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Flood Resilience and Adaptation in the Built Environment: How Far along Are We?

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Abstract: Cities are experiencing an increased rate of climate-related extreme events threats derived from climate change. Floods are one of the most challenging issues to address to reduce damages and losses in urban areas. Building resilience through adaptation to these changing conditions has become a common goal for different disciplines involving planning for the future. Adaptation planning is widely recognized as generally applicable to any field. However, there are current limitations to overcome for architectural and urban planning to switch from theory to practice. This paper proposes a critical overview of literature works on flood mitigative strategies and adaptive approaches considering uncertainties, linking strategies for the Built Environment (BE) to mitigate the effects of floods, and operative frameworks to pursue adaptation under changing environmental conditions. The literature selection accounts for the pivotal components of the BE: open spaces (OSs), buildings, and users. Next, we provide an overview of the most relevant adaptive methodologies that have emerged in literature, and, lastly, the planning strategies are discussed, considering the climate-related uncertainties that might undermine the effectiveness of the designed action. The present paper aimed to provide a contribution to the discussion regarding the necessity of making architectural and urban planning adaptive, providing a base for future studies for operative adaptation.

Keywords: urban resilience; built environment; climate change; adaptive planning; urban floods

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1. Introduction

Resilience is an increasingly important concept, applied to cities and the built environment under the term "urban resilience". Urban resilience is the capacity of an urban system to respond to shocks by preventing, adapting, or responding to them. When considering urban resilience, the built environment plays a fundamental role [1–4]. The term "built environment" (BE), which became common in 1990, refers to the result of human activities, and the research about this complex topic includes the fields of architecture, engineering, construction engineering, landscape, and urban planning [5]. More than half of the global population lives in cities [6], and to make them resilient is necessary to tackle the different sources of vulnerability deriving from climate change, earthquakes, epidemics, etc. However, in this study, we focus primarily on floods, as flood risk is increasing dramatically due to growing urbanization and climate change, especially in developing countries, where the impact is even greater [4,7,8].

The resilience of the BE and its community depends on the actions developed to prepare for the disastrous events [9]. A document shared by United Nations member states on the Sustainable Development Goals underlines the importance of pre-disaster planning in relation to the core objective of "human development" [9,10]. According to the general outlines of these documents, disaster risk reduction (DRR) actions are organized by themes, with a subdivision corresponding to the Disaster Life Cycle (DLC), as well as other kinds of emergency: prevention, preparedness, emergency response, and recovery. These four phases of the DLC correspond to four DRR strategies: prediction and warning; monitoring; impact assessment, response and management [9,10]. Each of these strategies then refers to a series of measures aimed at preventing or mitigating the impacts of floods, and these measures can be divided into structural and non-structural measures [11].

Structural measures are usually engineered interventions aimed at reducing the volume of floods, and among these, it is necessary include: retention ponds, dams, river improvement, urban drainage systems, evacuation shelters, and levees or dikes [9,12]. Non-structural measures aim to implement flood-adapted design and building codes, land-use planning laws and regulations, preparation and evacuation planning, public awareness programs, and flood insurance programs [9,12,13]. Both structural and non-structural measures can be reactive (response-oriented) or pro-active (risk reduction) [12]. Table 1 shows a scheme of these strategies and measures.

Table 1. Definition of strategies with structural and non-structural measures in the context of floods. Author elaboration from [10]; n/a means that no main and specific measure can be recognized.

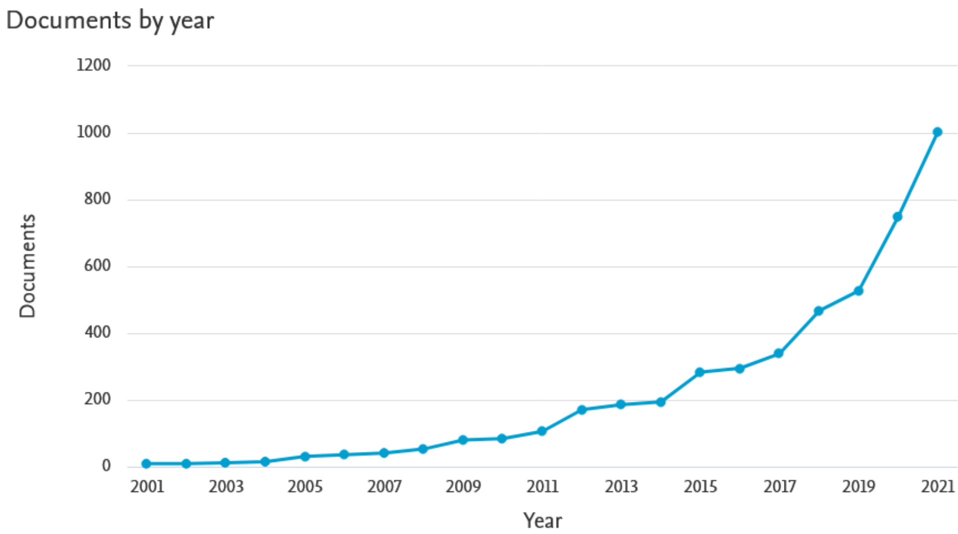
Strategy	Measure	
	Structural	**Non-Structural**
Monitoring	monitoring network (gauging stations, satellite, etc.)	
Prediction and warning	n/a	Assessment through numerical models
Impact assessment	n/a	Assessment through numerical models
Response and management	Retention ponds, dams, river improvement, urban drainage systems, evacuation shelters, reservoir, levees, emergency, diversion channel, temporary flood wall, water pump, etc.	Preparation and evacuation planning, public awareness programs, land-use planning, flood insurance, flood-adopted design and use of buildings, relocation, etc.

However, recently, the notion of resilience to climate-related challenges including floods encompasses adaptation. Accordingly, the European Commission adopted a new strategy for a climate-resilient Europe, recognizing the importance of seeking a flexible adaptation to extreme weather events [14]. Usually, BE components are widely considered as elements for deploying strategies that will be successful in the long-term, no matter how the future unfolds. This inherently deterministic approach at the base of the planning process in urban and architectural fields is no longer a feasible option in light of the dynamic changes that modify the conditions where plans rely on [2,15–18].

Therefore, thanks to a critical overview of literature works and approaches to flood adaptation, this work aimed at linking strategies for the BE to mitigate the effects of floods, and operative frameworks to pursue adaptation under changing environmental conditions. According to the literature selection (Section 2), an analysis of main reference works is performed by taking into account Open Spaces (OSs), Buildings, and Users as the BE essential components, and their related strategies [3,19–21] (Section 3). Then, given the overview of adaptive methodologies, considering the climate-related uncertainties that can undermine the success of the chosen strategies in the long term (Section 4), these strategies are discussed, for the first time to the best of the authors' knowledge, to highlight and discuss their limits of application and the relevant uncertainties that might undermine the effectiveness of the designed action (Section 5).

2. Literature Overview Detail

The search was carried out using the Scopus database (www.scopus.com; last accessed 28 February 2022). To develop an effective search strategy, the process of establishing the keywords to combine in a search code was iterative, and the impact in terms of the numbers and appropriateness of the results was checked. Figure 1a shows the general increasing trend in terms of documents concerning resilience and adaptation in view of BE (including their components) and considering flood risk, limiting the data to the last 20 years of research and to physical science and engineering subject areas, and excluding conference papers, editorials, and reports (overall number of 4690 documents) (Scopus query: ALL ("flood" AND "emergency" OR "evacuation" AND "behavior" OR "behaviour" AND "built environment" OR "building" OR "open space" OR "street" OR "square" OR "urban" AND "risk" OR "risks" OR "adaptation" OR "mitigation" OR "resilience") AND (EXCLUDE (SUBJAREA, "ECON") OR EXCLUDE (SUBJAREA, "BIOC") OR EXCLUDE (SUBJAREA, "NURS") OR EXCLUDE (SUBJAREA, "NEUR") OR EXCLUDE (SUBJAREA, "PHYS") OR EXCLUDE (SUBJAREA, "CHEM") OR EXCLUDE (SUBJAREA, "PHAR") OR EXCLUDE (SUBJAREA, "VETE") OR EXCLUDE (SUBJAREA, "IMMU") OR EXCLUDE (SUBJAREA, "Undefined") OR EXCLUDE (SUBJAREA, "MEDI") OR EXCLUDE (SUBJAREA, "BUSI") OR EXCLUDE (SUBJAREA, "AGRI") OR EXCLUDE (SUBJAREA, "HEAL")) AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "re") OR LIMIT-TO (DOCTYPE, "bk") OR LIMIT-TO (DOCTYPE, "ch"))).



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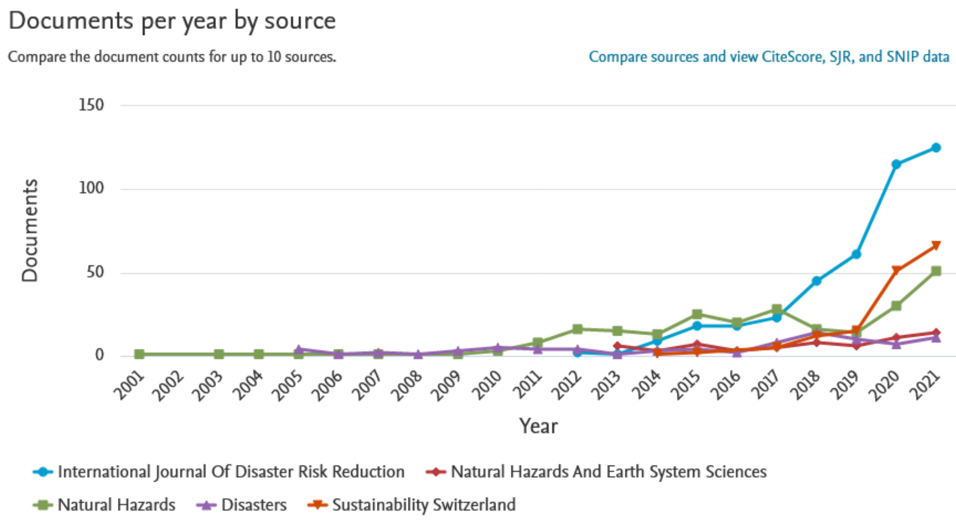

(**b**)

Figure 1. Number of documents concerning flood risk and the BE in view of resilience and adaptation: by year (**a**); by year by journal just considering the top 5 journals for such publications (**b**). Source: www.scopus.com (28 February 2022).

Considering journal papers (73.4% of the whole documents), the second image in Figure 1b shows the top five journals for publication, which essentially collects up to 10 papers on the matter. Most of the works are mainly centered on a few scientific journals. While a large number of works provided novel approaches, methodologies, and frameworks to design adaptation strategies considering uncertainties [22–24], several reports critically highlighted the lack of preparedness, as well as a reduced interest in the inclusion of BE components in the adaptation process as leading factors for resilience improvement [25]. Nevertheless, as for other kinds of disasters in both indoor and outdoor BEs [26,27], they have fundamental impacts on the risk factors, such as on flood hazard and spreading, exposure and social vulnerability, and physical vulnerability [2,18,28–33].

The bibliometric technique of recurrence analysis of keywords was applied to investigate these main issues. The bibliometric software VOSviewer [34] was used for the analysis; among the 103 keywords, those with recurrence at least equal to three were processed (65). The result was a neural network (Figure 2) in which the size of the individual elements represents the occurrence of a single term (the larger the size, the greater the occurrence), while the links between the elements represent the relationships between the terms in the documents analyzed.

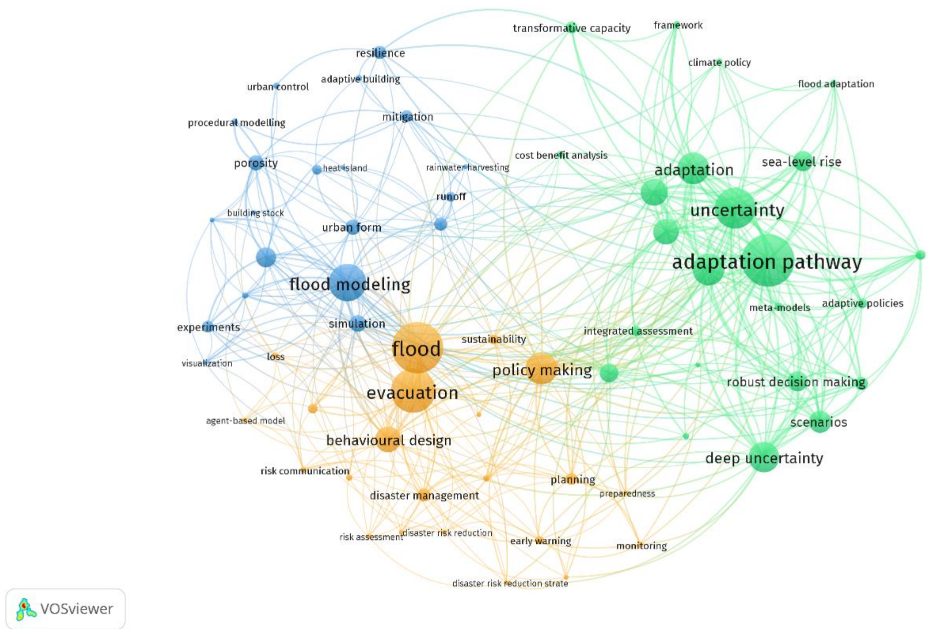

Figure 2. Neural network of main issues in current literature, developed through the bibliometric software VOSviewer.

In Figure 2, it is possible to observe three clusters, which show thematic grouping around different topics. Two clusters are related to the BE and its components: the blue cluster is related to BE solutions, both at the urban scale and at building scale; the orange cluster identifies behavioral-based studies that also connect flood risk with emergency management, thus focusing on the BE users as active components. These two clusters are considered for Section 3 overview. Finally, the green cluster is focused on uncertainties and adaptation pathways and is critically assessed in Section 4.

3. Overview of Significant Mitigative Strategies for BE

3.1. Strategies for the Open Spaces in the BE

The OS in the BE, including public–private interfaces [35], highly affects the floodwater spreading, and the local characterization of flooding level (e.g., depth, speed, and other floodwater parameters) because of their layout, as well as their being composed of parts and materials [36–38]. In this sense, buildings facing the OS constitute a significant interference element because they mainly alter floodwater runoff in relation to the OS infrastructures (e.g., sewers) [39,40]. Consequently, they both influence building damage due to floodwaters [41–43], as well as the immediate emergency response, including the evacuation process, in light of the availability of gathering areas and paths [44,45].

Hence, it is pivotal to outline the interaction systems in OSs according to a microscale approach that relies on the modeling of "each individual receptor at risk" [46]. Risk assessment models and related simulation tools can be built on such assumptions to support safety planners [2,32,45,46]. However, the systematization of knowledge on risk-affecting microscale factors should be improved to support researchers in developing related models, to define key performance indicators for a holistic analysis of flood risk, as well as to increase the decision-makers' risk awareness through the implementation of quick checklists on the matter [2,17].

The urban morphology [47] can influence the flooding spreading in the urban area, as well as the overall safety levels for citizens, in correlation to their risk perception and awareness [48,49], by causing life losses [50] with respect to specific scenarios. Such issues have a great impact, in reference to urban management strategies (also in emergency conditions) against hazard sources [49,51]. Microscale factors relate to the OSs themselves facing the buildings (Section 3.1), the buildings (Section 3.2), and the users' behavioral patterns in emergency conditions (Section 3.3).

The physical characteristics of urban OSs are of primary importance to enhance resilience and to mitigate flood vulnerability of the BE. These characteristics are directly connected to the interactions among the components of urban form: street network, plot pattern, and built form. Recently, urban morphometrics has systematically investigated the unintended interaction among urban form, flooding events, and human behavior [52–54].

Nevertheless, the majority of hydrology-based studies regarding pluvial flooding consider the urban form just as the spatial distribution of resistance parameters, useful to provide an accurate description of the event, while disregarding the comprehensiveness of the OSs' effect. On the one hand, most of the proposed parameters do not act as urban form indicators [38,55,56]. On the other hand, OS factors remain qualitative rather than quantitative [57,58].

In this framework, with reference to flood resilience of urban areas, it has been widely recognized the positive effects of introducing nature-based solutions (NBS) as design strategies for the transformation of the OS [59]. The importance of NBSs has grown, considering rapid urbanization and ongoing climate change. Following the increasing frequency of torrential downpours and disastrous cloudbursts in urban areas, several cities have adopted climate plans to increase flood resilience [60]. Within these plans, the creation of the green infrastructure of NBSs is of primary importance for the transformation of OSs and neighborhoods. Furthermore, these approaches show the effectiveness of combining several NBSs into the different spatial elements that compose the OS of our cities in the mitigation of urban flooding caused by high-frequency precipitation, as demonstrated by research studies developed for different climates, as reported by Huang et al. [61].

The appropriate design of this network of NBS can significantly reduce flow volumes, runoff volumes, and peak flow even up to 100% under specific conditions. A combination of design solutions such as rain gardens, bioswales, retention ponds, permeable pavements, water squares, and infiltration crates has a primary two-fold function: supporting grey infrastructures and increasing resilience to urban flooding, as well as increasing quality of life, promoting the transformation of urban OSs, and producing significant side benefits for citizens: promoting outdoor urban life, increasing vibrant OSs, introducing urban heavens that can act as means of climate adaptation, i.e., small spaces that promote outdoor comfort and counteract heat weaves and UHI; enhancing biodiversity in urban areas; reaching economic development goals by reducing costs.

The scientific discourse discussed in this section underlines that attention is rising in the hydrology field regarding the characteristics of urban form components and their effects on pluvial floods on design strategies [61]. First, researchers assert the importance of approaching modeling with a more accurate scale of analysis, essential for describing the complexity of the BE [32,62–64]. From this angle, pushing boundaries in urban morphometrics could be helpful because quantitative, comprehensive, and systematic methods and tools to measure the urban form have been developed [20,65]. Secondly, this knowledge helps characterize the urban spaces with the most reliable metrics at the most appropriate scale of analysis. In addition, researchers point out the mitigating effect of NBS on urban pluvial flooding and the importance of appropriate hydrology modeling [61]. In association with well-established statistical parameters, the introduction of OS and NBS metrics in flood modeling could represent a ground-breaking approach in the field. Furthermore, nowadays, the possibility of developing this approach is demonstrated by introducing novel digital tools for urban flood modeling that integrate parameters, spatial data, and design solutions that describe the characteristics of the urban space [66].

3.2. Building-Related Strategies

Buildings can integrate solutions that provide relief and resilience increases to flooding in the short-term, during the flooding, and in the aftermath of the event. A conscious design of buildings in flood-prone areas entails the choice of peculiar building typologies or the integration of different technological solutions, which have been developed and analyzed in the last years to be applied to buildings, so as to improve their performance with respect to flood vulnerability. However, in addition to such structural measures, in order to support buildings' strategies for flooding, also non-structural measures can be taken, such as regulating resilience by means of building codes and providing flood insurance for buildings in flood-prone areas.

In this section, structural measures embedded into the building are considered (Figure 3).

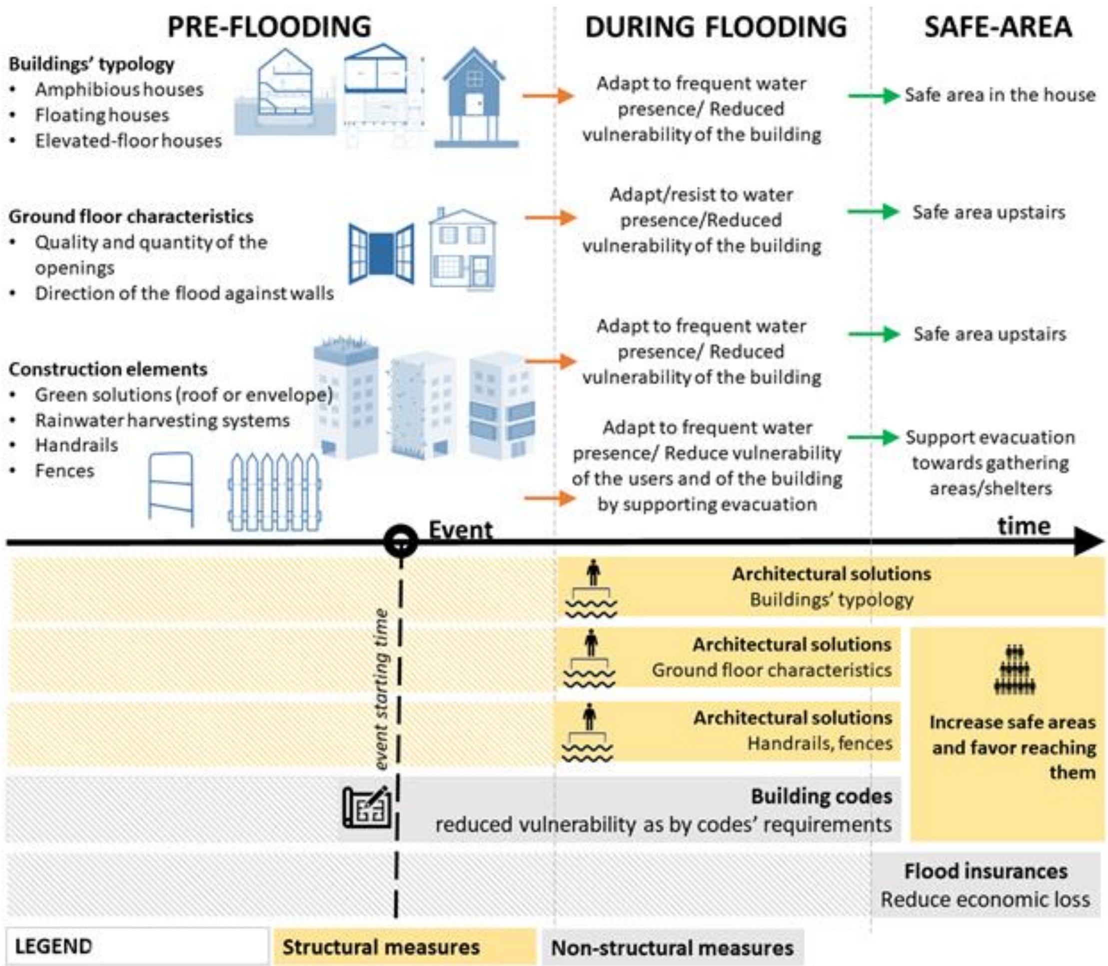

Figure 3. Behavior of the structural and non-structural short-term measures applied on the building.

Besides the physical vulnerability, involving possible damage to the buildings [41], intrinsic characteristics of the design of the building are relevant, such as the quality and quantity of openings, as well as the wall orientation with respect to water flow. These are fundamental factors, especially considering the characterization of the ground floor. Indeed, they influence the collection of floodwaters inside buildings and so risk and direct damages to people, furniture, and goods and chattels placed indoors [2,31,43].

The building itself can be designed to be more or less sensible to flooding, according to its typology. Indeed, peculiar typologies exist that are resilient, to different degrees, to flooding. Such peculiar typologies are designed to favor adaptation to areas that are characterized by frequent water presence or flooding. The building features themselves allow moving towards passive mitigation solutions, when the house itself is built to adapt to flood events, thus protecting its inhabitants. This is the case of amphibious and floating buildings, or houses with elevated floors [67–70], which have the ability, due to construction technology and suitable materials, to adapt to a marine or fluvial environment. In greater detail, amphibious houses are designed to coexist with periodic/frequent flooding. They are normally on the ground, but their foundations allow the house to rise and float, being fixed to poles, depending on flooding height. Examples are those by BACA Architects [71], located in the United Kingdom on the Thames. Floating buildings instead are constantly on water, and examples can be found in Northern Europe or in North America, for example [72–74]. Houses with elevated floors do not float but have the first floor/s empty, for water to flow during the flooding event, thus avoiding damages to the house and its inhabitants. Elevated houses also provide another advantage, which is possibly restituting soil to permeable paving, thus reducing runoff [69]. All these houses are able to adapt to a flood-prone area and to frequent water presence.

Other possible structural strategies to be applied to buildings consist of specific construction elements that can be integrated or added to the building itself, to reduce vulnerability to extreme rain events and flooding, either within the building or its immediate surroundings. These strategies allow one to gather rainwater and diminish and/or retard its flow from the building. These solutions also have an effect on the surrounding OS risk because they provide runoff retention, that is, the ability to reduce runoff from the building in the Oss [75–77]. The runoff retention is measured as the percentage of water retained by a specific element. Since these solutions allow one to gather rainwater and diminish and/or retard its flow from the building, they support the functioning of the sewer system and control rainwater volume and peak flow in the street.

Among these construction elements, green solutions can be applied to vertical and horizontal envelopes of buildings, such as green walls and green roofs, aimed at reducing vulnerability to floods by reducing runoff [75]. Such solutions are part of the SUDs, i.e., sustainable urban drainage systems [78], whose role is of primary importance in complementing grey engineering solutions to reduce flooding. There are a wide variety of green roofs and walls, as stated by the review of [76], and the main variables to be considered are (i) runoff retention and (ii) peak flow control. Runoff retention is the ability to reduce runoff from the building, and it is measured as the percentage of water retained by the roof. Studies on runoff retention of green solutions report values comprised between 45–93%, depending on the substrates composing the green system and their configuration, as well as roof slope for green roofs [79]. This variable is also linked to the characteristics of the rainfall event [80,81]. Peak flow control is referred to the above-mentioned characteristic of the green system of reducing and retarding the peak flow in the street. Concerning the peak flow control, previous work assessed values reductions by 10.5% and up to 90% [39], depending on the intensity of the rainfall. Moreover, parallel to mitigating flooding and runoff, green walls and roofs are an effective solution to reduce energy consumption for heating and cooling, and to improve thermal comfort in indoor spaces [76]. The main issue of green roofs and facades is related to their costs for construction and for their maintenance [76], leading to long payback periods, as well as their complex installation in existing BEs. Moreover, not all buildings are suitable for green roof/wall implementation, depending on the characteristics of the buildings. For example, a sloped roof steeper than 20° is not adequate for a green roof.

Finally, rainwater can be stored and retained in buildings by means of rainwater harvesting systems, which gather rainwater on the roof. As for green systems, rainwater harvesting systems reduce runoff and peak flows [82,83], but also allow building-scale savings related to water reuse after being filtered, with consequent environmental and economic benefits [77,84].

In addition to these strategies that allow improving the performance of the building with respect to the hazardous event, other design strategies can be applied to specifically reduce the vulnerability of their users in their movement and behaviors during the event; this is seen in the case of handrails, which can guide and support users' evacuation [45], as well as fences, which could constitute obstacles able to hold debris from hitting the building and evacuees [32], or protecting private areas from debris. Moreover, it has to be considered that some of these strategies are effective for both marine, fluvial, and pluvial flooding, while some others are effective for mitigating specific flooding types. For example, green roofs and rainwater harvesting systems allow reducing runoff, thus mitigating pluvial flooding, but are not effective against marine and fluvial flooding.

3.3. Strategies Users Oriented

Strategies oriented towards the users take into account the response to the disaster conditions in the flood-affected BE, and so they are mainly devoted to the immediate emergency response (including the evacuation) and the immediate aftermath (including evacuation sheltering) [16,85–87]. These strategies include both structural and non-structural measures for increasing the safety of users who can be initially exposed to the flood (e.g., because of their localization in the BE) and who can encounter potential threats over time (e.g., because they can move through or towards flood-affected areas). At the same time, they should be founded on the users' behavioral interactions with the surrounding BE and the flood effects on it, which change depending on the emergency management system, as well as on the users' individual features (e.g., motion abilities, age, gender, familiarity with the BE, risk perception) and the relationships with the surrounding users (including those in the same group/family) [85,88,89]. As for other kinds of disasters affecting the built environment [90,91], these behavioral interactions also vary over the emergency time, depending on three main phases [45]: pre-movement, that is before the evacuation starting; evacuation, which implies the users' motion towards a "safer" area; reaching a "safe" area and the immediate aftermath. In the following, risk-reduction measures to be implemented in short-terms strategies are discussed by referring to these phases, according to the scheme of Figure 4, which is based on general disaster and emergency timelines, based on the resistance of the BE and its users [92].

In the pre-movement phase, users can spend a significant time in activities not directly related to an effective movement towards a "safer" area [45,90,91,93], such as: (1) evaluating the effective flood risk where they are at the moment, as well in the immediate future, so as to decide if the evacuation is needed; (2) stopping previous activities performed in the BE (depending on the building's intended use) and collecting personal belongings, after they have decided to evacuate; (3) interacting and waiting for other users because of the influence of "social groups", after they have decided to evacuate. In particular, as for other kinds of emergencies [94], the evacuation decision can be supported by efficient Early Warning Systems (EWS) and rescuer–citizen information channels on the local scale, which can reduce the negative effects of misleading individuals' risk perception, and "social groups"-related effects (including both shared social identity factors and leader–followers influence) [95–97]. Flood forecasting tools can support EWS to move toward preventative information for users and also preventive evacuation [98,99]. They can reduce uncertainties within the exposed users by timely and properly supplying data on the flood event. Similarly, awareness-increasing solutions pursuing participatory and training-based approaches could additionally decrease possible delays in the evacuation decision [100,101].

The combination of such measures can increase the safety of users, especially if considering private buildings, where evacuation decisions and evacuation delays can exist because of a strong combination of individuals' risk perception and "attachment to belongings" behaviors, which can lead people to delay or even not to start the evacuation process, and remain home [45,95,101,102].

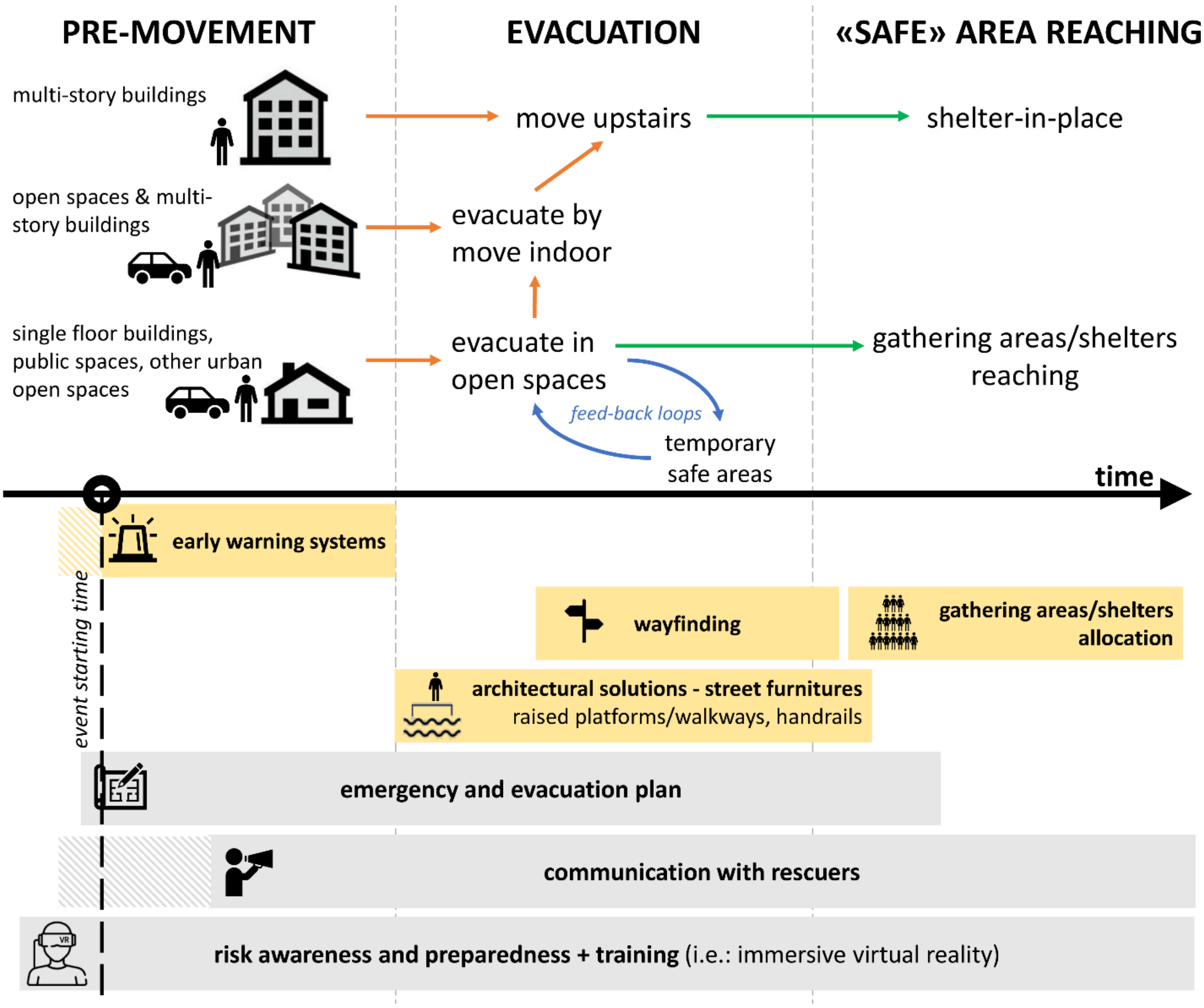

Figure 4. Emergency and evacuation timeline with respect to the users' behaviors and phases (upper part of the figure) and the main related risk-reduction measures discussed in the text, distinguishing between main structural (in the yellow boxes) and non-structural (in the grey boxes). The dashed areas of boxes refer to pre-disaster time measures based on flood forecasting tools.

After the pre-movement time, the evacuation starts, and the users' response is aimed at reaching an area where they can restore adequate safety levels [46,103]. Two main tasks are highlighted by previous studies: (1) the evacuation target selection [16,45,104]; (2) the local individual movement in floodwaters [88,89,105]. The correct evacuation target selection can be improved with different measures depending on the specific part of the BE where the users are placed.

In multi-story buildings, users could be encouraged to move upstairs, reaching the higher story or the roof [16]. A similar approach can be adopted in OSs in the BE surrounded by multi-story buildings, such as courtyards, streets and squares, so as to lead users to perform "shelter-in-place" responses by moving into buildings and then upstairs [90]. Users can be guided to gathering areas and shelters provided by emergency plans, by suggesting the proper evacuation path to be followed [85,86,106,107], especially if: (1) users cannot move upstairs, such as for those hosted in activities at the ground floors, and those placed in the OSs (including users moving by car in critical floodwater conditions); (2) risks for users in case of "shelter-in-place" strategies can become unacceptable over time; (3) rescuers' support is aimed at concentrating on the points of interest in the immediate aftermath.

First, emergency and evacuation planning could be supported by other non-structural measures based on awareness increases, such as plan dissemination towards citizens, to inform them before a disaster on the location of gathering areas/shelters and evacuation paths, as well as training campaigns, to make them aware of how to properly behave in case of an emergency. In this sense, virtual reality training through serious gaming seems to be one of the most powerful approaches for "evacuation knowledge delivery and behavior assessment", especially when performed in immersive environments, because "they are highly engaging and promote greater cognitive learning" [108].

Another significant element is related to the possibility of discussing the solution adopted in planning with different possibilities and quantitative approaches to the options evaluated. Pappalardo and Rosa [78] focus on less "conformative" approaches to preventive planning, and therefore are less tied to traditional planning and more oriented to Performance-Based Planning (PBP) regarding the reduction of flood risk. According to this approach, planning must be based on the demonstration of being capable of performing the agreed collective strategy, just like the performance-based design. This approach appears clearly in line with the strategies outlined and in compliance with the risk reduction objective.

Second, emergency and evacuation planning has to be efficiently combined with structural measures related to both gathering areas/shelter allocation, and architectural solutions for reducing user–floodwater interferences during motion [85,86,103,109]. In particular, gathering areas are more relevant to the immediate emergency response, since they collect users at the end of the evacuation process, and allow them to safely wait for the rescuers' arrival. They should be clearly identified by emergency signage [77], and placed in a widespread manner where floodwater depth D [m] and speed V [m/s] can always remain under the safe or low-risk threshold (up to DV = 0.06 m^2/s [44]), while balancing the possibility to be easily and quickly reached by rescuers. Similarly, evacuation paths to reach the gathering areas should minimize critical interaction with floodwaters that can slow down or even hinder the evacuation, because they can reduce the evacuation speed as well as can cause stability loss [88,89,105].

Floodwater effects are both present indoors (e.g., hindering doors' opening) and outdoors, and they also depend on the users' age, gender, motion ability, body mass and height, and on "social group" effects [16,88]. However, in general terms, more vulnerable users are those placed outdoors, especially the elderly and unassisted children. In this sense, architectural solutions to be implemented in the BE for mitigating floodwater effects and physically support users while evacuating can be mainly referred to [85]: (1) raised platforms and raised walkways, which can be also used as widespread temporary gathering areas; (2) handrails, where users can hang on while moving or standing for the rescuers' arrival in case of quick floodwater rising. These structural solutions have also recently considered by designers to be integrated into street furniture (e.g., see https://www.rogersarchitects.com/mta-flood-mitigation-street-furniture/, accessed on 28 February 2022), or the design of new squares with different ground levels also for floodwater collection purposes.

Finally, reaching a "safe" area allows users to stop the evacuation and wait for rescuers' support or autonomously organize the aftermath response and resilience behaviors because of "social groups" effects [45,110]. Users could also return home, if possible, because of attachment to belongings behavior. It is worthy of notice that these evacuation phases can be affected by "feed-back loops", due to the presence of particular local conditions driving the human reaction (e.g., evacuation movement can start again in case this reached safe area is affected by incoming critical flood conditions) [45,104]. In complex cases, e.g., in slow events or in case of floods in wide urban areas, the process timing can be significantly extended over time, due to the disaster spreading, by mainly causing specific differences in the starting time of the evacuation movement phase for buildings, or OSs located in the urban layout [16,51].

4. Adaptive Approaches' Background

What if the assumptions made in developing a plan will not be valid in the future?: this is the key question at the base of adaptive planning. Architectural and urban planning rely on an inherent determinism that once a plan is drawn, it will be successful, no matter how the future unfolds, which is becoming an unachievable and dangerous option. Therefore, there is a need to change from the "predict-then-act" to a "monitor-and-adapt" paradigm [111]. This shift has already been proven helpful in other planning disciplines [24] and the necessity of increasing the adaptivity of urban plans across different scales of intervention in order to improve resilience to climate changes is a recognized issue debated in the scientific literature [112–116].

Decision-makers, whether confronting short-term decisions or long-term objectives, face various uncertain factors, such as climate change, economic growth, social developments, etc. These uncertain factors have an impact on the planned actions and might undermine the success of the designed strategies in the future. Usually, planners rely on forecasts based on statistics, but if the future differs from the assumption made, the adopted measures can be insufficient, leading to undesirable outcomes.

Uncertainty is a multidimensional concept defined as any departure from the unachievable idea of determinism [117]. Three key dimensions of uncertainty are location, nature, and level. All the dimensions are important to decide the correct approach to deal with uncertainties, but the level is particularly relevant. The levels are divided between determinism and total ignorance as follows [118]:

- Level 1 of uncertainty. A situation where short-term decisions are taken and there are multiple alternatives with a specific probability assigned;
- Level 2 of uncertainty. In this case, there are different alternatives ranked by likelihood, but no additional information can be provided regarding quantifying them further;
- Level 3 of uncertainty or deep uncertainty. In this situation, several alternatives can be enumerated but not ranked or expressed in terms of plausibility;
- Level 4 of uncertainty. It is the deepest stage of uncertainty where it is impossible to enumerate the possibilities; we can still make assumptions but with the possibility of being wrong or surprised. These events, outside regular expectations, are called "black swans".

The challenges generated by uncertainty in different planning and decision-making fields have produced different approaches to deal with it. Typically, when dealing with deep uncertainty, we have a complex system that changes dynamically. Consequently, it is not easy to completely understand how the system works and the possible future outcomes. Simulation models are valid support to instantiate the system of interest, investigate plausible futures, and test interventions in the system considering the various uncertainties. The necessity of a computational approach is given by the system's complexity in case of deep uncertainties. The traditionally applied expert opinion is insufficient to provide significant outcomes, as the complexity cannot be reduced with a single scenario associated with the most likely future. Therefore, models coupled to human reasoning are more fit for purpose in a complex system under deep uncertainties. Once the information is organized, the simulation model is iteratively used to test the proposed actions in many plausible futures and to identify the most robust strategy [119], or, in other words, the strategy with the best performance or being the least affected by the uncertainties. As stated by Kwakkel et al. [120], the importance of the robustness of the planned actions considering the uncertainties has been widely recognized in the literature.

As a response to this challenge, Decision Making under Deep Uncertainty (DMDU) approaches have been developed to support the design of robust plans, meaning plans that are robust against uncertainties. Each DMDU approach [121–123] offers different analytical perspectives, and, according to the specific context, it can be beneficial to combine or swap the techniques. In the following subsection, a more in-depth description of each specific DMDU adaptive approach is provided.

This section provides an overview of the approaches mentioned above that could be a valuable aid for planners to tackle adaptation.

4.1. Adaptive Policymaking

Adaptive policymaking (APM) (Figure 5) is an approach developed to help decision-makers dealing with uncertainties by choosing the most robust policies for complex systems, whose behavior cannot be predicted with the aid of static analyses. Strategies must be decided, although the future might be different from the assumption made; therefore, they should be adaptive and change in light of new data, reducing the uncertainties [124].

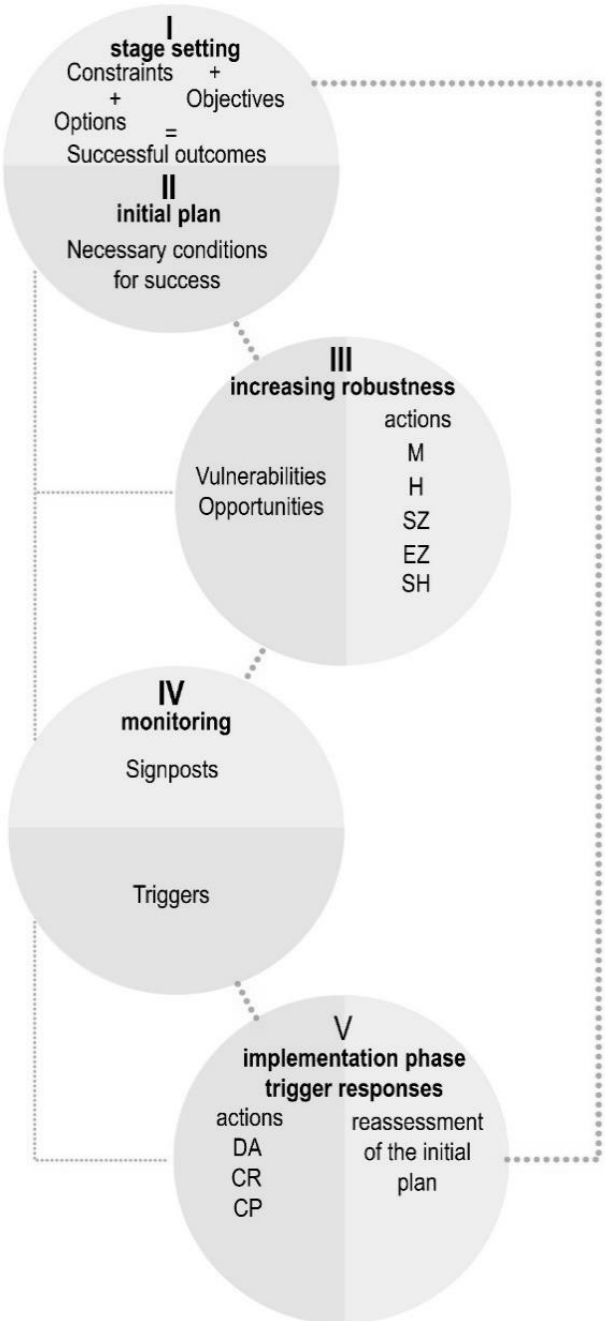

Figure 5. APM steps. Elaborated from [22].

It is divided into two phases: (i) thinking phase; (ii) implementation phase. The "thinking phase" is, in turn, divided into four different steps:

(1) In the first step, objectives are defined, constraints identified, and feasible options to meet the objectives are analyzed. Furthermore, a definition of success is given based on the outcomes obtained regarding the objectives and constraints;
(2) In the second step, the initial plan is assembled, and the necessary conditions for success are outlined;
(3) In the third step, the robustness of the initial plan is increased by identifying the vulnerabilities that minimize the chances of success or the opportunities that increase the plan's success. Different analytical approaches can be used, such as Exploratory Modeling and Analysis (EMA) [125], scenario analysis [126], or SWOT analysis [127]. Determining the scenarios where the plan would fail to meet the objectives is significant to find the vulnerabilities.

An approach based on EMA, scenario discovery [128], enables the analysis of scenarios, and then different kinds of action can be implemented to increase the robustness of the plan. The kind of actions that can be taken are divided into five groups [129]:

- Mitigating actions (M);
- Hedging actions (H);
- Seizing action (SZ);
- Exploiting actions (E);
- Shaping actions (SH).

The first two kinds of actions make the plan more robust, reducing the potential adverse effects caused by the vulnerabilities. Instead, seizing and exploiting actions focus on the opportunities that are very likely to happen; they are short-term actions to implement now and benefit from the change when the opportunities occur in the future. Shaping actions are proactive actions, and their focal point is to change the vulnerabilities or the opportunities to have outcomes relevant to the objectives of the plan;

(4) In the fourth step, the identified necessary conditions of success are transformed into indicators. Those indicators are called signposts, and a monitoring system is implemented to track them [130]. In this stage are also defined four groups of actions that can be taken to adapt to ensure that the objectives are achieved [129]:
    - Defensive actions (DA);
    - Corrective actions (CR);
    - Capitalizing actions (CP);
    - Reassessment actions (RE).

The defensive actions are taken in response to a trigger event. Defensive action aims to preserve the initial plan from being changed. Corrective actions are implemented to adjust the initial plan in response to triggers. Capitalizing actions are taken when opportunities that could improve the initial plan emerge. Reassessment is a process to revise the plan and the analyses when unexpected events, such as black swans, change the validity of the initial plan. Then, the adaptive plan is implemented in an iterative process;

(5) The "implementation phase" is set in motion while the future unfolds, and the signposts are monitored. If a signpost reaches a critical level, called a trigger, then actions to adapt the plan must be implemented to ensure the plan achieves the objectives identified in the previous phase.

4.2. Adaptation Pathways

Adaptation Pathways (AP) is a DMDU approach that explicitly considers time, sequences actions on alternative paths, and enhances the plan's flexibility as conditions change. As seen in APM, a first step towards the inclusion of time was done through integrating signposts, triggers, and the adaptation of the plan through actions associated with specific triggers [22]. The key idea of AP is to focus on expressing the conditions when the external changes are so significant that the plan can no longer meet the objectives. Those conditions are called "adaptation tipping point" (ATP) [131]. Once the timing is assessed through scenarios, a set of actions is developed to reach the objectives still. As a result, a pathway is structured composed of different actions over time. Moreover, different alternatives are presented, structuring a route map of pathways similar to a metro map. Different approaches can be used to identify the adaptation tipping point.

A bottom-up approach may be used, where a model-based assessment is useful to find under which condition the plan fails. Alternatively, a top-down approach is highly dependent on model-based assessment to investigate the uncertainties over time.

4.3. Dynamic Adaptive Policy Pathways

The Dynamic Adaptive Policy Pathways approach (DAPP) (Figure 6) is the combination of APM and AP [24]. The core idea in this to structure a plan from short-term actions, including the long-term options through different pathways.

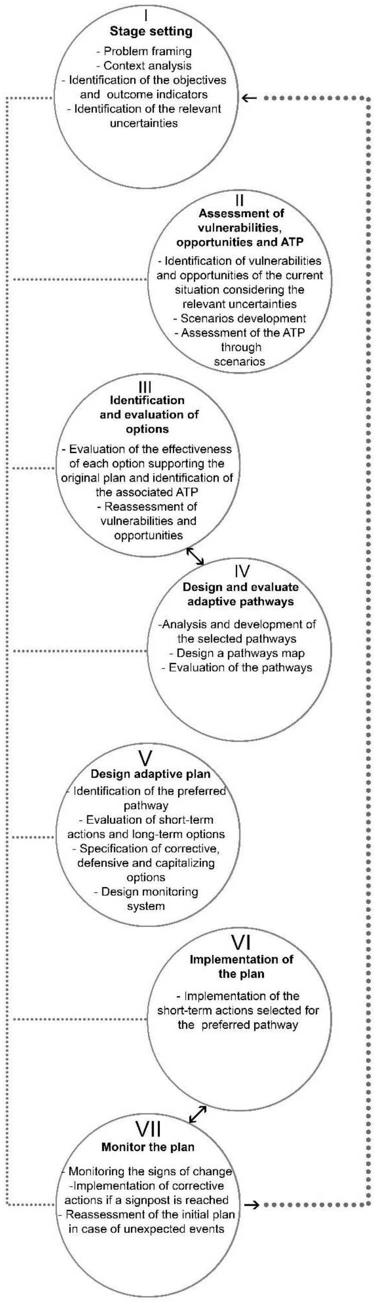

Figure 6. DAPP approach. Elaborated from [24].

The DAPP approach is structured as follows:

(1) *Decision Context*. The first step is the same as APM; the system is analyzed to highlight its characteristics, objectives, and constraints. In this phase are specified the objectives and the indicators to assess whether the outcomes are meeting the objectives. In this phase are also identified the relevant uncertainties that could influence the success of the plan in the future. The uncertainties are used to generate an ensemble of scenarios, which can be static or transient, to investigate plausible futures;
(2) *Assess vulnerabilities and opportunities of the case of interest and identify ATP*. The second step is to assess the robustness of the current situation using the prespecified indicators to assess when it fails to meet the objectives. Therefore, the scenarios are used to assess when and under which circumstances the plan fails to meet the objectives. Those transient scenarios are necessary to assess the ATPs for the current situation;
(3) *Identify contingent actions and assess their ATP*. From the previous analyses, alternative planning action can be identified to support the plan coping with vulnerabilities or seizing arising opportunities. The selected strategies are then tested to see when they reach an ATP, and the ones that still meet the objectives under dynamic conditions are used to structure the adaptive plan;
(4) *Design and evaluate the adaptive pathways.* Following the previous steps, the planner decides which of the analyzed strategies are best for the case of interest and develops the adaptive pathways. Visually, they have a similar structure as a metro map. Each "line" is a planning strategy or a more than one, and each "transfer station" is a point where we can switch on alternative routes before we run into an ATP;
(5) *Design adaptive strategies*. In this step are specified the short-term planning strategies and the long-term options for the preferred adaptive pathway. To ensure the robustness of the selected strategy and to stay on track of the route, support actions are used as specified in APM: corrective, defensive and capitalizing actions.

A monitoring system combining relevant triggers and signposts (i.e., environmental indicator) is associated to the plan to identify when is necessary to implement an action;

(6) *Implementation of the plan.* Operating phase, the plan is implemented according to the selected initial pathway with short-term actions decided by the planners;
(7) *Monitor the plan.* After implementing the short-term actions, the relevant signals of change are monitored. Once a signal is reached, contingent actions could be taken, or the plan could require a reassessment.

5. Discussion

Table 2 connects the mitigative strategies that emerged from the literature overview (Section 3) to the basic concepts of adaptative approaches. Then, considering the main aspects from the adaptive planning background, a limit is specified for each planning strategies, representing the boundary of effectiveness. The uncertainties affecting the expressed limit, which could compromise the effectiveness of the measure, are also pointed out.

It is worth noticing that some of the strategies, and hence their uncertainties and limits, are strongly interconnected in view of the users–open spaces–building interactions, both before and during the emergency and evacuation process. In particular, demographic and socio-economic changes could lead to interferences between the planned emergency response and the deployed emergency facilities. For instance, areas characterized by having elderly as the main users' typology should move from a dynamic response in emergency and evacuation to "shelter-in-place" strategies, as elderly users could not be able to reach a safe area which is not close by. In this sense, the effectiveness of architectural solutions and emergency areas for users' safety could be limited, while strategies based on architectural typologies, such as floating buildings, amphibious buildings, and elevated-floor houses should substitute them to reduce direct losses. In this sense, strategies based on EWS should be adapted to promote clear indications to the population.

On the contrary, Table 2 also shows that most of the strategies that are mainly related to the open spaces' layout, materials, and flood facilities could be always efficient, despite changes in users' features, unless private–public cooperation support the strategies (compare Section 3). Moreover, case-specific characteristics of the flood risk could be considered as a transversal limit for most of the strategies, including the user-centered ones. The Table can be considered as a synthetic database of mitigative measures for flooding, which, as an original contribution of this article, can be considered with respect to specific uncertainties that could affect their effectiveness.

Table 2. Mitigative strategies for the components of the BE, limits, and main uncertainties affecting the effectiveness.

Strategies	Uncertainties	Limit
Open Spaces		
Permeable pavings	Climate change related to rainfall profile and sea level rise, increased imperviousness	Case specific characteristics of the flood risk
Rain gardens	Climate change related to rainfall profile and sea level rise, increased imperviousness	Case specific characteristics of the flood risk; ineffective for runoff volume control
Flood parks	Climate change related to rainfall profile and sea level rise, increased imperviousness	Ineffective for runoff volume control
Floodable areas	Climate change related to rainfall profile and sea level rise, increased imperviousness	Ineffective for runoff volume reduction
Wetlands	Climate change related to rainfall profile and sea level rise, increased imperviousness	Ineffective for runoff volume reduction
Basins	Climate change related to rainfall profile and sea level rise, increased imperviousness	Ineffective for runoff volume reduction
Swales	Climate change related to rainfall profile and sea level rise, increased imperviousness	Case specific characteristics of the flood risk; ineffective for runoff volume reduction and control
Building-related		
Floating buildings	Climate change related to sea level rise, rainfall profile	Maximum height of the water is related to the design of the floating house lower than normal condition + 2.5–3 m; water velocity should be lower than 2 m/s
Amphibious buildings	Climate change related to sea level rise, rainfall profile	Maximum height of the water is related to the design of the amphibious house, lower than 2.5–3 m; water velocity should be lower than 2 m/s
Elevated-floor houses	Climate change related to sea level rise, rainfall profile	Maximum height of the water should be lower than the ground level height; Ground level structure should resist to flooding
Green solutions (roof and walls)	Climate change related to rainfall profile	It retards/diminish the peak flow; Effective under determined rainfall events
Rainwater harvesting systems	Climate change related to rainfall profile	It retards/diminish the peak flow; Effective under determined rainfall events
Users Oriented		
EWS	Demographic and socio-economic changes (also affecting "attachment to belongings", "social shared identity", "leader-followers" behaviors)	Users' preparedness; Effective communication strategies to the population; Case-specific characteristics of the flood risk
Emergency wayfinding and risk signs	Climate change related to sea-level rise and/or rainfall profile	Link between the plan of these emergency facilities; Possibility to dynamically adapt wayfinding/risk information depending on the effective context; Different hazard/risk maps depending on the flood source and hence on case-specific characteristics of the flood risk
Architectural solutions–raised platforms	Demographic changes, open space use and non-emergency facilities deployment	The population can actively evacuate the building or use the emergency facilities (e.g.: age, motion abilities); Link between the plan of these emergency facilities; Different hazard/risk maps depending on the flood source
Architectural solutions–street furniture	Demographic changes, open space use and non-emergency facilities deployment, public-private cooperation on building site frontiers	The population can actively evacuate the building or use the emergency facilities (e.g.: age, motion abilities); Link between the plan of these emergency facilities; Different hazard/risk maps depending on the flood source
Evacuation plan with identified safe areas	Demographic changes (ageing of population), Climate change related to sea-level rise and/or rainfall profile	The population can actively evacuate the building (e.g.: age, motion abilities.); Different hazard/risk maps depending on the flood source

6. Conclusions

This research performed an overview on resilience and adaptation to flooding, considering mitigation and adaptation measures to flooding, by also adding the perspective related to uncertainties due to dynamic and unexpected changes in future events, such as those related to climate changes. The article demonstrates how, currently, several frameworks and approaches have been put forward to increase flood resilience in the built environment, recognizing the importance of adapting cities to uncertain climate drivers. However, there still is a significant gap to fill in shifting from theory to practice. Architecture and urban planning base their strategies on data with an associated probability, without assessing how they could be adapted over time.

Overlooking uncertainties in the planning process is no longer feasible. Therefore, in this study, we presented the main strategies oriented toward the built environment (BE) components used in urban contexts to cope with floods, as well as adaptive methodologies that have been proven to be good supports in other disciplines that require planning under dynamically changing conditions. As highlighted, adaptive plans are based on the most resilient short-term actions for the current situation and are monitored and adapted as the future unfolds. Hence, the mitigative strategies for the different components of the BE have been synthesized in an adaptation-oriented framework. Results of this work highlight the related limit of effectiveness and the main uncertainties of the mitigative strategies that could affect their operating conditions, thus representing the first basis for the development of adaptation approaches that include BE components and their short-term to long-term strategies. The nature of the uncertainties also calls for attention to the interdisciplinarity of the issues, underlining how future research steps should be based on collaborations among experts from different fields to tackle climate adaptation in urban areas. Moreover, it is essential to underline that as of now, the available data and modeling tools are insufficiently integrated, thus suggesting that future works should be aimed at removing obstacles for the operational phase of adaptation of the BE.

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