on the south-western side of the Jutland peninsula, bordering the little belt area and the Kattegat sea. It has a little more than 115 thousand inhabitants, living on 1058 square kilometres, of which most people live in Vejle city (Danish Statistikbanken, 2020a,b). The major streams running through the municipality are Grejs Å and Vejle Å which created the stream valley where Vejle city is located, ending in Vejle Fjord (**Figure 4**, bottom panel).

The major physical hazards in Vejle are perceived to stem from too much water and the increase of sea level. As its most vulnerable parts such as Vejle city are closely built to the fjord and the rivers, the municipality frequently experiences floods from river runoff, heavy rain, and storm surges. As the river Grejs Å is flowing downhill to Vejle, the river levels can increase very quickly and potentially impact houses and infrastructure to a critical extent. Vejle is regularly challenged by flooding as the increased urbanisation of the area hinders the water from running off in its natural patterns. Vejle describes itself as being someway always hit by compound flooding events. One interviewee explained that "down here, it is somehow every time a combination" (**Table 1** Interview VK I). They understand compound events as heavy precipitation which increases the river water level and coincides with a high tide from the fjord.

Additionally, another compound effect was described as temporary cascading intense rain events. That set the soil in a position of being saturated and even smaller rain events increase the likelihood of floods, as the water cannot be absorbed by the earth as usual. Both in autumn 2019 and spring 2020, such a combination of the effect of heavy rain and increased water levels in the fjord and rivers created a considerable impact, as described in the introduction of this study (**Table 1** Interview VK I; Interview VK II).

4.3.1. Strategical Approach: Practical Approach

The application of the risk management approach from Vejle municipality is practiced through various tools. Beginning with the instruments related to information, the municipality is conducting some research themselves by analysing their water-system and monitoring their streams and precipitation, to increase their understanding of the whole water cycle. Thereby, they also look into past events and research where the water has been and in what ways it has moved. Additionally, Vejle is providing information about particularly vulnerable flood areas for developers to take into account while creating new housing or infrastructure. Furthermore, Vejle includes many voices, such as from local citizens through regular meetings, to collect local knowledge about physical drivers and their combinations. It is the goal that the affected population be encouraged to share their experiences, which can be used to design better risk management strategies (**Table 1** Interview VK I; Interview VK II).

Tools related to authority can be found through technical control and legal power to close the sluices, build barricades and direct the water into different streams to stop the water coming in. Moreover, through the creation of their risk management plan, the climate adaptation plan, the 100 resilient cities, and the upcoming DK2020, Vejle created a considerable network of various official planning instances pushing towards increased climate adaptation, risk management, and security/safety actions of the municipality. Thus, with the ability to urge new construction areas to include the consideration of waterways, catchment and other flood protection mechanisms, Vejle municipality is attempting to extend their authority to more areas of climate adaptation planning and execution within city planning (**Table 1** Interview VK I; Interview VK II).

With regards to financial tools, Vejle municipality can be assessed as having a considerable capacity to finance their projects, as one interviewee explained that "the municipality has paid most of this" (**Table 1** Interview VK II), describing past protection methods against floods. Sometimes, the partially municipality owned sewage company Spidevand Vejle or certain building companies contribute to climate adaptation projects as well. This provides Vejle with an increased capacity to act upon urgent major hazards, enabling them to use other tools such as more research, which compound events need increased special attention (**Table 1** Interview VK I; Interview VK II).

The tool related to organisation exists in Vejle in the form of its own team within the environmental department for emergency matters. This group watches the water developments and is responsible for making decisions if the forecasts are predicted as critical. Outside the short-term decision making of emergency planning, Vejle is currently undergoing a structural re-organisation which describes that "climate is more in focus and we have to get it into all our departments" (Interview VK II, 2020). Additionally, Vejle municipality participates in various external co-operations, such as in networks with other municipalities like Kolding, to exchange information on risk management practices. Yet, as their system is relatively unique, they "work in [their] own bubble" (**Table 1** Interview VK I), and thus use their own approaches and skills to risk management. That shows that Vejle rather focuses on its own handling than outside cooperation for risk minimisation. Therefore, Vejle can be seen as a front runner in climate risk management through its progressive approach to overall risk management of (compound) flood risks that employs a holistic approach (Vejle Kommune, 2014).

Overall, considering Vejle Municipality's strategical orientation, it can be described as having a particularly practical approach to its risk management of floods because of its relatively frequent exposure to them. According to specific sea, river and rainfall levels, the municipality reacts with respective action steps on what to do. However, it is described that the current national forecasts, especially for rain, are regarded as not particularly precise and solely available on rather large scales. For local management planning, it can be of significance to have data from local scales as smaller processes are currently not captured, which might be relevant for compound events. Yet, authorities try to combine the opportunities water can bring with its protection and safety measures. Generally, they work very closely with the population and related stakeholders, to initiate a process of problem-solving through many different perspectives and skills. An emphasis is put on the aim of following an approach of "[...] bottom up and not the top down" (**Table 1** Interview VK II), focusing on integrating the population. The overall planning strategy is steered by looking at past impacts, identifying where problems exist today and what potential future scenarios of climate change projections could bring. After assessing those perspectives, priorities have been set on what issues and areas projects should be started (Vejle Kommune, 2021).

5. DISCUSSION

5.1. Comparing the Three Municipalities

As argued above, the risk of compound events describes potential weather and climate events in which the combination of multiple drivers and hazards consolidate resulting in extreme socio-economic impacts (Raymond et al., 2020). With climate change, Danish municipalities are increasingly exposed to such events, which presents a significant challenge to risk management at the local level. The analysis showed that each of the three municipalities created a different nuanced understanding of what a "compound event" means. In particular, the municipalities differ in their perception of what constitutes such a combined incident and what consequences it has for the local management and thus their risk management practices, which is also true for other European countries (Bevacqua et al., 2021). The three municipalities face different experiences, strategies, tools, and challenges in generally handling the risk of flooding and

particularly compound flooding. The analysed municipalities show an awareness of the matter of compound events and have developed a specific standpoint on how to face these risks. In Hvidovre, the municipality nearly experienced events that could have been classified as compound events. It drives a course of risk minimisation through tools, predominately information sharing, research, creating guidelines, and external cooperation projects. As current action has been predominantly post-factum focused, a long term and more holistic approach is aimed at restructuring the preparation efforts of the municipality for future extreme incidents. As Hvidovre follows the logic of fact-based policy making and operates more in silos, a precautionary approach can be solely tentatively seen in their expression to rethink their long-term climate management system while facing an 'almost' compound event. In comparison, Odense Municipality has not experienced any compound events yet, but is aware of the risks and accepts their potential consequences. Due to its high level of protection standards through the ambitious vulnerability thresholds it has set for itself, it follows a holistic and precautionary approach towards risk management as it is equipped for unforeseen future developments. Lastly, Vejle Municipality is historically most challenged by floods from various sources, including combining factors and therefore has extensive experience of dealing with (compound) flood events. Through various networks and plans addressing the risks associated with floods, Vejle established a comprehensive and holistic risk management approach to handle the combined incidents of rain and increased water levels from the fjord and rivers. Due to its financial capacity, the frequent events and thus "fresh memory" of severe impacts, Vejle has an increased capacity to practice appropriate precautionary action to compound events and can be assessed as a front-runner in those adaptation approaches.

Specifically, compound events have been treated either as being a condition, something rather constant and all-surrounding, or as a situation, which implies a particular short-term point in time and space (Cutter, 2018, 2021). In Vejle, compound events have been described more as a condition, linking them to a long-term phenomenon that can develop and occur frequently due to, for instance, the saturation of the soil through temporary cascading rainfall. In Odense, compound events are rather perceived as a specific situation in which combined flood drivers of the sea and sky might collide at some point in the future. Hvidovre municipality exhibits both tendencies of seeing compound events as a situation during which a short time scale of miss-peaks could constitute a compound event through storm surge and precipitation and also as a condition, as it described similar preconditions of saturated soil and rainfall as in Vejle.

Thus, this distinction between condition and situation reflects a certain logic and attitude about how the uncertainty associated compound events in these municipalities is treated (Zscheischler et al., 2018). Municipalities that view the risk of compound events rather as a condition, describe the term rather objectively, as being already there and as "reality". Thus, it can be linked to being of an "unknown known" character, which describes the risk of being known in its shape but unknown in its details, and thus, potentially, to a more precautionary approach. The understanding of compound events as a situation, in contrast, has the nuance to be rather subjective, viewing the occurrence of such an event at an uncertain point in the future. That perspective describes how the logic of the "situation" understanding of compound events can be seen as an "unknown unknown" risk. These risks are characterised as being very difficult to predict and to manage, as their drivers and the situations in which the drivers will collide are nearly impossible to identify or imagine. Therefore, these perceptions of compound events shape the risk strategy of a municipality and the tools used to implement it. Seeing compound events as a situation could shift the focus towards more preparedness tools and emergency management where risk is either ignored, accepted, or transferred. Treating it as a condition can mean linking it to rather long-term approaches to risk management where risks are addressed through a logic of minimisation.

5.2. Reflections on Local Climate Risk Management to Compound Events

Two important considerations are inevitably linked to this variation between understanding compound risks as a situation or a condition. First, there seems to be a mismatch between responsibility and capacity to take action towards compound flood risk in Danish municipalities. These differing capacities are linked to social and spatial attributes such as geographic location, as well as access to and implementation of organisational tools that allow municipalities to live up to their responsibilities for handling risk associated with climate change. This represents a problem for governments as well as for research institutions. The inequalities that already exist in the planning and allocation of resources raise the problem of how researchers and research institutions involved in risk management and climate adaptation research can explain and forecast potential issues of compound events. A more interdisciplinary and integrated approach to assessing and modelling climate change risk would ensure a stronger basis for municipalities to make the necessary decisions and resource allocation towards the management of compound floods. It would also support a stronger research-based understanding of the compound events that municipalities experience and potentially inform municipalities with a predominantly reactive approach to dealing with compound risk.

Similarly, authorities across all levels of government should identify and engage with resource allocation issues related to the risk associated with compound events. This includes an assessment of the extent to which the resources delegated to municipalities match the services they are held accountable for. Ignoring the great variation in how municipalities experience and approach compound events may create unequal services and support to citizens living in different municipalities. Essentially, it puts citizens in some municipalities at greater risk than citizens living in other municipalities.

Second, looking across the three Danish municipalities, the classical separation of services is still very much present in the governmental agencies responsible for taking action on climate

change adaptation. These dynamics both play out horizontally (across the departments within the municipalities) and vertically (across the different governmental scales) involved in flood risk management. While scholars working on climate adaptation and disaster risk management have done substantial work on the integration between disciplines and practical fields (i.e., Thomalla et al., 2006; Schipper, 2009), frameworks, targets, and goals defined in each department are rarely informed by those of the other. The analysis of the three municipalities indicates that local government agencies involved in climate adaptation management are either working in silos or lack the tools to work beyond the boundaries of their mandate and tasks. This includes better integration with regional and national government units as well as integration across departments, which work is important for disaster risk management. For example, in Hvidovre the interview participants described the need to often convince other departments to include the possibility of flood hazards in their conception of new projects and general practices, as they presumably left those considerations of significant risk factors out of their planning approaches. This points to the need for municipalities and their climate planners to work with other departments and actors integral to local risk management processes.

Together, these two considerations call for a more targeted and coherent municipal effort in addressing compound events. While the analysis of the three municipalities showed how the municipalities, to some degree, are engaging in risk management through precautionary principles, there is still much to be done in terms of supporting this work. Not least, an overview and a plan for the overall risk landscape associated with compound events and the management tools currently in use to address those. If we are to address current and future risks stemming from climate change, municipalities' knowledge, and opportunities constitute an untapped potential. However, resources to understand the risk landscape, develop plans, and transcend current administrative structures are lacking. In particular, in a municipal reality where many other agendas are important "and often more visible" to citizens' everyday lives.

6. CONCLUSION

Compound events increase the challenge of climate change adaptation, as the previous perspective of univariant extremes in climate science potentially underestimated dependent factors leading to extreme events. If global warming continues, some rare compound extreme events will become more common, and events with unprecedented intensities, durations, and/or spatial extents will become more likely (*high confidence* in IPCC, 2021). The solution pathway is not straightforward but depends on the particular exposed factors and respective institutional capacity. Due to the complexity of multiple dependent factors influencing each other within the risk scenario of compound events, this study has demonstrated that the experience of involved governing entities is important to examine to find ways to manage the risk. The analysed municipalities perceive compound events in their geographical surrounding as a trend to be critically observed, demonstrating that the risk of compound events can be only conditionally be categorised as "underestimated" as Zscheischler et al. (2018) argue, since the analysed municipalities partially have taken actions against it. These actions have manifested in tailor-made solutions responsive to their risk assessment and governance capacity. Caution needs to be taken while applying the practices and tools used in each municipality to other municipalities within the country and even more abroad. Valuable lessons can be, however, drawn, especially for local governance practices of complex climate adaption challenges.

A great challenge of compound event research is to communicate the complexity in a simplistic way. To avoid grey zones, clear definitions and precise limitations can help to manage misunderstandings in research and practice, especially when working across disciplines. Ultimately, risk identification of compounding factors should not result in overwhelmed decision-makers who will not do anything but help in acknowledging its potential of helping to avoid even graver harm in the future. This study urges for further investigation of compound events in Denmark and beyond as they are deemed to be crucial due to their complexity, uncertainty and far-reaching socio-economic consequences. Thus, climate risk management practices and precise risk communication can be a powerful tool to spark change.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

L-CM: drafting of manuscript, interview the municipalities, analysis, and interpretation of data. JS: study conception and design, assist interview, analysis, and interpretation of data. AN: revision of manuscript, analysis, and interpretation of data. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

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