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Review

Flood Risk in Urban Areas: Modelling, Management and Adaptation to Climate Change. A Review

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Abstract: The modelling and management of flood risk in urban areas are increasingly recognized as global challenges. The complexity of these issues is a consequence of the existence of several distinct sources of risk, including not only fluvial, tidal and coastal flooding, but also exposure to urban runoff and local drainage failure, and the various management strategies that can be proposed. The high degree of vulnerability that characterizes such areas is expected to increase in the future due to the effects of climate change, the growth of the population living in cities, and urban densification. An increasing awareness of the socio-economic losses and environmental impact of urban flooding is clearly reflected in the recent expansion of the number of studies related to the modelling and management of urban flooding, sometimes within the framework of adaptation to climate change. The goal of the current paper is to provide a general review of the recent advances in flood-risk modelling and management, while also exploring future perspectives in these fields of research.

Keywords: flood management; flood modelling; flood resilience; flood risk; two-dimensional models

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1. Introduction

Flooding events are frequent and widespread natural hazards, often associated with severe socio-economic losses and environmental impacts. In urban areas, the impact can be particularly high, due to both the direct damage caused, through the inundation of property and critical infrastructure (e.g., electricity substations, bridges, and drainage systems), and indirect consequences, such as the loss of productivity and business opportunities [1]. The complexity of flooding is a consequence of the various sources of flood risk, including not only fluvial, tidal and coastal flooding but also exposure to urban runoff and local drainage failure, as well as the different management strategies that can be proposed. Climate change adds a further layer of complexity, with the impact of the processes of climate change likely to increase flood risk, both inland and coastal, in the future, due to rising sea levels and storm surges, as well as to the increased frequency of extreme precipitation events [2–7].

The increased incidence of urban flooding over recent years highlights the need for reliable flood-mitigation strategies, and hence flood-risk management (FRM) is increasingly recognized as a global challenge [8,9].

A standard approach to FRM has often been the adoption of flood-control measures (resistance-based strategies). Flood-control measures aim to reduce the probability of flooding through grey infrastructure (hard, conventional or engineering solutions), such as dikes, dams, embankments, and weirs. Although this approach can provide substantial protection against floods [10], it is generally accepted nowadays that risk cannot be managed solely by holding back water through a narrow focus on heavy civil-engineering works [11]. Moreover, there is a growing recognition that traditional measures: (1) will not be sufficient to cope with increasing and intensifying flood events due to climate change [12], (2) have negative impacts, including the degradation of freshwater ecosystems [13], and (3) create a false sense of security, since many governments and communities trust the protection given by such structures and in the case of failure they often find themselves underprepared to cope with the flooding effects [14,15].

This awareness has led to the transition from structural and large-scale flood-defense measures towards integrated FRM strategies, based on the assumption that absolute flood protection is unattainable, and focusing on how to reduce the vulnerability of flood-prone communities by taking a more holistic perspective [16,17]. The work here has been motivated in part by a recognition that under the effects of climate change, communities need to improve their resilience and their capacity to cope with flood risks as these increase over time [18,19]. Such an approach embraces all the temporal phases (pre-, during and post-event) involved in the occurrence of a flood hazard [20]. Therefore, the implementation of a risk-based approach is nowadays commonly accepted around the world as being necessary.

The aim of a risk-based approach is to reduce the overall flood risk, which can be defined as a combination of hazard, vulnerability, and exposure [21]. Hazard represents the probability of a hazardous event happening in a given place; vulnerability is a function of the potential damage suffered by a target due to the occurrence of the hazardous event; while exposure quantifies the presence of the target in the area where the hazardous event arises. Parameters that are generally used to quantify the flood hazard include flood extent, water depth, flow velocity, duration, and the rate at which the water rises [22]. These parameters can then be linked to estimates of the economic loss and damage that such a flood would generate in an affected area. Indeed, a suitable combination of flow depth and velocity, through properly devised vulnerability-damage curves, can be used for the estimation of the potential effects of the flow on a target, such as the assessment of direct potential damage to structures, buildings, people and vehicles.

The hydrodynamic variables mentioned above can be computed using numerical flood-inundation models, which constitute a well-established approach to the analysis of flood risk.

Early numerical models were based on the 1D Saint Venant equations, also known as 1D shallow-water equations (1D-SWEs). These models were used extensively in the 80s and 90s to model river flooding, with HEC-RAS 1D being the most widespread model. Computational capacity and the availability of data at the time made such models the most appropriate in terms of accuracy and computation time. However, 1D approximation has severe limitations when modelling floods in urban areas, as will be discussed in Section 2. Although 1D hydrodynamic models are still used in some applications [23–30], they have been progressively replaced by 2D models in order to reproduce the complex, multidirectional flow paths that occur in urban areas.

In the last decade, efforts have been made to develop models and methods for flood-risk management and modelling, ones which also take into account the need to adapt to climate change. However, significant challenges remain, as made clear in the papers published in the special issue of the journal *Hydrology*: "Advances and perspectives in flood-risk modelling, management and assessment".

Whereas some reviews have appeared in the literature, and these will be mentioned below, we still lack a unified view of urban flood modelling and management issues in the context of climate change. The goal of the present paper, then, is to provide a general review of the recent advances in flood-risk modelling and management, while also exploring some future perspectives in these fields of research.

2. Modelling and Evaluation of Flood Risk

The evaluation of flood risk in urban areas relies on the numerical modelling of free surface flows. Several approaches and methodologies can be implemented, depending on the type of flooding to be considered and on the scale of the study. This section will discuss some recent approaches related to the modelling of flood risk in urban areas, including the development, calibration, validation and application of numerical models.

2.1. Modelling Flood Hazard

Urban flood hazard has been extensively studied in recent decades, leading to the development and application of a number of numerical models to evaluate water depths and velocities during a flood.

The first numerical models were based on the 1D shallow-water equations (1D-SWEs), which are a set of two physically based partial differential equations that express, respectively, the conservation of mass and the section-averaged linear momentum. In these models the river is defined as a 1D line that represents its longitudinal axis and a set of cross sections perpendicular to the river axis.

The 1D approximation has severe limitations when modelling floods in urban areas, which mainly stem from the assumption of a uniform water velocity in the whole cross section, and from the act of discretizing the topography as a 1D line with a series of perpendicular cross sections.

The 1D approximation itself implies that it is necessary to define cross sections that are perpendicular to a longitudinal axis. This is difficult to achieve in rivers with high sinuosity or in urban river reaches, where the flood plain is generally occupied by buildings and other infrastructure. Moreover, in high-sinuosity rivers the streamlines might have very different trajectories during low and high flows, as shown in Figure 1.

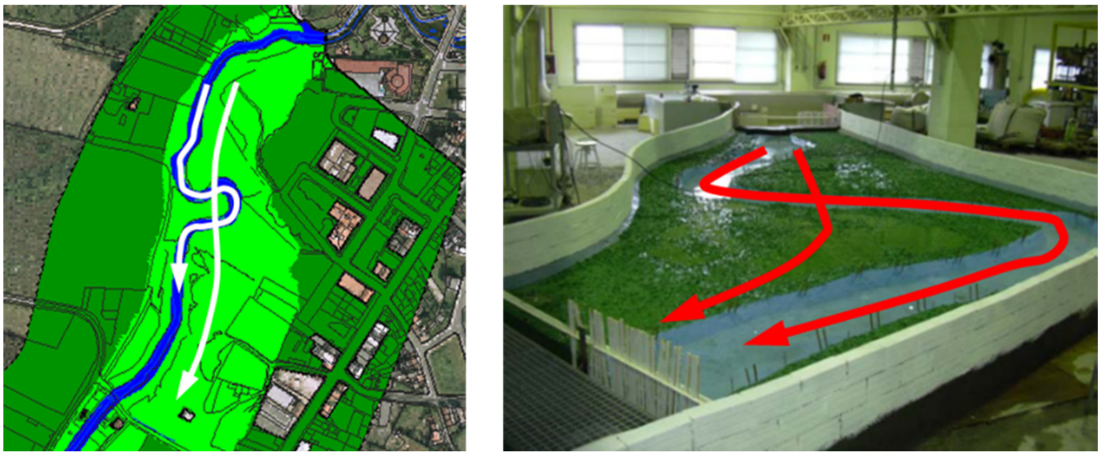

Figure 1. Streamlines during low and high flows in meandering rivers.

The flow in urban areas that are located in river confluences is also challenging for 1D models, since it is not straightforward to define the extension of the cross sections for each tributary in order to avoid overlapping. For instance, in Figure 2a, it is difficult to decide how the floodplain should be split between the left and the right tributaries.

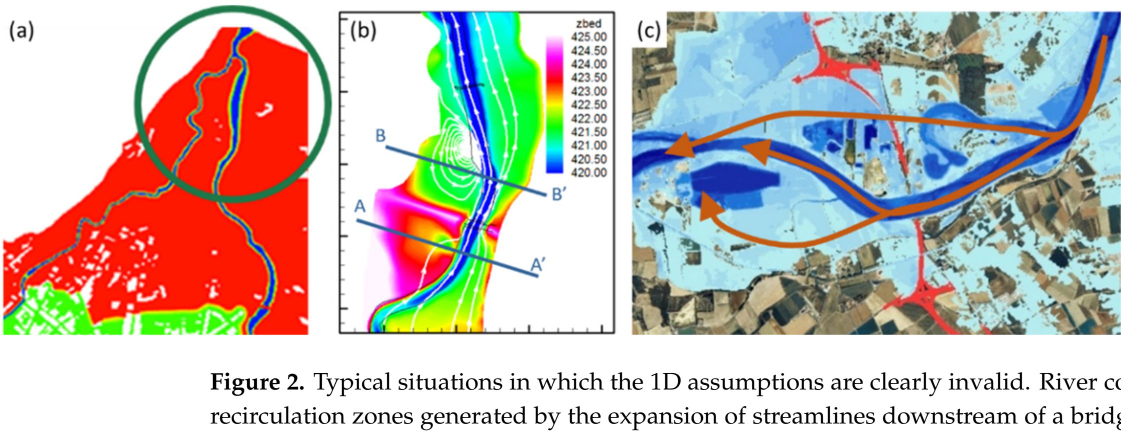

Figure 2. Typical situations in which the 1D assumptions are clearly invalid. River confluence (**a**), recirculation zones generated by the expansion of streamlines downstream of a bridge section (**b**) and flow paths in the main channel and floodplains during high-flow conditions (**c**).

Another limitation involves reaches located downstream and upstream of obstacles such as bridges or transverse embankments, where recirculation zones are generated due to the contraction and expansion of the streamlines (Figure 2b). In these recirculation areas the water velocity can take opposite directions over the same cross section, which clearly invalidates the 1D-SWE assumptions. The same happens, to a lesser extent, in reaches with highly vegetated flood plains (Figure 2c), where the water velocity in the flood plain is much lower than in the main channel, invalidating the uniform-velocity assumption.

In order to improve the predictions of the numerical models in the previous situations, and by taking advantage of the continued increase in computing performance, a large number of 2D models have been developed over the last three decades. These models solve the 2D Saint Venant equations, also known as 2D depth-averaged shallow-water equations (2D-SWEs), or simplifications of them, such as in the Simple-Inertia formulation [31–33], the Diffusive-Wave [34], and the Kinematic-Wave equations. The Simple-Inertia (SI), Diffusive-Wave (DW) and Kinematic-Wave (KW) simplifications were initially developed in order to avoid numerical difficulties and to diminish the computational burden of the numerical schemes required to solve the 2D-SWEs. Compared to the 2D-SWEs, the SI formulation neglects the advective inertial terms in the momentum-conservation equations [31,33], while the DW and KW formulations neglect both the local and advective inertial terms.

Several 2D software packages have also been developed. Worth mentioning in this context is the model benchmarking performed by [35] in which several benchmark test cases were presented, against which the most widely used 2D flood-inundation-modelling packages were tested and compared. The model benchmarking carried out by [35] has been used several times in the literature to check the performance of models for flood mapping [36–40].

Previous studies [32] have shown that the SI formulation works best when the Froude number is less than 0.5, and that as the Froude number increases towards 1 the SI equations deteriorate. This is also the case with the DW and KW equations, with the ratio of bed shear to advection forces being an indicator of the applicability of the DW approximation [41]. Similar studies have shown that, when applied to urban flooding, DW models underperform compared to 2D-SWE models, due to the fact that they ignore the inertial terms [34,42,43]. Therefore, the use of KW, DW and SI models should be restricted to flows that are mainly driven by gravity and bed friction, which is often the case with large scale models with a low grid resolution. Supercritical flow conditions, hydraulic jumps, and highly curved streamlines are not well represented by these simplified models [44,45]. The development of efficient and robust numerical schemes to solve the 2D-SWEs, together with the current availability of high-resolution and accurate Digital Terrain Models (DTMs) obtained with LIDAR, has meant that most of the numerical models used to evaluate urban floods nowadays are based on the fully dynamic 2D-SWEs, while simplified models based on the DW and SI formulations have been used less and less due to their lower capability to represent with a high spatial resolution the flow conditions that typically occur in urban areas.

Two-dimensional shallow-water-equation models have been extensively validated and applied to many urban-inundation studies over the last decade [46–53], showing their ability to represent urban-inundation processes and to efficiently deal with the presence of unsteady inundation fronts, small water depths, and high bed friction. Small-scale structural elements (e.g., buildings, walls) and small topographic variations can be explicitly represented in the model, instead of being parameterized, as long as the numerical mesh is fine enough [54–62]. The only empirical parameter that must be defined by the user is the Manning roughness coefficient, the values of which are relatively well established in river engineering manuals as a function of land uses. To further improve flood-risk estimations, especially in the presence of in-line structures such as bridges, additional processes that occur during floods can be included within the two-dimensional shallow-water modelling, such as the transport of sediment or wood [63–66], or mixed free-surface-pressurized flows in vertically confined river reaches [67].

The computational burden of inundation models based on the 2D-SWEs can be reduced by using coarser grids and including sub-grid models to account for topographical features and small-scale obstructions that are too small to be explicitly resolved with the computational mesh [68–75]. Details of velocity and water-depth patterns within a mesh element cannot be resolved with these approaches. Nevertheless, they are of interest in terms of taking advantage of the high-resolution LIDAR data that are available nowadays and which, in general, cannot be explicitly included in a 2D model since it would require numerical grids with hundreds of millions of computational cells. The use of nested grids has also been proposed in some studies that include a large computational domain [76,77]. Nested grids provide very high spatial resolution in selected areas of interest without incurring the high computational expense of fine grid resolution over the entire model domain. Other strategies focusing on specific grid-generation techniques can be found in [78–81].

When modelling pluvial flooding in urban environments, it might be necessary to include the effect of the storm-water sewer network on the drainage of the surface runoff. Storm-water drainage in urban areas has traditionally been modelled using semi-distributed equations, such as those included in the Storm-Water-Management Model (SWMM) from the United States Environmental Protection Agency (EPA). These models include a very detailed representation of the sewer network (which consists of 1D sewer elements, manholes, gullies, pumps, etc.). The overland flow, on the other hand, is represented using a semi-distributed approach, in which the urban district is discretized as a number of sub-basins that are modelled with a lumped formulation. The discretization of the surface in terms of sub-basins is not in itself trivial, and might condition the accuracy of the results [82]. This approach is very efficient in modelling the flow in the sewer network, but lacks the accuracy to represent the water depths and velocities on the urban surface, and thus is not appropriate for evaluating pluvial-flood hazard in urban areas. This led to the development of so-called dual-urban-drainage models, which couple a hydrodynamic overland-flow model with a sewer-network model (see Figure 3). Several examples of these approaches have been seen in recent years [83–90], including 1D–1D dual-drainage models [91,92], in which both the overland and sewer flows are computed with 1D equations, and 1D–2D dual-drainage models that consider the full interaction between the 2D overland flow and the 1D sewer network through gullies and manholes [83,86,93–95]. Along the same lines as the latter, several publications in recent years have presented dual-drainage models that couple a 2D inundation-flow model with the well-established Storm-Water-Management Model (SWMM) [93,94,96–101]. Other, simpler approaches that only account for the 2D overland flow and that do not resolve the flow within the sewer network have also been used to model pluvial flooding [101–103].

Currently, the implementation of 2D-SWE models to evaluate flood hazard is standard practice, and in recent years new developments have tended to focus on increasing their computational efficiency through the application of high-performance-computing (HPC) techniques that take advantage of the parallelization functionalities of central processing units (CPUs) and graphics processing units (GPUs). In fact, the use of GPUs for computational purposes in flood-inundation models has become quite common in recent years due to the high computational-efficiency-to-price ratio of these devices compared to a traditional cluster of CPUs. Moreover, the widespread availability of GPUs in personal computers has made them very attractive for computational purposes. The development of CUDA, a parallel-computing platform and programming model developed by NVIDIA for general computing on graphical processing units, has enabled modellers to develop GPU parallelizations of shallow-water codes applied to flood modelling that yield increases in the computational time of up to two orders of magnitude with respect to the standard sequential implementation on CPUs [104]. Some of these studies implement shared-memory GPU parallelization algorithms [39,98,105–110] while others go one step beyond with the implementation of multi-GPU parallelization schemes [111,112]. Although implementations on multiple CPUs are less common nowadays, several 2D flood-inundation models have also been parallelized using shared-memory (OpenMP) as well as distributed-memory (Message Passing Interface, MPI) standards [39,59,73,113–115]. Compared to a single-GPU parallelization scheme, the use of distributed memory is advantageous when running the code in an HPC-CPU cluster, in order to take advantage of a large number of CPU nodes.

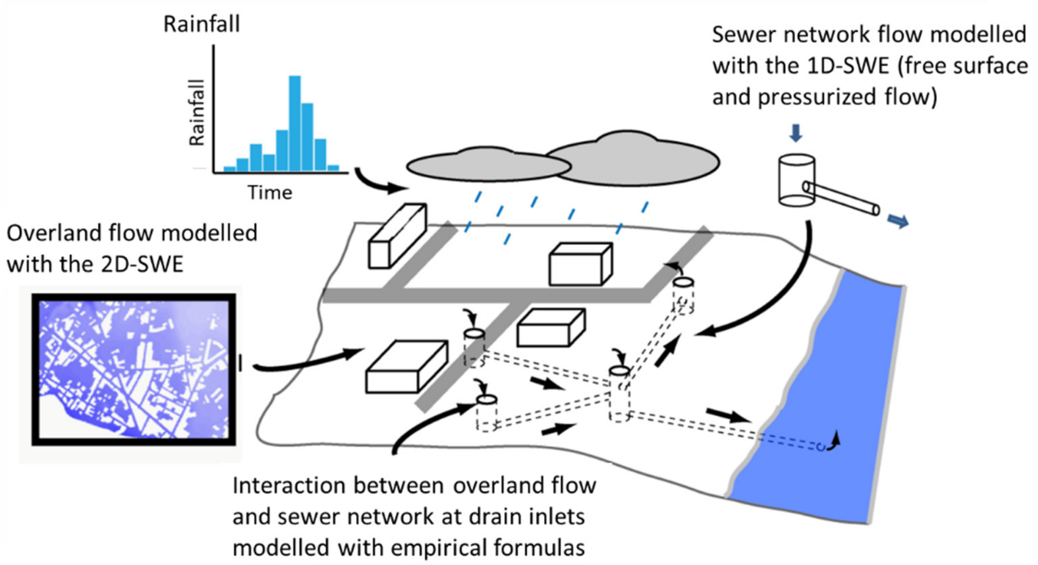

Figure 3. Schematic representation of the typical implementation of a 1D–2D dual-drainage model.

Another interesting and complementary line of work with the aim of reducing the computational time of 2D flood models is the development of surrogate models of the 2D-SWEs using machine-learning (ML) techniques. The idea of these approaches is to replace the predictions given by the 2D-SWEs with those of a previously trained surrogate model. This approach can be efficient for applications that need to produce results in a very short time or in cases where the model must be run thousands of times with different input parameters. Real-time flood forecasting within early-warning systems, or uncertainty and sensitivity analysis within a Monte Carlo framework, are two typical examples in which the use of a 2D-SWE model is penalized due to the computational burden of each model run or by the high number of model runs required, and thus the application of surrogate models might be of interest here. In our opinion, it is in applications of these kinds, where the main concern is to make fast and accurate predictions with limited interest in the physical analysis of the hydrological processes taking place, that ML-based models constitute a good alternative to physically based flood-inundation models that solve the 2D-SWEs. Several examples can be found in the recent literature, including surrogate models trained for a specific case study [116–119], and more ambitious approaches that try to develop generalized learning techniques that are capable of making predictions in case studies different from those that were used to train the algorithms [120,121]. There have also been attempts to integrate ML techniques within physically based numerical models by replacing the computationally expensive parts of the solver with simple and more efficient data-driven approximations [122]. Such an approach has the potential to achieve an improved generalization performance from one case study to another, but the computational improvement is much lower than that of surrogate models trained for a specific case study. All the aforementioned studies have shown that, once appropriately calibrated, such computationally less-demanding approaches can yield predictions comparable to physically based models.

2.2. Evaluation of River-Flood Risk in Urban Areas

River flooding occurs when the water discharge in a river exceeds the maximum capacity of the main channel, causing the water to flow onto the floodplains and the urban area. River flooding in urban areas has been extensively studied in recent years around the world, following the implementation of national flood directives. Particularly in Europe, the implementation of the EU Floods Directive 2007/60/CE [123] has led to the definition of so-called Areas of Potential Significant Flood Risk (APSFRs) in all EU member states, and to the development of detailed numerical models to evaluate the flood hazard for different return periods in all APSFRs (see also Section 3). Most of these inundation models were developed using well-established software that solves the 2D-SWEs, as noted in the previous section.

The required input data are a detailed DTM (typically with a spatial resolution of 1 m), a classification and spatial distribution of land uses in the study area, a detailed geometric definition of hydraulic structures such as bridges and weirs, and the river discharge for different return periods (typically from 5 years to 500 years). While these numerical computations are standard engineering practice nowadays, and thus it might seem that the problem of the evaluation of river-flood risk in urban areas has been solved, there are still some issues that require improvements and that have been addressed in recent studies.

From the modelling point of view, sub-grid modelling has received a great deal of attention in recent years, despite the concept not being new, due to the very high resolution DTMs that are currently available. In most engineering studies the use of computational grids with the same resolution as LIDAR-derived DTMs is not feasible because of the high computational burden it would imply. Thus, the numerical model must be constructed using a coarser grid than the DTM resolution, while a sub-grid model can be used to account for high-resolution topographic variability and other small-scale obstacles that are not explicitly resolved by the computational grid. Several approaches have been proposed, including so-called porosity shallow-water models that can account for small-scale obstructions and obstacles [57,68,70–72,124,125], and other formulations based on the intra-cell variability of the topography that can account for the presence of ditches, small channels and furrows not resolved in the computations mesh [69,73–75]. Sub-grid modelling is also especially important in large scale models such as global- or continental-scale river-inundation models, but those modelling approaches are not suitable for an accurate and detailed estimation of urban flood hazard, and are not considered in this review.

Another significant line of research addresses the evaluation of compound flooding in coastal river reaches due to the combined effect of river discharge, sea level, and ocean waves. The simultaneous occurrence of these flooding processes can lead to flood levels that are significantly greater than those from river flooding alone, and can have notable impacts on densely populated, low-elevation coastal areas and river deltas [126–129]. The main issue here is how to consider the joint probability of the occurrence of high values of sea level, ocean waves, and river discharge, as well as the mutual interaction between these different sources of flooding [130]. The most common method to address the problem is the joint-probability approach [131], in which the joint-probability-density function (PDF) of the forcing variables must be estimated from available data records. Estimating the joint PDF of more than two variables is rather complicated, especially if the variables are partially correlated, as is the case with river discharge, storm surge, and ocean waves. In addition, the definition of an extreme flood event that depends on several forcing variables is not straightforward [132,133]. For this reason, in practice this approach is generally limited to only two variables [131]. Once the joint PDF has been obtained, several characteristic cases must be modelled with a numerical model in order to map the flood extension and water levels for different return periods. At this stage it is not straightforward to select the characteristic cases from the joint PDF, since there is a continuous set of forcing variables associated with the same return period. Moreover, the same flood depth might result from different combinations of the forcing variables, each of these having a different return period. Several alternatives have been proposed in the literature regarding the most representative cases that should be simulated in applying a joint-probability approach, yet no simple and general solution exists [134–138].

An alternative approach to compound flooding is the so-called continuous-simulation approach, which consists of applying a univariate flood-frequency analysis to water-depth time series that are simulated with a numerical flood model, using long-term time series of the forcing variables as the boundary conditions in the model [139–141]. The application of the continuous-simulation approach is far less common than the joint-probability approach, since it implies running a large number of computationally demanding numerical runs. The aforementioned ML-based surrogate models of the 2D-SWEs can help to reduce the computational burden of this method. The continuous-simulation approach has some potential advantages, since the implementation of several forcing variables can be performed in a natural way in the numerical model, and non-stationary effects generated by seasonal variability, climate change, or anthropogenic changes might also be considered when generating the time series of the forcing variables. On the other hand, some of the questions that must be carefully addressed when applying these methods are the generation of continuous and correlated long-term time series of the forcing variables, and the computational requirements of a continuous simulation of these time series with a numerical model.

2.3. Evaluation of Pluvial-Flood Risk in Urban Areas

Pluvial floods are those generated by a local storm event and are generally characterized by very high rainfall intensities distributed over a short period of time and a relatively small area, producing a large amount of surface runoff that can cause flooding independently of the existence of an overflowing water stream. Therefore, pluvial floods can occur at any location and with little warning. Urban areas are especially prone to pluvial flooding, due to the high proportion of impervious surfaces, the relatively low roughness of land cover, and the presence of relatively high-terrain slopes ending in low-lying lands [142], all of which are factors that increase the net rainfall, favor high water velocities, and diminish the concentration time of the urban watershed. It is commonly the case that, due to the absence of a perennial water stream, people are less aware of being at risk of pluvial flooding than of river flooding. This leads to such areas being less prepared to cope with flooding, unless appropriate measures to communicate and explain the potential risks are taken.

While river floods have been extensively analyzed in recent years, following the implementation of various floods directives (such as the EU Floods Directive 2007/60/CE), far less attention has been paid to pluvial flooding [143], probably because this type of flooding is much more complicated to evaluate and forecast than river flooding. Numerical models for pluvial flooding that consider the interaction between the surface runoff and the sewer network, although currently available for practical applications [84,86,93–95,144], are more complex than river-flood models, and the required input data are more comprehensive (including the capacity and location of drain inlets, manholes, sewers, and other data about the sewer network that in the majority of urban settlements are not available). In many cases, information on the sewer network is missing or incomplete, so the models' capabilities cannot be exploited to their full extent [145]. In addition, flood-hazard evaluation and forecast are much more sensitive to the spatial and temporal resolution of rainfall. The result of a pluvial-flood event depends to a great degree on the intensity of spatially localized and short precipitation cells, and on how the sewer network reacts to that rainfall. As a consequence, most countries have not yet defined detailed hazard and risk maps relating to pluvial flooding, as they have already done for river flooding, and thus most flood-management plans that are presently being developed do not include measures to mitigate and manage pluvial flooding. Even if some countries have already started to define pluvial-flood-hazard maps using different approximations, the procedure is far from being standard and will probably be refined in the following years as more detailed data and accurate models become available.

The complexity of the models, and the lack of detailed data to feed them, has resulted in different numerical approximations being used to model pluvial flooding in urban areas [90]. Common approaches were mentioned in Section 2.1 above and range from simple 1D pipe-flow models to fully coupled 1D–2D dual-drainage models. The decision to use one pluvial model or another should ideally be the result of a detailed analysis of the availability of data for each specific case, plus a consideration of the specific aims of the study. For instance, a 1D sewer-flow model might be enough for the planning and management of a storm-water-drainage network [146,147] or for early-warning and emergency applications that require timely results. Models that consider only the 2D overland flow and treat the sewer system as an equivalent infiltration capacity, or simply consider an inlet drainage capacity without modelling the sewer-network flow, might be adequate for large scale studies [101,102], for regional and global pluvial-flood-hazard estimations [103], or for cases in which there are no available data to define the sewer network. When the details of a sewer network are known, dual-drainage models are currently the most detailed and comprehensive methods that can be applied. Considering the current availability and spatial resolution of topographic data obtained with LIDAR in many regions, and the computational performance of most 2D overland-flow solvers, we believe that 1D–2D dual-drainage models are the most suitable models in many cases, and their practical application to pluvial flooding will probably considerably increase in the years to come.

Drain inlets are a key component in dual-drainage models and merit special attention, since they represent the connection between the major surface-drainage system and the minor sewer-drainage system. Their position and drainage capacity control the amount of water that is exchanged between the surface and sewer systems. It is therefore important to correctly model the dynamic interaction between the major and minor drainage systems through inlets, and several studies have focused on different implementations [87,148,149]. In addition, even in cases where the sewer network is known in detail, comprehensive data on inlet locations are often missing or incomplete [145]. For this reason, many studies have focused on the numerical and experimental hydraulic characterization of drain inlets [150–159], as well as on the sensitivity of model results to the physical characteristics and location of inlets [97,145]. Inlet clogging due to a lack of maintenance and clearance has also been recognized as a major problem, indeed, one that can cause more flooding incidents than storm-sewer overloading does, especially in flat urban areas, leading to local flooding before the designed hydraulic capacity of the sewer network is reached [102,144,160]. Thus, the effects of inlet blockage have been extensively studied, both experimentally [157,161] and numerically [102,144].

The implementation of nature-based techniques in sustainable drainage systems (SuDS) is becoming increasingly frequent in order to improve the hydraulic capacity of conventional drainage systems and reduce the impact of surface runoff generated by new and existing urban developments. Urban-drainage models have been proven to have great potential in quantifying the effects and optimizing the design of SuDS techniques [162–165]. Hence, the development of new capabilities, as well as the application and validation of dual-drainage models in the field of SuDS is expected to increase in the following years, since these solutions will be more and more frequently used as a means to improve the resilience of cities to climate change.

Finally, it is worth mentioning work which seeks to experimentally validate pluvial-flood models. Here we should distinguish between laboratory and field studies. Calibration and validation under real pluvial-flood conditions implies that model performance is highly dependent on the quality and availability of observations. Observation and input data are usually incomplete, only available at a few control points, and have a high uncertainty. On the other hand, laboratory experiments can be used to evaluate the performance of a model under controlled conditions and much simpler configurations. Both kinds of studies are necessary and have their advantages and disadvantages. Laboratory experiments are better suited to evaluate the limitations of the model equations, while field observations can be used to evaluate the model uncertainty to input and calibration data, as well as the overall model performance and limitations in real applications [84,88,96,148,166]. Experimental configurations in the laboratory allow for a very detailed geometric definition of the drainage system, and permit very accurate measurements of the overland flow, the sewer flow, and the discharge through inlets, while having a very accurate representation of the rainfall input. The authors of [167] presented a review of more than 40 experimental laboratory studies of urban flooding. Most of these works focus only on the overland flow over streets and use an upstream water supply to generate the surface runoff. Just three use a rainfall simulator as the input of water [42,168,169], although we have identified a further two experimental studies using rainfall as the input to generate urban surface runoff that was then modelled with an urban-drainage model [96,170]. On the other hand, 12 papers focus on the experimental characterization of the vertical exchange between the surface and the sewer network. This suggests that there is a lack of experimental laboratory data that can be used to validate dual-urban-drainage models using rainfall as the input and including both the surface-drainage system and the sewer network.

2.4. Estimation and Quantification of Vulnerability

It is currently widely accepted that flood risk depends on the combination of flood hazard, exposure and vulnerability. However, while flood hazard has been extensively studied and quantified in recent decades with the aid of the numerical models described in the previous sections, the number of studies that address the estimation and quantification of vulnerability is still relatively small [171], even if in the last five years the number of research papers focusing on vulnerability has increased exponentially [172].

Vulnerability can be defined as the susceptibility of an element to suffer the impact of a flood hazard. Multiple indicators are commonly used to define and quantify vulnerability to floods, such as population density, illiteracy, unemployment, age, gender, education level, income, health, vehicles, house value, population below poverty levels, land use, forestry area, and artificial filled land [172–174]. As noted by [174], several of these indicators tend to be positively correlated, which should be taken into account when using them to quantify vulnerability. These indicators can be classified into four groups: social, economic, physical and coping capacity [172,174]. Therefore, approaches that solely consider economic losses and stage-damage functions only provide a partial characterization of vulnerability, ignoring the social and coping-capacity aspects, which are also important factors in assessing the impact of floods [175,176].

The most common approach in the current literature to characterize vulnerability is the use of indices that combine several indicators [175,177]. The methodology proposed by [178] to build a social vulnerability index (SoVI) has been one of the most frequently used in the literature to quantify social vulnerability, yet there is presently a large variety of other methods and variables in use to quantify vulnerability, and some recent studies have highlighted the limitations of such quantitative indices [179]. Tate et al. [172] presented a comprehensive review of the approaches that are commonly used in the construction of vulnerability indices and their current gaps. The differences between studies stem not only from the specific indicators used, but also from the quantification, normalization, aggregation and weighting of these indicators in a single vulnerability index.

A comprehensive quantification of social vulnerability was made in [177], who defined an Integrated social vulnerability index (ISVI) taking into account the combined effect of exposure, resilience and sensitivity to floods. To quantify these three components of vulnerability, they looked at 71 variables in 39 urban areas of the same region. After considering the statistical correlations between the original variables, they identified 55 different variables grouped into 11 factors, and these were then used to build the ISVI. The 11 factors considered were: total social exposure, exposure in the built-up urban environment, constructive exposure, constructive resilience, mature social resilience, economic resilience due to investment, youth social sensitivity, labor social sensitivity, social sensitivity due to dependency, social hospital sensitivity, and social health sensitivity.

Moreira et al. [173] performed a similar analysis in the conterminous United States, in this case looking at 29 social variables grouped into 7 factors to build the social vulnerability index. They identified the hotspots where high flood exposure and social vulnerability overlap, finding that mobile homes and racial minorities are over-represented in these hotspots. Roder et al. [180] used 12 social variables grouped into 4 factors to evaluate the SoVI in northern Italy, while Koks et al. [175] performed a simpler analysis to quantify the spatial heterogeneity of social vulnerability in Rotterdam by considering just five variables: socio-economic status, age, ethnicity, single-parent households, and construction year of the property. The spatial distribution of the social vulnerability index obtained by quantifying and combining these five variables is combined with hazard and exposure maps in order to analyze the relations between these five variables that contribute to flood risk.

These are just some examples of studies that mainly focus on the social aspects of vulnerability, using the methodology originally proposed by [178], or some modification of it, to combine several social indicators into a single social vulnerability index. Although some of the variables considered in [177] also represent physical aspects, such as the age, construction and condition of the housing stock, plus economic aspects, such as the rate of unemployment, most of the indicators considered in these studies largely relate to social factors. On the other hand, Milanesi et al. [181] solely focused on physical vulnerability by performing a detailed structural analysis of the damage caused by a flood in a building of traditional masonry. While their analysis is very detailed and useful towards analyzing the structural flood damage to a few specific buildings, including a finite-element structural analysis to characterize the collapse mechanisms of exposed walls, such an approach might be difficult to implement at larger scales in more comprehensive assessments of vulnerability, since it requires a very detailed definition of the building geometry and its physical characteristics. Specific physical-damage criteria have also been experimentally studied and assessed for vehicles [182,183] and pedestrians [184–186], which are most frequently exposed to floods in urban areas.

Another concept linked to vulnerability is the notion of equity, meaning that all citizens should be treated equally and have equal opportunity to have their flood risk managed [187]. Inequity might emerge not only from differences in legislation, climate, location, political ideology, or risk-management planning, but also between households within the same city [187]. The number of research studies related to social equity and flooding is not large, and future research on how inequities to flood exposure and damage can be diminished and managed is needed.

We can conclude, then, that despite significant progress over recent years in the definition and quantification of flood vulnerability, future research is still needed in order to improve flood-risk-management plans.

3. Flood-Risk Management

3.1. Moving from Resistance-Based towards Risk-Based Approaches

As noted in the Introduction, recent years have seen a shift in the way that flood risk is managed, moving from resistance-based strategies (based on hard civil-engineering infrastructure such as dikes, dams and embankments) to more holistic risk-based strategies in which the interconnections between natural and human systems are emphasized. This shift has been motivated by the recognition that traditional flood-defense measures have negative impacts on freshwater ecosystems, while not being able to attain absolute protection against floods, which are increasing in frequency and magnitude due to climate change [188]. The focus on resilience to climate change has also contributed to this change in strategy.

In Europe, the shift from the traditional approach of flood protection to a risk-based approach was institutionalized by the European Floods Directive (FD), 2007/60/EC [123]. This directive stated that FRM plans need to consider the harmful potential of floods and identify tangible measures that are capable of reducing exposure and vulnerability to floods, in order to improve risk governance. Therefore, the main objective of the FD has been to establish a framework for the assessment and management of flood risks in order to reduce their adverse consequences for human health, the environment, cultural heritage, and economic activity.

For this purpose, a three-stage process has been established (see Figure 4), which must be updated every six years in coordination with the Water Framework Directive [189]. The first step is a preliminary flood-risk assessment, characterized by the identification of the areas of potential significant flood risk (APSFRs) for each river basin. In the second stage, flood-hazard and flood-risk maps are drawn, showing the potential consequences of floods of different magnitudes. The final step involves the development of FRM plans, in which specific measures have to be implemented according to the characteristics of hazard and risk of each APSFR.

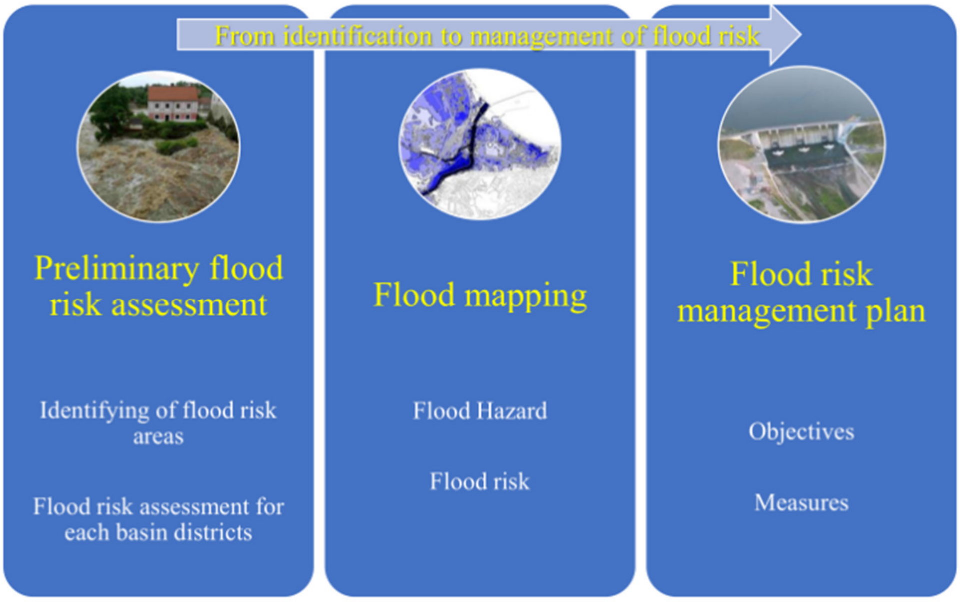

Figure 4. Three-stage process established by the European Flood Directive.

In the United States, the ASCE directive [190] also reflects the global paradigm shift in management philosophy away from flood control and towards flood-risk management. FRM is a portfolio of approaches for reducing risk, which are not limited to controlling flood waters with civil-engineering structures but also include effective-land-use planning, emergency response, and personal preparedness. Importantly, FRM accepts that absolute protection is not possible [191].

In general, five modes of FRM can be identified in the literature [192,193], namely prevention, defense, mitigation, preparedness and recovery (Figure 5):

(1) Flood-risk prevention is based on measures aimed at decreasing the exposure of people/property by methods that prohibit or discourage development in areas that are at risk of flooding (e.g., spatial planning, re-allotment, expropriations, etc.). The main focus is on "keeping people away from water" by only building outside flood-prone areas. This is a proactive strategy that focuses both on probability reduction and on the consequences of flooding.

(2) Flood protection aims to decrease the probability of flooding areas through engineering works, mostly referred to as flood-control measures. This view is based on "keeping water away from people".

(3) Flood-risk mitigation focuses on decreasing the consequences of floods through measures within the vulnerable area. Consequences can be moderated by a smart design of the flood-prone area. Flood-risk mitigation includes all measures to flood-proof the built environment as well as measures to retain or store water.

(4) Flood preparation: Consequences of floods can also be alleviated by being prepared for a flood event. Measures include developing flood forecasting and early-warning systems, as well as preparing disaster-management and evacuation plans.

(5) Flood recovery facilitates an effective return to normality after a flood event. Measures include reconstruction or rebuilding plans as well as compensation or insurance systems.

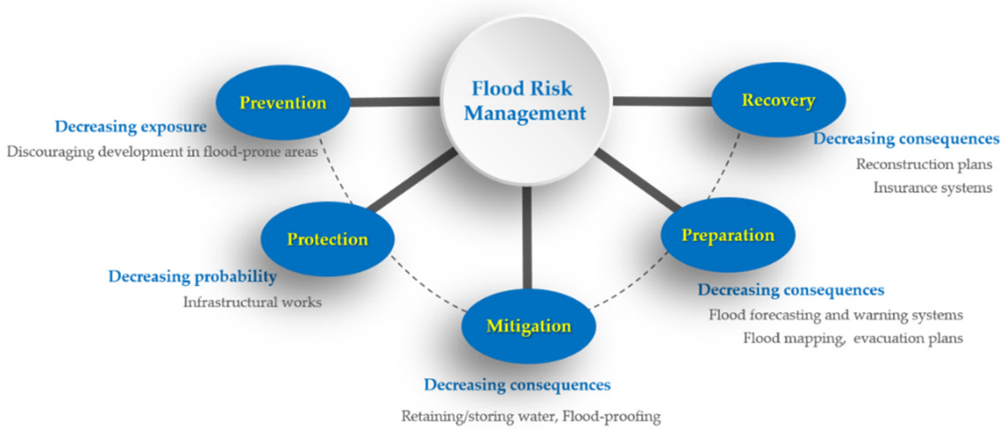

Figure 5. Modes of flood-risk management.

Each of these modes differs in its focus on the reduction of flood probability, flood exposure, and flood consequences. Therefore, it is increasingly argued that a diversification of FRM strategies will make urban agglomerations more resilient to flood risks, by tailoring these approaches to the magnitude of the risk and to the types of flooding, e.g., pluvial, fluvial, coastal, and flash floods [194]. Moreover, an adequate combination of non-structural measures with structural measures not only reduces flood losses but also makes it possible for the maximum advantage to be taken of land use in terms of economic rent [195].

3.2. Flood Resilience

Flood resilience is increasingly seen as a complement to existing flood-risk-management approaches, being as it is a promising concept for dealing with the increasingly severe consequences of climate change in general, and with increasing flood risk in particular [196]. Much work in the literature has been dedicated to defining resilience as a concept to use in flood management [197–200]. Basically, the concept of flood resilience constitutes an acceptance that floods may happen, despite flood defenses being in place, and it also emphasizes the importance of reducing potential flood consequences and the notion of "living with floods" [201,202].

The term "flood resilience" broadly refers to the presence of multiple complementary capacities [194,203–205]: the capacity to resist, the capacity to absorb and recover, and the capacity to transform and adapt (Figure 6). The capacity to resist refers to the ability to avoid being adversely affected by floods. This is achieved by increasing the threshold above which floods can cause harm, which requires timely implementation of effective structural measures that improve our resistance to floods. The capacity to absorb and recover is associated with the ability of a flood-affected area to remain functioning and is based on the timely implementation of effective measures that allow for responses to and/or recovery from floods. Among these are flood awareness, insurance systems, early-warning systems and crisis management. Finally, the capacity to transform and adapt implies the ability of a system to adjust to external drivers that affect the exposure of people and economic assets to floods (including climate change, demographic changes, and urbanization and land-use changes), to adjust to moderate potential damages, to take advantage of opportunities, and to cope with the consequences of flooding. It requires the presence of institutionalized mechanisms for learning.

Figure 6. Flood resilience as a result of multiple complementary capacities.

Whereas the flood-defense approach contributes towards improving the capacity to resist, the other four strategies mentioned in Section 3.1 contribute to the capacity to absorb and recover and the capacity to adapt and transform [193].

It is important to measure and quantify flood resilience in order that it be of use in the decision-making process. Since resilience reflects a global picture, by combining many components for a broader analysis, there is great potential for the creation of the management tools of tomorrow [206].

Two common approaches for evaluating resilience are multi-criteria index-based metrics and performance-based metrics, which have been proposed by several authors [99,207–209]. The former approach constructs multi-index systems and then quantifies resilience by assigning a different weight to each index. An integrated metric, called the Flood-Resilience Index, was developed by [210] both to support the decision-making process and to select design alternatives to improve flood-control responses when the design standards were exceeded. Bertilsson [206] proposed a multi-criteria index called the Spatialized Urban Flood-Resilience Index (S-FRESI), based on the integration of hazards, exposure, and susceptibility, which was then used to evaluate and map flood resilience over time. Although multi-criteria index-based metrics have strong systematic logic and are easy to manipulate [211], they are affected by significant uncertainty due to the subjective selection of indices and to the weight-calculation methods that must be determined by experts.

Performance-based metrics are often based on the results of hydrological or hydraulic models and are, therefore, considered to be more precise and objective than multi-criteria index-based metrics [212]. Assuming resilience as the degree to which the system minimizes levels of service failure, Ref. [213] evaluated the performance of an urban drainage system when subjected to a wide range of functional and structural failure scenarios. The loss of system functionality (impacts) is determined on the basis of the total flood volume (failure magnitude) and average flood duration (failure duration). By combining the failure magnitude and duration into a single metric, a new resilience index is derived to quantify the residual system functionality at each considered failure level. The authors of [214] developed a resilience index for urban drainage systems based on flood damage, which occurs only when flood depth reaches a certain point. Wang et al. [215] proposed a grid-based resilience metric based on the system-performance curve, defined as the ratio of the number of unflooded grid cells to the total number of grid cells, to assess urban pluvial-flood resilience in an urban watershed. Within this framework, resilience metrics that also consider human risk perceptions have recently been proposed [212].

A recent review on the characteristics, dimensions, and methods of assessment for urban resilience to climate change was proposed by [216].

3.3. Recent Trends in Flood-Risk Management and Flood Resilience

Climate-change-adaptation and disaster-risk-reduction measures are supporting the advancement of a policy framework towards sustainable and cost-effective options which will address the impacts of climate change on water availability, people, and their properties [217]. In this context, recent international initiatives are fostering the promotion of early-warning systems, along the lines of several studies that illustrate the significant benefits of these (exceeding their costs) in relation to disaster-risk reduction and climate-change adaptation [218–220]. At the same time, biodiversity and ecosystem services can play an important role in responding to climate-related challenges, so that mitigation and adaptation strategies are increasingly taking into consideration a variety of nature-based solutions (NBSs) as effective and sustainable measures. NBSs open up the possibility of working closely with nature in adapting to future changes, reducing the impact of climate change, and improving human well-being [221]. More holistic flood-risk-management approaches that try "to work with nature" and "to live with the water" are attracting increasing attention [222–225]. Innovative spatial solutions that create more space for water, such as flood-retention areas and river-widening measures, form an important part of these approaches. Finally, more holistic perspectives are being adopted, which consider a diverse set of FRM measures including bottom-up approaches based on social issues and ideas, such as active stakeholder participation, public communication, and raising awareness [200].

As shown in Figure 7, the need of integrating risk-management and flood-mapping issues within sustainability, ecosystem restoration and resilience to climate change (blue ellipses), has fostered important advances in related fields of research such as early-warning systems, citizen science and stakeholder involvement, nature-based solutions, risk communication and perception (see orange ellipses).

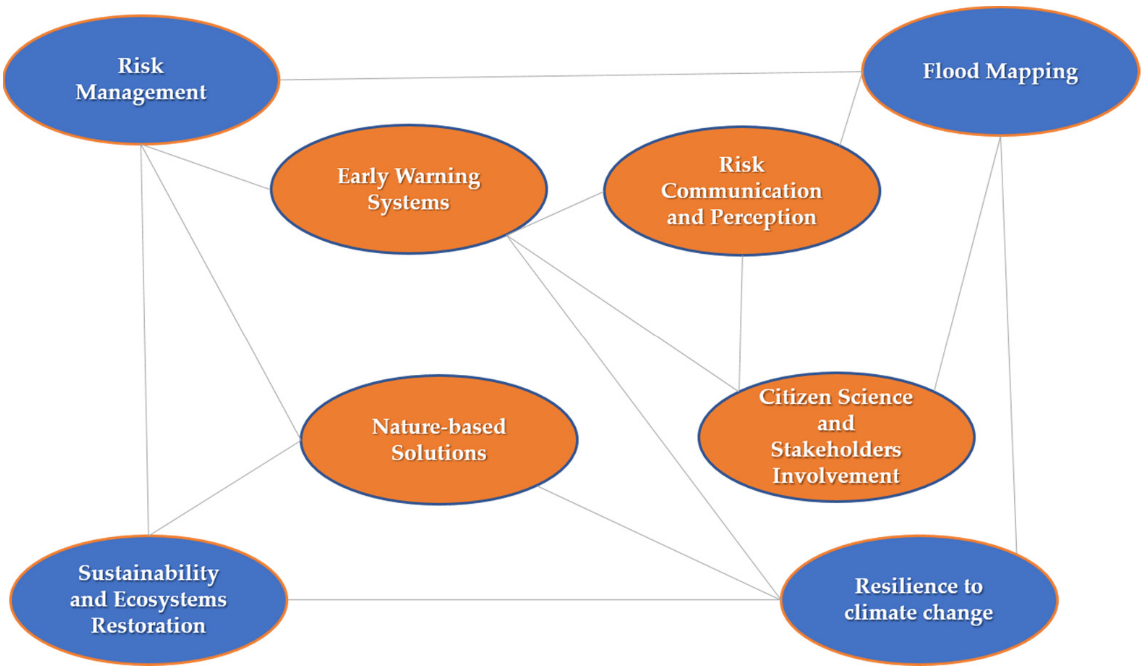

Figure 7. Potential links among research trends in flood-risk management and resilience.

In the following sections, the progress in the above-mentioned trends are discussed, highlighting all potential interconnections between them (Figure 7).

3.3.1. Nature-Based Solutions

The capacity to anticipate, prepare for, respond to, and recover from multi-hazard threats with minimum damage to socio-economic well-being and the environment, through a balanced ecosystem-based approach to hazard evaluation, is of world-wide interest [226]. Along these lines, approaches oriented towards sustainable flood management are of growing interest, assuming that risk reduction should be obtained through a range of measures that are more economically and environmentally sustainable than relying on structural measures alone [227]. Natural flood management is part of this new philosophy, embracing related terms such as "making space for the river", "ecosystem-based flood-risk management" "engineering with nature" and "working with natural processes" [228].

This new approach is supported by a range of European policies, legislation and global agendas, such as the Sendai Framework for Disaster Risk Reduction (2015–2030) [229], the Sustainable Development Goals [230], the Paris Climate Agreement [231], and the EU Strategy on Adaptation to Climate Change. As a consequence, flood-risk-mitigation measures should be compatible with the preservation of the water bodies that are in good condition and the conservation/restoration of water-related ecosystems (see for example the European Water Framework directive [189]).

These new approaches to disaster-risk reduction, water security, and resilience to climate change, which have the potential to be more effective and sustainable than traditional measures, are currently referred to as nature-based solutions (NBSs) (Figure 8). The term NBS refers to innovative solutions for solving a range of societal and environmental challenges based on natural processes and ecosystems. NBSs use nature and natural processes to reduce disaster risk and enhance environmental, economic, and social benefits [232]. They represent a set of new concepts in engineering, economics, and environmental planning and they also provide simultaneous benefits for human and natural systems by maintaining and/or restoring hydrological functions [233]. Therefore, they are able to effectively and adaptively address water problems through sustainably managing and restoring natural or modified ecosystems, while alleviating the adverse impacts of climate change [234].

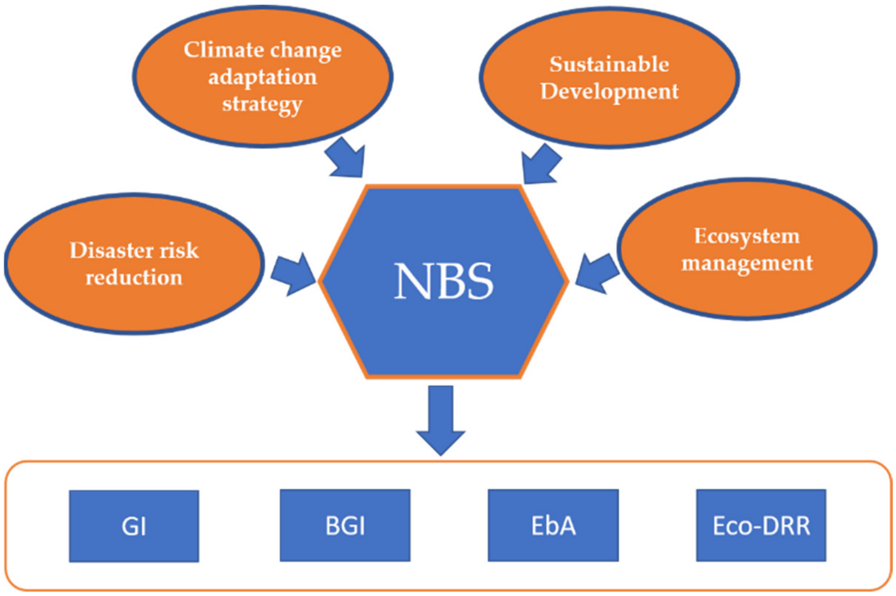

Figure 8. Nature-based solutions as an approach towards risk reduction, sustainable development, and conservation/restoration of water-related ecosystems within a climate-change-adaptation strategy.

The NBS is considered to be an "umbrella concept" covering a range of different ecosystem-related approaches and linked concepts [221,235] and has been widely used as a reference point for various alternative terms throughout the world (Figure 8). These alternatives originate in different regions with their own histories and emphasize different aspects of natural processes or functions [235,236]. Among these: green infrastructure (GI), blue–green infrastructure (BGI), ecosystem-based adaptation (EbA), and ecosystem-based disaster-risk reduction (Eco-DRR).

In terms of the scale of implementation, NBSs can be divided into small- and large-scale solutions. Small-scale NBSs are implemented on an urban or local scale [237], whereas large-scale ones are implemented at the regional level in rural and mountainous areas and/or river basins and coastal zones [236,238]. Typical examples of small-scale NBSs are green roofs, rain gardens, rainwater harvesting, dry detention ponds, permeable pavements, bio-retention, vegetated swales, and trees. The implementation of small-scale NBSs for flood-risk mitigation aims to achieve the following objectives: flood-peak reduction [239–241], flood-peak delay [242], and reduction of runoff volume [243]. Green rooves perform better in reducing peak flows for small and frequent storms [239], while rain gardens cope more effectively with small quantities of rainwater [242]. Klijn et al. [233] indicated that the effectiveness of such measures is directly related to their storage capacity and the availability of open spaces.

At the catchment scale, NBSs entail slowing the movement of water through the landscape by coordinating river management and land use across catchment landscapes so as to (re)-shape hydrological and morphological processes [244]. Measures to achieve this are diverse, and include installing upland wetlands and ponds, restoring intertidal habitat, placing woody debris instream, re-meandering river channels, and planting trees or other ground cover. The most common large-scale NBSs are: flood-storage basins [245], preservation and regeneration of forests in flood-prone areas [246], making more room for the river [222], river restoration [247], wetlands [248], and mountain forestation [249].

Although several studies address the usefulness and potential of NBSs in water management and flood mitigation [163,238], very limited information is available regarding their effectiveness in flood mitigation [250]. The effects of NBSs on flood extent, water depth, and flow velocity are still poorly known [251], yet are crucial for implementing NBSs [252]. Furthermore, the effectiveness of NBSs has been found to vary with different storms [253].

NBS measures are thought to reduce flows in floods with small return periods, but there is less certainty about their effectiveness in larger flood events. In this context, some authors argue for a deeper understanding of the hydro-ecological effects of NBSs on different scales and within a diversity of environmental conditions [235,254].

Although the effectiveness of flood reduction during high-intensity precipitation has been questioned, when NBSs are combined with gray infrastructures such as flood-risk-management measures, they can more effectively mitigate the urban flooding caused by low/moderate-intensity precipitation [252].

A recent review of NBSs for hydro-meteorological risk reduction can be found in [236].

3.3.2. Preparedness and Early-Warning Systems

Preparedness for natural hazards is a key factor in the reduction of their impact on lives, livelihoods and communities [255]. Preparation measures can include: (i) readiness for intervention; (ii) emergency operation and rescue; (iii) early-warning systems (EWSs); (iv) recovery and recondition. Whereas all these measures are essential [256–258], the need for an effective EWS to span all components, from hazard detection to community response, has been underlined in particular by the United Nations Framework Convention on Climate Change and through the Paris Agreement and the sustainable-development goals [230,231], as well as being further articulated in the Sendai Framework for Disaster Risk Reduction [229]. These documents highlighted the features and roles that should characterize an effective EWS, which are based on a set of capabilities needed to generate and disseminate timely and meaningful warning information to enable individuals, communities and organizations threatened by a hazard to prepare and act appropriately in sufficient time in order to reduce the possibility of harm or loss. As a consequence, EWSs are commonly agreed to consist of four components: (1) risk knowledge, (2) monitoring, forecasting and warning, (3) communication of an early warning, and (4) response capability (Figure 9). Most studies on EWSs address risk knowledge, monitoring, forecasting and warning.

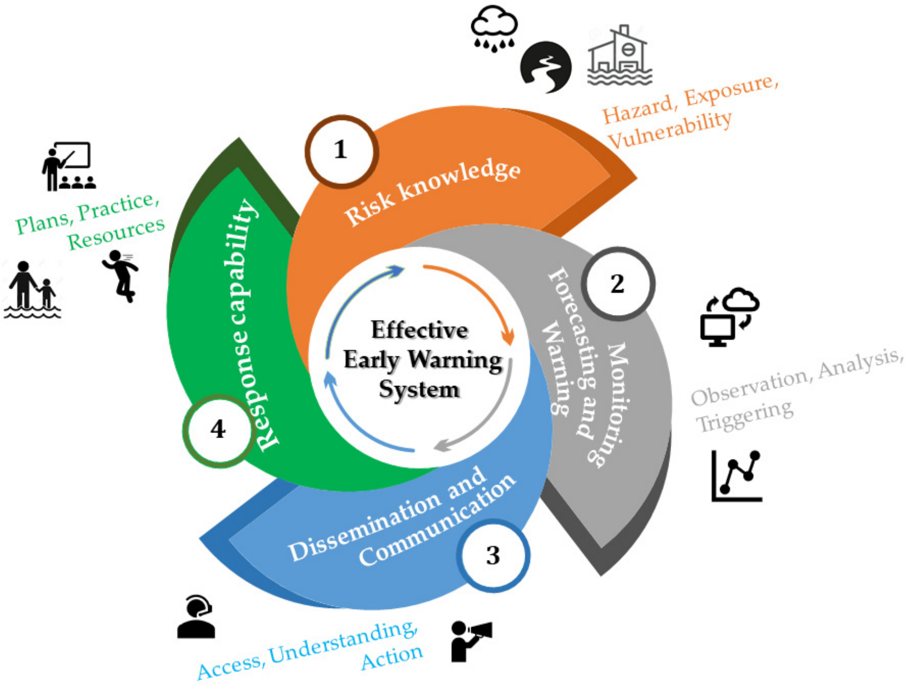

Figure 9. The four pillars of an effective EWS.

Flood forecasting begins with the acquisition of meteorological data. Numerical weather predictions (NWPs) have become the basis for several flood-related warning systems, enabling the detection of hazardous events with sufficient lead-time to prepare effective emergency and response plans. These data usually consist of forecasts that can achieve spatial resolutions of a few kilometers and temporal resolutions of less than an hour. Despite significant technological advances in forecasting techniques, such as radar nowcasting and ensemble numerical weather forecasting, and the growing availability of high-resolution satellite data [218,255,259], this stage represents the main source of uncertainty in flood forecasting [260]. The second step of an EWS is to transform meteorological forecasts into discharge predictions. This can be done using a variety of approaches, ranging from lumped, semi-distributed and distributed hydrological models [261–264] to artificial-intelligence techniques [265,266]. In this context, a proper characterization of the antecedent soil-moisture content is essential to significantly improve the predictions of rainfall-runoff models [267–271]. EWSs may include a third step, in which the forecasted discharges are used as the input for a hydraulic model to compute the spatial distribution of water depth and velocity. Hydraulic models allow for an accurate estimation of the flood extent, but in the past their computational burden limited their implementation in EWSs. Nowadays, thanks to high-performance-computing techniques and increases in computational power, this approach is more feasible, as shown in several recent studies [272–274]. Further recent examples of EWSs can be found in [275–281].

Despite substantial technical progress, major challenges remain from an operational point of view in terms of achieving the full potential benefits of EWSs, in particular in effectively communicating risk information and early warnings to emergency services and to the population at risk, in order to trigger the necessary response actions [282]. Some authors have focused on the social-science aspects of EWSs, discussing best practices and challenges for the communication of flood alerts and also the role of community participation by means of integrating local flood knowledge into EWSs [283–286]. It is also recognized that the potential benefits of scientifically sound forecasting systems will not materialize if a warning is not understood, is not useable, or does not result in emergency-response action. An extensive recent review on this is provided in [287]. Moreover, it has been quantitatively demonstrated that EWSs are only effective in reducing monetary losses when people know what to do after receiving the warning, which in turn affects the long-term preparedness for flood mitigation [288].

A general overview of the developments in hydro-meteorological forecasting and their use in supporting decision making by first responders and emergency managers, including the emergence of operational surface-water flood-forecasting systems and the increased use of crowdsourced data to support such systems, has been recently presented by [289].

3.3.3. Risk Communication and Perception

The diversification of FRM strategies requires the involvement of private actors, including individual citizens and citizen groups [193]. Research has found evidence of an emerging role for communities and citizens in local FRM that can have implications for the development of local flood resilience and more holistic FRM approaches [290,291].

The development of a shared understanding of current flood risk amongst stakeholders is essential, meaning that everybody should understand the probability of flooding in their own location, the likely inundation zone of a given flood, the potential impacts on their property and assets, and the self-protection measures that they can take to mitigate risks [292]. In this context, an emerging line of research is focused on risk perception and communication towards processes of citizen and stakeholder participation, including formal participation of citizens in decision making [293]. The role of citizens and stakeholders, and the methods for their involvement in FRM, has been investigated in terms of public participation, collaboration, co-production, communication between groups, networks, relations between stakeholders and governmental agencies, and perceptions of flood risk [294].

Risk communication is a significant part of FRM and involves the population at risk being prepared for an emergency situation [295,296]. Potentially valuable tools for improving this understanding include flood maps, since they generally seek to raise public awareness about flood impacts and impart flood-preparedness advice [256,292]. However, it has been observed that poor use is often made of traditional risk maps for supporting decisions [297]. Moreover, they do not afford a non-expert audience an immediate understanding of what is shown, in that the general public may not be aware of flooding impacts. The major limitations of traditional risk maps for risk communication are: (1) Existing flood-hazard maps or web GIS are not characterized by a useful balance between simplicity and complexity, that is, with adequate readability and usability for the public [298]; (2) Lay-people experience difficulties in understanding and interpreting probabilistic risk information, such as the return period, that characterizes flood maps [299,300]; (3) Many people have no direct experience with floods [301], underlining the fact that people find it difficult to imagine a flood occurring, and this is especially the case for individuals living in flood-prone areas that are protected by dikes [302,303].

On the other hand, the most significant data represented in flood maps are essentially communicated according to a top-down approach, which means that stakeholders are simply considered as the final recipients of information, and are not directly involved in the overall production of the flood-mapping process. Moreover, it is often the case that flood maps do not meet the users' needs. That is, the content of a flood map is not focused on its end-users, and this represents a major limitation in flood-risk communication [304]. For example, Rollason et al. [305] reported that members of a group want to know the predicted flood levels implied for their properties and the potential impacts on these in comparison to past events. In this context, it is worth mentioning the study in [191], where it was shown how a set of baseline maps simulated by engineers using a 2D model was further refined through end-user focus groups, this leading to additional modelling scenarios and map revisions.

Risk communication also influences the perception of flood risk [298,300]. In this regard, the extent to which a community can demonstrate resilience after a flood largely depends on human perception, which in turn is related to the social context in which a given event occurs [306,307].

Perception plays an important role in how individuals and communities respond to risk and provides links between emotions, risk perceptions, and behaviors [308–310]. The manner in which people (households, businesses, governance bodies, etc.) perceive and understand flood risk is at the core of the judgements they make and the actions they take in preparing for and responding to flood events [303,311,312]. The role of public perception in developing flood-risk strategies and enhancing resilience has recently been explored in several studies [299,301,313–315]. Some studies also focus on the social aspects of flood-risk management and perception, in that the latter can influence how individuals and groups prepare (or not) for these hazards, and how they respond to information or hazard warnings [313]. Among the approaches used to explain how people judge a risk and the factors that influence the perception of risk, particularly relevant has been the so-called psychometric model, developed in the areas of psychology and decision research, and based on representations of the perception of the risk, using metrics, scaling, and statistics. There are numerous factors in operation here during risk perception, which can be characterized as a combination of awareness, worry and preparedness [301]. These studies have highlighted the issue of how far we currently are from an effective application of FRM policy that is mainly based on minimizing flooding consequences and embracing participation in which stakeholder engagement and acts of communication are constantly complemented by modelling and communication tools [295,316–318].

In this context, a significant contribution may be provided by 3D representations of flood inundation through emerging formats in virtual and augmented realities, which provide new platforms with which to substantively engage with stakeholders [319]. This approach is generally referred to as realistic visualization, the aim of which is "to add drama to the scenarios while adhering to representation of accurate scientific representation" [320]. More specifically, there is some evidence in regard to urban flooding that coping responses to flooding risks could be enhanced in a 3D environment [321] which, at least, improves the interpretability of disaster data and the effectiveness of decision-making processes [322]. So, the potential of 3D visual representation in flood-risk communication is gradually starting to be systematically discussed in the literature [323–331], showing that supplementing flood maps with 3D-visualization techniques is increasingly seen as a powerful tool with which to engage people in relation to flood hazards.

3.3.4. Citizen Science

The involvement of citizens in collecting data, developing models, and decision-support systems has come to be seen as being of key importance. This has led to so-called citizen science, defined as a collaborative form of research involving members of the public at different stages within the scientific-research process [332]. In this context, citizens perform research design, data collection and interpretation, the sharing of knowledge and/or analyses alongside professional scientists [333]. Many related terms have been used in the literature to describe the different ways in which citizens are involved in such a process [334,335]. Among these: volunteered geographic information [336,337], crowdsourcing [338–340], and citizen observatories [341,342]. The common element in all these concepts is a broader vision of the involvement of the general public in the co-generation of scientific knowledge and the associated opportunities for learning and collaboration [343,344].

One way of classifying citizen science is in terms of increasing levels of engagement. According to [345], four levels of citizen participation can be identified (Figure 10a): (1) participation only as data collectors (crowdsourcing), (2) interpreters of data (distributed intelligence), (3) participation also in defining the problem (participatory science), (4) participation from problem definition to the analysis and dissemination of results (extreme citizen science).

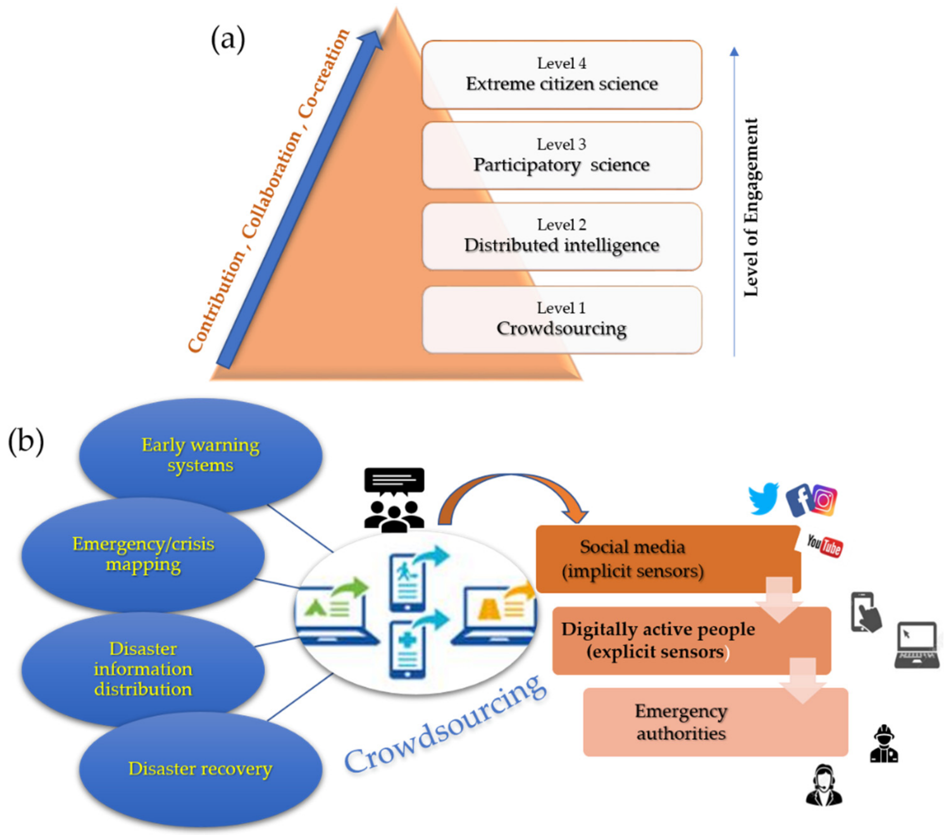

Figure 10. Classification of citizen science by increasing levels of engagement, according to Haklay, 2013 (**a**) and role of crowdsourcing (**b**).

Citizen science is not a new concept and enjoys a substantial tradition in several fields of research [346]. What is new and different in the current environment is the widespread availability of internet-based networks and social media [347]. This has been fostered by broadband internet, the development of mobile communication, and progress in global-positioning technology, in particular with portable GPS receivers that are now inexpensive and are often integrated into smartphones and tablets along with cameras and other useful sensors [339]. Therefore, data shared by citizens via social media (i.e., Twitter and Instagram) have become a useful source of information (Figure 10b).

Within this framework, the contribution of citizen science may be seen during flood events, in the use of social media [348–350] or mobile apps [338,351] for post-flood-event analysis [352,353], validation of models, or in relation to the information provided for forecasting models [354–357].

There are many types of flood-related data that can be collected by citizens, but water levels are the most frequent, due to the ease of data collection, which consists primarily of comparing the water level against a clearly defined reference. In some cases, the reference is a water-level gauge, the comparison is made by citizens, and readings are submitted to researchers [358,359]. Sometimes texts from citizens are used (e.g., 'water above the knee') to provide estimates of water-level values [360]. Flood extent, like water level, is simple to measure, as it consists of binary values (flooded or non-flooded area). In some studies, texts and images have served to indicate whether a location is flooded [355,360], whilst in others, further processing is used to infer the presence of inundated areas in the surroundings [361–363].

Reviews of citizen-science applications, plus challenges and future opportunities for flood-risk management, can be found in [334,335,364,365].

Finally, it should be noted that interactions between citizens and authorities can lead to changes in the distribution of tasks and responsibilities between the government and local citizens, with the government potentially delegating some of its former tasks [366]. Therefore, it is important not only to understand the emerging roles of citizens in local FRM, but also to see how they influence the division of responsibilities in local flood resilience [202].

4. Conclusions

The effects of climate change and the growth of population concentrations in cities will probably increase future flood risk in these already vulnerable areas, making the need for reliable methods and advances in the context of flood-risk management imperative, something which is currently recognized as a global challenge. This is clearly reflected in the large number of studies published in recent years related to the modelling, management, and adaptation to flood risk.

Notable progress has been made in the development of numerical inundation models in recent decades, and it is clear that fully dynamic 2D shallow-water equations have now become established as the most effective equations for the study of floods in urban areas. In parallel, the availability of digital data has greatly increased over the last decade, in particular LIDAR-based DTMs with a high spatial resolution (1 m or higher). This has resulted in many recent studies primarily focusing on the development of high-performance-computing techniques to minimize the computational time of 2D shallow-water-equation solvers, in order to be able to work with very high-resolution models over large spatial domains (models with several million cells are common nowadays). GPU-based parallelization techniques seem to be the most cost-efficient and widespread means of improving the computational efficiency of a 2D inundation model. In the case of pluvial flooding, 1D–2D dual-drainage models have also become common, showing a great potential to design and analyze the effectiveness of drainage systems and the incorporation of SuDS techniques to improve their resilience. The main obstacle today to the routine application of 1D–2D dual models is the availability of detailed and accurate definitions of sewer networks, the absence of which makes it impossible to exploit these models to their full potential.

The main challenge in the coming years will probably not be focused on the development of new urban-inundation models but on fully exploiting the capabilities of the actual ones, in order to take advantage of highly accurate input data. The characterization of vulnerability and damage functions, as another component of flood risk, also needs to be further developed, since today there is not a standard procedure to combine vulnerability and hazard.

The shift that has taken place over recent years in the way that flood risk is evaluated and managed, as well as the increasing focus on building up our resilience to climate change, has led to many publications dealing with the quantification of flood resilience, the development of nature-based solutions, and the communication and perception of flood risk to the population. There is increasing interest and research activity, that will probably continue in the coming years, on the social aspects of floods and how to involve citizens in the evaluation and management of floods, since it has been recognized that this is the only way to take advantage of all the technical information that is being globally generated through the application of national and international flood directives.

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