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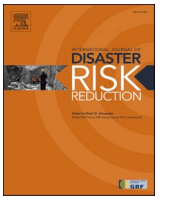

Prioritise risks and improve adaptation strategies in the Veneto coast through the application of a custom AI tool

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A B S T R A C T

Climate change has emerged as one of the most severe global challenges of our time, with rising temperatures and unprecedented shifts in climate patterns. Coastal areas are particularly vulnerable, facing compounded impacts from sea-level rise and increasingly frequent extreme weather events, demanding urgent need for proactive and comprehensive adaptation measures to protect coastal regions, recently defined as sentinels of climate change.

A paradigm shift towards a multi-hazard risk perspective is increasingly recognised as essential in risk assessment and management. Moreover, Artificial Intelligence (AI) have emerged as promising tools to aid decision-making processes in coastal risk management and climate change adaptation. This study introduces COAST-AId, a custom Large Language Model designed to facilitate the analysis and synthesis of diverse information relevant for climate risk assessment and management along the Veneto coast. The tool facilitates the application of the risk assessment framework proposed in the European Climate Risk Assessment analysing the specific climate risk challenges of this region. The framework combines three key dimensions – i.e., risk identification, risk analysis, policy analysis – to prioritise risks and define urgent actions. The application of the COAST-AId tool was performed in close cooperation with local stakeholders involved in the MYRIAD-EU project where a systemic multi-hazard risk framework is considered to support the development of disaster risk management and climate adaptation pathways.

The tool's performance was evaluated by stakeholders, highlighting critical risks in the Veneto coastal as well as opportunities for enhancing coastal resilience and improving risk reduction and adaptation strategies at the regional to local scale.

1. Introduction

Climate change impacts have become increasingly severe along coastal areas worldwide, where climate-related threats, such as rising sea-levels and changing patterns, frequency and intensity of extreme events (e.g., coastal storms, floods; [1,2] [3]), affect natural ecosystems and the communities ([1,2]). Addressing these challenges requires a shift from traditional single hazard assessment to a multi-hazard and multi-risk framework, analysing the complexity and spatio-temporal overlapping nature of multi-risk events [4–7]. This paradigm shift allows for a more comprehensive understanding of hazards, simplifying the development of targeted solutions to address multiple risks that coastal areas face. These interactions can intensify impacts, resulting in more severe outcomes, which requires holistic approaches that consider multi-hazard, multi-scale, and multi-sector perspectives [8–11].

Coastal local authorities and policymakers are increasingly faced with the challenging task of balancing coastal development with

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risk management. An integrated approach to assess multiple risks along coastal areas is needed to identify, on one hand, the main causes contributing to this rise of coastal risks and to identify, on the other hand, the most appropriate adaptation and risk management measures.

According to the framework developed within the H2020 MYRIAD-EU project [12], this study uses a multi-risk assessment approach and follows the international and European risk assessment guidelines for climate change adaptation and disaster risk reduction [13–18] and the international ISO standard (ISO/IEC 31010:2019) to perform a scoping climate risk assessment at the regional to local scale. Risk assessment is used to facilitate a shared understanding of the risks affecting the Veneto region, as well as their relative significance (priority) in the context of both current (reference) and future scenarios. The identified, assessed and prioritized risks are then used as the basis for risk management planning and, therefore, the identification of risk reduction measures.

More specifically, the research activities in this study involved the identification and prioritization of the main climate-related hazards and risks affecting the coastal areas of the Veneto region, and followed the main phases of the standard [19], i.e., *problem formulation*, *risk identification*, *risk analysis*, *risk evaluation* and *risk treatment*.

Furthermore, advances in Machine Learning (ML) and Artificial Intelligence (AI) in general have opened new possibilities for multi-risk assessment, exploiting vast data sources for environmental observation and monitoring (e.g., remote sensing data from Copernicus Sentinels, USGS Earth Explorer; [20–23]). In particular, custom Large Language Models (LLMs), such as those based on OpenAI's Generative Pre-training Transformers (GPTs; [24]), have shown potential in analysing and synthesizing diverse data sources to create enhanced frameworks for multi-risk assessment and resilience building. These models operate as context-enhancing tools, leveraging extensive pre-training on vast datasets to provide nuanced insights across domains [25]. Unlike other methods such as retrieval-augmented generation (RAG) or fine-tuning, custom GPTs allow to use a combination of prompt engineering and instruction tuning to align outputs with specific user needs, incorporating domain-specific knowledge uploaded on a size-limited vector database, without requiring extensive retraining [26]. This setup allows these tools to adapt flexibly to varied applications, including multi-risk assessment, where they synthesize information from sources such as scientific studies, historical data, and real-time inputs [25,27].

This paper introduces COAST-AId, *COastal multi-risk Assessment* SupporTed *by AI-baseD tools*, a custom GPT-based tool designed to support multi-risk assessment and management in the Veneto coastal area, one of the climate change hotspots in the Mediterranean basin [28,29]. COAST-AId follows the approach proposed in the first European Climate Risk Assessment (EUCRA) report, which provides an evaluation of climate risks across Europe [16]. The report identifies 36 major climate risks that threaten European critical

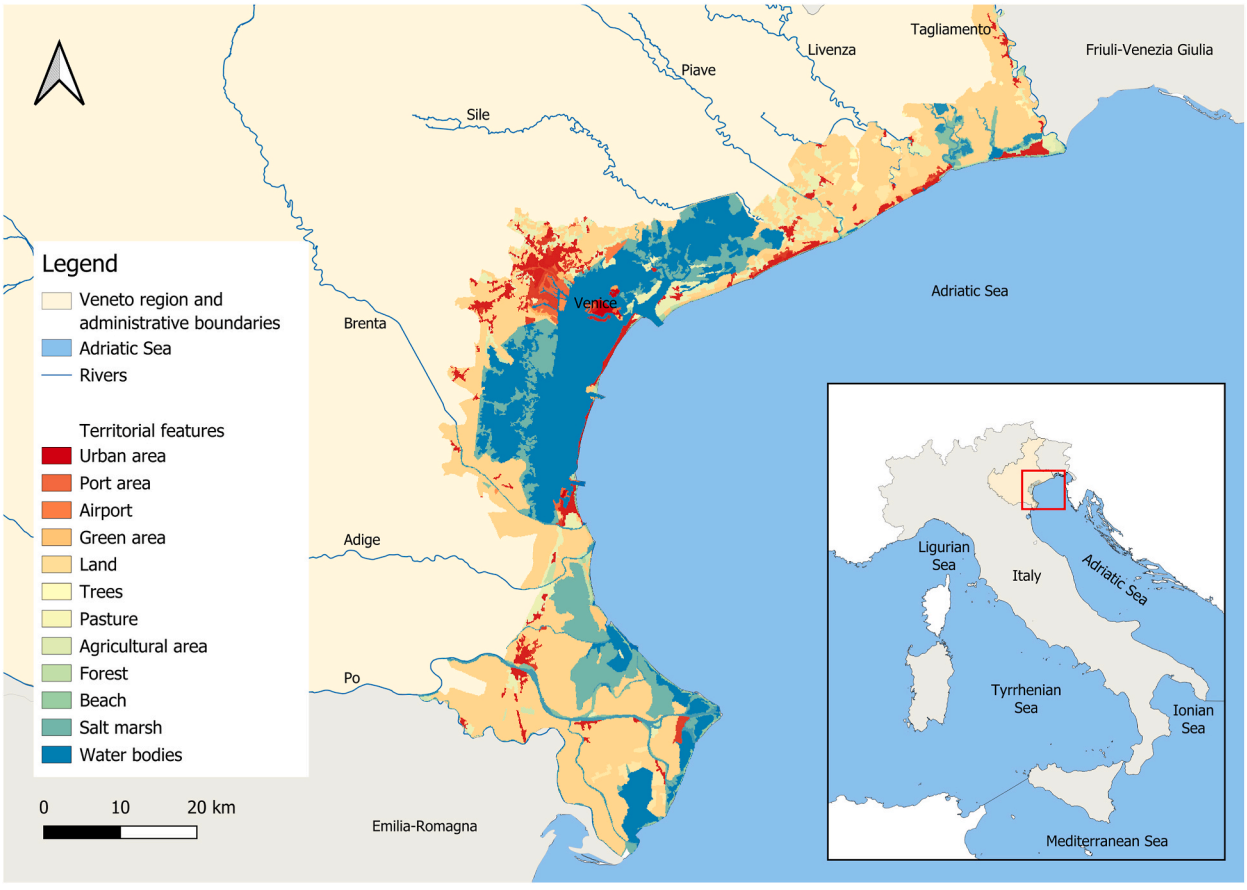

Fig. 1. The case study area: the coastal areas of the Veneto region (Italy).

sectors, including food, ecosystems, infrastructure, economy and finance, and health. Many of these risks have already reached critical levels and could escalate to catastrophic consequences without urgent and decisive action. The EUCRA approach includes four consecutive steps, i.e. (i) *risk identification*, (ii) *risk analysis*, (iii) *policy analysis*, and (iv) *urgency evaluation*.

In the *risk identification*, the major climate risks have been selected for the European regions through an initial screening of the relevant scientific literature, which followed the criteria adopted by the IPCC AR6 (e.g., high magnitude and likelihood of severe consequences, high irreversibility, potential cascading effects beyond system borders, worsening effect of climate change over time).

The *risk analysis* step assesses the severity of each major climate risk (classified as limited, substantial, critical, or catastrophic) across three timeframes (current, mid-century, or late century). Furthermore, the confidence level is determined based on the type, quantity, quality, and consistency of evidence, as well as the degree of agreement among the sources.

The *policy analysis* step evaluates temporal horizon, ownership and readiness of EU policies to examine the level of risk recognition and management.

Finally, the *urgency to act* is determined by combining the findings from the previous steps into a matrix, hereinafter referred as the "EUCRA matrix". The outcome considers five categories: watching in brief, sustain current action, further investigation, more action needed e urgent action needed. For more details on the classification of each level, refer to Supplementary Material SM1.

COAST-AId is designed to support the application of the EUCRA approach to the regional (subnational) scale, rapidly delivering accessible and actionable information on key risks impacting the Veneto coastal area. This enables local policymakers and stakeholders to enhance their risk knowledge and foster adaptation strategies, paving the way for more effective and sustainable regional resilience planning. Therefore, following the EUCRA approach, COAST-AId supports three primary objectives: (i) identifying major risks for the Veneto coast – *risk identification*, (ii) analysing the severity of these risks – *risk analysis*, and (iii) evaluating current policies and adaptation strategies – *policy analysis*. Following the performance evaluation provided by local stakeholders and AI-experts, these outputs are incorporated into the EUCRA matrix applied to calculate the *urgency to act* for the identified major coastal risk within the Veneto region. This integration offers valuable insights to refine local policies and supports the development of a resilient coastal management plan aligned with the 2024 Regional Strategy for Climate Change Adaptation in the Veneto region (Regione del Veneto, 2024).

This paper explores the application of COAST-AId, carried out in close collaboration with local stakeholders. The tool represents a preliminary attempt to apply the EUCRA approach at a regional-to-local scale, with a specific focus on the Veneto coast (Section 3). Key outputs, including the stakeholders' evaluation of COAST-AId's performance, are discussed in Section 4.

2. Case study area

The coastal area of the Veneto region (Fig. 1), stretching approximately 169 km along the North Adriatic Sea, presents a diverse and complex landscape shaped by both natural and anthropogenic influences [30].

The coastaline belongs to the provinces of Venice and Rovigo, and is characterised by low-lying sandy shores across the entire littoral, which is predominantly shaped by the presence of six river outlets (i.e., Adige, Piave, Brenta, Tagliamento, Livenza, Sile) and the delta system of the Po river [31,32]. Due to wave and tidal energy, these shores feature prominent spits and barrier islands belonging to the city of Venice (i.e., Lido and Pellestrina), enclosing morphologically distinct lagoons connected to the sea through tidal inlets. The evolution of these beaches relies on a delicate balance between the transgressive marine regime, driven by rising sea levels, and the diminishing fluvial sediment supply.

These natural sites are deeply blended with the urban area, which have seen substantial expansion since the post-war economic boom and the subsequent rise of mass tourism throughout the region, which have significantly altered the natural sediment balance, reducing the resilience to coastal hazards [33].

This unique geomorphology renders the region particularly susceptible to extreme events as a result of a multitude of hazards [9, 33–37]. In particular, rising sea-levels, intensified storm surges, and increased frequency of extreme weather events have amplified coastal related risks, impacting water quality, biodiversity, and the livelihoods of local communities [21,36,38]. Recent notable extreme events include the exceptional high tide of November 2019 and the compound hazard events that led to the Vaia storm (also known as Storm Adrian) between October and November 2018 [36]. The November 2019 high tide was driven by a combination of atmospheric and oceanographic factors, including strong Sirocco winds across the Adriatic basin, a peak in the astronomical tide, an unusually high average sea-level in the Adriatic and the passage of a small cyclone over the Northern Adriatic and the Venice lagoon [36]. The Vaia storm, a powerful Mediterranean storm with hurricane-force wind gusts and heavy rainfall, predominantly impacted the mountainous areas of the Veneto region, causing extensive forest destruction [39]. It also triggered an unusually prolonged high tide in Venice, leading to storm surge events along the coastline and sediment overflow at the Veneto river mouths [40].

In response to these unprecedented multi-hazard and multi-risk scenarios, various strategies have been implemented to safeguard coastal zones and enhance urban resilience. The most implemented measures, aimed at managing coastal-related risks, include both 'grey infrastructure', such as groins, breakwaters, and tidal gates, as well as 'nature-based solutions' like beach nourishment, dune restoration and conservation of natural areas (Regione del Veneto, 2024). Recently, the Environment and Ecological Transition Unit of the Veneto Region drafted the prelimary document of the Regional Strategy for Climate Change Adaptation (SRACC; Regione del Veneto, 2024). The SRACC outlines an adaptive framework tailored to the region's diverse geographic and environmental features,

encompassing alpine, riverine, lacustrine and coastal areas.

The strategy has been conceived as a strategic document built upon the findings of five technical-scientific reports,[1] which provide a comprehensive foundation on climatic conditions, existing adaptation plans, and multi-hazard analyses related to climate change. Notably, indices have been developed to classify relative risk levels across multiple climate-related hazards in the Veneto Region (Regione del Veneto, 2024). Among these risks, coastal flooding is the only coastal risk explicitly addressed in the current strategy, with its impacts projected to intensify significantly due to climate change, leading to an increased number of affected receptors (Regione del Veneto, 2024). However, the land-sea interface in the Veneto region is exposed to a broader spectrum of critical coastal risks that remains unaddressed [21,41]. This study aims to fill this gap by conducting an analysis of coastal risks in the Veneto region. Specifically, it aims to identify and prioritise the major coastal risks and to offer robust evaluation guidelines that could inform regional adaptation and risk management planning processes, making them effectively respond to the complex and evolving challenges posed by climate change.

3. Methodology

This study aims to support the prioritization of coastal risks and enhance adaptation and risk management strategies for coastal areas in the Veneto region, addressing climate change challenges through the application of a customized tool based on a pre-trained large language model (LLM), GPT4o [42].

The proposed methodology followed four steps, as depicted in Fig. 2. Fist, COAST-AId's instructions and knowledge were designed and prepared (Section 3.1). Then, the tool was applied to the coastal areas of the Veneto region following the *European Climate Risk Assessment* (EUCRA) approach as a reference framework and methodological guide. This application was aimed to identify the region's most significant coastal risks, assess their severity, and evaluate current policy readiness to address these challenges (Section 3.2). To ensure the reliability of the results, AI experts and local stakeholders were actively engaged in evaluating COAST-AId's performance and outputs (Section 3.3). This validation was a crucial step towards achieving the overarching goal of determining the urgency of actions required to reduce the identified coastal risks (Section 3.4). The following sections provide a detailed description of each phase.

3.1. COAST-AId development

The assessment of multiple risks within the complex system of the Veneto region's coastal area required the integration and analysis of a wide range of data sources in PDF format. These include reports, peer-reviewed papers, and deliverables from EU- and nationally funded projects focusing on the investigated area.

To address this challenge and extract the most relevant information for coastal risk assessment, a custom large language model (LLM), called COAST-AId (*COastal multi-risk Assessment* SupporTed *by AI-baseD tools*, https://chatgpt.com/g/g-12xYfUHJh-coast-aid), was developed.

COAST-AId was preferred over off-the-shelf models as it ensures higher contextual relevance, domain-specific accuracy, and stronger alignment with the project's objectives. Preliminary tests with general-purpose models (e.g., ChatGPT-3.5) revealed limitations in maintaining factual consistency and adequately capturing the complexity of coastal multi-risk dynamics. These findings underscored the need for a structured, prompt-engineered approach capable of reducing factual drift and enhancing domain alignment. To achieve this, COAST-AId was developed as a custom LLM trained exclusively on climate-related sources, including scientific literature, technical reports, and policy documents. By operating within a closed, vetted dataset, the tool minimizes hallucinations and factual inaccuracies, while preserving transparency over data provenance. Moreover, the model allows the integration of user-defined instructions to prioritise specific objectives (e.g., identifying key risks for a case study), thereby ensuring outputs remain tailored to real-world decision-making needs. These features are essential for supporting multi-risk climate assessments, which demand flexibility, contextual depth, and methodological rigor.

COAST-AId was built entirely within OpenAI's custom GPT (Generative Pre-trained Transformer) environment, using the GPT-4o architecture. No external infrastructure, fine-tuning, or local implementation of retrieval-augmented generation (RAG) was applied. Instead, the system leverages OpenAI's GPT-4o's native capabilities as a state-of-the-art multimodal transformer, capable of processing long-context text and structured documents with high reasoning efficiency [43,44].

All customization of COAST-AId was achieved through prompt engineering, rather than altering model weights or applying supervised fine-tuning. Custom behavior was implemented using system-level instructions and curated few-shot examples. This approach enabled domain-aligned reasoning and task-specific formatting, drawing on well-established prompting strategies such as chain-of-thought, decomposition, and few-shot prompting [26].

Knowledge integration was conducted through OpenAI's native file upload functionality within the Custom GPT interface. Input documents, including scientific publications, policy reports, and stakeholder contributions, were uploaded directly to the platform. Upon upload, OpenAI's backend automatically performed semantic chunking, embedding generation, and indexing into an internal vector store. At inference time, user prompts are transformed into embeddings and semantically matched against the uploaded knowledge base using OpenAI's built-in vector search. The most relevant content chunks are then dynamically injected into the model's output pipeline [45].

[1] Technical-Scientific Reports produced to support the Veneto Region Strategy for Climate Change Adaptation (SRACC): https://www.regione.veneto.it/web/ambiente-e-territorio/rapporti-tecnico-scientifici.

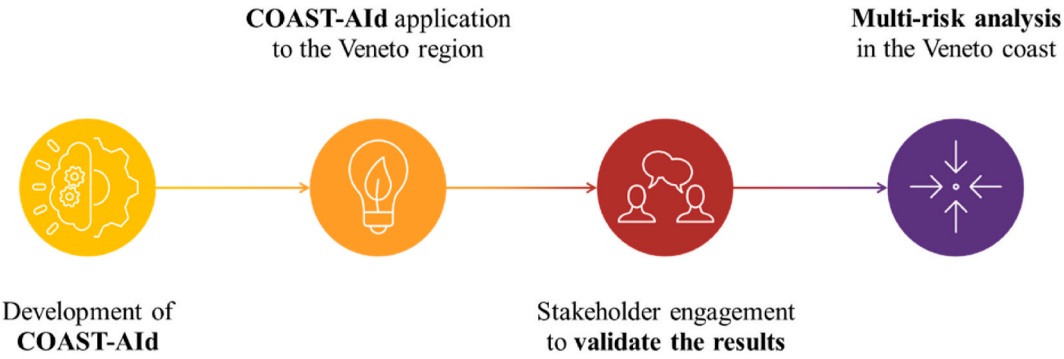

Fig. 2. Workflow adopted to prioritise risks and improve current adaptation strategies in the Veneto coast.

Table 1
Final set of prompts used for applying the EUCRA approach to the coastal areas of the Veneto region.

EUCRA level	Prompts	Technique
Risk identification	*Previous assessments have identified sea-level rise as a significant climatic hazard and urban development as a non-climatic hazard responsible of the occurrence of coastal erosion risk in the Veneto coastal area. Considering this example, list the most important climatic (atmospheric, marine, and terrestrial) and non-climatic hazards responsible for each coastal risks in the Veneto coastal area.*	Few-Shot Prompting [46]
	First, identify the most relevant coastal risks occurring along the Veneto coastal area. Next, for each risk, list the combinations of climatic and non-climatic hazards previously identified as the most important hazards responsible for these risks. Explain how these hazard combinations contribute to each specific risk in the coastal areas of the Veneto region.	Decomposition [49]
Risk analysis	*First, explain the rationale behind the management measures implemented for each coastal risk in the Veneto coastal area. Then, assess how these measures have either reduced or increased the impacts of the other risks, considering only the risks identified so far for the Veneto coastal area. Provide examples and explain why these effects occurred.*	Step-Back Prompting [50]
	As a data analyst, review each attached file and count the number of documents focused on each coastal risk identified so far for the Veneto coastal area. Provide a step-by-step summary of your counting process for each file.	Role Prompting [48]
	For each coastal risk identified so far for the Veneto coastal area, provide: • the climatic and non-climatic hazards responsible for the risk. • *the level of severity (Catastrophic, Critical, Substantial, Limited – based on the European Climate Risk Assessment classification) for the* current *situation (until 2040), mid-century (2040–2060), and end of the century (until 2100).* • *for each* time *frame, explain in detail the reasons for the assigned severity level, reasoning step-by-step.* • *the measures* implemented *to address the risk.* • *the sectors* affected *by this risk.*	Zero-Shot Chain-of-Thought Prompting [51]
Policy analysis	*Using the provided definition of 'policy horizon', determine the policy horizon along the Veneto coastal area related to each coastal risk identified so far for the Veneto coastal area as a consequence of climatic and non-climatic hazards. Explain your reasoning step-by-step, considering the severity of the risk over time.*	Chain-of-Thought Prompting [47]
	As a policy analyst, identify the policies issued by at the sub-national/local scale of the Veneto region that cover each coastal risk identified so far for the Veneto coastal area. Provide brief descriptions of each policy and explain how they address each Veneto coastal risk.	Role Prompting [48]
	Using the provided categories of 'policy readiness', evaluate the norms and policies related to each coastal risk identified so far for the coastal area of the Veneto region. Explain your reasoning step-by-step to determine whether the policy readiness is Low, Medium, Advanced, or Very Advanced.	Chain-of-Thought Prompting [47]
Urgency to act	*First, summarize the information related to 'risk severity', 'confidence', 'policy horizon', and 'policy readiness' for each coastal risk identified so far for the Veneto coastal area. Next, using the European Climate Risk Assessment classification, identify the appropriate class of 'urgency to act' (i.e., 'urgent act needed', 'more action needed', 'further investigation', 'sustain current action', 'watching brief'). Explain your reasoning step-by-step.*	Decomposition [49]

All input documents were uploaded during the development and configuration of the tool, which means that COAST-AId's knowledge is strictly limited to those specific sources. It does not access external web-based inputs. A complete list of input documents is provided in Supplementary Material SM2.

Currently, the prototype tool is set to private mode, due to the inclusion of various non-open-source materials, such as subscription-based scientific papers and regional reports shared under restricted agreements. To promote transparency and ensure replicability, web search functionality was disabled, allowing the authors full control over all input data used during model operation.

In the initial stages of the development, COAST-AId was tested iteratively using a subset of the 60 documents from the final dataset. This approach supported the refinement of both the tool's linguistic behaviour and its understanding of domain-specific terminology. Starting with a smaller, curated selection of documents, allowed identification of comprehension gaps and informed improvements in

output quality.

This phase concluded with the integration of advanced prompt design techniques, balancing technical expertise and creative intuition to enhance user interaction with the model. The prompting strategies adopted were guided by the framework proposed by Schulhoff et al. [26], and include.

- *Few-Shot Prompting*, providing the model with a few examples to learn from, enabling the generation of contextually relevant and informed responses [46].
- *Chain-of-Thought Prompting*, encouraging the model to reason step-by-step through a problem, promoting logical reasoning and ensuring structured and accurate responses [47].
- *Role Prompting*, instructing the model to adopt the role of an expert (e.g., jurist, data analyst), ensuring methodological task execution within the context of that role [48].
- *Decomposition*, breaking down a complex task into smaller, manageable steps, allowing the model to address each part accurately [49].
- *Step-Back Prompting*, where the model reflects on broader implications, promoting deeper analysis and thoughtful conclusions [50].
- *Zero-Shot Chain-of-Thought Prompting*, directing the model to provide step-by-step reasoning, guiding it to produce detailed and well-reasoned responses without prior examples [51].

These prompting techniques were pivotal in fine-tuning the interaction between COAST-AId and the user, culminating in a refined set of prompts specifically designed to apply the EUCRA approach to the Veneto region's coast, as further detailed in Section 4.1 and Supplementary Material SM4.

3.2. Application of COAST-AId to the veneto region

COAST-AId was created aiming to facilitate the application of the EUCRA approach to the local scale, making the complex data landscape of the Veneto coastal area more accessible to policymakers and stakeholders. The European approach includes four consecutive steps: *risk identification*, *risk analysis*, *policy analysis*, and *urgency evaluation*, which will be introduced in the following sections.

3.2.1. Risk identification

To support the identification of major climate risks (first level of the EUCRA approach, see Section 1) affecting the coastal area of the Veneto region, the input documents (detailed in Supplementary Material SM2) were analysed and synthesised using the COAST-AId tool. The prompts specifically designed for this step aimed to generate a comprehensive understanding of the Veneto coastal system, encompassing both climatic and non-climatic drivers, as well as their interactions leading to the identified coastal risk.

The final output of this step is a conceptual framework that provides a comprehensive overview of the Veneto coastal system, which will be presented in Section 4.2, and laying the foundation for the subsequent *risk analysis*, presented in Section 3.2.2.

3.2.2. Risk analysis

As outlined in Section 1, the second level of the EUCRA approach involves risk analysis, focusing on the assessment of both the severity of each identified major coastal risk and the corresponding confidence level. The classification for risk severity follows the EUCRA framework (i.e., limited, substantial, critical, catastrophic) across three distinct timeframes (i.e., current, mid-century, late century), as detailed in Supplementary Material SM1. To assess the EUCRA-defined confidence level, the volume of information available for each major risk derived directly from the input documents of the COAST-AId tool was used as a proxy. This adjustment ensured that the assessment aligns with the data availability and context-specific characteristics of the Veneto region while maintaining methodological consistency with the overall risk analysis framework. In particular, the greater the quantity and relevance of the information, the higher the confidence level is assigned to that coastal risk, ensuring a tailored evaluation that accurately reflects the data's robustness. In particular, the confidence levels are categorised as follows: low if a maximum of five documents are identified, medium for six to ten documents, high for more than ten documents concerning the designated risk for the Veneto coast.

3.2.3. Policy analysis

Following the EUCRA approach outlined Section 1, the third level encompasses the analysis of current policies, including evaluations of risk ownership, policy horizon and policy readiness. As at the European level, where the 2021 EU adaptation strategy provides an overarching framework for adaptation policies, but implementation is mainly through sectoral policies [16], the Strategy for Climate Change Adaptation of the Veneto Region (i.e., *Strategia Regionale di Adattamento ai Cambiamenti Climatici per il Veneto* – SRACC; [52]) sets strategic objectives to be implemented and/or being implemented within sectoral planning processes. The SRACC itself provides a comprehensive list and preliminary analysis of existing plans that include a number of adaptation and risk reduction measures. For the purpose of this study, which focuses on the regional level and aims at supporting policy makers in Veneto, only policy and plans associated with regional ownership were processed by COAST-AId.

For the remining policy indicators (i.e., temporal horizon and policy readiness) the classification aligns with the EUCRA framework, reported in Supplementary Material SM1.

3.3. Engaging experts and local stakeholder to evaluate COAST-AId performance

The deployment of LLMs in real life settings is still in its infancy and it has been limited by challenges related to their reliability, the generation of hallucinations, and replicability in different contexts. To address these challenges, several frameworks have been developed to systematically assess LLM outputs, most of which rely on human evaluation [53].

In this study, experts and local stakeholders were engaged during the MYRIAD-EU project workshop in which the COAST-AId tool and its outputs were presented. The tool was developed as a web-based, chat-style interface within the OpenAI Custom GPT environment. However, stakeholders did not interact directly with the tool. Instead, they were exposed to a curated selection of responses generated by COAST-AId and presented by the research team during the project's workshop.

Following the presentation, participants were requested to evaluate the outputs and articulate their levels of agreement or disagreement through structured questionnaires and interviews. The evaluation was conducted based on recent frameworks commonly used for LLM benchmarking [54–56], which identify five key criteria: accuracy, relevance, clarity, completeness and conciseness. *Accuracy* assesses whether the LLM's response is factually correct, aligned with verifiable data, or grounded in trusted external sources. In critical applications such as environmental risk management or financial services, incorrect information can lead to severe consequences. *Relevance* measures how well the response addresses the specific prompt. Outputs should be focused and aligned with the topic at hand [53]. For instance, when evaluating risks in the Veneto coastal area, responses must provide information pertinent to the location and associated hazards. *Clarity* refers to the ease with which the response can be understood by the user. A well-structured, easy-to-follow response ensures that even complex information is digestible. This is particularly important for decision-makers who need quick, actionable insights. *Completeness* ensures that all components of the prompt are addressed in the response. For multi-part questions or prompts requiring detailed lists (e.g., hazard identification, risk ownership), it is crucial that no critical information is omitted. *Conciseness* evaluates whether the LLM delivers the required information efficiently, without unnecessary verbosity. Responses should be brief yet comprehensive, avoiding excessive elaboration that may obscure important points. This indirect evaluation approach allowed for the identification of content gaps and inconsistencies, which were addressed through manual updates to the prompt structure and expansion of the input dataset. For instance, a key information related to saltwater intrusion was found absent, prompting the addition of further technical documentation to improve the model's coverage and accuracy.

The evaluation approach adopted differs from standard model validation practices, as the primary objective was to develop and qualitatively assess a prototype tool rather than to provide a cross-validation framework for numerical models. This methodological choice reflects the exploratory and interdisciplinary nature of COAST-AId, while future developments could include sensitivity analyses to assess the tool's transferability to other regional contexts and the upscaling potential at EU-level.

The insights gained from these evaluations were synthesised into the final COAST-AId results, contributing comprehensive information on *risk identification*, *risk analysis*, and *policy analysis* for the Veneto coastal area, which will be detailed in Section 4.3.

3.4. Veneto coastal multi-risk assessment and management

The last step of the EUCRA approach involves determine the urgency and type of policy action [16].

When focusing on the coastal area of the Veneto region, the urgency to act was determined in two different ways. First, COAST-AId

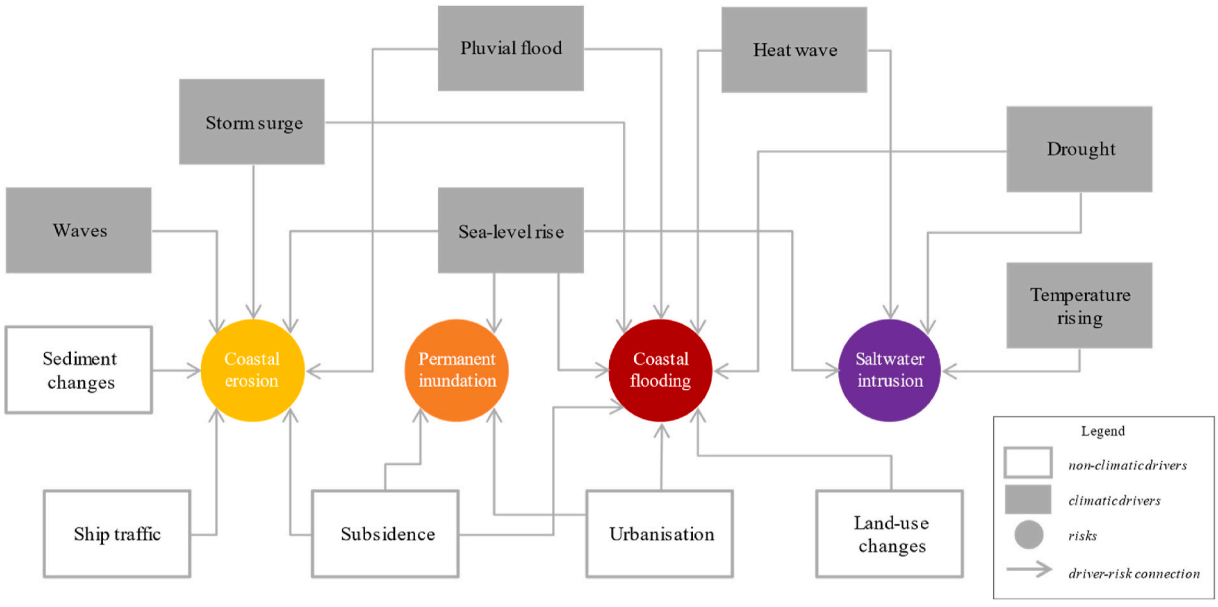

Fig. 3. Conceptual framework for coastal risk assessment in the Veneto region (Italy).

outputs from the previous steps were integrated into the EUCRA matrix. Then, COAST-AId was employed one final time to independently calculate the urgency to act. Both results - those calculated by the EUCRA matrix and those determined by COAST-AId - were categorised into five levels of urgency (i.e., watching in brief, sustain current action, further investigation, more action needed, and urgent action needed). More details on these categories are provided in Supplementary Material SM1.

This approach enabled a comparative analysis of the results produced by the EUCRA matrix and COAST-AId, presented in Section 4.4.

4. Results and discussion

4.1. COAST-AId development

The development of COAST-AId was a comprehensive and iterative process, culminating in the identification and refinement of the final set of prompts, reported in Table 1.

The initial application of the tool revealed challenges related to hallucinations, which were effectively mitigated through structured prompting techniques (outlined in Section 3.1) and multiple rounds of refinement. These improvements significantly enhanced the reliability and accuracy of responses, ensuring that the tool's outputs aligned more closely with the input data and were more applicable for decision-making processes.

A crucial factor in strengthening COAST-AId's reliability was its co-development with local stakeholders, whose in-depth knowledge of territorial characteristics, challenges, and needs proved invaluable. Their expertise, as discussed in Section 4.3, played a pivotal role in refining the tool's functionality, ensuring that the generated insights were both contextually relevant and scientifically sound.

Given that LLMs are still in the early stages of their application, adopting structured prompting techniques and actively involving domain experts in the validation process remains essential. While these tools can streamline and expedite desk reviews, their inherent limitations must be acknowledged. Therefore, the iterative refinement of AI-assisted tools, such as COAST-AId, combined with expert engagement, ensures they serve as valuable instruments for analysing complex, multi-dimensional risks while maintaining scientific rigor.

4.2. Application of COAST-AId to the veneto region

The proposed study aims to apply the EUCRA approach to the local context of the Veneto coast, harnessing the capabilities of the COAST-AId tool. The following sections provide a comprehensive breakdown of the outcomes from each step of the EUCRA approach (detailed in Section 3.2), with the corresponding COAST-AId outputs reported in Supplementary Material SM3. In particular, Section 4.2.1 covers risk identification, risk analysis is discussed in Section 4.2.2, and finally policy analysis is presented in Section 4.2.3.

4.2.1. Risk identification

COAST-AId was employed to identify the major climate risks impacting the coastal area of the Veneto region, through a set of specific risk related prompts, encouraging the retrieval of relevant information from the documents available in the tool. This application provided a comprehensive understanding of the Veneto coastal system, culminating in the development of the conceptual framework presented in Fig. 3.

The conceptual framework illustrates the interplay between climatic-related hazards and non-climatic risk drivers, which together shape the major climate-related risks identified in the case study.

Coastal erosion is driven by an intricate combination of climate-related hazards, including storm surge, sea-level rise, and pluvial flooding [23]. These hazards, exacerbated by the increasing frequency of extreme weather events observed over recent decades [9] and projected to intensify in the future [57], collectively reshape shorelines, redistribute sediments, and destabilize coastal ecosystems [21]. When these hazards interact, their impacts often reveal the compounding nature of extreme events [9]. For instance, sea-level rise amplifies the effects of storm surges and wave impacts, whereas the combination of pluvial flooding and storm surge-induced coastal inundation accelerates sediment displacement and erosion [21,58].

Non-climatic risk drivers, such as sediment changes, shipping traffic and subsidence, further exacerbate this unstable situation by disrupting the physical processes that regulate sediment dynamics and shoreline stability. Although not directly linked to climate change, these factors (such as land subsidence and anthropogenic pressures) significantly increase the susceptibility of coastal system

Table 2
COAST-AId outputs related to risk analysis, which includes risk severity across three different temporal timeframes (current, mid-term, long-term) and the confidence level for the Veneto coastal area.

Risks	Risk severity			Confidence level
	Current	Mid-term	Long-term	
Coastal erosion	**Substantial**	**Critical**	**Catastrophic**	++
Permanent inundation	**Limited**	**Substantial**	**Critical**	+
Coastal flooding	**Substantial**	**Critical**	**Catastrophic**	+++
Saltwater intrusion	**Limited**	**Substantial**	**Critical**	+

to climatic hazards like wave action and storm events [59,60]. The combined effects of subsidence and sea-level rise are particularly concerning, as they increase relative sea-level changes and heighten the risk of coastal flooding and permanent inundation [61,62]. This dynamic is especially pronounced in the Veneto region, characterised by low-lying topography prone to flooding [58,63,64], dense coastal development that amplifies exposure [59,60], and reliance on artificial water management systems (e.g., MOSE system), which face escalating challenges from these rising hazards [65,66].

Saltwater intrusion arises from a feedback loop involving subsidence, rising sea-levels and temperatures, drought, and heatwaves, all of which amplify coastal risks [41,67]. Subsidence reduces land elevation, increasing vulnerability to saltwater intrusion during droughts and heat waves. Concurrently, rising temperatures and heat waves diminish freshwater availability, weakening natural hydrological defences [41,68,69]. Human activities, such as excessive groundwater extraction for irrigation and urban development, further exacerbate these risks by intensifying subsidence and depleting freshwater reserves [70,71]

4.2.2. Risk analysis

Following the identification of the major risks affecting the coastal area of the Veneto region (i.e., coastal erosion, permanent flooding, coastal flooding, and saltwater intrusion), the COAST-AId tool was employed to conduct a detailed risk analysis through a set of specific prompts to retrieve the relevant information from the documents available in the tool. This analysis assessed both the severity of each coastal risk, and the confidence level associated with the supporting documentation. The resulting matrix (Table 2) offers a clear visual representation of the methodology detailed in Section 3.2.2. It enables the understanding and effective prioritization of the intensifying risks affecting the Veneto coast, while capturing the temporal evolution of these risks across current, mid-term, and long-term scenarios.

Coastal erosion, driven by rising sea levels, storm surges, and reduced by beach nourishment and dune restoration efforts [21,23], currently poses a *Substantial* risk. However, mid-term classification indicates an escalation to *Critical*, fuelled by accelerating sea-level rise and increasing storm intensity [22]. In the long term, unchecked erosion could lead to *Catastrophic* consequences for coastal infrastructure, ecosystems, and local communities. These findings align with regional studies, which emphasise the compounded impacts of geomorphological vulnerabilities and anthropogenic pressures, such as urbanization and tourism development [72–74].

A similar pattern is observed for coastal flooding, exacerbated by the Veneto coast's peculiar geomorphology, characterized by low-lying littoral zones [31,32]. The situation is further strained by the existing flood defence infrastructures (e.g., MOSE system) which may require substantial upgrades to address the growing magnitude and frequency of extreme weather events [36,66,75].

The interplay of sea-level rise and land subsidence are making the Veneto coast increasingly vulnerable to permanent inundation [61,62]. While currently classified as a *Limited* risk, this coastal risk is projected to become *Substantial* in the mid-term and *Critical* in the long-term, particularly under high-emission scenarios such as RCP8.5 [22,61].

Similarly, saltwater intrusion, currently set as a *Limited* risk, is projected to intensify as rising sea levels diminish freshwater flow [70,71]. Mid-term and long-term scenarios elevate this risk to *Substantial* and *Critical*, respectively, posing significant threats to agriculture and freshwater availability, underscoring the need for proactive water management strategies to limit this risk [76].

Finally, as detailed in Section 3.2.2, the confidence level was directly derived from the input documents of the COAST-AId tool, serving as a reliable proxy of the EUCRA-defined confidence level. Specifically, COAST-AId quantified the number of documents associated with each risk identified in Section 4.2.1. The analysis revealed that coastal flooding had the highest number of related documents (16), followed by coastal erosion (10) and permanent inundation (5). Saltwater intrusion had the lowest level of documentation (4), reflecting a relatively recent – but growing – concern within the scientific community.

4.2.3. Policy analysis

Major coastal risks identified for the Veneto region include coastal erosion, coastal flooding, permanent inundation, and saltwater intrusion, driven by both climatic and non-climatic drivers.

To conduct a preliminary assessment of existing regional policies, strategies, and plans, the COAST-AId tool was employed through a set of specific prompts to retrieve relevant information with the aim of applying the EUCRA approach [16] to the Veneto coast. The policy analysis followed the EUCRA methodology, thus assessing *risk ownership*, *policy horizon*, and *policy readiness*, as illustrated in Table 3. The analysis considered all sectoral plans included in the SRACC, through which the Veneto Region intends to achieve strategic objectives to foster transformative adaptation.

The assessment of policy readiness reveals varying levels of maturity across the different risks. Coastal erosion and saltwater intrusion policies are categorised as having a *medium* level of readiness, reflecting ongoing efforts to develop both grey and nature-based solutions, such as dune restoration and sediment management [72,77]. Similarly, readiness for permanent inundation is also rated as *medium*, with efforts focused on enhancing spatial planning, restoring floodplains, and strengthening critical infrastructure [66]. In contrast, policies addressing coastal flooding demonstrate an *advanced* level of readiness, bolstered by the MOSE system,

Table 3
COAST-AId outputs for policy analysis, including risk ownership, policy horizon and policy readiness for the Veneto coastal area.

Risks	Risk ownership	Policy horizon	Policy readiness
Coastal erosion	Veneto	**Mid- to Long-term**	**Medium**
Permanent inundation	Veneto	**Long-term**	**Medium**
Coastal flooding	Veneto	**Long-term**	**Advanced**
Saltwater intrusion	Veneto	**Mid- to Long-term**	**Medium**

which has significantly enhanced the region's capacity to manage storm surges and extreme flooding events [78].

Overall, the policy readiness assessment shows positive results across the identified major risks, proving that several risk reduction measures have been planned and implemented in Veneto over the past decades to address coastal risks [72]. However, these measures have often been designed with a single-risk focus, overlooking that risk management measures targeting one risk can create synergies or a-synergies with other risks [6]. For instance, coastal infrastructure, such as groins and breakwaters, has been built to protect and stabilise the coastline [21,79]. While effective in localised contexts, these structures often disrupt the natural southward sediment drift, affecting coastal dynamics and introducing unintended consequences [80].

Although the recently published Strategy for Climate Change Adaptation in the Veneto Region (i.e., *Strategia Regionale di Adattamento ai Cambiamenti Climatici per il Veneto* – SRACC; [52]) represents a significant step towards transformative adaptation, the analysis conducted shows that a single-risk approach is still in place and that further effort is needed to achieve a holistic perspective in coastal risk management. Future revisions of the Strategy represent an excellent opportunity to implement a paradigm shift in coastal risk governance by fostering a multi-risk framework, thus abandoning a siloed approach in both risk assessment and management. Incorporating mechanisms to assess and manage cascading effects would improve the strategy's robustness and align with the most recent international best practices in disaster risk management and climate adaptation (IPCC, 2023; [5]).

The COAST-AId tool was also used to evaluate the temporal horizons of the SRACC sectoral plans for addressing the major costal risks in the Veneto region. Temporal horizons refer to the timeframe required for plans, strategies, and policies to become effective in reducing risks, influenced by the lead time of adaptation actions and the lifespan of current adaptation decisions (Section 3.2.3). The tool highlighted that policies for coastal erosion and saltwater intrusion will achieve efficacy in the mid-to long-term timeframe, while policies for permanent inundation and coastal flooding require a long-term horizon.

The long-term horizon for coastal flooding policies is surprising, considering the urgency of the issue in the region and the various plans and measures already in action. In particular, following severe floods across Europe between 1998 and 2004, an European Floods Directive (Dir.2007/60/EC) was introduced to mandate comprehensive flood risk management. This directive requires an integrated approach combining prevention, protection, and preparedness measures, including flood forecasting and alert systems, addressing both land management and regional civil protection. Conversely, the medium-to-long-term horizon assigned to saltwater intrusion policies is unexpected, as this coastal risk has only recently gained attention and remains under-investigated.

To address these observations, the insights were discussed with local stakeholders to refine the inputs for EUCRA matrix application (Section 4.3). The results of this application will be presented and analysed in Section 4.4, aimed to define the urgency levels for each major coastal risk in the Veneto region. This process seeks to provide valuable support to decision-makers in identifying necessary improvements to current plans, strategies, and policies.

4.3. Engaging experts and local stakeholder to evaluate COAST-AId performance

To evaluate COAST-AId results discussed in the previous sections, experts and local stakeholders were engaged during the MYRIAD-EU project workshop in which the COAST-AId tool and its outputs were presented. As detailed in Section 3.3, the assessment was conducted based on five key criteria (i.e., accuracy, relevance, clarity, completeness and conciseness), whose outputs have been collected in Supplementary Material SM4.

The *accuracy* evaluation of COAST-AId was conducted with the active participation of local stakeholders through a structured process involving a questionnaire followed by one-to-one interviews. These stakeholders, representing both public and private local authorities, provided invaluable insights into the Veneto region's territorial context. In particular, the stakeholders included a heterogeneous pool of domain experts from different disciplinary backgrounds, including local and regional authorities, regional agencies, and private sectoral representatives for the case study. This diverse composition of stakeholders ensured a comprehensive range of perspectives, enriching the evaluation process and fostering a more robust discussion.

The overall accuracy of COAST-AId was deemed satisfactory, with stakeholders positively evaluating its performance. However, *saltwater intrusion* emerged as a notable exception (Table 4), with the risk severity being underestimated by the custom LLM. During the dialogue with the stakeholders, it became evident that the current and future severity level of saltwater intrusion should be revised. Stakeholders highlighted that the risk should be elevated from *limited* to *substantial* in the current period, from *substantial* to *critical* for the mid-term period, and from *critical* to *catastrophic* by the end of the century. Their feedback was further corroborated by additional documentation provided during the interviews, which not only supported the need for revised severity levels but also enhanced the confidence level associated with this specific coastal risk. The evaluation also revealed shortcomings in the policy readiness for addressing saltwater intrusion. Stakeholders emphasized that existing regional plans are insufficient to mitigate this risk effectively. Unless significant interventions are made, the region's capacity to address saltwater intrusion would remain limited, with meaningful

Table 4
Summary of risk analysis and policy analysis after the stakeholders' inputs.

Risks	Risk severity			Confidence level	Risk ownership	Policy horizon	Policy readiness
	Current	Mid-term	Long-term				
Coastal erosion	**Substantial**	**Critical**	**Catastrophic**	++	Veneto	**M – L**	**Medium**
Permanent inundation	**Limited**	**Substantial**	**Critical**	+	Veneto	**L**	**Medium**
Coastal flooding	**Substantial**	**Critical**	**Catastrophic**	+++	Veneto	**M - L**	**Advanced**
Saltwater intrusion	**Substantial**	**Critical**	**Catastrophic**	++	Veneto	**L**	**Medium**

Table 5
Resulting output of the multi-risk assessment for the Veneto coastal area, including both applications - i.e., COAST-AId and the adapted EUCRA matrix for the Veneto case study.

Risks	Urgency to act (COAST-AId tool)	Urgency to act (EUCRA matrix)
Coastal erosion	**More action needed**	**Urgent action needed**
Permanent inundation	**More action needed**	**More action needed**
Coastal flooding	**Urgent action needed**	**More action needed**
Saltwater intrusion	**More action needed**	**Urgent action needed**

policy readiness unlikely to materialise before the end of the century.

These insights were used to refine the COAST-AId input dataset and improve prompt design, enhancing the model's ability to reflect context-specific risks more accurately.

This finding underscores the need for targeted policy development and implementation to address this escalating threat, which will be discussed in Section 4.4.

Furthermore, a panel of six AI experts, from the environmental and informatics departments of universities and research centres, was convened to assess the performance of the COAST-AId tool based on the remaining four key evaluation criteria: relevance, clarity, completeness, and conciseness. These experts provided comprehensive feedback, highlighting the tool's capability to generate responses that are contextually pertinent, well-articulated, and thorough while maintaining a concise format. Overall, their evaluation was positive, underscoring the significant potential of COAST-AId to advance multi-risk assessment frameworks. As detailed in Supplementary Material SM4, the criteria of relevance, clarity, and conciseness received the highest ratings (i.e., high to very high). However, the completeness criterion garnered some medium to low score, particularly in the context of policy analysis. This highlights an area for further refinement, suggesting that future iterations of the tool should focus on improving its ability to provide more comprehensive insights when addressing complex policy-related challenges, thereby ensuring an even greater impact in its application.

4.4. Veneto coastal multi-risk assessment and management

The final stage of the coastal risk assessment for the Veneto region focused on determining the levels of *urgency to act* required to address the identified risks. The results, summarised in Table 5, provide a comprehensive framework incorporating findings from two methodologies: *(i)* the final application of COAST-AId, and *(ii)* the EUCRA matrix calculations, which enable a direct comparison of the results from both methods.

The COAST-AId tool was employed to generate a final prompt assessing the urgency to act, drawing on information extracted from the input documents. This tool demonstrates significant potential by facilitating the analysis and synthesis of complex information, while providing practical recommendations for decision-making processes. Its ability to streamline data review and interpretation significantly reduces the time required for these tasks [81]. In particular, the integration of LLM-based tools like COAST-AId offers considerable advantages in processing and analysing large volumes of information [82]. This feature is especially critical for multi-risk assessments in well-documented case studies, such as the Veneto region, where diverse datasets and reports need to be carefully considered (Supplementary Material SM2).

Furthermore, the flexible design of COAST-AId ensures its adaptability to other case studies with similarly extensive documentation. Such tool holds transformative potential for addressing complex, multi-dimensional challenges in coastal risk management, paving the way for more efficient and effective adaptation strategies [83].

However, it is important to note that COAST-AId's performance is strictly dependent on the quality and comprehensiveness of the input documents, selected by the authors. This selection process was refined only after discussions with the local stakeholders, as detailed in Section 4.3. A comparison of findings between COAST-AId and the EUCRA approach (Table 5) reveals notable discrepancies. Despite these differences, both approaches highlight the urgency of prioritising the identified coastal risks. When the EUCRA

Table 6
EUCRA matrix integrating the classification for each assessment level (i.e., risk identification, risk analysis, policy analysis, and urgency to act) to evaluate and prioritise major coastal risks in the Veneto region.

		Coastal erosion	Permanent inundation	Coastal flooding	Saltwater intrusion
Urgency to act		**Urgent action needed**	**More action needed**	**More action needed**	**Urgent action needed**
Confidence		Medium	Low	High	Medium
Risk severity	Current	Substantial	Limited	Substantial	Substantial
	Mid-century	Critical	Substantial	Critical	Critical
	End-century	Catastrophic	Critical	Catastrophic	Catastrophic
Policy analysis	Ownership	Regional	Regional	Regional	Regional
	Readiness	Medium-low	Medium-low	High	Medium-low
	Horizon	Medium-term	Long-term	Long-term	Long-term
Urgency	Near-term	More action needed	Watching in brief	Sustain current action	More action needed
–	Mid-term	Urgent action needed	Further investigation	Sustain current action	Urgent action needed
single period	Long-term	Urgent action needed	More action needed	More action needed	Urgent action needed

matrix was applied to the coastal area of the Veneto region (Table 6) the results were further evaluated by local stakeholders. This collaborative evaluation process enhances the reliability of the outcomes.

The final urgency level was calculated by integrating information from the three previous levels of coastal risk assessment (i.e., risk identification, risk analysis, and policy analysis). The COAST-AId tool's outputs, combined with stakeholder evaluations, were used to populate the EUCRA matrix. This matrix integrates scores for key indicators, including risk severity, confidence, policy ownership, policy readiness, and policy temporal horizon, to determine the urgency level for each major coastal risk. The ultimate urgency levels, derived through the EUCRA matrix, provide a structured and actionable framework for addressing coastal risks in the Veneto region.

Coastal flooding is acknowledged as a critical issue by local stakeholders due to its profound impacts on livelihoods, tourism, and economic activities. Efforts to address this risk have been bolstered by the MOSE system, a sophisticated flood barrier activated in October 2020, which has significantly reduced flooding-related damages in Venice [66,75]. Despite these successes, projections suggest that the MOSE system may face limitations under high-emission scenarios by the end of the century. These include the possibility of prolonged gate closures, increased financial and ecological losses, and the eventual inadequacy of gate heights to counteract rising water levels [78,84,85]. Such projections underscore the need for additional, long-term strategies to complement existing measures. These include integrating adaptive engineering solutions, refining policy frameworks, and fostering community engagement to ensure sustainable protection for Venice and surrounding areas against the escalating threat of coastal flooding and potential permanent inundation.

Coastal erosion is closely monitored by the Veneto Region authority, which plays a central role in planning and implementing protective measures. Activities such as dredging river mouths, rehabilitating coastal zones, and constructing structural infrastructures like groins and breakwaters have been critical in mitigating erosion [21,72]. However, these interventions have altered natural shoreline dynamics, creating zones of both accretion and erosion.

Beach nourishment efforts, involving the extraction of millions of cubic meters of sand, play a pivotal role in preparing the Veneto coastline for tourism, particularly after extreme storm surges. However, as the frequency and intensity of these events are projected to rise [57], current plans require urgent updates to maintain the coastline's resilience and economic viability. Adaptive measures should focus on enhancing the sustainability of nourishment practices and integrating nature-based solutions to balance ecological and economic priorities.

Saltwater intrusion poses an escalating risk to coastal agriculture in the Veneto region, leading to soil degradation and crop damage [71,86]. The freshwater-saltwater boundary has retreated significantly inland in recent years, exacerbated by rising sea levels, decreased freshwater input, and prolonged drought conditions [87–89]. While past reclamation efforts have provided temporary relief, long-term strategies remain absent. To address this risk, policymakers must implement robust measures such as constructing artificial barriers to limit saltwater encroachment, developing freshwater channels to counteract salinization, and strategically realigning agricultural boundaries [67,90]. These actions are critical to preserving agricultural productivity and environmental integrity in the region [71].

Through comprehensive planning and collaborative action, the Veneto region could strengthen its resilience to climate change impacts, setting a precedent for other coastal areas facing similar challenges. This approach will not only mitigate immediate risks, but also ensure long-term sustainability for the environment, economy, and communities in the region. In particular, the discrepancies between COAST-AId and the EUCRA matrix underscore the importance of combining data-driven assessments with stakeholder inputs to achieve comprehensive risk prioritization. More specifically, plans must prioritise.

1. long-term resilience, by developing adaptation and risk reduction strategies that account for projected changes in climate and sea levels, but also environmental and socio-economic changes. This approach ensures the longevity and effectiveness of protective measures.
2. capacity building, which could offer stakeholders, communities, and authorities the knowledge, tools, and collaborative frameworks needed to implement sustainable solutions [91–93].
3. integrated approaches, by fostering synergy between engineering solutions, policy development, and community engagement to address risks effectively.
4. establishment robust monitoring systems to evaluate the effectiveness of implemented measures and adapt strategies as conditions evolve [71].

4.5. Ethics implications

The use of LLM-based tools such as COAST-AId in the risk assessment and management field raises important ethical considerations related to bias, explainability, and transparency. As with all foundation models, COAST-AId inherits potential biases from its base architecture (GPT-4o) and from the selection of input documents. While input data was curated from authoritative and region-specific sources (SM2), certain coastal risks for the case study (i.e., saltwater intrusion) were initially underrepresented, as highlighted by stakeholders.

To improve transparency and traceability, the prompts and classification framework used are fully documented (Table 1), and all outputs are version-controlled and stored (Supplementary Materials SM4 and SM3). Stakeholders and domain experts participated in structured evaluations of the tool's outputs, enhancing the tool's alignment with real-world knowledge and expectations.

COAST-AId was developed in line with the European Commission's guidelines on Trustworthy AI and the principles laid out in the EU AI Act. These include transparency, human oversight, and accountability. The tool is clearly positioned as a decision support system, not a replacement for expert judgment. All outputs are meant to be reviewed and interpreted by qualified professionals.

5. Conclusion

This study was aimed at developing and implementing COAST-AId (*COastal multi-risk Assessment* SupporTed *by AI-baseD tools*), an innovative AI tool that leverages advances in Large Language Models (LLMs), to assess coastal risks and evaluate adaptation strategies in the Veneto region. By applying the European Climate Risk Assessment (EUCRA) approach to the specific challenges of the Veneto coastal area, COAST-AId successfully develop a comprehensive multi-risk assessment framework that aligns with European and international guidelines.

The results highlight the tool's ability to process extensive and heterogeneous data sources, such as scientific studies and policy documents, to generate actionable insights. The integration of LLMs allowed for the analysis and synthesis of complex information, facilitating policymakers in the identification of major risks that needs to be urgently addressed to effectively strengthen resilience. Furthermore, COAST-AId's adaptability and capacity to integrate new datasets ensure its continued relevance, making it a dynamic tool for addressing the evolving challenges of climate change.

Despite these achievements, several challenges were encountered. The reliance on local data highlighted the importance of well-curated and comprehensive information, underscoring the need for a robust repository of supplementary materials to facilitate replication in other regions. Stakeholder engagement revealed occasional misalignments between the tool's outputs and user expectations, demonstrating the necessity of context-sensitive calibration. Additionally, during the initial phases of application, occasional LLM hallucinations required manual verification to ensure accuracy, highlighting an area for future improvement to enhance reliability and user trust. To address this, future developments will focus on integrating grounding mechanisms, including specific nodes for cross-checking model outputs and detecting hallucinations, as well as for easing the text analysis, also from different languages. Planned improvements also include the integration of both qualitative and quantitative datasets, enhancements in processing speed and efficiency, the addition of multilingual language support beyond Italian and English, enabling broader regional applicability, and the introduction of explainability overlays (e.g., citation displays) to increase transparency and user trust. These improvements will advance transparency, trust, and the overall reliability of AI-assisted tools for climate transformative adaptation.

In terms of scalability, COAST-AId relies on a prompt-driven architecture, which enables reuse across different regions without the need for retraining or model fine-tuning. Localization is achieved by uploading region-specific documents into the custom GPT interface, while reusing or adapting prompt templates to fit the new context.

This study identifies significant opportunities for the further development and expansion of COAST-AId. Extending its applicability to other coastal and non-coastal regions offers promising potential, provided the tool is applied to local contexts. Moreover, developing an independent, open-access chatbot could enhance accessibility and usability for local communities, empowering users with a user-friendly interface to better understand and address risks.

It is important to acknowledge limitations related to the scale of analysis. In particular, a mismatch may occur between the scale of natural processes (e.g., coastal erosion, saltwater intrusion) and the socio-economic or governance levels addressed in the input documents (e.g., municipal vs. regional). Since COAST-AId operates on document-based evidence, its outputs reflect the scope and priorities embedded in those sources, potentially omitting important cross-scale interactions or dynamics. This limitation reinforces the need for multi-level stakeholder engagement and careful contextual interpretation of the tool's findings.

To conclude, COAST-AId represents a systematic experimental tool that integrates the EUCRA framework at the regional (sub-national) and local scales, specifically in the Veneto coastal area. The approach effectively bridges the gap between scientific analysis and actionable policy, providing a valuable resource for enhancing and developing coastal adaptation plans. While challenges remain, this study underscores the potential of custom LLMs in advancing sustainable and resilient coastal management, laying a foundation for future innovations in risk assessment and adaptation planning through AI-driven solutions.

CRediT authorship contribution statement

Maria Katherina Dal Barco: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization, Software, Writing – review & editing. **Veronica Casartelli:** Validation, Supervision, Methodology, Investigation, Conceptualization, Writing – review & editing. **Marcello Sanò:** Methodology, Conceptualization. **Sebastiano Vascon:** Validation, Supervision, Methodology. **Silvia Torresan:** Validation, Supervision, Funding acquisition, Conceptualization, Project administration, Writing – review & editing. **Andrea Critto:** Supervision, Conceptualization.

Declaration of competing interest

All of the reported work in the attached manuscript is original and the manuscript has not been previous published in whole or in part. I also have read and abided by the statement of ethical standards for manuscripts submitted to this journal. All authors have seen the manuscript and approved its submission to the *International Journal of Disaster Risk Reduction.*

Moreover, all the authors declare that they have no known competing financial interests or personal relationships that could had influenced the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijdrr.2025.105818.

Data availability

Data will be made available on request.

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