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AI-assisted Real-Time Spatial Delphi: integrating artificial intelligence models for advancing future scenarios analysis

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Abstract

The Real-Time Spatial Delphi represents an innovative method tailored to navigate the complexities of uncertain spatial issues. Adopted in Future Studies contexts, this method excels in developing spatial scenarios and leveraging the collaborative insights of experts within a virtual environment to achieve a consensus regarding territorial dynamics. However, while this method yields invaluable spatial insights and statistical metrics, the final outputs often remain confined to expert circles due to their technical complexity. In addition, the outcomes often lack direct policy implications, as they primarily provide an expansive overview of potential future scenarios. In response to these challenges, this paper proposes integrating text-to-image models and generative pre-trained transformers, into the Real-Time Spatial Delphi process. By adopting these advanced tools during the visioning and planning phases, the method endeavors to transform spatial judgments into visually immersive scenarios, while concurrently crafting actionable policy recommendations suitable for evaluation. To validate the approach, we present a case study in the environmental context, for the cities of Cork, Galway, and Limerick, located in Ireland. Through this application, we contribute to Futures Studies by illustrating the method's capacity to envision plausible futures in the form of real images, considering the formulation of policies to support decision-making.

Keywords Real-Time Spatial Delphi · Artificial intelligence · Future scenarios · Text-to-image models · Generative pre-trained transformers

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1 Introduction

Spatial complexity denotes the intricate and unpredictable patterns and interactions (i.e., physical, social, or infrastructural) occurring within a specified physical area (Papadimitriou 2020). This entails analyzing various components, including objects, organisms, or processes, and their distribution and interactions within a specified spatial framework. Tangible components might include physical features (e.g., buildings, landscapes, infrastructure) or living entities (e.g., plants, animals). Intangible components could involve conceptual elements like demographic patterns, cultural factors, or economic activities that influence spatial dynamics. This complexity is shaped by diverse natural, social, and architectural environments, and grasping it is essential for tackling a broad spectrum of future challenges, spanning from urban planning and environmental management to biological conservation and economic development (Haaland and van Den Bosch 2015). Hence, it is imperative to meticulously scrutinize potential future dystopian implications to inform the development of concrete actions and policies in the present for effective planning. To address this challenge, within the context of Futures Studies (FS), spatial scenarios are frequently utilized to depict and elucidate potential spatial arrangements or configurations that might arise under various conditions. In the historical evolution of FS, Kuosa (2011) identifies three paradigmatic shifts. The first paradigm focuses on forecasting singular future events, exemplified by methods such as the traditional Delphi technique (Rowe and Wright 1999). The second paradigm adopts scenario planning to explore multiple plausible futures amidst uncertainty (Kim et al. 2019). The third paradigm recognizes the limitations of both forecasting and foresight, emphasizing systemic resilience and the need for active stakeholder engagement. Specifically, spatial scenarios are typically crafted using statistical models (e.g., regression analysis to assess land-use patterns), simulations (e.g., agent-based models to explore urban growth), or other analytical tools (e.g., geographic information systems for spatial data visualization) to explore how changes could impact spatial dynamics over time (first paradigm). However, due to the unpredictable nature of the future, even the most sophisticated statistical models often cannot be deemed reliable for long-term forecasting (Makridakis 1996). In scientific literature, a real shift occurs from what is traditionally considered forecasting methods (e.g., quantitative spatial analysis, statistical modeling, agent modeling) to foresight approaches (second paradigm) (Martin 1995). Foresight is oriented towards exploring various potential futures to propose actionable measures in the real world and to facilitate or counteract events by remaining vigilant and adaptable. Among the many methods adopted for the development of spatial scenarios, the Real-Time Spatial Delphi (RTSD) (Di Zio et al. 2017), is widely employed in complex contexts. RTSD originates from the traditional version of the Delphi method (Linstone and Turoff 1975), a structured communication technique used to gather the knowledge and opinions of a group of experts to obtain a consensus or stability (Dajani et al. 1979) on a particular topic or issue. Compared to the traditional version of the Delphi method, RTSD is particularly suitable for spatial contexts. It is fully implemented in a virtual environment where experts can answer questions by placing one or more opinion points on a dynamic map in real time, thus providing feedback in the formulation of the scenarios. In RTSD, consensus is measured considering the most widely used indicators of the Delphi method, such as the interquartile range (IQR), implemented in a computational algorithm in the form of a geometric element represented by a circle C. The outputs of RTSD, derived from real-time collaboration among experts, can be divided into two main categories: (1) *Spatial outputs*: these include the final maps containing the opinion points expressed by experts, along with the convergence circle and any reference spatial analyses. (2) *Indicator outputs*: this encompasses all components of descriptive statistics, results of convergence indicators, and any analysis of expert comments. It becomes essential to emphasize that in this approach, spatial scenarios are constructed by incorporating various elements, rather than solely depending on spatial outputs, as seen in traditional forecasting methodologies. This is because creating diverse exploration of the "futures" necessitates a comprehensive array of information. However, since the dissemination and communication of scenarios are crucial for raising awareness among citizens and policymakers, they must be conducted with care and precision. As expressed by Calleo et al. (2023), scenarios could potentially be too technical and not suitable for the intended audience. Since the future is unpredictable, citizens or policymakers participating in informative workshops may struggle to grasp the concepts presented if good communication skills are not used (Carvalho et al. 2016). In our context, we acknowledge the limitation that the outputs arising from the spatial analyses of the dynamic convergence process may prove challenging to comprehend and visualize for individuals outside the sector or those lacking sufficient information regarding the indicators. Moreover, the absence of suggested policies for addressing or facilitating the scenarios that emerged from RTSD can be considered a lack of efficient strategies, which is the main purpose of the process.

To overcome these challenges, this paper proposes to enhance the Real-Time Spatial Delphi method by integrating modern Artificial Intelligence (AI) models in the last stages of the process (*Visioning*, *Planning*, and *Acting* phase). Specifically, in our method two models are employed: Text-to-Image (T2I) models, adept at generating real images of future scenarios from spatial inputs provided by experts, and the renowned Chat Generative Pre-Trained Transformer (ChatGPT), utilized for formulating a draft list of policies/strategies ready for evaluation. For FS, this contribution represents a significant innovation, particularly as the concluding phases of scenario planning present the greatest challenge. Normally, FS methods emerged mainly during the first and second paradigms, with few methodological advancements in the third. However, the adoption of digital technologies has revitalized traditional methods, making them more relevant in the third paradigm by improving efficiency and enabling greater stakeholder participation. By advancing the Real-Time Spatial Delphi method, AI technologies enhance stakeholder engagement and visualization, aligning with the third paradigm's objectives of fostering resilience and actionable insights. In our context, the primary challenge is attributed to the difficulty of disseminating and effectively communicating the final results, as well as implementing actions in reality. To demonstrate and validate our approach, we suggest a case study focused on climate change threats, developing spatial scenarios for 2050 for the cities of Cork, Galway, and Limerick, located in Ireland. Overall, the research objectives of this contribution can be summarized in:

1. $\boldsymbol{RO}_1$: Enhancing the Real-Time Spatial Delphi method by integrating Artificial Intelligence models in the final stages of the process.
2. $\boldsymbol{RO}_2$: Performing text-to-image models to generate realistic visual depictions of scenarios by incorporating outputs from the Real-Time Spatial Delphi method.
3. $\boldsymbol{RO}_3$: Integrating the outcomes of Real-Time Spatial Delphi into generative pre-trained transformers to generate a draft list of potential territorial policies ready for further evaluation.

This approach fills a crucial limitation in the process of developing future scenarios by incorporating visual features into the existing textual, spatial, and statistical components. Ultimately, it streamlines the timeline for policy development suitable for immediate territorial implementation, thereby easing the burden on policymakers. The paper is organized as follows: Sect. Introduction introduces the contribution by outlining the main research objectives. Section Technical framework presents a technical framework concerning the Real-Time Spatial Delphi, Text-to-Image models, and Generative Pretrained Transformers. In Sect. AI-assisted Real-Time Spatial Delphi, the method foundation is presented, highlighting the overall process, and discussing how AI can enhance the generation of images and presentation of possible policies. Section Results and discussion discusses the results obtained, followed by a presentation of the results. Finally, in Sect. Concluding remarks and future works, the work concludes with a discussion on possible future avenues for research.

2 Technical framework

2.1 Real-time spatial delphi

The Real-Time Spatial Delphi (Di Zio et al. 2017) is an advanced variation of the traditional Delphi method, a decision-making technique used to gather opinions from a panel of experts through a real-time spatial survey. In RTSD, experts are typically geographically dispersed and communicate remotely using technology systems designed for real-time interaction (Calleo et al. 2023). In this instance, the system is specifically crafted to conduct a spatial questionnaire in real-time where experts can sign up via the provided link and respond anonymously to questions by placing one or more judgments in the form of N points (with $e = 1, 2, \ldots, E$ the label of the user) on an interactive map (Di Zio and Pacinelli 2011). The anonymous judgments are then synthesized into the main users' interface and can be revised by placing more points, adding comments, and viewing statistical summaries in real time, thus enhancing effective cooperation. One of the primary advancements of this approach lies in the overarching goal of obtaining consensus among experts with different perspectives, instead of simply representing judgments in the form of N points on the map.

To pursue this objective, RTSD employs a computation algorithm performed in real-time integrated in the main system. From the first point acquired, a set of N judgments are considered ($N = \sum_{e=1}^{E} N_e$), and for each question, a geometric element identified as a circle C is displayed, representing the spatial consensus on the territory. The algorithm, similar to the IQR range adopted in the traditional Delphi method, finds a circle C, the smallest one among the possible C_i, containing half of the N opinion points and is fully described and discussed in Calleo et al. (2023), and Calleo and Pilla (2024). In this setting, RTSD emerges as a valuable asset due to its adaptable application, proving beneficial across all decision-making processes requiring territorial assessment, including the development of scenarios. In scientific literature, Calleo et al. (2023) suggests the methodological guidelines for developing spatial scenarios utilizing RTSD. The authors propose integrating a refined methodology that incorporates the approach proposed by Bishop et al. (2007) in strategic foresight with the conventional Delphi method (Brown 1968). This procedure encompasses six primary phases, flexible based on the research objectives, including framing, scanning, forecasting, visioning, planning, and acting. These phases are critical for effectively executing envisioned futures. For this reason, we propose leveraging recent advancements in

AI models to develop a robust framework for these final stages. This framework should facilitate the visualization and communication of scenarios through the creation of realistic images depicting potential futures. Moreover, it enables the formulation of a draft list of policies ready for evaluation, considering the insights gleaned from the entire process. This holistic approach will enhance the utility and applicability of the method, bridging the gap between scenario development and actionable policy formulation.

2.2 Text-to-image models

In recent years, the intersection of Natural Language Processing (NLP) and computer vision witnessed remarkable advancements, with text-to-image models emerging as a pivotal area of research (Reed et al. 2016). T2I models, also known as text-to-picture or text-to-visual models, are a class of AI systems designed to generate realistic images from textual descriptions. This fusion of language and visual representation implies profound aspects across various domains, including content generation, creative design, virtual environments, and accessibility aids. Indeed, these models overcome the semantic disparity between textual and visual domains, empowering machines to comprehend and generate images that correlate with human-written descriptions (Zhou et al. 2022). Text-to-image models evolved significantly since their inception, owing to breakthroughs in deep learning architectures and the availability of large-scale datasets.

Early approaches primarily relied on traditional machine learning methods, such as conditional generative models (Sohn et al. 2015), which struggled to capture the complexity and diversity of natural language and visual content. Nevertheless, with the advent of deep neural networks, particularly generative adversarial networks (GANs) and transformer-based architectures, text-to-image generation witnessed substantial progress (Creswell et al. 2018). The development of landmark models like Generative Adversarial Networks with Auxiliary Classifier (ACGAN), AttnGAN, DALL-E, and Adobe Firefly (used in this study), propelled the field forward, enabling the generation of high-fidelity images conditioned on textual prompts (Jabbar et al. 2021). Adobe Firefly represents a significant advancement in the domain of generative artificial intelligence, distinguishing itself as a highly capable tool within the creative industries. Unlike many other generative AI systems, Firefly is fully integrated into Adobe's well-established Creative Cloud suite, providing users with a streamlined approach to workflow enhancement. This integration ensures that professionals using software such as Photoshop, Illustrator, and Premiere Pro can leverage advanced AI capabilities directly within familiar environments, thereby maintaining continuity and efficiency in their creative processes. This model leverages techniques such as attention mechanisms, hierarchical structure learning, and multimodal embeddings to align textual descriptions with corresponding visual features, facilitating the generation of coherent and contextually relevant images. T2I models typically comprise several key components and architectures tailored to handle the intricacies of both textual and visual data. These components include: (1) *Text embedding*: where descriptions are encoded into a continuous vector space using techniques of word embeddings or transformer-based models. This representation captures semantic information essential for aligning text with visual features. (2) *Image encoder*: visual inputs, such as images or image regions, are encoded into feature vectors through convolutional neural networks (CNNs) or transformer-based vision models (Gu et al. 2018). These feature vectors encapsulate visual semantics and serve as a basis for generating images. (3) *Multimodal fusion*: the encoded text and image features are fused using attention mechanisms or concatenation operations, enabling the model to integrate textual context with visual information effectively. (4) *Image decoder*: finally, the fused representations are decoded into realistic images through generative modules, such as deconvolutional networks or transformer-based decoders. To provide a practical example, GANs are composed of two neural networks: a Generator (G) responsible for producing images and a Discriminator (D) tasked with discerning between real and fake images. D operates by assessing features extracted from training images to classify them as authentic or counterfeit. On the other hand, G aims not to predict specific labels but rather to generate image details consistent with a hypothetical label. In the adversarial game between G and D, the parameter of G are adjusted based on the performance of D, and vice versa, fostering a competitive dynamic (Mishra et al. 2020). In recent years, T2I models found diverse applications across various domains, such as content generation, virtual environments, accessibility aids, and creative tools (Frolov et al. 2021). In the FS context, there is a growing fascination with incorporating AI models into the scenario development process. However, scant attention is directed towards the visual dimension (Anonymous, 2023). Instead, efforts are primarily channeled into AI-driven aspects of scenario development (see Spaniol and Rowland 2023). This element could enhance the scenario process by incorporating realistic visuals of potential futures, utilizing readily available models that offer swift implementation and produce highly satisfactory results to anchor into a new reality.

2.3 Generative pre-trained transformer

The second model explored for the objectives of our paper is based on generative pre-trained transformer models, a groundbreaking architecture in the NLP context, capable of transforming the landscape of text generation tasks (Frantar et al. 2022). Developed by OpenAI, GPT leverages transformer-based deep learning models to generate coherent and contextually relevant text across a wide range of applications (Roumeliotis and Tselikas 2023). Since its introduction, GPT has undergone several iterations, with each version pushing the boundaries of language understanding and generation capabilities. The development of GPT stems from the need for more sophisticated language models capable of understanding and generating human-like text. The original GPT model, introduced in 2018, laid the foundation by demonstrating the efficacy of unsupervised pretraining followed by fine-tuning specific downstream tasks (Fuchs 2023). Subsequent iterations, including GPT-2 and GPT-3, progressively increase model size, training data, and performance. GPT-3, the most recent iteration, is particularly notable for its unprecedented scale, boasting 175 billion parameters and exhibiting remarkable proficiency across diverse NLP tasks without task-specific fine-tuning. This evolution underscores the continuous efforts to push the boundaries of language generation and understanding through larger models and more extensive training data. GPT models, including GPT-2 and GPT-3, are characterized by several key components and architectural innovations, including: (1) *Transformer architecture*: based on transformer architectures, which facilitates parallel processing and captures long-range dependencies in text sequences through self-attention mechanisms. This architecture enables effective modeling of contextual relationships, crucial for generating coherent and contextually relevant text. (2) *Unsupervised pretraining*: they undergo unsupervised pretraining on large corpora of text data, such as books, articles, and websites, to learn rich representations of language. During pretraining, the model learns to predict the next word in a sequence given the preceding context, leveraging self-supervised learning objectives like masked language modeling. (3) *Fine-tuning and transfer learning*: following pretraining, GPT models can be fine-tuned on specific downstream tasks with labeled data, allowing them to adapt to task-specific objectives and domains. This transfer learning paradigm enables GPT to excel in a wide array of NLP tasks, including language translation, text summarization, question answering, and dialogue generation. (4) *Scalability and parameterization*: GPT-3's remarkable scale, with 175 billion parameters, enables it to capture intricate linguistic nuances and generate highly fluent and contextually diverse text.

The massive parameterization empowers the model to exhibit human-like language understanding and produce coherent and contextually relevant responses across varied prompts and domains. GPT models have found widespread applications across numerous domains and use cases, however, they face several challenges and opportunities for future research and development, including bias mitigation, controlled generation, and ethical considerations. In FS, Spaniol and Rowland (2023) made an intriguing contribution by discussing the utilization of GPT for scenario generation, raising awareness within the scientific community regarding the application of AI tools in scenario development. In line with the authors' assertions, we advocate for a shift in focus. Rather than pursuing the identification of a model for generating future scenarios, efforts should be directed toward discerning how AI can effectively support experts in scenario development. As mentioned earlier, GPTs rely on historical data and thus produce predictions akin to statistical models, rendering them unsuitable for long-term anticipation.

3 AI-assisted real-time spatial delphi

3.1 Experimental framework

In this section, we present the method adopted where it is crucial to establish a robust research design (see Fig. 1). Each component warrants meticulous evaluation, as potential methodological errors can influence the ultimate outcomes (Järvensivu et al. 2021). In our context, it is imperative to thoroughly analyze the geographical area of focus, including its boundaries and climate-related risks, to ensure comprehensive consideration of all pertinent factors. This process naturally progresses to conducting desk research, aimed at identifying relevant literature, document collections, and spatial analyses derived from other contributions. The paper presents the validation of this novel approach using Ireland as a test case.

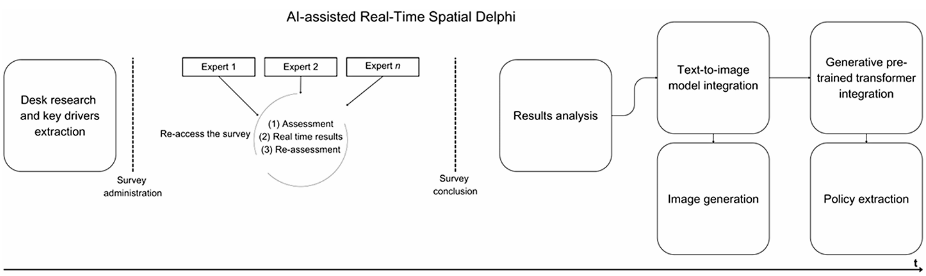

Fig. 1 AI-assisted Real-Time Spatial Delphi

Ireland is greatly affected by climate change, so many stakeholders at local and national levels are actively crafting tailored plans to prevent future threats through present-day policies. As such, we engaged with stakeholders in the cities of Cork, Galway, and Limerick to validate our methodology. These cities, situated in different regions of Ireland, offer a comprehensive view of the territory and its diverse challenges.

At this stage, one of the decisions to address is establishing a reference time horizon. In our case, we opt for a horizon that strikes a balance between not being too short or too long, set at the year 2050 (Sweeney et al. 2002), in line with other studies correlated with climate change (i.e., UN and EU). Specifically, for the development of spatial scenarios, we consider the indicator I corresponding to the plausibility of occurrence that a specific phenomenon will happen in the referenced area by 2050. With our attention directed towards examining climate repercussions in 2050, especially in pinpointing regions prone to significant impact, we undertake a comprehensive examination of literature, consultations with stakeholders, and accessible data to evaluate the hurdles and vulnerabilities encountered by different urban centers. Our case study extends to the aforementioned cities grappling with diverse challenges, aiming to develop actionable strategies for the present circumstances. Given these foundations, to conduct the survey, we require a technological tool that facilitates real-time administration and fosters collaboration among experts. In our research, we employ the most recent version (v 3.0) of the Real-Time Geo-Spatial Consensus System (https://rtgscs.com/faq/), a novel web-based open platform designed for administeri ng spatial questionnaires and conducting various real-time analyses to achieve territorial consensus adopting the Real-Time Spatial Delphi method (Di Zio et al. 2017; Calleo et al. 2023). Prior to starting our study, however, thorough testing was conducted involving desk research to identify any emerging issues, including computational challenges (i.e., stress testing, performance bottlenecks), or potential bugs (i.e., systematic checks of code to identify errors or inconsistencies).

3.2 Climate threats and proposed questions

With our study framework established and all necessary literature, spatial data, and expert guidelines prepared, we move forward by compiling a preliminary list of key factors (K). In our context, K represents the potential environmental threats that the cities under examination may face. Traditionally, in conventional Delphi processes, key drivers are derived through a laborious and resource-intensive procedure involving the assembly of industry experts and conducting workshops to formulate the list. However, in our case, these threats have already been implicitly assessed by experts, as they are incorporated into the territorial plans endorsed by the municipalities and are thus accessible through updated reports online. By leveraging the existing assessments embedded in the territorial plans endorsed by the municipalities, we were able to streamline the RTSD process significantly. This approach enables us to work with a refined list of key factors, thereby reducing the time required for decision-making. For each city, we establish the top three environmental threats (Table 1) as key factors. This strategy serves two primary purposes, firstly, to prevent potential dropouts among the experts due to an excessive number of questions, and secondly, to streamline the presentation of our method. Nevertheless, it is important to note that this approach remains flexible and adaptable to changes or modifications that may be necessary to align with the specific research objectives.

Table 1 Key drivers

Area	Key drivers		
	k_1	k_2	k_3
Cork	Flood risk	Snowfall	Windstorm
Galway	Flood risk	Snowfall	Windstorm
Limerick	Flood risk	Sea levels rise	Rainfall

Table 2 Proposed questions

Area	Research Questions		
	RQ_1	RQ_2	RQ_3
Cork	Which area will be most at risk of flooding?	Which area will be most at risk of impact from snowfall?	Which area will be most at risk of impact from windstorms?
Galway	Which area will be most at risk of flooding?	Which area will be most at risk of impact from snowfall?	Which area will be most at risk of impact from windstorms?
Limerick	Which area will be most at risk of flooding?	Which area will be most at risk of impact from sea level rise?	Which area will be most at risk of impact from rainfall?

Table 1 showcases the primary threats identified through expert evaluations across four municipalities, encompassing the risks of flooding, abrupt snowfall, severe windstorms, and intense rainfall. These recognized factors present substantial risks, such as potential damage to both commercial and residential buildings, loss of tourism income, public health concerns, and difficulties in transportation.

In summary, we have pinpointed a total of $K = 9$ factors affecting the three territories. For each city, we have formulated nine research questions (RQ) to present to the experts. These questions follow a precise framework and consider semantic reference factors in their formulation. Specifically, we construct the questions by first considering the time horizon, followed by the pertinent area, and finally the reference factor (e.g., "*Thinking about 2050... Which area of Cork will be most at risk of flooding?*"). At this stage, we meticulously assess the questions for semantic consistency and comprehensibility before proceeding to input them into the system. The final questions (Table 2) are categorized according to geographical reference and paired with their respective x, y coordinates. This ensures that when experts choose a particular question, they are redirected to the corresponding territory, minimizing search times, and preventing potential confusion post-selection.

3.3 Panel of experts and survey administration

At this stage, concurrently with uploading the questions into the system, we initiate the selection process for the panel of experts who will participate in our undertaking. As frequently observed in Delphi methodologies, as well as in most participatory processes, a significant challenge often lies in the methodology employed for selecting a suitable sample of experts. In our situation, lacking a reference population precludes the use of probabilistic methods for randomly selecting experts. Nonetheless, a purposive approach, known in the literature for engaging diverse parties with varied expertise, can effectively form a multidisciplinary panel (Baker et al. 2006). Given that developing future scenarios demands not only deep subject knowledge but also the capacity to envision the future, diversifying expertise is imperative for the process. Another constraint worth noting is the size of the sample utilized, as there is not a precise figure for the number of experts to engage. According to Calleo and Pilla (2023), a small sample (e.g., $N < 10$) might not yield meaningful results in achieving consensus, whereas an excessively large sample ($N > 100$) can become unwieldy to handle and may not generate significant outcomes due to invitation numbers surpassing actual responses, as highlighted by Hsu and Sandford (2007). Taking this fundamental aspect into consideration, we opted to assemble a sample of experts comprising diverse individuals with varying degrees of expertise. Devaney and Henchion (2018) suggest the Delphi expert panel selection should be carefully considered to match the appropriate knowledge and expertise needed for engaging in multiple ranges of futures. Specifically, we extended invitations to specialists possessing expertise in environmental science and climate change. This included:

1. *Academic experts*: bringing deep knowledge and research expertise in various aspects of environmental science, climate change, and related fields. They can provide insights based on their scholarly work and contribute to the development of evidence-based scenarios.
2. *Local authorities*: playing a crucial role in implementing policies and initiatives to address climate change at the community level. Their practical experience and knowledge of local environmental challenges and opportunities can inform the panel's discussions and recommendations.
3. *Industry members*: offering insights into technological innovations, sustainable practices, and potential barriers to implementation, essential for understanding the practical implications of climate policies and strategies.
4. *Environmental association members*: they can provide grassroots perspectives, highlight environmental priorities, and offer solutions from civil society's standpoint. Their involvement helps ensure that the panel considers the values and concerns of environmental stakeholders, promoting transparency and accountability in decision-making processes.
5. *Experts in strategic foresight*: specialists in strategic foresight bring valuable skills in our case since their expertise can help the panel anticipate potential future developments, assess the effectiveness of proposed interventions, and identify emerging trends in climate change impacts and mitigation efforts.

Once the potential panel of experts was identified (Table 3.), we proceeded to dispatch invitations via email, providing comprehensive technical details, deadlines, guidelines, and system instructions. Table 3 highlights the experts invited to participate in the survey for each of the four cities, along with those who ultimately participated. In this context, a participant is defined as an expert who contributes by inserting at least one n_i point on the dynamic map. Notably, there is a conspicuous trend of more invitations extended than participants engaged, a common occurrence in Delphi panels due to the busy schedules of experts. In total, our panel comprises 176 invitees, out of which $E = 79$ actively participated (of which 65% are female and the remaining are male, mainly from the reference city or affiliated with it), constituting a comprehensive panel for our research objectives.

Table 3 Panel of experts

Area	Contacted panelists				Participating panelists			
	Cork	Galway	Limerick	**Total**	Cork	Galway	Limerick	**Total**
Academia	20	15	13	**48**	8	7	8	23
Local authority	8	6	9	**23**	2	3	3	8
Industry	15	10	13	**38**	3	1	3	7
Association	19	21	16	**56**	3	3	4	10
Strategic foresight	5	3	3	**11**	2	1	1	4
Total	**67**	**55**	**54**	**176**	**18**	**15**	**19**	**52**

From the first invitation, experts' emails are automatically registered in the system, enabling them to commence answering questions by accessing the private session link provided by the facilitators. As previously outlined, the survey is meticulously organized, with research questions outlined in Table 2. Upon accessing the system, experts are presented with a real-time spatial questionnaire featuring a dynamic map and sidebar tools. Within the sidebar, we have prioritized the inclusion of essential elements to provide experts with comprehensive information on the subject matter. These elements encompass reports stemming from municipality assessments, prior studies, reference spatial analyses, and survey guidelines. By having these documents readily accessible for consultation, we mitigate the need for email exchanges and attachments, thereby streamlining the process and saving time. With the pertinent documents reviewed, experts can then proceed to address the questions based on their geographical expertise and competencies. Once the experts select a question, they gain the ability to pinpoint the pertinent area by adding a new opinion point on the map. Importantly, the expert retains the autonomy to choose the type of spatial information to input, comprising: (1) *Consensus point*: this denotes the most pivotal spatial input within the process, directly influencing the calculation of spatial consensus. (2) *Descriptive point*: this option allows for the insertion of a point without altering the consensus circle area, facilitating the inclusion of textual reference information. This is particularly useful if an expert wishes to provide insights to the facilitator that are external to the convergence process. (3) *Polygons*: experts can leverage this option to delineate actual areas on the map by adding specific comments. All the types of information are open to anonymous commentary by experts in real time, thereby triggering a dynamic and proactive discussion throughout the process. When considering where to position a new consensus point to address a query, an automatic window emerges, prompting individuals to evaluate the plausibility of their judgment on a scale ranging from 1 to 5 ($w = 1 - 5$). This component furnishes supplementary data for subsequent spatial analyses and considers the identified indicator I for the research objectives (for step-by-step guidelines see Calleo et al. (2023).

At this stage, the process unfolds whereby, with each point added, the currently engaged experts observe the consensus circle dynamically expand, contract, resize, and traverse the territory. Following the prescribed algorithm, if an expert positions a point, n_i within the perimeter of circle C, it modifies its dimensions and/or position according to the reference coordinates, demonstrating conformity with the prevailing viewpoints. On the contrary, if experts position a point beyond the circle's perimeter, diverging from the prevailing consensus, the circle will enlarge, and they will be prompted via an automated interface to justify their perspective with a textual explanation. This explanation is highlighted in the comments section, clearly marked with a red flag to alert other experts about the assessment of the proposal and its reasoning. This procedure seeks to determine if an expert offers further insights and sparks a pursuit of consensus. Overall, the main interface is depicted in Fig. 2.

However, as emerges in the study by von der Gracht (2012), consensus cannot be considered the only criterion to be evaluated in a Delphi process. Nonetheless, ensuring stability across iterative rounds remains crucial, and since our approach is conducted in real-time, therefore it does not deal with iterative rounds but a single real-time round, implying the difficulty of understanding when to stop the survey.

We, therefore, decided to offer experts a 30-day working slot, where the first 20 days are used by panelists for working, while the last 10 days are used to achieve stability. In fact, after 20 working days, the panel is asked to validate the scenarios one last time by reviewing the information provided. They are encouraged to contribute insights and explanations for responses diverging from the geo-consensus circle, providing experts with a final opportunity to validate scenarios before closure. This step entails revisiting the platform, closely analyzing response concentrations, and either identifying new areas within the circle or offering rationales for locations outside it.

3.4 Spatial analysis and statistical indicators

From the survey conducted, we, therefore, obtain two sets of results: 1) *Geographical outputs*: representing the final circle area for each question, encompassing $\frac{N}{2}$ of the overall cloud of N points provided by experts. These results are easily interpretable and beneficial through the map interface without additional processing. However, to ensure an accurate depiction of the final results, we retrieve and import the data matrices containing pertinent information such as spatial coordinates, circle area, and point weights derived from I, for each of the n_i points within ArcGIS PRO software. At this point, we offer a satellite view of the generated maps, as we believe it provides a more illustrative representation of the topological and morphological characteristics of the territory. Moreover, assuming each point n_i is assigned a weight $w = 1 - 5$, reflecting the plausibility of the event, we employ these

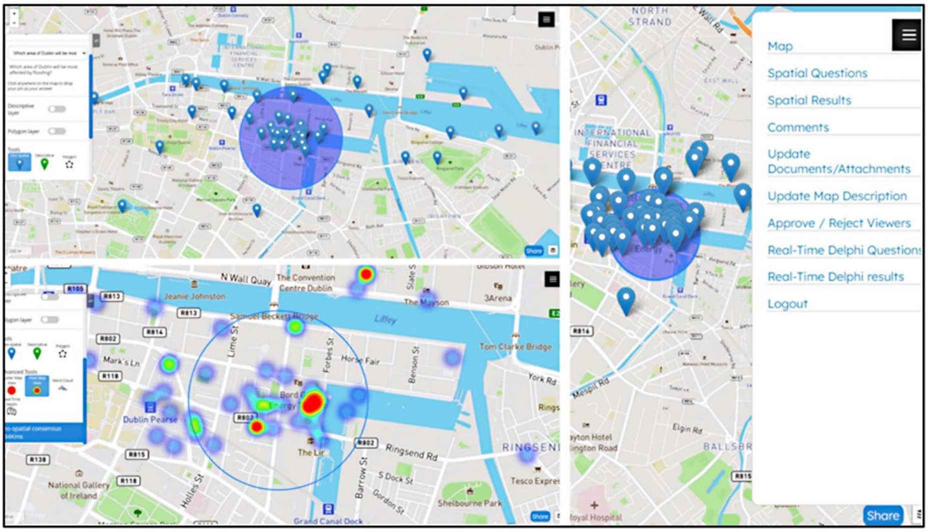

Fig. 2 Survey administration system

weights to create heat maps. These heat maps are tailored to visualize the spatial distribution of these weights, allowing us to identify hotspots characterized by concentrated high values and cold spots denoting areas with lower values.

Nevertheless, solely relying on graphical representation may lack the necessary analytical depth for conveying the ultimate conclusions. Thus, we delve into 2) *Non-geographical results*: concentrating on data primarily designed to gauge spatial consensus using three key indicators (Di Zio et al. 2017): M_1, M_2, M_3. In this case, $M_1 = FC\left(km^2\right)$, where FC represents the final area identified by the experts in km^2. This first indicator can be considered as an absolute value not considering the size of the study area and the initial size of C, inadequate for assessing spatial consensus. To overcome this challenge, we adopt a second indicator $M_2 = 1 - \frac{FC}{S}$, calculating the ratio between the final circle's area (FC) and the city's surface area (S). We assess the degree of spatial consensus where the more $M_2 \to 1$ the smaller C compared to S, and vice versa. To analyse the specific dynamic cooperation of experts in the real-time process, we adopt a third indicator $M_3 = \frac{FC}{IC} \bullet 100$. M_3, measures the degree of consensus and is expressed as a percentage, by calculating the ratio between the final circle area FC and the initial circle area IC. For this indicator, the higher the value ($M_3 \to 100\%$) the lower the convergence of opinions among panellists, the closer the value to zero, the higher the achieved consensus. Concerning this aspect, IC is assessed following the placement of the second point. This is because the initial point placement displays an approximate circle $C = km^2$ set a priori, as it is impractical to compute a single point following our algorithm. Similarly, it is analogous to determining the IQR of a single response on a scale in the traditional Delphi method.

A crucial element of all participatory spatial scenarios involves expert commentary, which serves to consolidate quantitative inputs into descriptive explanations and rationales. In this case, as the system generates a set of comments (M) for each question, the outcomes are visualized in real-time through the utilization of word clouds. These word clouds dynamically update as new comments are added, providing a visual representation of the data. Consequently, we proceed to present the word clouds at the conclusion of the survey, offering valuable input for the application of subsequent AI models. Upon finishing the exercise, we acquire a conclusive distribution of T days linked to circle size areas A_i , enabling us to engage in diverse analyses, such as time series modelling. Analyzing the time series is instrumental in gaining deeper insights into the process dynamics over time, elucidating how the curve responds to the progression of T concerning the rise, stability, or decline of A_i.

3.5 Artificial intelligence modelling

Following the acquisition of results from spatial analyses, textual analyses, and indicator analyses, we can advance to the implementation of the two proposed artificial intelligence models. To demonstrate our method, we consider $min\left(A\right)$ for each question in every city under examination, or the identified area where potential environmental threats may have consequences in 2050. However, additional points can also be considered, as the approach remains flexible to changes. Since each point comprises geographical coordinates, we extract them from the last $n_{i(x,y)}$ which forms the center of the circle C, inserted and import them into a tool capable of visualizing the real image of the territory, thus circumventing the need for expending time and resources on physical site visits (e.g., Google Street View). The image serves as input for the T2I model utilized in this application case, specifically Adobe Firefly Image 2 (www.firefly.adobe.com), an immensely valuable tool for generating images from a text prompt. However, in our scenario, we have a different approach, as we already possess an initial image available as input. Therefore, we utilize the "*Generative Fill*" tool to import the real image, and after successfully loading the image, the next step involves selecting a Region of Interest (ROI). This entails pinpointing the specific portion of the image where the model will operate based on the textual input provided. In this case, the textual input assumes crucial significance, as the model's actions are contingent upon it. In our study, we advocate for a general approach in crafting the prompt Q, as overly specific requests could potentially yield misleading results or introduce biases stemming from the facilitator's subjectivity. Specifically, for each city we propose the prompt highlighted in Table 4, starting from the introductory statement "*Generate…[…]*".

In addressing the given prompt, the model suggests three distinct alternatives for each image, referred to as scenarios hereafter. In this investigation, to mitigate potential biases stemming from subjective preferences, we focus on images devoid of graphical distortions or display issues arising from generation (Calleo et al. 2024. Presently, we have nine scenarios visualized as images, potentially depicting the landscape of 2050 and ready for communication. Nevertheless, communication is not the sole objective of scenario development within the context of FS. A significant emphasis should be placed on crafting active policies derived from these scenarios. These policies aim to propose potential changes aimed at averting future threats and implementing strategies in the present. To address this aspect, we employ GPT models, particularly GPT-3 (www.chat.openai.com) to generate a preliminary list of policies derived from the scenarios identified in the RTSD outputs. We consider the following outputs of each question to include in the prompt for the GPT: (1) *Key factor*: crucial to identify the specific threat at hand, pinpointing the pivotal point of reference. (2) *Geographic coordinates*: to provide information regarding the area identified through the entry of the last $n_{i(x,y)}$ point resulting in $min\,(A)$. (3) *Plausibility of occurrence*: to provide the model with the most indicated value corresponding to the scale ($w = 1 - 5$) for the points within $min\,(A)$, reflecting the event's plausibility. (4) *Experts' comments*: incorporating all the experts' comments in the form of feedback, suggestions, and personal opinions. Thus, ensuring a broader perspective for GPT. In this case, we choose not to furnish the model with the outputs of convergence indicators $M_1, M_2,\ M_3$, as we deem them irrelevant to policy production. Indeed, understanding the precise degree of consensus or stability among experts would not alter the reference strategies. After identifying the parameters to provide to the model, we proceed to evaluate the following prompt for each city and scenario, as depicted in Fig. 3.

The description of the prompt holds significance as it influences the eventual outcomes. Thus, we offer an initial directive to the model, instructing it to devise potential policies akin to policymakers. Following this, we tasked GPT with generating a list of 10 potential

Table 4 Text-to-image prompts

City	Q_1	Q_2	Q_3
Cork	A flooded area	A snow-affected area	A windstorm-affected area
Galway	A flooded area	A snow-affected area	A windstorm-affected area
Limerick	A flooded area	An area impacted by rising sea levels	A rainfall-affected area

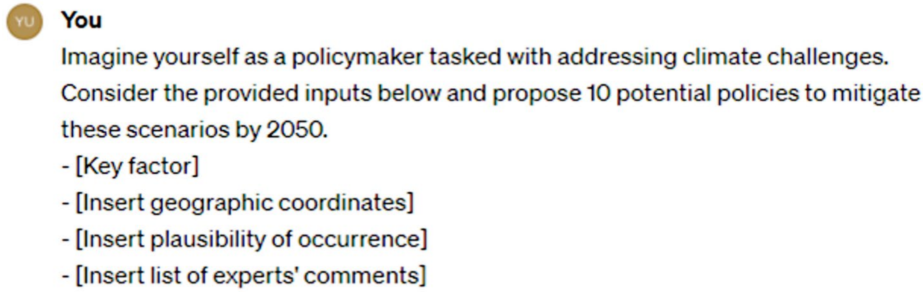

Fig. 3 Example of prompt

policies aimed at mitigating the impacts of the envisaged scenarios by the year 2050. Subsequently, we incorporate the previously established parameters to yield a preliminary draft of territorial policies or strategies. This approach addresses a notable gap within scientific literature, particularly in the latter stages of the Real-Time Spatial Delphi process, during the presentation of results and policy formulation. By adopting this method, even individuals lacking expertise can gain insight into potential scenarios, thus fostering broader awareness. Moreover, it streamlines the time and resources required for conducting workshops or iterative rounds to identify draft lists of territorial policies ready for assessment by policymakers for climate change mitigation (Giuffrida et al. 2024).

4 Results and discussion

4.1 Spatial patterns

The obtained outcomes thoroughly fulfill the research objectives, demonstrating the efficiency of the method in crafting impactful and informative spatial scenarios. The panel session started on February 1, 2024, and concluded on March 2, 2024, for a total of $T = 30$ days, achieving a significant level of spatial consensus and addressing all the queries posed on the main system. Following the order proposed in the methodology section, we present the results of the collaborative efforts made by experts (see Fig. 4) to identify spatial scenarios for the three cities. Experts have pinpointed three potential scenarios in which climate threats could affect the city of Cork by the year 2050. For Sc.1, the area identified as susceptible to flooding is situated in close proximity to the river Lee, with careful consideration given to the potential for heightened impacts on the safety of both the territory and its citizens. Likewise, concerning the potential impacts of sudden snowfall (Sc.2), the central area encompassing residential areas, schools, and colleges was assessed to bear the highest risk. Indeed, experts suggest (as elaborated in the following paragraph) that such occurrences could result in hazardous transportation disruptions and pose risks to citizens, particularly children and the elderly. In conclusion, concerning the potential impacts of heavy windstorms (Sc.3), the central area emerged as the most vulnerable, with the likelihood of significant damage to structures, as well as risks such as falling trees and branches leading to disruptions in transportation and jeopardizing public safety.

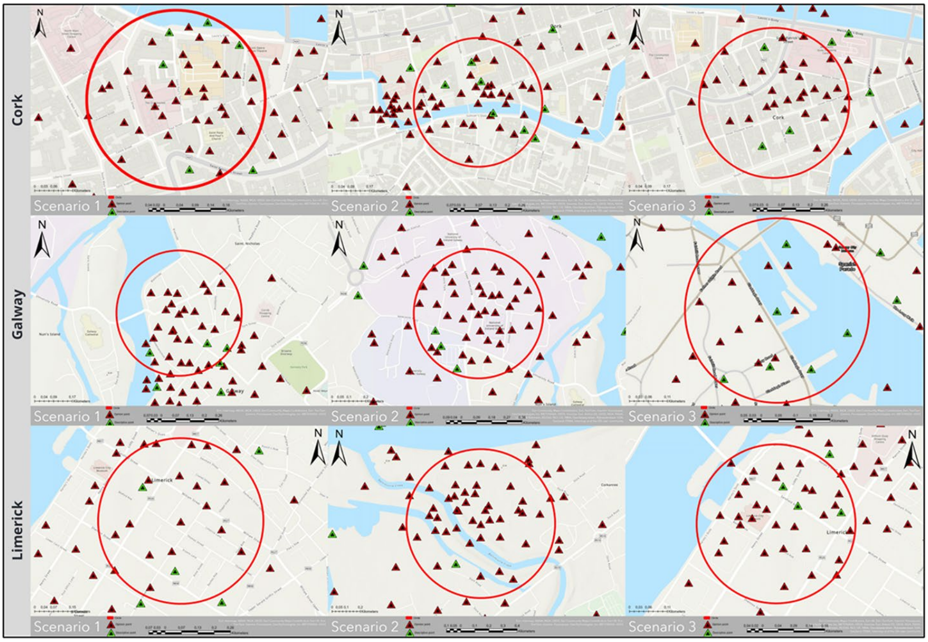

Fig. 4 Spatial scenarios

In Galway City (Sc.1), the primary area expected to bear the brunt of potential flooding by 2050 lies predominantly to the west of the city center, where the river Corrib flows, posing risks to lives, property damage, and potential disruptions to public services. Following this, in assessing the potential implications of sudden snowfalls on the city in the future (Sc. 2), the pinpointed area is indeed the city center, housing shops, residences, essential transportation networks, and vital amenities. In Sc. 3, the area identified as susceptible to impact events from sudden and intense windstorms will be situated to the southeast of the city, close to Galway station and the coastline. According to experts, this could result in damage to the area's territory, population, and production systems. In the case of Limerick, experts express serious concerns regarding the high plausibility of flooding, as highlighted in Sc.1, particularly in the town near the River Shannon. The potential flooding of the river raises significant worries among experts due to its possible negative implications and long-term consequences. According to the panel, by 2050, Cork City is anticipated to face the repercussions of rising sea levels (Sc. 2), particularly near its entry into the county. This poses potential threats to the population, infrastructure, and all economic activities within the area. Lastly, the area identified for potential impact from powerful and sudden rains (Sc.3) is situated in the city center along the river's edge, where numerous commercial shops are located. This area is at risk of possible flooding as a result of such rain events.

After identifying the main areas, the next step is to illustrate the results (Fig. 5) obtained from the heatmap analysis with weights assigned by the experts ($w = 1 - 5$) to evaluate the plausibility of the event.

This analysis is crucial because one might assume that the area identified by $min\,(A)$ consistently contains the major points with high plausibility. However, due to the real-time

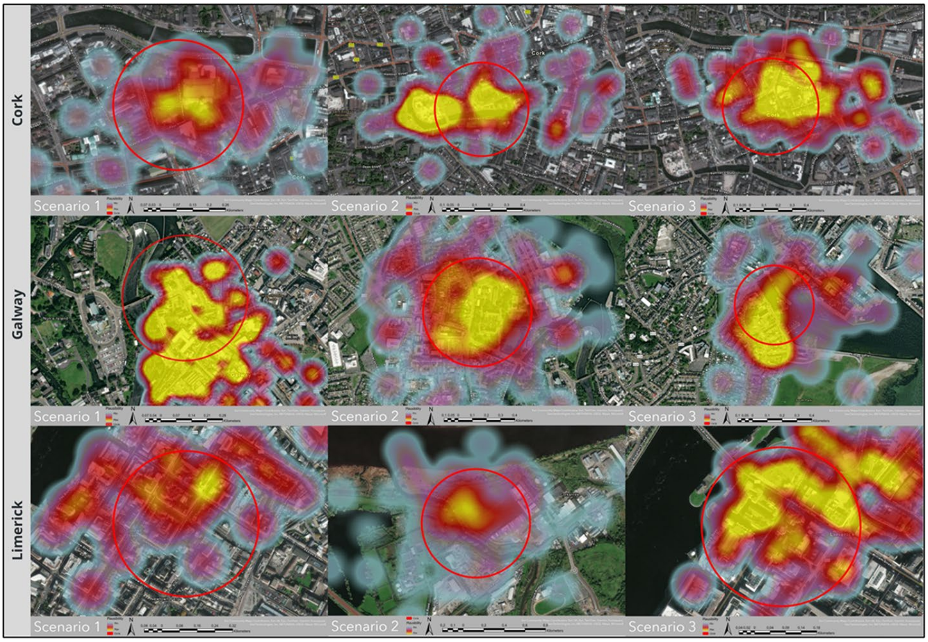

Fig. 5 Weighted heat map analysis

nature of the process, this is not always the case. A point with $w = 5$ located within the circle at the start of the process may not fall within $min\,(A)$ at the end. Nonetheless, it is generally observed that points inside $min\,(A)$ tend to exhibit high levels of plausibility. In our case, regarding the city of Cork, Sc.1 shows a high probability with a score of $w = 4$, with the majority of points located within $min\,(A)$. In Sc. 2, although most experts attributed $w = 4$, some points are outside $min\,(A)$, depicting how the circle moves throughout the process towards convergence (see Fig. 5). Finally, for Sc.3, the highest values are within the identified area, with most indicating $w = 3$, signifying medium plausibility. In the case of Galway, for Sc.1, there is a high probability with a $w = 4$, which tends towards $w = 5$, with points distributed more within the area, although many are close to the perimeter of $min\,(A)$. Similarly, for Sc. 2, there is a comparable situation with many points indicating a high plausibility of $w = 4$, located inside the convergence circle. Finally, for Sc. 3, the points are more dispersed, with most panellists indicating a value of $w = 4$, tending towards $w = 3$ inside the circle, and some high values outside. In the analysis of Limerick, significant plausibility is observed across all scenarios. For Sc. 1, most experts indicate a high plausibility ($w = 4$) of the event occurring in the specific area, although many points fall outside the designated area. In Sc. 2, the plausibility slightly decreases outside, while it concentrates inside the circle with a medium to high plausibility. Lastly, for Sc. 3, a high plausibility can be denoted ($w = 4$) observing both inside and outside of $min\,(A)$, thus indicating a dynamic and discussed convergence process.

4.2 Statistical indicators and word cloud analysis

Based on the results derived from the convergence metrics, it can be affirmed that the experts effectively and actively collaborated in seeking spatial consensus, achieving it across all scenarios for the indicators M_1, M_2, M_3 (Table 5). In the case of Cork, with a relatively extensive surface area of $S = 187\,km^2$, in Sc. 1 we observed a reduction in the circle's area from $IC = 1.41$ to $M_1 = 0.16$, with an overall of $N = 71$ opinion point. However, as mentioned earlier, this reduction represents absolute values and does not fully illustrate the dynamics of convergence. Therefore, we have employed the M_2 indicator to specifically gauge spatial consensus concerning the reference territory, resulting in $M_2 = 0.999$. This indicates a high consensus, as $M_2 \rightarrow 1$. Additionally, considering the last indicator, M_3, which examines the dynamic consensus process among experts, we observe a value of $M_3 = 11$. In this context, consensus can be considered achieved as $M_3 \leq 20$. The reference value is defined in the literature by von der Gracht (2012), since in classical Delphi methods, IRQ is commonly utilized as a primary indicator of convergence, and consensus is typically deemed satisfactory when it represents less than 20% of the measurement scale. Continuing further, Sc. 2, we gathered a total of $N = 88$ opinions, witnessing a reduction in the circle's area from $IC = 2.28$ to $M_1 = 0.18$. The indicators $M_2 = 0.999$ and $M_3 = 7\%$ exhibit a high consensus among experts. Similarly, in Sc. 3 involving a total of $N = 58$ points, we observed a reduction in the circle's area to $M_1 = 0.14$. Both the spatial consensus indicator $M_2 = 0.999$ and the indicator $M_3 = 7\%$ indicate a convergence of opinions. Concluding, in Sc. 3 with $N = 58$ opinion points, we observed a reduction in the circle's area from $IC = 1.28$ to $M_1 = 0.14$. Both the spatial consensus indicator $M_2 = 0.999$ and the convergence process indicator $M_3 = 10\%$ provide strong evidence of opinion convergence. For the Galway city scenarios, consensus among experts is also evident, where the surface area is $S = 57.3\,km^2$. In Sc. 1, with a total of $N = 80$ points, there was a significant reduction in the initial circle's area ($M_1 = 0.17$), accompanied by indicators $M_2 = 0.997$ and $M_3 = 12\%$, indicating a high level of spatial consensus and a notable convergence process among experts. In Sc. 2, where $N = 90$ points were inserted, starting from an initial area of $IC = 2.42$, a substantial reduction occurred, resulting in $M_1 = 0.10$. Similarly, there was a very high spatial consensus with $M_2 = 0.998$, and the convergence process among experts yielded $M_3 = 4\%$, demonstrating strong agreement. Lastly, in Sc. 3, with $N = 58$ inserted points, there was a reduction in IC towards $M_1 = 0.16$, with a spatial consensus of $M_2 = 0.997$. The resulting $M_3 = 10\%$ indicates a convergence pro-

Table 5 Descriptive statistics and indicator results

City	Scenario	$S(km^2)$	IC	$FC(M_1)$	M_2	M_1 (%)	N	M
Cork	Sc.1	187	1.41	0.16	0.999	11%	71	10
Cork	Sc.2	187	2.28	0.18	0.999	7%	88	13
Cork	Sc.3	187	1.28	0.14	0.999	10%	58	9
Galway	Sc.1	57.3	1.32	0.17	0.997	12%	80	8
Galway	Sc.2	57.3	2.42	0.10	0.998	4%	90	12
Galway	Sc.3	57.3	1.51	0.16	0.997	10%	58	9
Limerick	Sc.1	61.3	1.41	0.20	0.996	14%	44	6
Limerick	Sc.2	61.3	3.10	0.32	0.994	10%	60	8
Limerick	Sc.3	61.3	2.55	0.14	0.997	5%	55	11
Total							**604**	**96**

cess well below the threshold of $M_3 \leq 20$, affirming a robust level of consensus among experts. Finally, for the city of Limerick, with an extensive area of $S = 61.3\,km^2$, the obtained results can be deemed optimal. In Sc. 1, we gathered $N = 44$ spatial points, in Sc. 2, $N = 60$ points, and in Sc. 3, $N = 55$ points. Despite the initial circle area being much larger, we achieved a reduction in IC in all three scenarios. This can be attributed to the presence of greater clusters in the area, although they did not significantly affect the process. Concerning the indicator M_2, for Sc. 1 we observed $M_2 = 0.996$, for Sc. 2 $M_2 = 0.994$, and for Sc. 3, $M_2 = 0.997$, all close to 1, indicating a high level of spatial consensus. Finally, upon observing the convergence process as indicated by the M_3 values, we notice that, with the exception of the last scenario which shows the highest values, they consistently remain below the maximum threshold compared to the values of Cork and Galway. In Sc. 1, where $M_3 = 14\%$, it represents the highest result among all 9 scenarios. This outcome is attributed to experts identifying strategic and plausible points, widely dispersed within the city, particularly in the initial stages. In Sc. 2, with $M_3 = 10\%$, we achieved an excellent result considering the diversity of points. Lastly, in Sc. 3, with $M_3 = 5\%$, the convergence process is also considered positive for our study objectives. Overall, in light of the $N = 604$ opinion points received the results derived from the convergence measures are highly positive and represent a valuable resource for future RTSD studies. Indeed, while the convergence measures provide valuable insights, they become even more interesting when combined with other components, particularly the expert comments offered during the process. Integrating these diverse elements enriches the understanding of the findings and enhances spatial scenario development.

In our case, we collected a total of $M = 96$ comments from the experts, which will be instrumental in the subsequent integration of the GPT model. From Fig. 6, we can observe a real-time generated word cloud, showcasing the top 50 keywords in terms of absolute frequency (excluding stop words) for each city and scenario, supporting experts during the process. For the topic concerning flooding (Sc.1 across the three cities), the most notable keywords include "impacts", "resilience", "measures", "vulnerability", "proactive", "par-

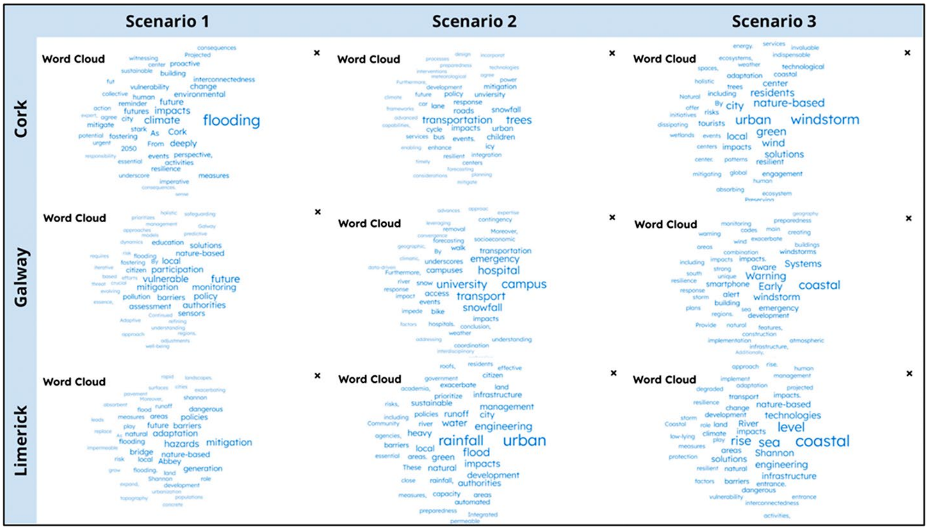

Fig. 6 System-generated word clouds

ticipation", "monitoring", "barriers" "nature-based (solutions)" "pavement" and "adaptation". Regarding sudden and heavy atmospheric phenomena such as snowfalls (Sc. 2 for Cork and Galway), rainfalls (Sc. 3 for Limerick), and windstorms (Sc. 3 for Cork and Galway), keywords include "transportation", "trees", "university", "policy", "wind", "technological", "green", "engagement", "hospital", "emergency", "socioeconomic", "warning" and "management" For Sc. 2, which concerns the rise of sea levels for the city of Limerick, identified words include "infrastructure", "nature-based (solutions)", "barriers", "technologies", "impacts", "adaptation", "low-lying" and "protection".

Overall, experts emphasize vulnerability assessment and proactive approaches to enhance resilience, often advocating for community participation in decision-making processes. Monitoring of flood-prone areas and identifying barriers to effective flood management are also key areas of focus and nature-based solutions, such as green infrastructure and permeable pavement, are increasingly being explored as viable adaptation strategies. Furthermore, from what emerged from the comments, discussions revolve around transportation disruptions, tree damage, and the impact on critical infrastructure like universities, hospitals, and emergency services. Policymakers are urged to implement effective management strategies, including technological advancements for early warning systems and engagement with affected communities. Socioeconomic considerations are paramount in addressing the aftermath of such events, highlighting the need for comprehensive emergency response plans. Finally, experts focus on infrastructure resilience, including barriers to protect against coastal erosion and technologies for monitoring sea level rise and assessing its impacts. Finally, the discussion emphasizes the need for adaptive measures in low-lying areas and the importance of protecting vulnerable coastal communities through proactive protection measures.

Before advancing to the performance of generative artificial intelligence models, it is crucial to analyze time series data. This aids in comprehending the consensus trend within the consensus area over the preceding days, employing an exponential curve. Through our examination of the indicator results, we have observed a favorable convergence of opinions across all nine scenarios. Notably, as illustrated in Fig. 7, consensus is achieved swiftly in comparison to traditional Delphi processes, which typically involve prolonged durations. Specifically, in the case of Cork City, the trends for all three scenarios exhibit a downward trajectory. For Sc. 1, initial fluctuations were followed by an exponential decrease starting from the 7th day, culminating in a consensus by the 14th day. In Sc. 2, the curve descended from the outset, reaching a consensus by the 15th day and stabilizing by the 21st day. As for Sc. 3, variations in responses were observed within the first 4 days, leading to a consensus by the 13th day after several circle area adjustments.

In the case of Galway City, the analysis reveals distinct patterns across the three scenarios. In Sc.1, the initial two days witnessed fluctuations in the consensus circle, with continued changes up to the 5th day. Subsequently, a consensus was achieved, leading to stability by the 13th day. Conversely, Sc. 2 exhibited a more pronounced downward trend, allowing for earlier consensus attainment, even before the 14th day, with only one adjustment occurring on the 18th day and stability established by the 24th day. Finally, in Scenario 3, notable shifts in the consensus circle were observed on the 3rd and 7th days, indicating increased activity among experts. Consequently, a consensus was reached, followed by stability on the 16th day. Regarding the latest city examined, Limerick, Sc. 1 witnessed a reduction in the consensus area, initially displaying greater inclusivity which gradually converged by the

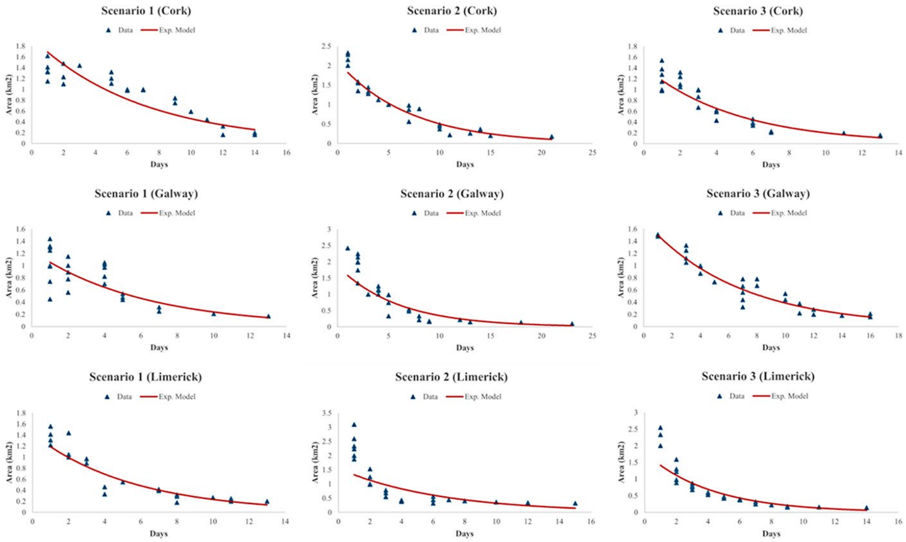

Fig. 7 Time series analysis

13th day. Conversely, Sc. 2 exhibited a rapid decrease in consensus area, notably from the 2nd day, starting with $IC = 3.10$, significantly higher compared to other scenarios. Consensus was achieved with stability by the 15th day. Finally, in Sc. 3, a consistent decreasing trend in the consensus area was observed throughout the days, culminating in consensus and stability attained by the 14th day.

In essence, the time series analysis revealed intriguing findings regarding the evolution of consensus over time, highlighting that a real-time Delphi system promotes swifter collaboration leading to a quick convergence of opinions among experts.

4.3 Scenarios visualization and policy list

After a careful analysis of the spatial and convergence results, we move on to visualizing the scenarios using the T2I model, following the methodology outlined in par. 3.5. To mitigate potential subjective influences from the facilitator, we opted to set the ROI to full width, encompassing the entire image without emphasizing specific areas. In the future, the model retains its flexibility, allowing for the selection of specific "areas of intervention" as needed, such as during the planning phase or the development of policies for particular regions within the image. As part of our study, we also assessed the model's performance by evaluating its generation speed – the average time between sending the prompt and the completion of generation. This speed can vary depending on factors like the size of the file being processed and the quality of the internet connection. Nevertheless, we achieved a remarkably positive result, with an average generation time of $\bar{x}= 0.13$ seconds.

The images presented in Fig. 8 illustrate nine scenarios for each city, utilizing authentic territorial photographs augmented with AI-generated elements. For instance, in Sc. 1 across all three cities, the model effectively simulates floods, despite minor graphical imperfections providing a glimpse into what 2050 might hold. These depictions avoid utopian ideals,

Fig. 8 Text-to-image model outputs

which might be challenging for those outside the field to conceptualize, yet effectively convey the looming dangers within the real imagery. Regarding atmospheric impacts such as snowfall (Sc. 2 for Cork and Galway), windstorms (Sc. 3 for Cork and Galway), and heavy rain (Sc. 3 for Limerick), the model convincingly generates potential inconveniences that the territory and its inhabitants are likely to face. Furthermore, Sc. 2 illustrates the potential rise in sea levels for Limerick city, resulting in flooding, effectively describing the spatial scenario with a flooded area near the riverbanks entering the city.

This implementation marks a significant innovation within Real-Time Spatial Delphi. Moreover, it could extend beyond territorial considerations and be applicable in scenario planning processes involving diverse domains such as product development, corporate strategies, and security planning. Conventional graphic software, as often used in decision-making processes (see Choi and Choi 2016), presents inherent challenges, including biases introduced by human designers and resource inefficiencies. AI models, despite being in developmental stages with inherent limitations, offer promising support for decision-making processes, particularly in scenario development, mitigating biases and resource wastage associated with conventional graphic design approaches (Calleo et al. 2024).

Upon visualizing our scenarios to depict plausible future outcomes, the subsequent phase involves utilizing the GPT model to generate a prospective compilation of ten policies corresponding to each scenario (Appendix A). The GPT model effectively formulated reference policies for the three cities, demonstrating efficiency and potential support for the final planning endeavors. Nevertheless, it is essential to emphasize that these policies represent a preliminary list, serving as a foundational framework for policymakers, yet requiring further refinement/adaptation before application. Overall, the policies proposed for Cork, Galway, and Limerick (Sc.1) offer comprehensive strategies to tackle the threat of flooding expected by 2050. They emphasize investing in flood defense infrastructure, promoting green solutions, engaging communities, integrating climate considerations, and fostering collaboration. These measures aim to protect vulnerable areas, enhance urban resilience, and ensure sustainable development in the face of climate change. For scenarios regarding the possibility of impacts due to snowstorms (Sc. 2, Cork, and Galway), the policies proposed in response to anticipated snowfall impacts in 2050 emphasize proactive measures to ensure safety, resilience, and continuity of essential services during winter months. Key strategies include developing comprehensive winter maintenance plans, investing in snow removal equipment and infrastructure, enhancing emergency response coordination, fostering community involvement, and promoting climate-resilient infrastructure planning. These policies reflect a forward-thinking approach to addressing the challenges posed by increased snowfall, aiming to minimize disruptions and safeguard public well-being in the face of changing climate conditions. Moreover, for Sc.3 of Cork and Galway, the policies proposed to address windstorm impacts by 2050 prioritize measures such as enforcing resilient building codes, enhancing emergency preparedness, investing in green infrastructure, and fostering cross-sector collaboration. These strategies aim to minimize windstorm damage, protect communities and infrastructure, and promote overall resilience in the face of severe weather events. Finally, Sc. 2 and Sc.3 of Limerick, demonstrate a comprehensive approach first to mitigating flood risks and enhancing resilience. They encompass a wide range of strategies, including infrastructure development, community engagement, urban planning, and natural resource management. By investing in coastal protection, elevating critical infrastructure, promoting green infrastructure, and fostering community resilience, Limerick aims to minimize the impact of flooding and ensure the long-term sustainability of its coastal and urban areas. Additionally, initiatives such as flood-resilient construction incentives, early warning systems, and nature-based flood management further contribute to enhancing preparedness and reducing vulnerability to future flood events. These policies reflect a proactive stance towards addressing the challenges posed by climate change and aim to safeguard both residents and infrastructure from the adverse effects of sea level rise and heavy rainfall.

5 Concluding remarks and future works

In this study, we have proposed an innovative approach to enhance the Real-Time Spatial Delphi method by integrating modern Artificial Intelligence (AI) models in the final stages of the process. This integration aims to address the challenges associated with disseminating and communicating spatial scenarios effectively, as well as formulating actionable policies and strategies for implementation. By leveraging T2I models and the ChatGPT, we bridge the gap between textual, spatial, and statistical components, thus facilitating a more comprehensive understanding and visualization of future scenarios. Our proposed methodology fills a crucial gap in the process of scenario planning by providing realistic visual depictions of potential spatial arrangements and generating draft lists of territorial policies ready for evaluation. By streamlining the timeline for policy development and easing the burden on policymakers, our approach enables more informed decision-making and proactive measures to address complex spatial challenges. Our proposed methodology represents a significant contribution to both the Real-Time Spatial Delphi method and the broader field of Futures Studies. One of the primary contributions lies in the enhanced visualization offered by our approach. Through T2I models, we enable the generation of realistic visual depictions of future scenarios based on spatial inputs provided by experts. This enhancement allows stakeholders to better comprehend and visualize potential spatial arrangements, thereby facilitating more informed decision-making processes. This type of foresight process is important as it exposes decision-makers to plausible potential risks. This is in line with the policy operations room, where the visualization of the challenges depicted in scenarios is often hard to interpret. Here the use of AI as a visualization tool offers a plausible and relevant grounding for discussions, to bring future issues into the present. These are not abstract but believable experiences based on carefully modelled visualizations. Moreover, our methodology streamlines the process of policy formulation within the RTSD framework. On the other hand, by integrating ChatGPT, we are able to generate a draft list of potential territorial policies ready for further evaluation. This not only accelerates the policy development process but also reduces the burden on policymakers by providing them with actionable insights derived from AI-driven scenario planning. Furthermore, our approach fosters comprehensive scenario development by bridging the gap between textual, spatial, and statistical components. By incorporating AI models, we create a more holistic understanding of future scenarios, thus facilitating more robust and adaptable strategies for addressing complex spatial challenges. In essence, our contribution enhances the RTSD method by leveraging AI technologies to provide stakeholders with richer, more actionable insights into future spatial dynamics. By doing so, we not only advance the capabilities of scenario planning but also empower decision-makers to navigate an increasingly complex and uncertain future with confidence. This is in line with the identified need for long-term engagement in developing scenarios based on urgent decision-making (Järvensivu et al. 2021).

While our study represents a significant advancement in the field of Futures Studies, there are several avenues for future research to explore: (1) *Refinement of AI Models*: Further refinement and optimization of Text-to-Image models and Chat Generative Pre-Trained Transformers can enhance the accuracy and realism of generated images and policy suggestions. (2) *Integration of Stakeholder Feedback*: Incorporating feedback from stakeholders, including citizens and policymakers, into the AI-driven scenario development process can improve the relevance and applicability of generated scenarios and policies. (3) *Validation and Testing*: Conducting rigorous validation and testing of the proposed methodology across diverse spatial contexts and scenarios can validate its effectiveness and reliability in real-world applications. (4) *Ethical Considerations*: Addressing ethical considerations surrounding the use of AI in scenario planning, including issues related to bias, transparency, and accountability, is essential to ensure the responsible and equitable deployment of these technologies. (5) *Long-Term Impact Assessment*: Assessing the long-term impact of implemented policies and strategies derived from AI-driven scenario planning can provide insights into their effectiveness and inform future decision-making processes. By addressing these areas of research, we can further advance the integration of AI technologies into spatial scenario planning and contribute to more sustainable and resilient spatial development strategies.

Appendix A

Table A1 Policy AI outputs (Sc.1 Cork)

Id.	Policy
1	**Investment in Flood Defence Infrastructure**: Allocate funds for the construction and maintenance of robust flood defence systems, such as barriers, levees, and stormwater management infrastructure, to protect vulnerable areas in Cork from flooding.
2	**Green Infrastructure Development**: Promote the implementation of green infrastructure solutions like green roofs, permeable pavements, and urban green spaces to absorb rainfall, reduce runoff, and mitigate flood risks while enhancing biodiversity and urban aesthetics.

Table A1 Policy AI outputs (Sc.1 Cork)

Id.	Policy
3	**Floodplain Management and Zoning**: Implement strict regulations on land use and development in flood-prone areas, including zoning restrictions and incentives for resilient building practices to minimize exposure to flood risks.
4	**Climate-Resilient Building Standards**: Enforce stringent building codes that require new constructions and renovations to incorporate climate-resilient design features, such as elevated foundations, flood-proofing measures, and resilient materials to withstand flooding events.
5	**Public Awareness and Education Campaigns**: Launch comprehensive public awareness campaigns to educate residents about flood risks, emergency preparedness, evacuation routes, and the importance of adopting flood-resilient behaviours and measures at the individual and community levels.
6	**Integration of Climate Considerations in Urban Planning**: Integrate climate change considerations into urban planning processes by prioritizing climate adaptation and resilience in development plans, transportation infrastructure, and land-use decisions to minimize flood exposure and enhance city resilience.
7	**Nature-Based Solutions**: Implement nature-based solutions like restoring wetlands, creating vegetative buffers along waterways, and enhancing natural floodplain storage to attenuate floodwaters, improve water quality, and provide additional ecosystem benefits while reducing flood risks in Cork.
8	**Investment in Early Warning Systems**: Invest in advanced technology and early warning systems for flood forecasting and monitoring to provide timely alerts to residents, emergency responders, and local authorities, enabling proactive responses and reducing flood-related damages and losses.
9	**Community Engagement and Participation: Foster** community engagement and participation through community-based flood risk management initiatives, neighbourhood associations, and participatory decision-making processes to empower local residents in identifying, prioritizing, and implementing flood resilience measures tailored to their specific needs and circumstances.
10	**Cross-Sectoral Collaboration and Partnerships**: Establish collaborative partnerships between government agencies, academic institutions, private sector stakeholders, and community organizations to leverage resources, expertise, and innovation in implementing holistic flood risk management strategies, sharing best practices, and building collective resilience against climate-induced flooding in Cork.

Table A2 Policy AI outputs (Sc.2 Cork)

Id.	Policy
1	**Winter Maintenance Plan**: Develop a comprehensive winter maintenance plan that includes protocols for snow removal, de-icing, and road clearance to ensure safe transportation routes and minimize disruptions during snow events.
2	**Investment in Snow Removal Equipment**: Allocate resources for the acquisition and maintenance of snow removal equipment, such as plows, salt spreaders, and snow blowers, to efficiently clear roads, sidewalks, and public spaces affected by snow accumulation.
3	**Emergency Response Coordination**: Enhance coordination among emergency services, local authorities, and relevant agencies to facilitate rapid response and assistance during snowstorms, including provisions for medical emergencies, shelter, and evacuation if necessary.
4	**Public Transport Resilience**: Improve the resilience of public transportation systems to withstand snow-related disruptions by investing in snow-resistant infrastructure, backup power systems, and alternative transportation modes to ensure continuity of service during adverse weather conditions.
5	**Winterization of Infrastructure**: Retrofit critical infrastructure, such as bridges, utilities, and public buildings, to withstand snow loads, prevent damage from freezing temperatures, and ensure uninterrupted service delivery during winter months.
6	**Community Snow Preparedness Campaigns**: Launch educational campaigns to raise awareness among residents about snow preparedness, winter safety tips, and the importance of maintaining clear pathways for pedestrian mobility to reduce accidents and injuries during snowy conditions.

Table A2 Policy AI outputs (Sc.2 Cork)

Id.	Policy
7	**Snow Emergency Communication Protocol**: Establish clear communication channels and protocols for disseminating timely updates, advisories, and warnings to the public regarding snow-related emergencies, road closures, and alternative travel routes through various media platforms and emergency notification systems.
8	**Support for Vulnerable Populations**: Implement targeted assistance programs to support vulnerable populations, including the elderly, people with disabilities, and low-income families, by providing access to emergency shelters, transportation services, and essential supplies during snow emergencies.
9	**Collaboration with Snow Clearing Volunteers**: Encourage community involvement in snow clearing efforts by organizing volunteer groups, neighbourhood associations, and business partnerships to assist with clearing snow from sidewalks, public spaces, and residential areas, supplementing municipal snow removal efforts.
10	**Climate-Resilient Infrastructure Planning**: Integrate climate resilience considerations into infrastructure planning and development processes by designing future infrastructure projects with climate change projections in mind, including considerations for increased snowfall, extreme cold events, and changing precipitation patterns in Cork.

Table A3 Policy AI outputs (Sc.3 Cork)

Id.	Policy
1	**Windstorm Resilient Building Codes**: Enforce stringent building codes that require structures to be designed and constructed to withstand high winds, including specifications for roof anchoring, window reinforcements, and structural integrity to minimize windstorm damage to buildings and infrastructure.
2	**Community Emergency Preparedness**: Implement community-based emergency preparedness programs to educate residents about windstorm risks, evacuation procedures, and shelter-in-place strategies, including the establishment of designated storm shelters equipped with emergency supplies and backup power.
3	**Vegetation Management and Tree Maintenance**: Implement regular vegetation management and tree maintenance programs to mitigate the risk of falling trees and branches during windstorms, including tree pruning, removal of dead or diseased trees, and planting wind-resistant tree species.
4	**Storm Surge Protection**: Invest in coastal defence measures, such as seawalls, dikes, and beach nourishment projects, to protect vulnerable coastal areas in Cork from storm surges and coastal erosion caused by intense windstorms and sea level rise.
5	**Early Warning Systems**: Strengthen early warning systems for severe weather events, including windstorms, by investing in advanced meteorological monitoring technologies, public alert systems, and communication networks to provide timely warnings and advisories to residents and local authorities.
6	**Critical Infrastructure Resilience**: Enhance the resilience of critical infrastructure, including power grids, telecommunications networks, and transportation systems, to withstand windstorm impacts through measures such as undergrounding power lines, backup power generation, and redundancy planning.
7	**Coastal Zone Management**: Implement comprehensive coastal zone management strategies to minimize vulnerability to windstorm hazards, including land-use planning, setback requirements, and ecosystem-based approaches to coastal protection and restoration.
8	**Insurance and Financial Assistance Programs**: Develop insurance and financial assistance programs to help homeowners, businesses, and communities recover from windstorm damage, including affordable insurance options, low-interest loans, and grants for retrofitting vulnerable properties and infrastructure.
9	**Cross-Sectoral Coordination**: Facilitate collaboration and coordination among government agencies, emergency services, utilities, businesses, and community organizations to ensure a cohesive and effective response to windstorm events, including joint training exercises, resource sharing agreements, and mutual aid networks.

Table A3 Policy AI outputs (Sc.3 Cork)

Id.	Policy
10	**Climate-Resilient Urban Design**: Integrate climate resilience principles into urban design and planning processes by incorporating wind-resistant building materials, green infrastructure, and natural windbreaks into the built environment to reduce wind exposure and enhance urban resilience to windstorms in Cork.

Table A4 Policy AI outputs (Sc.1 Galway)

Id.	Policy
1	**Investment in Flood Defence Infrastructure**: Implement a comprehensive plan to upgrade and strengthen flood defences such as levees, flood walls, and stormwater drainage systems in vulnerable areas of Galway.
2	**Green Infrastructure Development**: Promote the implementation of green infrastructure solutions such as green roofs, permeable pavements, and rain gardens to absorb stormwater runoff and reduce the risk of flooding.
3	**Wetland Restoration and Preservation**: Restore and preserve wetlands in and around Galway to act as natural buffers against flooding by absorbing excess water and reducing flood peak flows.
4	**Zoning and Land-Use Planning**: Enforce strict zoning regulations and land-use planning policies to prevent further development in flood-prone areas and encourage sustainable development practices in safer zones.
5	**Public Awareness and Education Campaigns**: Launch extensive public awareness and education campaigns to inform residents about flood risks, proper flood preparedness measures, and the importance of mitigating climate change impacts.
6	**Early Warning Systems**: Invest in advanced early warning systems and flood forecasting technologies to provide timely alerts to residents and emergency responders, allowing for better preparedness and response to flood events.
7	**Community-Based Flood Resilience Programs**: Establish community-based flood resilience programs that engage local residents, businesses, and organizations in developing and implementing flood mitigation strategies tailored to the specific needs of neighbourhoods within Galway.
8	**Incentivize Green Building Practices**: Provide financial incentives and tax breaks for developers and homeowners who incorporate flood-resistant design features and sustainable building practices into their construction projects.
9	**Integrated Water Management**: Adopt an integrated water management approach that combines flood risk reduction efforts with initiatives to improve water quality, enhance ecosystem health, and promote sustainable water use in Galway.
10	**Green Transportation Initiatives**: Implement policies to reduce carbon emissions from transportation, such as promoting the use of electric vehicles (EVs), expanding public transportation infrastructure, creating more pedestrian-friendly spaces, and incentivizing cycling through bike-sharing programs and dedicated bike lanes.

Table A5 Policy AI outputs (Sc.2 Galway)

Id.	Policy
1	**Snow Clearing and Removal Infrastructure**: Invest in enhanced snow clearing and removal infrastructure, including snowploughs, snow melters, and salt storage facilities, to ensure efficient and timely clearance of snow from roads, sidewalks, and public spaces.
2	**Winter Emergency Preparedness Plans**: Develop comprehensive winter emergency preparedness plans that outline protocols for snowstorm response, coordination among relevant agencies, and communication with residents to minimize disruptions and ensure public safety during heavy snowfalls.
3	**Climate-Resilient Road Maintenance**: Implement climate-resilient road maintenance practices, such as upgrading road surfaces with materials that are more resistant to freeze-thaw cycles and developing innovative technologies to prevent ice buildup on roads during heavy snow events.

Table A5 Policy AI outputs (Sc.2 Galway)

Id.	Policy
4	**Community Snow Clearing Programs**: Establish community-based snow clearing programs that mobilize residents to assist with clearing snow from neighbourhood sidewalks, pathways, and communal spaces, fostering a sense of solidarity and shared responsibility during snowstorms.
5	**Green Infrastructure for Snow Management**: Integrate green infrastructure solutions, such as vegetated swales and permeable pavements, into urban design to manage snowmelt runoff more effectively, reduce the risk of flooding from rapid snowmelt, and mitigate the urban heat island effect.
6	**Public Transportation Resilience**: Enhance the resilience of public transportation systems to heavy snowfalls by investing in snow-resistant infrastructure, equipping vehicles with snow tires or chains, and implementing backup plans to ensure continued service during severe winter weather conditions.
7	**Snow Load Regulations for Buildings**: Enforce stringent snow load regulations for building design and construction to ensure that structures are capable of withstanding heavy snow accumulations without compromising their structural integrity or posing risks to occupants and neighboring properties.
8	**Winter Storm Risk Communication**: Improve public awareness and communication about winter storm risks through education campaigns, weather alerts, and community outreach initiatives, empowering residents to take proactive measures to prepare for and respond to heavy snowfalls effectively.
9	**Research and Development for Snow Management**: Allocate resources to research and development initiatives aimed at advancing snow management technologies, such as remote sensing for snowpack monitoring, predictive modeling for snowfall forecasting, and innovative snow removal techniques.
10	**Collaboration with Regional Partners**: Foster collaboration with neighbouring regions and municipalities to coordinate snowstorm response efforts, share resources and expertise, and develop regional snow management strategies that prioritize resilience, sustainability, and equitable access to snow clearing services.

Table A6 Policy AI outputs (Sc.3 Galway)

Id.	Policy
1	**Enhanced Building Codes**: Update building codes to ensure that new constructions and renovations meet higher standards for wind resistance, including requirements for reinforced structures, secure roofing materials, and impact-resistant windows.
2	**Community Resilience Planning**: Develop community resilience plans that include strategies for strengthening infrastructure, establishing emergency shelters, and organizing neighborhood response teams to mitigate the impacts of heavy windstorms and ensure swift recovery.
3	**Green Infrastructure Investment**: Invest in green infrastructure projects such as urban forests, windbreaks, and vegetative barriers to reduce wind speeds, minimize wind damage, and enhance the resilience of urban areas to heavy windstorms.
4	**Storm-Resilient Power Grids**: Upgrade power grids to withstand extreme wind events by burying power lines, installing wind-resistant utility poles, and incorporating smart grid technologies for quicker detection and response to power outages.
5	**Public Education and Awareness Campaigns**: Launch public education campaigns to raise awareness about the risks associated with heavy windstorms, provide guidance on preparedness measures, and promote community engagement in resilience-building activities.
6	**Storm-Resistant Land Use Planning**: Incorporate storm-resistant land use planning practices into urban development strategies, such as limiting construction in high-risk coastal areas, preserving natural buffers, and implementing setback requirements for new developments.
7	**Green Roof Incentives**: Offer incentives and rebates for the installation of green roofs on buildings, which can help absorb wind energy, reduce wind-induced pressure on structures, and improve overall urban resilience to heavy windstorms.

Table A6 Policy AI outputs (Sc.3 Galway)

Id.	Policy
8	**Strengthened Building Inspections**: Implement rigorous building inspection programs to ensure that existing structures meet safety standards for wind resistance and require retrofitting or reinforcement where necessary to reduce vulnerability to wind damage.
9	**Climate-Resilient Transportation Infrastructure**: Upgrade transportation infrastructure to withstand heavy windstorms, including securing road signs and traffic signals, reinforcing bridges and overpasses, and establishing emergency response protocols for road closures and debris removal.
10	**Cross-Sector Collaboration**: Foster collaboration among government agencies, businesses, community organizations, and research institutions to develop and implement comprehensive strategies for mitigating the impacts of heavy windstorms, sharing resources, expertise, and best practices to enhance overall resilience in Galway.

Table A7 Policy AI outputs (Sc.1 Limerick)

Id.	Policy
1	**Investment in Flood Defence Infrastructure**: Implement a comprehensive plan to build and strengthen flood defences such as levees, flood walls, and stormwater management systems to protect vulnerable areas in Limerick from flooding events.
2	**Green Infrastructure Development**: Promote the use of green infrastructure, such as green roofs, permeable pavements, and rain gardens, to absorb excess rainwater and reduce surface runoff, thereby mitigating the risk of flooding.
3	**Wetland Restoration and Preservation**: Restore and preserve wetlands in and around Limerick to act as natural buffers against flooding, as wetlands can absorb and store large amounts of water during heavy rainfall events.
4	**Land-Use Planning Regulations**: Enforce strict land-use planning regulations to prevent further development in flood-prone areas and incentivize relocation of vulnerable communities to safer zones.
5	**Flood Risk Assessment and Mapping**: Conduct regular flood risk assessments and update flood hazard maps to identify high-risk areas accurately and inform decision-making regarding infrastructure development and emergency response planning.
6	**Public Awareness and Education Campaigns**: Launch public awareness campaigns to educate residents and businesses about flood risks, emergency preparedness, and the importance of adopting flood-resilient practices such as elevating properties and purchasing flood insurance.
7	**Incentives for Resilient Infrastructure**: Provide financial incentives, tax breaks, or subsidies to property owners and developers who invest in flood-resilient infrastructure measures, such as elevating buildings above flood levels and installing flood barriers.
8	**Climate-Resilient Building Codes**: Strengthen building codes to ensure that new construction and infrastructure projects in Limerick are designed and constructed to withstand the impacts of climate change, including increased flooding risks.
9	**Integration of Nature-Based Solutions**: Integrate nature-based solutions, such as green corridors and riparian buffers, into urban planning and development strategies to enhance natural flood mitigation measures and improve overall resilience to climate change.
10	**Collaboration and Coordination**: Foster collaboration and coordination among government agencies, local authorities, community organizations, and stakeholders to develop and implement holistic flood management strategies that address the multifaceted nature of the issue and ensure effective response and recovery efforts during flooding events.

Table A8 Policy AI outputs (Sc.2 Limerick)

Id.	Policy
1	**Construction of Coastal Protection Infrastructure**: Implement a strategic plan to construct coastal protection infrastructure such as seawalls, revetments, and flood barriers to shield vulnerable areas of Limerick from rising sea levels and storm surges.

Table A8 Policy AI outputs (Sc.2 Limerick)

Id.	Policy
2	**Elevation of Critical Infrastructure**: Require critical infrastructure, such as power plants, hospitals, and transportation hubs, to be elevated above projected sea level rise to ensure their continued functionality and resilience to flooding.
3	**Investment in Natural Buffer Zones**: Invest in the creation and restoration of natural buffer zones, such as mangrove forests and coastal wetlands, to absorb wave energy, reduce erosion, and provide habitat for biodiversity while mitigating the impacts of rising sea levels.
4	**Integration of Climate Adaptation into Urban Planning**: Integrate climate adaptation considerations, including projected sea level rise, into urban planning processes to guide development away from high-risk coastal areas and towards safer locations.
5	**Promotion of Green Infrastructure**: Promote the implementation of green infrastructure solutions, such as vegetated dunes, living shorelines, and green roofs, to enhance coastal resilience, improve water quality, and mitigate the impacts of rising sea levels in Limerick.
6	**Community Resilience Building**: Facilitate community-led resilience building initiatives, such as community emergency response teams and neighbourhood adaptation plans, to empower residents to prepare for and respond to flooding events associated with rising sea levels.
7	**Incentives for Flood-Resilient Construction**: Offer financial incentives, tax breaks, or subsidies to property owners and developers who invest in flood-resilient construction techniques and elevate buildings above projected sea level rise.
8	**Flood Risk Communication and Education**: Launch public awareness campaigns to educate residents and businesses about the risks associated with rising sea levels, the importance of flood preparedness, and the need for adaptive measures to protect lives and property.
9	**Development of Climate-Resilient Transportation Networks**: Develop climate-resilient transportation networks that prioritize the protection of critical transportation infrastructure, such as roads, bridges, and ports, from the impacts of rising sea levels and flooding.
10	**International Collaboration and Knowledge Sharing**: Foster collaboration and knowledge sharing with other coastal cities facing similar challenges to exchange best practices, innovative solutions, and lessons learned in adapting to and mitigating the impacts of rising sea levels.

Table A9 Policy AI outputs (Sc.3 Limerick)

Id.	Policy
1	**Stormwater Management Infrastructure Improvement**: Upgrade stormwater drainage systems in the city centre area to increase capacity and reduce the risk of urban flooding during heavy rainfall events.
2	**Green Roof Incentive Program**: Implement a program offering incentives, such as tax breaks or grants, for property owners in the city center to install green roofs, which absorb and retain rainwater, reducing runoff and alleviating strain on drainage systems.
3	**Permeable Pavement Mandate**: Mandate the use of permeable pavement for new construction and redevelopment projects to allow rainwater to infiltrate the ground instead of contributing to surface runoff and flooding.
4	**Creation of Urban Green Spaces**: Increase the number of urban green spaces, such as parks and gardens, in the city centre to provide natural areas for rainwater absorption and reduce the risk of flooding.
5	**Public Transportation Promotion**: Promote the use of public transportation, cycling, and walking as alternative modes of transportation to reduce reliance on cars, which contribute to impervious surfaces and increase runoff during heavy rainfall events.
6	**Flood-Resilient Building Standards**: Establish and enforce building standards that require new construction and renovation projects in the city centre to incorporate flood-resilient design features, such as elevated ground floors and flood-proofing measures.
7	**Early Warning Systems**: Implement early warning systems for extreme weather events, including heavy rainfall, to alert residents and businesses in the city centre area and enable timely evacuation and emergency response.

Table A9 Policy AI outputs (Sc.3 Limerick)

Id.	Policy
8	**Community Flood Preparedness Education**: Conduct educational campaigns to raise awareness about flood risks and provide residents and businesses with information on flood preparedness measures, including emergency kits and evacuation plans.
9	**Nature-Based Flood Management**: Utilize nature-based solutions, such as constructed wetlands and green corridors, to manage stormwater and reduce the impact of heavy rainfall events on the city centre area.
10	**Integrated Urban Planning**: Integrate urban planning initiatives across departments to ensure that infrastructure development, land use decisions, and environmental protection efforts in the city centre area are coordinated and address the challenges posed by heavy rainfall impacts.

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Declarations

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