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Unveiling the assessment process behind an integrated flood risk management plan

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ABSTRACT

In the context of the European Floods Directive, flood risk assessment is a critical component for the definition of an integrated management plan that operates within a multidimensional landscape shaped by intricate interactions. This study explores this complex interplay using a comprehensive framework, aimed at enlightening the non-linear pathways that flood risk assessments can traverse. It adopts the Gioia Methodology within the Grounded Theory approaches, enabling a nuanced exploration of flood risk assessment dynamics. Utilizing data from an Italian case study in the Po River District, this study unveils the flood risk assessment process framework by identifying 13 first-order codes, 6 s-order themes and 3 aggregate dimensions. It introduces a qualitative self-assessment tool to facilitate integration across dimensions and enhance Directive alignment, offering valuable insights for future flood risk assessment implementations.

1. Introduction

Over the past decade, flood impacts have significantly increased in Europe [1] and across the world, especially in low- and middle-income countries [2]. As a result of climate change [3] and increased exposure [4], this growth is expected to continue in the future. Accordingly, the need foreffective flood risk management is imperative today more than ever.

After the destructive floods that hit central Europe in 2002, the EU recognized the seriousness of the flood threat in its territory and the need for incisive measures to deal with it. Consequently, in 2007, the European Floods Directive (FD) [5] was issued to provide Member States with guidance on the formulation of Flood Risk Management Plans (FRMPs), with the main aim of reducing the adverse consequences of floods on exposed assets (i.e., human health, environment, cultural heritage and economic activity) in the EU member states. The implementation of the FD at the river district scale is based on three consecutive steps 1) a preliminary delineation of flood-prone areas (i.e., Areas of Potentially Significant Flood Risk, APSFRs); 2) the elaboration, for such areas, of flood hazard and risk maps; and 3) the establishment of Flood Risk Management Plan (FRMP).

Flood hazard maps must combine hydrological and hydraulic models to show the highest hazard intensity (i.e., in terms of flood water depth, velocity, duration) in the whole domain, associated with specific return period flood scenarios. For each of these scenar-

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ios, flood risk maps must show the potential adverse consequences of floods based on indicators, such as the number of potentially affected inhabitants and economic activities, the indication of areas where floods with a high content of transported sediments and debris flow can occur and information on significant sources of water pollution. Finally, based on hazard and risk maps, FRMPs should include the objectives of flood risk management, the summary of the risk management measures and their prioritization, and, when applicable, a description of the methodology used for their prioritization, e.g., by means of Cost-Benefit Analysis (CBA). In particular, in Chapter IV of the FD (i.e., "Flood Risk Management Plans"), Art. 7 requires the definition of appropriate objectives for the management of flood risks, focusing on the reduction of potential adverse consequences of flooding on multiple assets, such as "*human health, the environment, cultural heritage and economic activity*". Most importantly, the FD foresees the establishment of FRMPs in coordination among all the interested actors, such as Member States and Local Authorities at river district level.

The FD stipulates an iterative approach for evaluating and mapping flood risks and requires the development, updating, and implementation of FRMPs every 6 years. By the end of 2021, the second set of FRMPs had been completed in European countries. However, even today, the current approaches used in Flood Risk Assessment (FRA) and Management (FRM) fail to fully account for the complexity of a system exposed to flood [6–9]. Complexity arises from at least three "dimensions". The first is related to the heterogeneity of flood-exposed elements and related impacts, which calls for a multisectoral and multiscale assessment and management, involving different disciplines and interventions at multiple levels, ranging from addressing local problems to aligning and shaping funding and regulatory frameworks at the regional, national, or international levels [10]. It is important to recognize that the reach of flood risk extends beyond the boundaries of a river district. The increasing inter-sectoral dependence is a growing threat to the well-being of communities, as became evident during the 2011 floods in Thailand. The long-lasting event led to a significant disruption of production chains in the automotive and electronic industries, which had a ripple effect beyond Thailand's borders, resulting in unexpected economic losses globally [11]. The domino effect caught the insurance industry, which had previously overlooked the temporal dynamics of global supply chains in its risk models [12]. Moreover, recent observations from the 2021 western European flood event have highlighted the limitations of large-scale risk assessments in accounting for localized but severe impacts on critical infrastructures that can lead to cascading effects (Koks et al., 2022; Mohr et al., 2023). Therefore, new methods considering indirect and systemic effects in addition to direct impacts are necessary to address the spread of flood risk [6,13–15]. The second dimension is linked to the dynamic behavior of risk determinants (like change in flood hazard due to climate change or change in exposure and vulnerability due to urbanization/development processes) that calls for a dynamic rather than static risk assessment [16–18]. At last, the implementation of flood risk management strategies involves multiple sectors with varying interests and responsibilities. The diversity and multiplicity of stakeholder perspectives on flood risk (management) are well-known to professionals involved in participatory planning processes [15,19]. Consequently, flood risk management involve a complex web of actors, rules, conventions, processes, and mechanisms ([20]; Alexander, Priest and Mees, 2016).

An improved understanding and more comprehensive estimation of flood risk are then crucial for informed decision-making on flood risk management. Likewise, the concept of integration is frequently called for within flood risk management policy development and implementation [21], where integration may refer to different complexities characterizing the flood risk management process. Moreover, integration is being increasingly advocated for managing "wicked problems", which are complex policy issues characterized by uncertainty and involving multiple actors with conflicting interests [22]. Russel et al. [23] describe connections among actors operating at different levels or across sectors, Van den Hove [24] shows the linkage between science and policy, Brown and Damery [25] between social and technical perspectives, while Anselmo et al. [26] between different modelling tools. According to Schröter et al. [14], an integrated approach across sectors and between spatial levels can optimize synergies and/or create new opportunities for flood risk management. Nonetheless, an integrated approach that considers the interdependencies across sector objectives and works within governance structures to manage them is key to understand and address challenges such as flood risk management, which lie outside one sector's remit [27,28].

To address the above problem from a technical point of view and starting from the investigation of one of the preliminary steps for flood risk management, i.e., Flood Risk Assessment (FRA), the present paper aims to achieve the following objectives:

1) unveil the framework of the FRA process (par. 3.1) for which no standardized tools and procedure are available (Borowska-Stefańska, 2024): this analysis, based on Grounded Theory (GT), will provide insights into the dynamics and domain of the FRA process, shedding light on the interplay between different stakeholders and factors influencing the assessment outcomes;
2) propose a qualitative tool to self-assess the FRA process (par. 3.2): by recognizing the need for a practical approach, we propose a qualitative tool that allows stakeholders to self-assess their progress in the FD implementation. This tool, based on the identified FRA framework, will enable practitioners to evaluate the level of advancement and integration within their specific assessments, facilitating continuous improvement and refinement;
3) highlight lessons learned for FRA implementation (par. 4): from the analysis of a real-world Italian case study, we extract valuable insights from the implementation of FRA process. By examining the challenges, successes, and limitations encountered, we aim to contribute to the broader understanding of FRA practices and their implications.

In summary, this study introduces a novel application of Grounded Theory to FRA, aiming to enhance decision-making processes and promote continuous improvement in the field by equipping stakeholders with tools for critical evaluation and advancement of their FRA practices, thereby fostering a more effective and informed approach to flood risk management.

2. Methods and data

In the context of the empirical research and theoretical understanding surrounding the process of FRA, within the broader activities to implement FRMPs, this work aims at advancing research by building theory. In recent years, while there has been a recognized technical advancement in FRA, challenges have been highlighted in flood risk governance in relation to actors and rules (Dieperink et al., 2016; Matczak and Hegger, 2021) and cooperation among stakeholders, which ultimately drives the need for context-specific models (Ishiwatari, 2019). To enable in depth understanding and explanation of FRA and its underlying processes, Grounded Theory approaches [29] have been shown to be suitable for building theory. As underlined by Kathy Charmaz [30], the "*Glaser and Strauss's book (1967) first articulated these strategies and advocated developing theories from research grounded in data rather than deducing testable hypotheses from existing theories*". The research paradigms that underlie GT are applied to a dynamic and co-created system whose parts are so interconnected that one part inevitably influences the others. Therefore, to understand a phenomenon, one cannot separate its parts but it is necessary to examine the process in its wider context by applying a holistic approach [31]. As stated in the introduction, FRA is characterized by strong interacting levels of scientific and technical analysis, high number of actors, variables and different spatial contexts involved, as well as a multi- and interdisciplinary orientation. Collectively, these peculiarities enable FRA to take advantage from the GT's perspective [32], being such approach well-suited for addressing "how" questions [33] in new and poorly understood phenomena [34,35], while preserving the generalizability of findings [36]. Case studies (see section 2.1) have proven valuable for theory-building in situations where existing theories are inadequate or absent (i.e., "*for building theory in situations where there is either no theory or a problematic one*", [35]) or when processes are complex. Therefore, we believe our research can contribute to the knowledge base surrounding the multidimensional processes behind FRA by uncovering novel ideas, effective processes or dynamics, etc.

In the context of GT, many authors have proposed inductive and grounded research approaches [37,38], with an increasing recent trend toward more quantitative approaches [39] to address the criticism directed at existing qualitative research (Christopher A. [40]), which has been challenged in terms of its perceived credibility [41]. Despite this criticism, within the qualitative methodological approaches, the Gioia Methodology (GM) [42,43] can meet the rigorous standards of trustworthy research [44]. GM has been developed on the hypothesis that the purpose of discovery-oriented research is to generate a plausible and defensible explanation of how and/or why a phenomenon occurs (see Ref. [45]).

To provide insights on how FRA processes can be approached, following the GM in the context of grounded theory, we derived theory from research based on data rather than formulating testable hypotheses from pre-existing theories. To accomplish this, we initiated from the selection of a case study (i.e., FD implementation in Italy outlined in section 2.1). Section 2.2 describes in detail the data collection from the scientific experts who were involved in the process of the case study and, finally, we conducted a rigorous data analysis following the principles of GT to identify threads of inquiry that might help to understand FRM processes. The details of data analysis implementations are outlined in section 2.3.

2.1. Case selection

The Po River District Authority (AdBPo, North of Italy) signed in May 2020 an agreement with 20 Italian Universities and the Italian National Research Council (CNR). The aim of this agreement was to transfer the state of the art about modelling into the development and updating of flood risk maps, which serve as essential information for the formulation of FRMPs, as mandated by the FD and implemented in Italy through Legislative Decree 49/2010. Within this consortium agreement, we focused and gathered information from the Team of Scientific Experts (TSEs) involved in the development of methods and tools devoted to flood damage modelling (i.e., the MOVIDA project, [63]; https://sites.google.com/view/movida-project). Each TSE involved in gathering information typically comprised 3 to 4 academic researchers hailing from various universities collaborating on the project, totaling approximately 20 researchers. Each researcher possesses academic expertise in the study of flood hazard and the assessment of risk associated with different assets. This process started in June 2020 and concluded after 18 months in December 2021.

The objective of MOVIDA was the development of tools for the analytical evaluation and mapping of expected flood damage in the Areas of Potential Significant Flood Risk (APSFRs) of the district. Proper damage assessment tools were identified for all the six categories of exposed assets included in the FD: population, infrastructures (classified as: strategic buildings, roads and railways), economic activities (classified as: residential buildings, industrial/commercial and agricultural activities), environmental and cultural heritage, and na-tech sites. The damage assessment varied for each category and sub-category of exposed assets and the resulting methodologies were implemented at the district level for three hazard scenarios (corresponding to low, medium and high probability of occurrence according to the FD). The MOVIDA procedure was finally implemented in all the APSFRs of the Po District, applying an ad-hoc GIS tool (i.e., ISYDE) developed for the project, and the final results have been published by AdBPo (https://pianoalluvioni.adbpo.it/piano-gestione-rischio-alluvioni-2021/).

2.2. Data collection

Primary data collection involved gathering information from TSEs who were actively involved in the MOVIDA project. Structured questionnaires were distributed by email to TSEs involved in 6 assessment themes (i.e., residential building, transport infrastructures, economic activities, agriculture, environmental and cultural heritage) between December 2022 and March 2023. The selection of TSEs was based on their direct involvement in the process, with each TSE being responsible for a specific category of exposed asset; the decision regarding which expert to involve was primarily guided by their theoretical background and their possession of information-rich knowledge rather than aiming for representativeness [46]. Each TSE replied to the questionnaire independently.

In the framework of the MOVIDA project, a structured questionnaire (see Appendix A) was devised and disseminated among the diverse TSEs involved and each TSE discussed the questions internally and returned the completed questionnaire for analysis. This questionnaire, tailored to each asset under consideration within the project scope, served as a comprehensive tool to elicit targeted information pertinent to the assessment process.

Primarily, respondents were tasked with delineating the specific aim of the assessment pertaining to the given asset. This initial inquiry sought to elucidate the overarching objective guiding the analytical endeavor, thereby contextualizing subsequent responses within a defined framework of inquiry. Subsequently, TSEs were prompted to provide an overview of the current state of the art in scientific literature pertaining to methodological approaches relevant to the assessment domain. This directive aimed at synthesizing existing knowledge and methodologies within the scientific community, thereby informing and enriching the assessment process with established best practices and advancements. Furthermore, TSEs were invited to expound upon the contextual considerations specific to the application of the MOVIDA framework to the designated asset. This component of the questionnaire facilitated the identification and clarification of pertinent contextual factors and practical challenges encountered within the project's operational environment. For each surveyed aspect, TSEs were required to delineate the targeted objectives, enumerate the principal outcomes derived from the assessment, and describe in a critical discourse regarding potential gaps and areas necessitating further improvements. In particular, the protocol included the following elements:

- definition of the asset;
- definition of the aim of the assessment;
- specific questions about the target, main outcomes, discussion gaps and needs in relation to the following dimensions:
  - o overview of the scientific state of the art;
  - o input data;
  - o methodology and operational implementation within the MOVIDA project in terms of spatial and temporal scale and resolution.

Specific sets of sub-questions were provided for each element to facilitate uniform completion and ensuring consistency in data collection across various TSEs. This structured questionnaire ensured a comprehensive exploration of each asset, fostering a nuanced understanding of its assessment within the broader MOVIDA framework. After the questionnaires were filled, follow-up meetings were conducted to allow for in-depth clarification of the responses. These meetings occurred between the lead author of the article, who developed the questionnaires, and each of the TSEs. These meetings were convened to resolve any interpretation doubts regarding certain elements of the questionnaire, particularly when referencing the state-of-the-art context and the MOVIDA project context. For instance, discussions arose when determining whether gaps and needs should pertain to theoretical or implementation levels, and whether they should be focused on the objectives of implementing the FD, the MOVIDA project, or a more academic theoretical context. During these meetings, additional questions were formulated based on emerging terms from the informants with the aim of stimulating the development of new concepts and constructs. Field notes that captured any additional comments, along with general observations and details about the TSE's experience accompanied each TSE's questionnaire.

2.3. Data analysis

Upon data collection, the GT inductive data analysis was carried out with the aim of identifying threads of inquiry that might help to understand the multi-dimensional process of FRA. GM data analysis comprises three main stages: 1) developing a data structure (Table 1); 2) developing an illustrative grounded model (Fig. 2) and 3) critically discussing convincing findings (section 3).

Table 1
Data structure.

1st order codes	2nd order themes	Aggregate dimensions
The exposed assets require a classification both in terms of "*definition and taxonomy*" (A.I.1)	Exposure classification (A.I)	Data(A)
The ancillary data about the asset with a network structure requires information for both "*elements and flow*" (A.I.2)		
The data need to be "*available and accessible*" for the entire area of the assessment (A.II.1)	Data effectiveness (A.II)	
The level of data aggregation needs to be "*useful*" for the scope of the analysis (A.II.2)		
The approach needs to assess the "*expected impacts or resilience*" of the exposed asset (B.I.1)	Purposes and scope (B.I)	Knowledge (B)
Adoption of a "*scenario or probabilistic*" approach, from both hazard and exposure perspectives (B.I.2)		
Evaluate both "*tangible and intangible*" dimensions at the same time (B.I.3)		
Identify and represent the "*asset and impact localization*" (B.II.1)	Methodological indications (B.II)	
Assess the "*exposure time variability*" specific for each exposure asset (B.II.2)		
The methodologies for single asset and the overall FRA should be assessed by "*validation*" process (B.II.3)		
Define the "*spatial domain or geographical boundary*" of the assessment (C.I.1)	Boundary of assessment actions (C.I)	Stakeholder(C)
Define the "*temporal framework*" of the assessment (C.I.2)		
The need of a dialogue between actors to meet the inevitable difference between many "*points of views*" (C.II.1)	Steer priority directions (C.II)	
Define the "*list of asset priorities*" to meet the objectives in respect to the implementation constrains (C.II.2)		

The systematic research approach of GT involves in the first stage the creation of analytic categories, assembled into a data structure containing 1st-order codes, which are informant centered information, 2nd-order themes and aggregate dimensions that are theory centered (see Fig. 1). The data structure allows to show how the informant-based (1st-order) codes relate to researched-based (2nd-order) themes and dimensions. The generation of 2nd-order themes and aggregate dimensions requires a process of sorting, reduction and aggregation of 1st-order codes using increasingly abstract categories and combining existing theory and empirical evidence.

In the second stage, the grounded theoretical model is developed to: 1) support some existing concepts and interrelationships; 2) extend existing knowledge and generate new concepts. The grounded model should show the most likely explanation of the phenomena of interest. Gioia [47] presented the data structure as a static representation of the inductive model, like a photograph of the theory that has emerged. Conversely, the illustrative grounded model is a dynamic depiction, akin to a movie version of the theory. At the third stage, the study's findings are presented by means of a detailed, data-based narrative, usually using the 2nd-order themes and aggregated dimensions, with frequent reference to informants' 1st-order quotations.

According to this methodology, we started by reading the forms provided by each TSEs, analyzing similarities and differences among emerging categories and addressing problems of interpretation that could be identified by emerging patterns and contrasting notions. In line with open coding [48], we retained the experts' own terms, whenever possible [35,49], and identified first-order codes. The informant-based (1st-order) findings were then derived from responses collected from individual questionnaires. To illustrate, a detailed examination of some examples of first-order insights derived from various assets will be conducted. Regarding the 1st-order A.I.1-"definition and taxonomy," when it comes to strategic buildings, it becomes evident that a universally accepted definition is lacking (i.e., "there appears to be no unambiguous definition of what a 'strategic building' is."). Similarly, within the environmental domain, the absence of an official dataset, compiled with standardized criteria for classifying environmental assets, presents a notable hurdle (i.e., "There is a lack of an official dataset obtained with standard criteria for classifying environmental assets."). Addi-

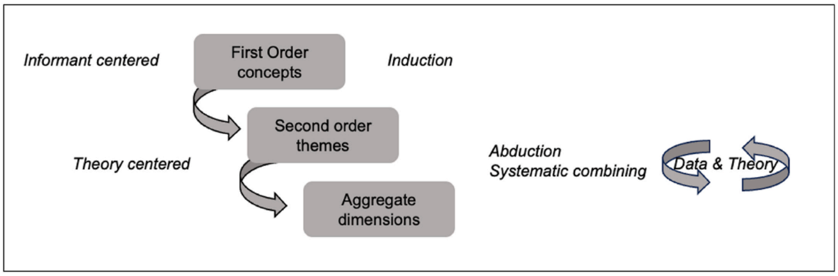

Fig. 1. The inferential process in developing a Data Structure (Adapted from Ref. [62]).

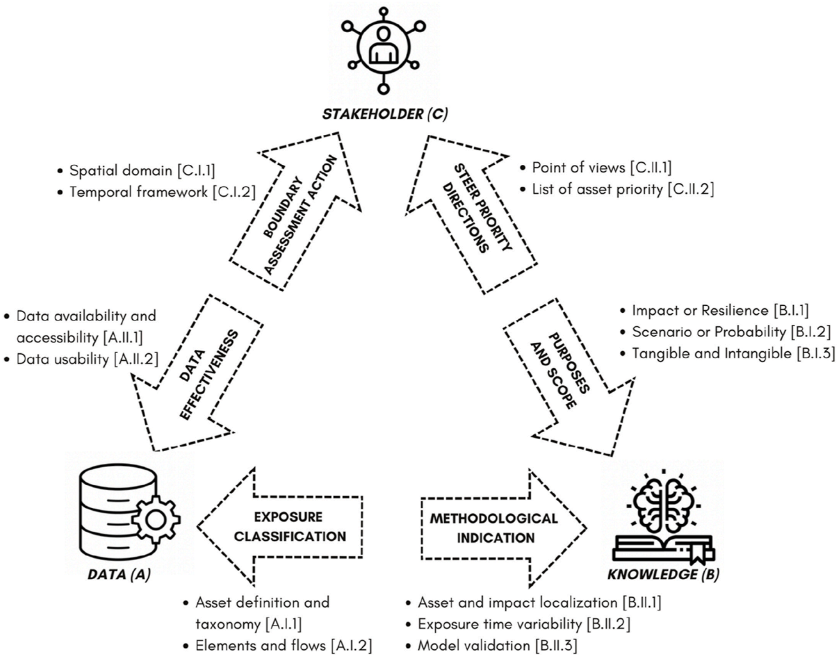

Fig. 2. FRA process framework.

tionally, when assessing transport infrastructure, issues arise regarding the consistency and clarity in defining the network across different territories (i.e., “Characterization of the network not homogeneous and unambiguously defined over the territory.”). Considering another example of 1st-order A.II.1-"availability and accessibility", a common concern emerges across different assets. For instance, in the realm of cultural heritage, there is a notable dearth of systematic information regarding visitor demographics and the associated economic impact (i.e., “Lack of systematic information on visitors to the assets and the economic turnover they generate”). Similarly, within the agricultural sector, data accessibility poses challenges, coupled with difficulties in georeferencing and discrepancies in territorial coverage, resulting in a static representation of crop dynamics (i.e., “Data are not always publicly accessible; difficult georeferencing; partial coverage of the territory; they provide a static vs. dynamic representation of crops”). Furthermore, with regards to transport infrastructure, while data do exist, their distribution is not uniform, presenting challenges in obtaining comprehensive and homogeneous datasets across districts (i.e., “Data, however, not widespread and not homogeneous over the district.”).

Later, we proceeded with axial coding, seeking to uncover relationships and structures by approaching the theoretical realm and further exploring the literature, thus identifying second-order themes. In the third step, we focused on identifying aggregate dimensions, examining the relationships among and within second-order themes. Finally, based on the second-order themes and aggregate dimensions, we returned to each case to establish a process model [50] capable of summarizing how FRA occurs.

3. Findings

In the following sections we present 13 first-order codes, 6 s-order themes and 3 aggregate dimensions identified in the analysis and illustrated in the data structure (Table 1). The following paragraphs summarize the findings by showcasing some illustrative examples from various categories of exposed assets, while underscoring the significance of each theme and dimension observed throughout the assets.

The first aggregated dimension concerns data (A) and, specifically, exposure classification (A.I) and data effectiveness (A.II) across the different assets. The second regards scientific and technical knowledge to properly identify the purposes and scope (B.I) and adopt or develop appropriate methodologies (B.II). Finally, the third aggregated dimension remarks the role of stakeholder (C), its representatives and regulatory instruments, in defining the boundaries of assessment actions (C.I) and steering priority directions (C.II) between different interests and assets.

3.1. Data (A)

The first set of 2nd -order themes pertains to the data dimension, which focuses on exposure classification and data effectiveness across the different assets.

3.1.1. Exposure classification (A.I)

A crucial aspect in each assessment process, as in MOVIDA, is the establishment of a common classification, in terms of “*definition and taxonomy*” (A.I.1). While certain assets can already count on established and widely accepted classifications (e.g., for residential buildings [51] or, crops [52]), others have multiple classifications that are not always consistent or lack standardized categorization (e.g., strategic buildings, transport infrastructures, environment, cultural heritage). In such specific cases, it was first necessary to develop a custom taxonomy tailored to the specific asset (e.g., cultural heritage, [53]). Furthermore, for network assets (e.g., transport infrastructure) it was also important to ensure a coherent and consistent characterization across the entire case study area to assess systemic interdependencies.

The exposure classification process also revealed the need to include ancillary data about the assets (e.g., building characteristics, crop stages, roads, etc.), which included, in certain cases, information on the flow between elements (e.g., traffic volume, typology of traffic, economic input and output, etc.). This aspect was particularly evident for assets like transport infrastructures and economic activities, where the characterization required data on both “*elements and flow*” (A.I.2).

3.1.2. Data effectiveness (A.II)

Considering the relevant extension of the Po River basin (nearly 71,057 km^2), there was not a unique dataset that provided a comprehensive description of the exposed assets throughout the entire basin, making “*data availability and accessibility*” a challenge (A.II.1). This lack of data standardization was evident across various assets, such as regional-based data for crops or buildings. Furthermore, data accessibility also posed a challenge, as in certain cases the data were either private and/or necessitated the payment of a fee (e.g., database with information of economic activities). Additionally, for linear transport infrastructures, essential dynamic information for simulating their functioning (e.g., direction of travel) was often not available, limiting the possibility to estimate flood impacts accurately. Even in cases where data were accessible, the task of georeferencing or ensuring a consistent spatial coverage for the analysis (e.g., crops) proved to be challenging; some “*data*” were also deemed as “*not useful*” (A.II.2) if their level of aggregation was not significant for the scope of the analysis (e.g., infrastructures).

3.2. Knowledge (B)

The consultation, by structured questionaries and the follow-up meetings, with experts involved in the MOVIDA project yielded scientific and technical insights identified by the first-order codes. This enabled a thorough identification of secondary elements influencing and guiding the FRMP. These elements stem from evaluations and decisions concerning the purpose and scope (B.I), the existence or potential implementation of methodologies (B.II), as well as priority directions (C.II) outlined by the aggregated dimension stakeholders (C) and the constraints of the exposure classification (A.I) within the information layer (A).

3.2.1. Purposes and scope (B.I)

The identification of the assessment purpose and scope (B.I), and its consistent application across all category assets, is the first crucial step in the knowledge aggregated dimension. To ensure compliance with the FD's requirement for impact assessment, it is crucial to identify the assessment's purpose, which is either to evaluate the "*expected impacts or the resilience*" (B.I.1) of the exposed categories of assets. This difference in FRA approaches is not uniform across all types of assets: for instance, residential buildings benefit from well-established methodologies based on expected physical damages, as opposed to, e.g., transport infrastructures, which lack a comparable degree of advancement. In fact, existing literature reveals a multitude of approaches [54–59], each driven by distinct objectives, which raise the crucial question of selecting and adopting the most suitable methodologies that are aligned with the objectives of the FD and flood risk assessment. The differences in the approaches extend beyond mere semantic issues, but they concern the adoption of central methodological hypotheses, such as, for instance, the choice of the timing for the assessment (e.g., evaluating the impact at the moment of contact with floodwater or after a fixed time lag). If assessing after a time lag, the approach should consider the potential increase (e.g., cascading effects) or decrease (e.g., adaptive capacity) of the impact. The ability to cope and adapt is particularly relevant for all those assets that have a potential "capacity" to absorb damage (e.g., the warehouse stock for economic assets or redundant paths in transport infrastructures) and, therefore, defining an appropriate time lag for assessment is crucial for these types of assets.

Another essential aspect that steers the purpose and scope is the adoption of a "*scenario or a probabilistic*" approach (B.I.2), from both hazard and exposure perspectives. Regarding the hazard perspective, according to the FD requirements, the MOVIDA project adopted three flood scenarios associated with different return period (i.e., probability of occurrence). The small area portions of the APSFRs can have their flood probability directly adopted, but the probability of the whole district experiencing the same hazard scenario at the same time is much lower. Therefore, in MOVIDA, the evaluation of the impacts was limited to the specific hazard scenarios in each APSFRs, without taking into account all possible combinations of events or their likelihoods. A scenario approach was also used for exposure assessment, assuming static values for all variables over time. The adoption of a probabilistic approach for all exposed items was not indeed feasible due to the unavailability of data to characterize the non-static nature of certain assets. Agricultural activities were an exception, with the inclusion of seasonal phenological variations in crop vulnerability.

Finally, one of the greatest difficulties in identifying purpose and scope coherence between different categories of assets, in the case of multidimensional evaluations, is the assessment of both "*tangible* (e.g., building damages, agriculture loss) *and intangible*" dimensions (e.g., cultural and environmental value) simultaneously (B.I.3). The assignment of a "value" to all exposed assets remains mandatory to overcome the challenges associated with data dimensions discussed earlier and to be able to estimate the impacts and risk. For some of them (e.g., residential buildings [60]), the scientific and practical community agrees on the metrics for exposure (e.g., reconstruction cost, market values, depending on the aim of the analysis). However, for other assets, different approaches may exist: for instance, road infrastructures can be valued based on road length, road type or traffic volume, while agricultural assets based on the annual gross output of the crop. On the contrary, there are assets such as "environment" and "cultural heritage" whose value is mostly unmonetizable and will require either further advancements of the state of the art, or the use of proxies of "value" to perform an exposure ranking. In MOVIDA, an ad-hoc qualitative damage indicator has been specifically developed for cultural heritage. This indicator relied on the classification of heritage type and its level of significance, enabling the derivation of a unitary damage metric [53].

3.2.2. Methodological indications (B.II)

In line with the identified purposes and scope, it is necessary to adopt or develop appropriate validated (B.II.3) methodologies that identify and represent asset and impact localization (B.II.1), accounting also for their variability over time (B.II.2).

The inclusion in the analysis of heterogeneous assets (e.g., single buildings, cultivated fields, population, cultural items, etc.) presents challenges regarding their spatial representation (point, line or polygon), the identification of their flood-affected portions and the aggregation of the impacts at different scales. Assets represented by points, e.g., cultural heritage and population, are affected by some issues in the spatial intersection between hazard and exposure. For example, using only the asset's centroid in the analysis may not accurately reflect its exposure, as in the case of a cultural heritage asset composed by a built structure surrounded by hectares of park. For polygon-based assets (e.g., environment), the same surface area might correspond to different overlapping protected assets, such as a forest (on the ground) and an area of aquifer recharge (underground). In addition to the challenges posed by asset localization, there may be difficulties in aggregating values at the selected resolution (e.g., census area in the MOVIDA project). Aggregating values from different sectors within an area can be suitable for certain assets (e.g., all buildings and crop fields inside the same census area). However, this approach would be less appropriate for systemic assets (e.g., roads), as their impacts extend beyond individual, spatially confined areas. Furthermore, although assessments for the economic activities can be also performed at the census area scale, these would not be able to capture possible disruptions in the supply chain, which may extend beyond relatively small administrative units.

The assumption of static exposure may be deemed reasonable for certain assets (e.g., residential buildings), but it becomes less rigorous for others that exhibit more dynamic characteristics, such as population, traffic variations throughout different hours of the day or the phenological phases of the crops during different seasons. In these cases, the estimation of the "*exposure time variability*" (B.II.2) is crucial for properly assessing the risk of potential flood impacts.

Finally, the single methodologies for each asset and the overall methodologies for the FRA should be subjected to a comprehensive "*validation*" process (B.II.3). Based on the aforementioned results concerning the informative layer and available knowledge, validation can currently be performed only for some specific assets (e.g., residential buildings, certain crops) and purpose and scope (e.g., physical direct damage under specific scenario) in few areas with ex-post data availability (i.e., information about damage after events).

3.3. Stakeholder (C)

In addition to scientific and technical aspects, the investigation highlighted the role of society, its representatives and regulatory instruments, in defining the boundaries of assessment actions (C.I) and steering priority directions (C.II) between different interests and assets. It is important to note that this consultation was conducted solely with the scientific partners involved in the MOVIDA project and not with other stakeholders like the district basin authority, ministerial representatives from the sectors of transport, agriculture, culture, environment, and energy safety, regional representatives, and the Department of Civil Protection. However, it is worth mentioning that scientists did interact with various stakeholders throughout the project. Therefore, these results reflect the scientists' perspective in defining the role of the different stakeholders involved in FRMP according to the Flood Directive.

3.3.1. Boundary assessment actions (C.I)

In the case study, the boundaries of the assessment were defined by the FD that identifies the geographical limits of the district authorities. A domain represented by the river basin is suitable for evaluating the risk, as there is a direct correlation between the implementation of the management plan by the authorities and the physical process that leads to flooding. Conversely, the identification of the domain affected by the floods is not straightforward and unequivocal, as evident from extensive debates in the scientific community on the choice of the boundary and types of interconnected systems [61]. For example, in the case of agricultural and economic activities, the "*spatial domain or geographical boundary*" (C.I.1) depends on the size of the supply chain and, therefore, the choice between flooded area, APSFR, municipality, region, entire district, or even a wider area, is not immediately evident. The management plan of the AdBPo defined the APSFRs for detailed analyses, which however limited the possibility of considering the interdependences among the systems at stake. Similar considerations are also valid for the temporal dimension, given that, as mentioned earlier, some assets exhibit a variability in exposure over time. These variations can occur in the short term (e.g., from hourly to seasonal variations) or in the long term (e.g., urbanization processes). In the long-term case, it is important to clearly define the "*temporal framework*" (C.I.2) in which the assessment should be performed, i.e., deciding whether to consider the current (or recent past) situation and/or incorporate possible future scenarios.

3.3.2. Steer priority directions (C.II)

As highlighted in the previous sections, a clear definition of priority directions and objectives for the society is essential for adopting appropriate methodologies, leading to informative and effective assessments. In addition, a continuous dialogue between institutions, technicians and scientific researchers is necessary to ensure the implementation of stakeholder's will, while acknowledging the natural differences between many "*points of views*" (C.II.1) among different actors. The dialogue between the stakeholders should be a two-way process, with institutions and technicians being conscious of the current knowledge and data limitations, thus ensuring that the assessment approaches are aligned with the societal priorities and implementation constraints. Based on these considerations, institutions need to define achievable objectives, while technicians develop consistent approaches with those objectives. In this framework, as emerged from the case study, the definition of a "*list of asset priorities*" (C.II.2) would be important to tackle the challenges of pursuing a coherent FRA for multiple assets at large-scale within the integrated flood risk management process.

3.4. FRA process framework

3.4.1. FRA process domain

The FRA process can be conceptualized as a framework where three main dimensions, i.e., data, knowledge, and stakeholder, act as "agents" that interact with each other through six interaction "forces" represented by the second-order themes discussed earlier (see Table 1). The interaction forces play a crucial role in shaping and influencing the process, determining the final paths taken for assessing the risk for each asset.

As illustrated in Fig. 2, in the proposed FRA process framework, the three dimensions are positioned at the corners of a triangle domain, where each side is represented by the two themes associated with the closest dimension. This domain serves as the space within which FRA pathways for each asset can be developed and outcomes realized.

The dimensions play a central role in steering and influencing the FRA based on the intensity of each single theme, as exemplified from the outcomes of the case study. For each specific aggregated dimension, the force intensities are inversely proportional to the level of advancement of the corresponding 2nd order theme associated with that force. Forces associated with less advanced concepts exert higher intensities and guide the process toward their respective agents. For instance, in the case of economic activities, the force intensity of data effectiveness forces is very high due to the restricted accessibility to private datasets (e.g., balance sheets or income statements). The high intensity of the force makes the data dimension a relevant attractor that steer the process in comparison to other two agents that need to adapt and cope with this condition imposed by the data effectiveness.

The forces of the various agents assume a different role in each single asset, leading to different paths and outcomes. Fig. 3 illustrates the process path for two examples: residential sector and cultural heritage.

For the residential sector (path on the left in Fig. 3), the knowledge dimension (B) initially steers the process, acting as a strong attractor. However, as the process develops, the path is attracted by the level of data effectiveness (A.II) on the entire area of analysis, which requires the methodological indications (B.II) to adapt and propose tailored methodologies for the specific case. This new proposal needs then to align with the purpose and scope (B.I) and steer directions (C.II) set by the stakeholder. The final solution, which

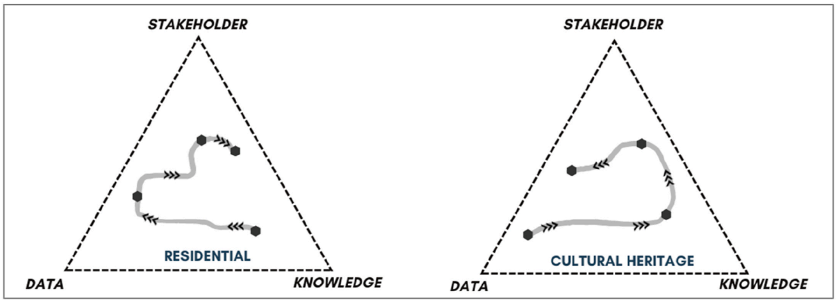

Fig. 3. Examples of FRA path for the residential sector and cultural heritage.

involves quantitatively (economic) assessing the damage estimation, is located between the stakeholder (C) and the knowledge (B) agents, with the informative layer (A) becoming relatively less important.

On the other hand, for cultural heritage, the data dimension (A) acts as the driving attractor from the beginning of the process. In fact, the intensity of the data effectiveness force (A.II) is very high due to the limited data availability (A.II.1) and lack of a codified taxonomy (A.I.1). In the case study, the knowledge dimension (B) then first needs to define the taxonomy (A.I.1) and then engage with the stakeholder to find a shared solution, that is closer to the data and stakeholder dimensions and far from the knowledge one. As a result, for this asset it was not possible to estimate a quantitative damage but only a qualitative damage metric.

These two examples demonstrate how the FRA process can unfold differently for different assets, with varying intensities of forces and attractors. The interplay between the agents and forces determines the direction and outcomes of the assessment process, highlighting the need for adaptive approaches and collaboration among stakeholders to address the specific challenges and characteristics of each type of asset.

3.4.2. FRA self-assess tool

To ensure the proper execution of FRA as mandated by the Flood Directive for various assets, it is essential to understand the scope of each asset, compare the different domains and results, and evaluate the relative significance of each dimension across assets. Therefore, there is a need for a tool to accomplish all these tasks by those responsible for conducting FRA for the flood directive. We propose a self-assessment tool based on the FRA process framework presented in the previous section.

The FRA process's domain is determined by the three dimensions and the depth of inquiry associated with them. The domains of the different assets could be represented and compared by means of a synthetic spider plot (Fig. 4) which represent the FRA self-assessment tool providing information on the level of integration between dimensions in a FRA, while also enabling the comparison of the domain of the FRA process across different categories of exposed assets. Each axis of the plot, corresponding to one of the dimensions, is divided into 4 semi-quantitative grades illustrated in Table 2, which characterize their depth of assessment. The self-assessment tool is intended to be utilized by all stakeholders involved in the FRA process. Each participant should evaluate the depth of inquiry according to the guidelines provided in Table 2. Each grading represents a quantitative indication, and intermediate values

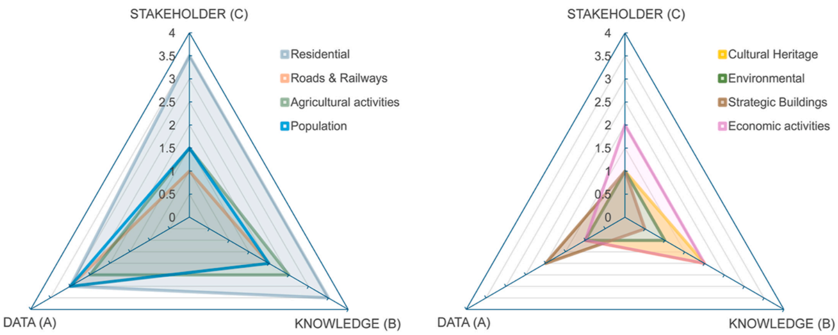

Fig. 4. Examples of spider plots for describing different levels of advancement in the three dimensions.

Table 2
Description of the depth of inquiry.

Description of the depth of inquiry	Spider plot grading in each dimension (A, B, C)
Asset not considered	0
Surface questions and inadequate answers	1
Surface questions and adequate answers	2
Deep questions and inadequate answers	3
Deep questions and adequate answers	4

can also be employed to reflect nuanced assessments, considering that the evaluation is subjective to each single participant that adopt the tool. The specific numerical values assigned to each grading are not relevant di per se; rather, the primary focus should be on ensuring the relative importance among dimensions and assets.

In detail, the triangle's area extension and shape provide a measure of the level of advancement of the assessment, with larger domains and shapes closer to an equilateral triangle implying a more integrated FRA. In fact, assets with greater domain areas exhibit a higher depth of inquiry and an equilateral triangle signify a more coherent depth of inquiries across dimensions. As an example, Fig. 4 shows the FRA process's domains for the 8 assets adopted in the MOVIDA project. Residential Buildings has much larger domain than any other sectors. In particular, the domain of the Residential Buildings shows an imbalance toward the Knowledge, while Cultural Heritage has a similarly imbalance but with lower level of depth of inquiry in all three dimensions.

In addition to facilitating comparisons of domains across assets and dimensions, the tool also serves as an internal communication instrument among the various stakeholders involved in FRA for the flood directive. When each actor executes the assessment tool, alignment on each dimension and for all relevant assets specific to the FD implementation is achieved. When multiple users execute the tool, it is also possible to obtain different results. Therefore, it is important for them to compare their assessments to align on shared values. In cases where it is objectively impossible to achieve the same value, reporting the average values on the spider plot suffices. As mentioned earlier, the significance lies not in individual values but in their relative weighting. Consequently, it becomes a useful tool for making more cohesive and aligned decisions, consistent with both the objectives of the FD and compatible with available resources and methodologies.

4. Discussion

The process of FRA unfolds within a multifaceted realm shaped by the interplay of data, knowledge, and stakeholder involvement, alongside the influences they exert. The existence of a multidimensional space with various potential outcomes thus indicates that there is no single predetermined path for process realization, but rather multiple options are available. This is evident from the differences in methods and approaches chosen by various European authorities that have formulated FRMPs to meet the FD's requirements, as a consequence of the wide-ranging heterogeneity in physical processes, stakeholders, data availability, and expertise characterizing the different member States.

The illustrative example presented here demonstrated the relevance of all the identified agents and forces in shaping the process. This results in a nonlinear pathway that depends on the specific context and the relative depth of investigation into each agent and force. Given the complexity of the context, the nonlinear nature of the process, and the non-uniform level of inquiry across dimensions, it is then essential to establish robust interactions and integration among all parties involved in the process in order to ensure a consistent implementation within and across assets, while aligning with the objectives of the FD.

In consideration of the vastness and complexity of the potential flood impacts (both direct and indirect), it is important for stakeholders to engage in reflection and decision-making regarding the spatial and temporal boundaries of these impacts, as well as the prioritization of the assets and the depth of analysis to be undertaken. This is necessary to ensure compliance with the FD, alongside with data availability and methodological constraints. Indeed, the wide-ranging nature and depth of the assessment necessitates a substantial volume of data, which can present challenges in terms of accessibility and consistent aggregation. Additionally, for certain assets, there still remains a need to establish a clear taxonomy and more attention is required to focus on the flow of information. Considering the broad scope of assets, it is crucial to ensure that the assessment methodologies employed are appropriate for each one and align with regulatory requirements. This calls for careful clarification for each asset, addressing questions such as whether the focus is on impact and non-resilience, whether scenario or probabilistic approaches are applicable.

The proposed self-assessment tool can be used for enhancing the collaboration and integration among various stakeholders involved in FRMPs. By utilizing the tool, stakeholders can materialize aspects of the assessment phase that are often undervalued although crucial for influencing the effectiveness of management procedures, both in terms of medium-term risk management and short-term emergency response. It is intended for use by all actors involved in the different phases of FRMPs. Each stakeholder is encouraged to independently complete the tool for each asset and utilize it to compare their assessments with others. The tool could be employed at the beginning of each phase of FRMPs to ensure its integration into the decision-making process from the outset. Moreover, the potential of the tool to improve the Floods Directive, including expanding its scope and requesting implementation, should also be acknowledged. Through this approach, stakeholders can evaluate the depth of analysis within each dimension, considering the various themes they encompass, it could contribute to the development of a consistent and directive-aligned process. Moreover, although it was not the focus of this manuscript, the utilization of the self-assessment tool can lead to more comprehensive Cost Benefit Analysis (CBAs), as required by the FD, thereby facilitating decision-making on the prioritization of the mitigation measures. Given these considerations, we advocate the implementation of this tool as a viable solution across EU states required to comply with the directive.

However, it is important to acknowledge that the case study examined in this manuscript still has certain limitations. Firstly, it is important to note that the consulted experts are all Italian, which may lead to a bias shaped by the Italian context due for example to the specific territorial characteristics, various types of local needs, and the degree of integration across different administration bodies. Therefore, future work is encouraged in different European contexts (both socio-cultural and morphological aspects) where the FD is active. Secondly, as outlined in the methodology, the results are solely focused on the perspective of risk assessment experts, without incorporating the viewpoints of non-scientific stakeholders involved. While this approach aligns with the scope and limitations of the current study (i.e., FRA), it would become essential to involve other actors if the scope was to extend to other FRM activities. Furthermore, while the study encompassed several assets, there were others that were not considered, such as ecosystem services or lifeline utilities as water, energy and telecommunication networks. Additionally, the study concentrated solely on tangible effects, neglecting intangible consequences, such as the emotional impact on individuals and the potential implications of polluted water on human health. Future research should aim to explore potential differences among European contexts, variations across types of river basins, perspectives of different stakeholders involved, and the specific assets analyzed. These additional future applications could not only provide elements for comparison with the results obtained from different case studies, but also offer valuable insights into the diverse challenges and opportunities associated with FRA and flood risk mitigation strategies across different settings within the FRMPs. Finally, the data analysis carried out in this study focused on assessing each individual asset in isolation, without investigating the interplay between them. Accordingly, while the proposed tool can serve as a valuable resource for analyzing individual assets, it is important to undertake further exploration of the degree of integration among different assets, which will be the next step in the development of a comprehensive multi-criteria analysis.

5. Conclusion

The outcomes of the current research, which focused on uncovering the mechanisms underlying the implementation of an integrated flood risk management plan in general and of FRA in particular, can be summarized into three major aspects: 1) the devised framework, 2) the proposed self-assessment tool, and 3) the adoption of the case study.

The research methodology employed in this study aimed to address the complexities of FRA processes using Gioia Methodology within Grounded Theory approaches, particularly focusing on the case study of the Flood Directive implementation in Italy. Considering the intricate and interconnected nature of FRA, GM's holistic perspective was deemed suitable. GM, emphasizing theory building from data, was applied to the dynamic, multifaceted system of FRA, acknowledging its multi- and interdisciplinary orientation. This study's strength lies in its focus on understanding the FRA process within a specific, real-world context. Through systematic data collection and analysis, this study aimed to unravel the intricacies of FRA processes, shedding light on novel ideas and effective dynamics within this vital domain.

Finally, exploring the potential applications of the framework and tool developed in this study in other contexts where the FD is utilized could be of significant interest. This could serve the dual purpose of either affirming the framework's effectiveness across diverse settings or identifying potential adjustments for improved performance.

CRediT authorship contribution statement

M. Arosio: Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Funding acquisition, Data curation, Conceptualization. **C. Arrighi:** Writing – review & editing, Writing – original draft, Conceptualization. **R. Bonomelli:** Writing – review & editing, Methodology, Data curation. **A. Domeneghetti:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **G. Farina:** Writing – review & editing, Visualization. **D. Molinari:** Writing – review & editing, Writing – original draft, Methodology, Data curation. **B. Monteleone:** Writing – review & editing, Visualization, Supervision. **A.R. Scorzini:** Writing – review & editing, Writing – original draft, Methodology, Data curation. **M. Martina:** Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

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

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Data availability

Data will be made available on request.

Appendix A. Questionnaire

Questionnaire protocol shared across the different assets.

Asset	*E.g., Residential Building*
Aim of the assessment	Estimating impacts to decide/plan mitigation measures that maximize impact reduction at equivalent "cost/investment
In the scientific community	

(*continued on next page*)

Dimension	Target	Main outcomes	Discussion: gap & needs
Methodology	*E.g., adopt a shared methodology for estimating indirect damages of Residential Building assets for the aforementioned purpose.*	Report the state of the art in the scientific community regarding the methodology to achieve the identified target. For consistency across contributions, use the following questions as a guide: • Is there a unanimous definition of what impacts are? • Is there a general consensus in the scientific community on a single methodological approach (Exposure, Vulnerability, etc.)? What is it? • Conversely, is there a debate on different approaches? What are they? • Is there consensus on the generic approach (what is it?), but are there different methodologies? What are they? • Is the approach probabilistic or scenario-based? • Is it possible to estimate risk or impact? +Is the probability of occurrence considered? How? Currently, there is no consensus. Why not?	*E.g.,* • *Certain methodology details need further exploration (e.g., uncertainty estimation).* • *Multiple applications are necessary to confirm a preferred methodology over others.* • *Methodology validation is required, either in general or specific contexts.* • *Impact indicators need to be defined.*

In MOVIDA

Dimension	Target	Main outcomes	Discussion: gap & needs
Data	*E.g., having digitized data for variables x and y available and accessible uniformly across the entire basin.*	Based on your experience in MOVIDA project, the following key observations were made in the data. For consistency across contributions, use the following questions as a guide: • What data exists and is available at the basin level? • Is the data source reliable? • Were the data open access? • Were the data digitized? • Were the data georeferenced?	*Es.* • *Following data are missing: …* • *Open data exists but is unreliable and not uniformly distributed in the basin.* • *"Official" data is not digitized and georeferenced.*
Spatial/Temporal resolution	*E.g., the required resolution for the above purpose is 3m × 3m.*	Based on your experience in MOVIDA, please provide the main observations regarding the resolution. For consistency across contributions, use the following questions as a guide: • Was it possible to adopt a clear and unambiguous spatial calculation unit? • Is there ambiguity in aggregating information/data at different resolutions? • Is temporal resolution crucial? If yes, why?	Discuss what is the most appropriate spatial/temporal resolution
Spatial/Temporal scale	*E.g., the scale corresponds to the entire basin.*	Based on your experience in MOVIDA, please provide the main observations regarding the scale. For consistency across contributions, use the following questions as a guide: • Is the temporal scale crucial? If so, why? • Is the spatial area crucial to evaluating the result? • How have scales such as APSFRs, regions, or basins made estimation more challenging?	*E.g., the aggregation process does not allow for the best representation of the impact propagation process because …*
Methodology	*E.g., adopt a shared methodology for estimating damages of Residential Building assets for the above-mentioned purpose.*	Based on your experience in MOVIDA, please provide the main observations regarding the methodology. For consistency across contributions, use the following questions as a guide: • Was it possible to apply the scientific state of the art? If not, why? What barriers were encountered? • Was any novelty developed? What type? • What criticalities do the adopted indicators have concerning the evaluation purposes?	*E.g., apply the developed methodology in other contexts or able to assess only exposure and not the risk*
Implementation	*E.g., obtain results useful for the final decision-making process of stakeholders.*	Based on your experience in MOVIDA, please provide the main observations regarding the implementation. For consistency across contributions, use the following questions as a guide: • Were there non-scientific limitations encountered in the implementation?	*E.g., operational timelines, budget constraints, computational efforts for extensive areas, and …*

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