Multidimensional Aspects of Floods: Nature-Based Mitigation Measures from Basin to River Reach Scale

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Contents

Abstract This chapter aims to deliver a brief overview of flood mitigation and protective measures at different scales within the catchment area and identify the main factors to be considered in flood risk management. It stands on an extensive literature review of the ongoing scholarly discourse on the topic. The main focus is given to novel approaches that are based on Nature-Based Solutions (NBS)

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principles, which are aligned with emerging public awareness not only towards cost-effective solutions but also towards sustainable proposals which go in harmony with the environment and natural landscapes. First, we provide a synopsis on the main aspects influencing the flood events such as Land-Use/Land Cover (LULC), topography, hydrometeorology, and hydraulics of the river. Later we included novel concepts such as "Sponge Cities", Integrated Water Resource Management (IWRM), and the Sustainable Urban Drainage System (SuDS) as examples of mitigation practices which simultaneously integrate cost-effective non-structural and structural mitigation measures. Further on, we give some insight on the recommendations on the most pressing research questions and conclude the key issues to be considered in the flood risk management concerning NBS approaches. As a result, the study highlights two among many recommendations as to the foremost crucial ones. First, the flood risk reduction agendas must adopt a spatially comprehensive and cross-scale approach while considering flood events. Finally, natural properties of the context such as LULC, topography, hydrometeorology, and hydraulics must be considered simultaneously to utilise the full natural capacity of the context in flood risk mitigation.

Keywords Flood mitigation upscaling, Integrated water resource management, LULC, Nature-based solutions, Sponge city

1 Introduction

1.1 Climate Change and Uncertainty in Flood Risk Management

Flooding is one of the most devastating and frequent natural hazards with enormous impacts on the environment, people, and economy over the globe [1]. Flooding occurs due to the overflow of fluvial systems, small streams, or lakes, influenced by heavy and/or intense rainfall. Floods have triggered irreversible tragedies and property damages over decades, where one of the major tragedies is the one of 1931 in Huang He River in China, where more 3.7 million of people had died [2]. Floods frequency, magnitude, duration, timing, as well as severity, differ between regions and depend on several factors such as LULC, meteorological conditions, the geomorphological context of the region [3], and geomorphology of the fluvial system among others [4, 5]. Figure 1 shows where flooding occurs more frequently. Namely, it shows hydrological floodplain defined by bankfull elevation.

In contrast, the topographic floodplain includes the hydrologic floodplain and other lands (flood fringes) up to a defined elevation; usually, it corresponds to 100-year floodplain. Very often, the settlements are placed near or in the zone of the 100-year floodplain. Therefore, they are vulnerable to flood events.

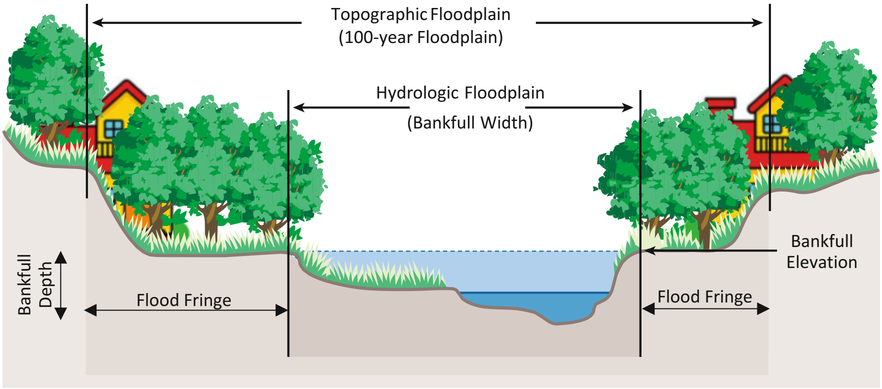

Fig. 1 Cross-section view shows the flood occurrence with regard to water level and floodplain width; it shows hydrologic and topographic floodplains, respectively, modified after Carolyn et al. [6]

In general, fluvial floods in lowland rivers characterised by broad and flat floodplains reveal to be more destructive as people historically tend to reside near to the rivers, which is particularly common in developing countries [1, 4]. Uncontrolled and rapid urbanisation has increased the risk of floods disproportionally; millions of people who live in informal buildings of low standards remain highly vulnerable [7]. Due to precipitation patterns alteration driven mainly by climate changes as a result of the unprecedented increase in greenhouse gas concentrations in the global atmosphere, floods are becoming more frequent and extreme [8, 9]. Climate change has already shifted the timing of fluvial floods. It is also anticipated to intensify their magnitude in the northern hemisphere, particularly in Europe [10]. In such circumstances, the management of an intensified flood risk due to more extensive and frequent floods is becoming more challenging. In a simplified view, flood risk management represents the required strategies of managing existing and potential future flood risk situation, while in a more holistic prospect, it includes several processes such as the planning, design, and implementation of the systems, which intend to reduce the flood risk [11].

Risk management is an intensively discussed and studied topic which regardless of the stakeholder's involvement, consists of three different sets of actions: (1) operation level – defining the actions which are needed to operate an existing system, (2) actions related to project planning level, which is used in case of new projects or regarding re-conceptualisation/revisions of existing projects, and (3) actions that are taken on a project design level, which represents an advanced stage of the second level and provides technical details on the design to achieve an optimal solution for the project implementation [12]. The effectiveness of risk management strategies is also closely connected to the way how people perceive and their willingness to respond to a potential risk that may be induced by floods. In this regard, the so-called protection motivation theory defines the self-preservation behaviour driven by four main factors: (1) the degree of perceived severity of a threat from floods, (2) the perceived probability of the frequency of extreme floods, (3) the effectiveness of any potential recommended response by respective institutions, and finally (4) perceived ability to implement a response (protective and mitigation measures) [13]. Traditional engineering practices referring to protective and mitigation measures include building structures such as dikes and deflectors in the areas vulnerable to floods [14]. Nevertheless, feasibility and effectiveness of such measures in many cases remain questionable as they are meant to provide local protection only.

Furthermore, local protection measures transfer the accumulated risk downstream increasing the burden of the community residing in those areas. Therefore, risk management should be done in a more holistic approach, in larger scale rather than river reach scale by considering many factors triggering the floods and also affected by floods [15]. In this context, the Nature-Based Solutions (NBS) concept has proved to be practical, feasible, and eco-friendly as they offer flood protection without imposing substantial modification in the environment [16].

1.2 Importance of Upscaling in Flood Mitigation

Although floods may affect large areas by causing substantial life losses and damage to the properties, periodic monitoring, planning, and management can reduce the devastating impacts of floods. Integrating NBS as a complementary alternative into the standard civil engineering measures has provided more room for sustainable solutions but in the meantime, defining specific flood protection and/or mitigation strategies is becoming more sophisticated and challenging due to exponential increase of urbanisation [17]. Upscaling prevention or mitigation measures consist of composite measures taken at different spatial scale within the basin, as it considers the enhancement of land cover and implementing mainly structural and/or non-structural measures from basin scale to river reach scale (Fig. 2).

Allocation of an enormous amount of water volume during instantaneous floods is challenging, particularly in urban areas. In this regard, when Flood-Excess Volume (FEV) is reached, the damage risk is higher. In such circumstances, Square-lake mitigation measures proposed by Bokhove et al. [18] (Fig. 3) is a cost-effective solution to manage a high volume of water during extreme floods.

Although square-lake or leaky dam concepts, a flooding prevention measure, moderating the flow of water downstream [19], might be feasible in terms of cost, their effectiveness may not be guaranteed if simultaneously additional measures do not take place at a large scale, i.e., within the entire catchment/basin. Indeed, measures taken within the catchment area can mitigate the risk of extreme floods significantly by ensuring the high effectiveness of the protective measures implemented in the river reach scale [20, 21]. Upscaling of mitigation measures is particularly important because the non-adequate placement of measures can simply transfer the flood burden downstream by increasing the risk, losses, and costs even more [22]. In this context, Fig. 4 shows the importance of upscaling of the mitigation measures and also how local measures alone fail to prevent flooding.

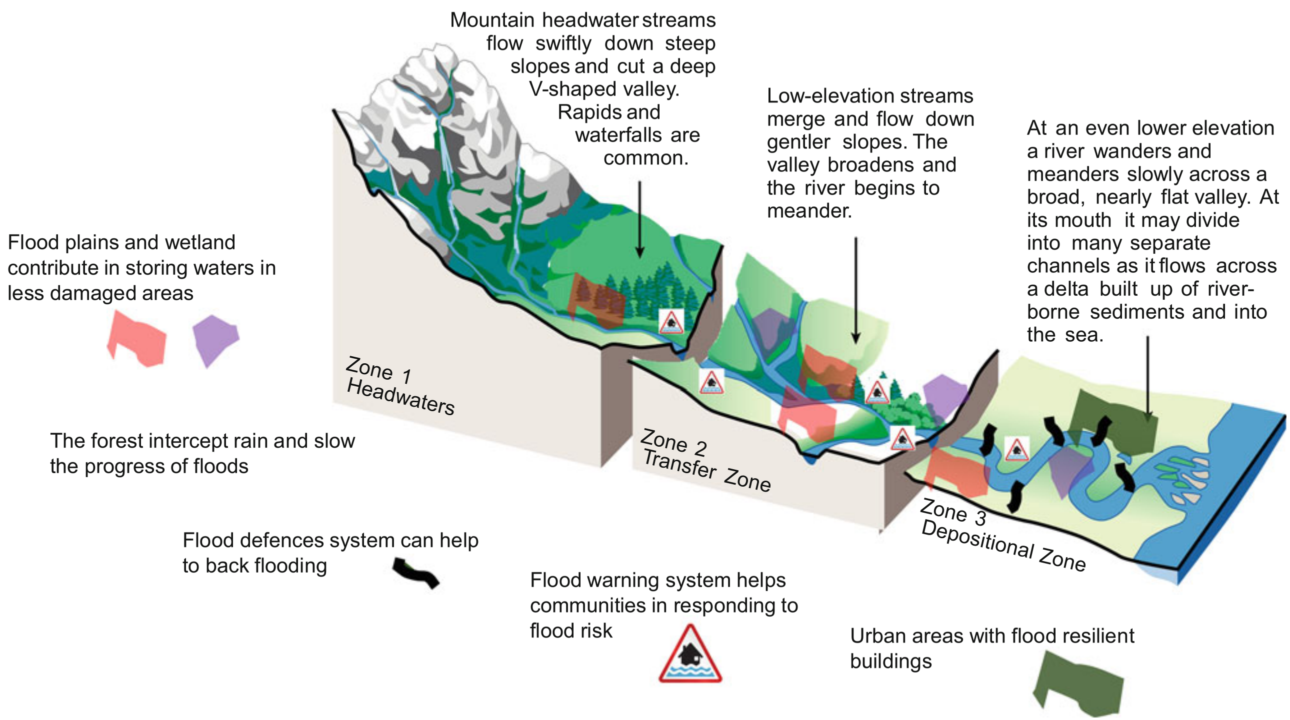

Fig. 2 Characterisation of the rivers Hydrogeomorphological process from basin to river reach scale and actions need to be taken a different spatial scale, modified after Carolyn et al. [6]

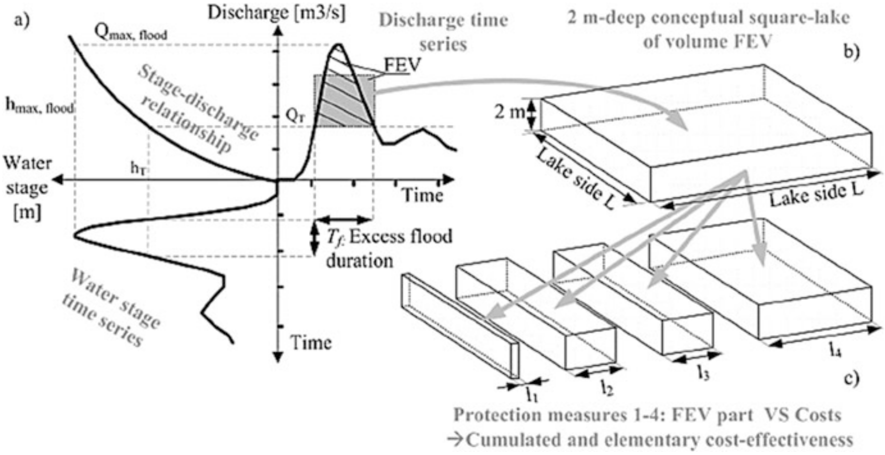

Fig. 3 Schematic representation of square-lake concept for allocation of Flood-Excess Volume (FEV): (**a**) stage–discharge relationship, (**b**) FEV square-lake concept representation, (**c**) FEV-effectiveness assessment considering equivalent measures, afterBokhove et al. [18]

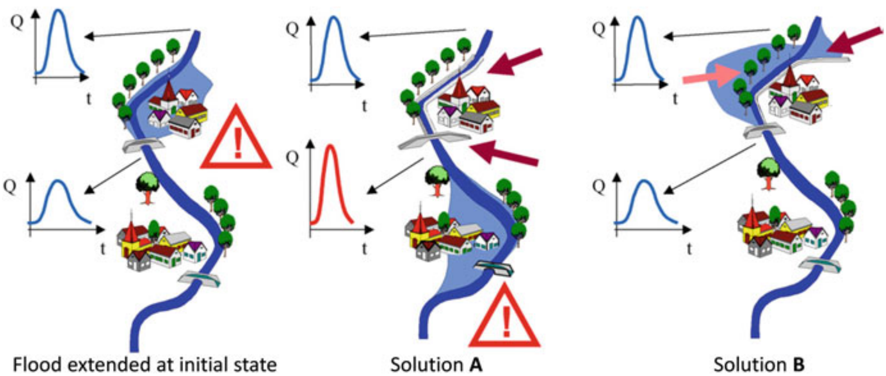

Fig. 4 Flood mitigation upscaling: (**a**) it involves dykes along both sides of the river and channel enlargement, which successfully prevents flooding in one village, (**b**) floods are mitigated in natural flood expansion areas or dry dams/retention basins while local protections and river training are kept to a minimum, after Poulard et al. [14]

As regional flooding tends to be frequent and long-lasting, local planners should adjust the floods mitigation policies based on previous experiences with such devastating events, and this is an opportunity to consider more effective measures at different spatial scales overtime to shield the adverse effects of subsequent floods events [23]. Therefore, a better understanding of the interaction between mitigation and protective measures against flooding at different spatial scales is critical in flood risk management and in implementing the most cost-effective solutions.

This chapter intends to give a brief overview of flood mitigation and protective measures at different scales within the catchment area and also aims to identify the main factors related to different scale to be considered in flood risk management. Namely, the main focus is given to innovative NBS approaches which are not only cost-effective but also a sustainable solution in terms of environment and natural landscape conservation. The chapter is organised as follows: Section 2 presents a synopsis on the main factors influencing flood events; Section 3 describes some of most common and cost-effective non-structural and structural mitigation measures as well as their eco-friendliness; Section 4 gives some insight into recommendations on the most pressing research questions; finally, Section 5 presents a conclusion of the critical issues to be considered in flood risk management concerning NBS approaches.

2 Multidimensional Aspects of Flood Mitigation at the Basin Scale

2.1 Influence of Geomorphological Properties of Earth Surface on Flooding Regimes

Engineered solutions widely control flood risk at the expense of altered flow and sediment regimes, as well as the ecological properties within the riparian zone and beyond [24]. Both elevation profile (i.e. topography and geomorphology) and soil texture (i.e. land cover) features are reported to have a significant impact not only on the physical properties of the basin but also on the functional composition of the riparian lands along the watercourse [25]. For example, floodplain ponds and gravel bars enable inundations. They are reported to have a considerable effect on the enrichment of flora and fauna assemblages along the riparian zone [26]. Therefore, topography and land surface composition are both considered in multi-criteria flood susceptibility assessment procedures and modelling [27].

In this section, we bring a split into two different spatial scales while considering the implications of LULC and topography on flood dynamics (Table 1). Both land surface cover and topographical properties can have different effects on the flood

Table 1 Implications of LULC and topography on hydrodynamics at both basin and riparian scale

Context			Implications	
Zone	Scope	Scale	Topography	LULC
Basin, watershed, catchment area	Regional, national, cross-boundary	>1:5,000	The geomorphology of the watershed contributes to the stream orders, runoff flow, and accumulation	It is affecting the runoff speed and accumulation of water – rainwater carrying capacity of leaves
Riparian zone	Local, site scale	<1:5,000	Define the morphology of the river, riverbanks, and the flood plain, affecting the flood-carrying capacity of the channel	Affecting the riverbank erosion dynamics and land degradation. Slowing down the water flow speed during flooding seasons

risk and preventive capacities at the basin scale as well as in the riparian zone (i.e. it refers to river reach scale). While the spatial scope of the former is expanding to the regional, national, or even international territories, the scope of riparian zone is related to the local and site scale, especially in urbanised lands where the flood risk is highest.

2.2 LULC Data Utility in Flood Risk Mitigation

Generally, LULC is monitored to understand the dynamics of landscape change at a gradient of spatial and temporal scales. The assessment of long-term alterations of the surface cover is useful in understanding landscape dynamics in the territory, especially in areas that are prone to different natural hazards. For example, the vegetation encroachment processes in flood-prone areas along highly modified large rivers are accepted as an issue to be carefully managed [28]. For example, in some cases, this problem is avoided by removing wild vegetation to adjust the width of the channel and to decrease the roughness of the watercourse to increase the discharge rates and avoid flooding [29]. These attempts increase flood prevention capacities as the riparian vegetation is reported to have a considerable impact on the flow friction and flood level [30]. The model developed by Anderson et al. [31] demonstrates that the properties of the riparian zone and the coarseness of the flow channel are determining factors of flow speed, being vital in propagating of flood waves. Thus, the land cover typology like wetlands along the riparian zone have a considerable impact on flood risk reduction [32] and must be comprehensively assessed.

LULC analysis can supply useful spatial information about the surface cover along the waterways. Generally, they are analysed within the riparian zone along the watercourse, which is defined via either fixed or altering width buffer. This approach leads to limitations to the significance that LULC has on the watershed scale as it is unable to reveal the connectivity of natural surfaces starting from the water source to further inland. To cope with this shortcoming, other scholars have highlighted the importance of the transversal (lateral) analysis of LULC (Fig. 5) in relation with the water sources (i.e. ocean, lake, and river) [33, 34]. Analysing LULC beyond the riparian zone helps in defining corridors of natural surfaces in the lateral direction, which can significantly contribute to the water retention capacities and a moderated rainwater discharge into the mainstream.

At the basin scale, the vegetation structure of the land surface on both sides of the watercourse is crucial for defining the roughness of the surfaces of the valley, thus, enabling runoff reduction during the flooding season. The more connected natural surfaces are in the transversal direction, the more moderated the runoff regimes from uplands to the watercourse will be.

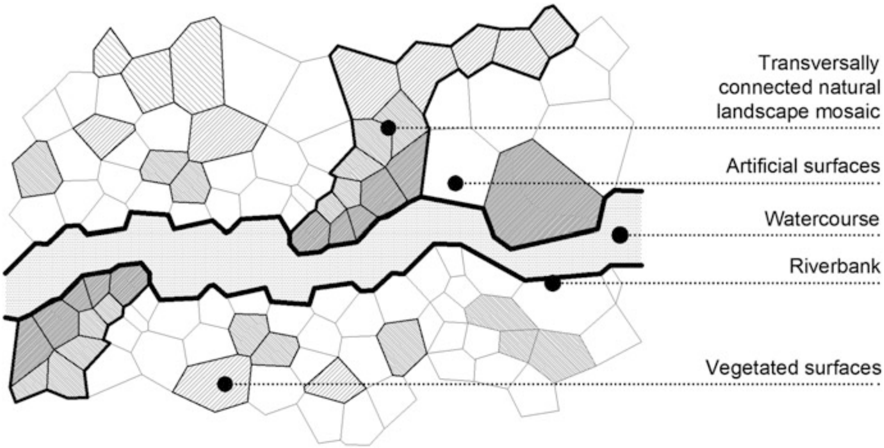

Fig. 5 Conceptual diagram of transversal connectivity of vegetated areas along the watercourse, after Hysa et al. [35]

2.3 Topography as a Static Driver of Water Flow Regime

The implications of topography on flood risk mitigation vary on different spatial scales. For example, while the geomorphology of the watershed (i.e. basin scale) has a direct impact on the runoff amount and speed from the uplands to the main channel, the topography of the riparian zone (i.e. site/river reach scale) holds potential areas suitable for temporarily accommodating water by reducing the flood risk downstream.

The risk-reducing utility of topography is proven by long-run applications of multi-purpose artificial reservoirs constructed on the upstream sub-basins within the watershed. For example, 2.6 million small artificial water bodies in North America contribute to water cycle management by diverting and delaying downstream water flow [36]. While the reservoirs reduce the runoff during high rates of precipitation, they supply restored water for diverse types of usages (i.e. agriculture, recreational, domestic, wildlife, etc.). Moreover, these added water surfaces lead to the flourishing of vegetated surfaces on the upstream lands, thus, enhancing the roughness of the basin surfaces and reducing their runoff capacity. Consequently, the topography and the LULC of the watershed must both be considered when drafting nature-based flooding mitigation.

2.4 Hydrometeorological Aspects of Floods

Flood characteristics change along the seasons and also differ between regions. The hydrometeorological conditions (i.e. precipitation and temperature regimes) represent the main drivers of a flood's typology [37]. In this regard, there are five main typology types, namely: long-rain floods, short-rain floods, flash floods, rain-on-snow, and snowmelt floods [38]. Long-rain floods are characterised by low-intensity rainfall, frontal type storms, they last from days to weeks and in general cover large areas; they are found very often in continental climate [39]. Short-rain floods or the so-called flash floods, characterised by a short duration of rainfall but high intensity, depending on the cloud pattern they occur locally or on a regional scale [38]. Flash floods occur more frequently in arid and semi-arid regions. They are characterised by local high rainfall intensity as well as fast-flowing runoff due to land cover features characterising those type of regions [9, 37].

The rainfall regime in arid and semi-arid regions is a localised structure called convective rain which is one of the primary drivers of several meteorological phenomena, including extreme floods [2, 39]. Because of the high temporal variability of the atmosphere recirculation, flooding in arid and semi-arid regions is very complex, and the occurrence and time duration are hard to predict [8]. Extreme floods occurring during the monsoon season in Asia, mainly in India are main natural hazards threatening millions of people lives [40]. In general, floods driven by high-intensity precipitations are the most unpredictable and destructive ones; in contrast, floods originating from snowmelt are highly predictable and therefore less devastating [2]. However, the latter one depends on several meteorological factors such as short-wave radiation, energy balance, and temperature variability, among others [10]. For instance, rain-on-snow floods originate as a result of a mixture of rainfall and existing snowpack. In this regard, moderate rainfall mixed with snow can generate substantial floods, although not intense [41]. Finally, snowmelt floods occur seasonally, namely during late Spring and early Summer seasons. As mentioned above, this type of flood is not risky in terms of intensity since the snow melting occurs at a low rate [42]. Blöschl et al. [10] proposed several indicators to identify flood typology. Nevertheless, the storm duration is one of the most common indicators that do that. Storm duration depends on factors such as topography and climatology, which may drive substantial spatial differences of the storm type itself [43].

2.5 Hydraulic Aspects of Floods

Indeed, there is a mutual linkage between flood regime and river geomorphology. The typology of floods not only affects humans but also has a substantial impact on several fluvial geomorphological processes; affects both the main channel and the floodplain [40]. Furthermore, it alters sediment transport in longitudinal and horizontal directions, i.e., causing erosion and deposition at a different section of the rivers (Fig. 6).

The type of roughness and river morphology can influence the flood travel time as well as stage – discharge relation [4, 45, 46]. Hydrodynamic modelling is a useful tool in the simulation of flood events to identify the most vulnerable areas. Nevertheless, it requires accurate information about the hydraulic conditions of the river

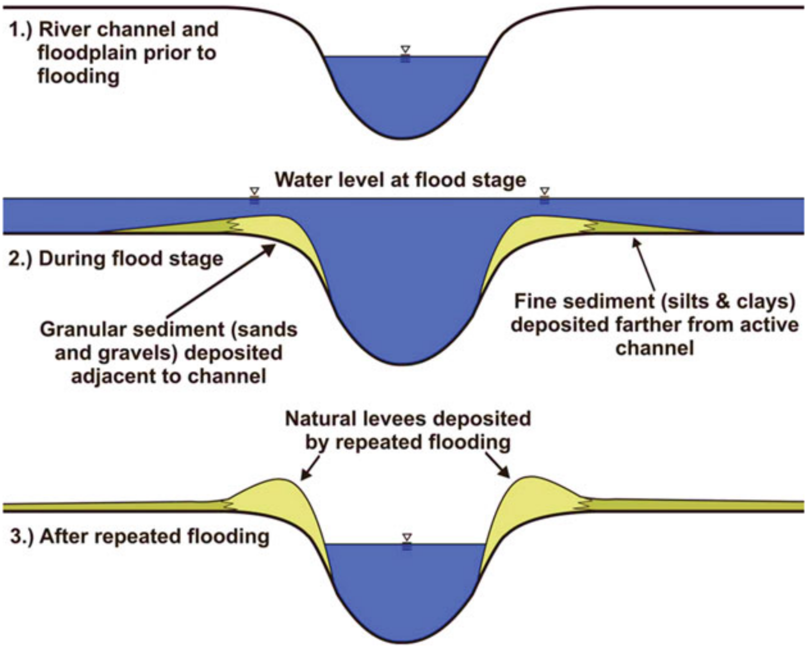

Fig. 6 Floods, river geomorphology precedes interlinkage before and after flooding, after Rogers [44]

channel [4, 47]. In general, 2D hydraulic models are most commonly applied in practice for flood modelling because of their ability in considering both spatial and flow variability in time. Accurate hydraulic information of natural rivers is particularly crucial for generating flood risk maps in high populated areas like urban and peri-urban lands, because it may prevent proper flood management measures or in a worse scenario lead to failure of the implemented measures [47]. Flow resistance is an important parameter that influences the stage–discharge relationship in natural channels [48]. Natural river channels usually have no regular cross-sections. They have variable roughness along the wetter perimeter, which therefore influences the flow resistance.

Moreover, flow resistance is additionally influenced by the longitudinal geomorphology of the river, such as sinuosity and meandering, among others [49]. The hydraulic conditions of a river channel can be improved by periodic cleaning of debris, vegetation, large woody trees, etc., which can enhance the conveyance capacity of the river channel [3]. The unsteady non-uniform hydraulic regime characterises floods. Another important hydraulic factor that influences the shape of the flood hydrograph is the backwater effect created due to water storage or geomorphological irregularities of the river [48]. The backwater effect conveys the secondary flows backwards. It substantially affects the flood routing leading to the formation of a sinuous pattern in the upstream part [50]. The hydraulic regime also influences several physical and biogeochemical processes of the fluvial ecosystem

[51]. Thus, the high variability of the hydraulic regime, such as turbulence could considerably affect the fluvial ecosystem habitat [4, 49, 52]. In this regard, the upstream hydraulic response to the backwater effect of a downstream riffle crest imposes a natural analogy associated with flood-induced channel change [53].

3 Sustainable Flood Mitigation Measures in Support of Integrated Flood Management

3.1 Non-structural Measures

Modern flood risk management practices and strategies aim to reduce the risk of flooding by considering a mix of management options which extend beyond traditional engineering measures the so-called non-structural measures and integrate a wide range of instruments [54]. Non-structural measures are those not involving physical intervention but instead use knowledge, public awareness-raising, previous experiences, training and education, and specific laws, to reduce floods risks. In general, the non-structural measures intend to modify susceptibility to floods to protect people and properties from the flood hazard.

To assure the effectiveness of flood risk management, it is essential to have accurate information on the flood occurrence and typology obtained from non-structural measures, which can significantly decrease the costs of floods for households [55]. Non-structural measures include real-time flood forecasting and warning systems, evacuation systems, land-use planning, flood zoning, preservation of retention ponds, and emergency services, among others [56]. To better manage the risk of floods, a spatial zonation of the flood risk based on Digital Elevation Model (DEM) predictions can provide important information through inundation colour-coded in different flood-vulnerable areas, where different colour may correspond to different levels of flooding [54]. This practical approach would allow people to relate the colour-coded of DEMs to flood warning posts and enable them to take appropriate actions. Other semi-structural or non-structural measures that can reduce the risk of flooding considerably involve wet-proofing approaches such as solidification of walls against water pressure, adapting the flood-prone parts of the settlements with waterproof materials, moving vulnerable instruments to upper floors, risk transfer instruments, flood insurance, evacuation, installing one-way valves on water evacuation pipes to stop the waters from inflowing the house through the pipes and storing paints, and chemicals in the upper parts of the home among others [57]. These kinds of non-structural measures aim to stop the water from inflowing into the house at the highest level as well as they adopt the house to cut the damage in case of flooding. Nevertheless, the efficacy of non-structural measures is sensitive to socio-economic changes and governance provisions policies [54]. Non-structural measures are in better agreement with sustainable development than traditional engineering structural measures, as they are more adjustable, commonly accepted, and environmentally-friendly [58].

Overall, non-structural measures have several benefits such as low implementation cost reducing vulnerability, and easily adaptable; the later on is particularly advantageous considering the uncertainties resulting from climate changes [22].

3.2 Structural Measures

Even though the non-structural measures offer several benefits concerning flood risk management, they would be less effective in many cases without combination with structural measures. Structural river protection and/or mitigation measures such as dams and dikes are among old and traditionally-known measures. They have been constructed for at least four thousand years [11]. Management of an area that is vulnerable to flooding undergoes complex decision-making processes regarding the measures to be implemented in compatibility with land-use related activities and the risk to which environment, human, and their properties are subjected [59]. Structural measures, besides attempts to reduce the water load, contribute to enhancing the resilience of the entire flood defence system, and also promote the readiness to somehow live with floods. Structural flood defences systems may boost urban development at-risk areas. At the same time, the recovery instruments might also provide preventive measures for flood risk management [11]. Before implementing new measures, it is essential to explore if it is possible to create a new space in the existing channel to allocate an extra volume of water to reduce the costs (Fig. 7).

Although structural flood mitigation measures are the most commonly used in practice as proved of being effective in many highly urbanised flood-prone areas, poor implementation and management of these infrastructures may lead to irreversible environmental, geomorphological, and social consequences [60]. Some of the measures may be implemented temporarily to avoid spontaneous risk (Fig. 8).

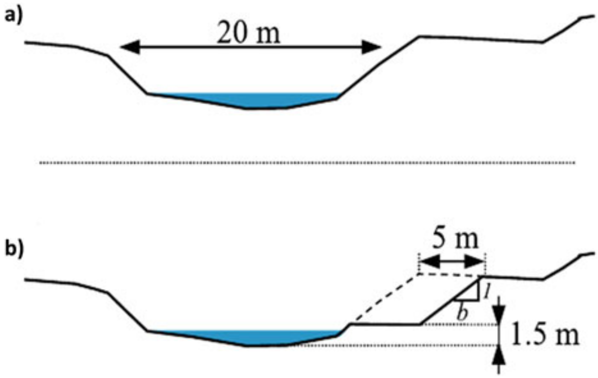

Fig. 7 Schematic representation of side-channel digging to create new room for the extra volume of water (**a**) current profile and (**b**) profile of the giving-room-to-the-river scenario, 5 m wider at 1.5 m high, with the same bank slope *b,* adopted after Bokhove et al. [17]

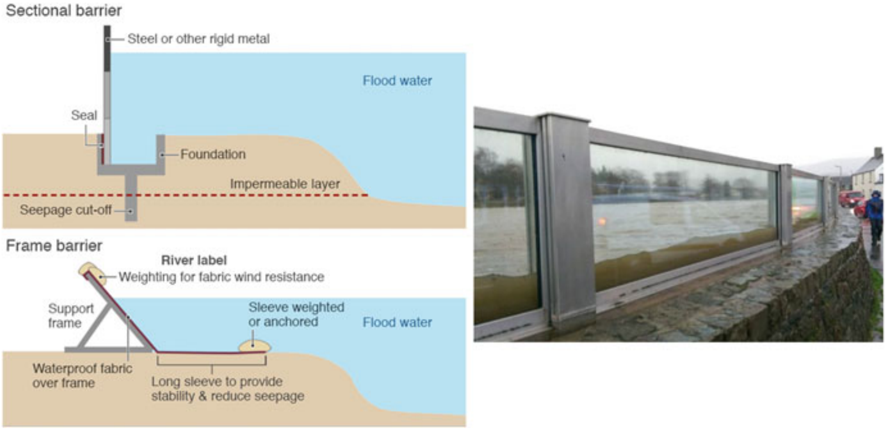

Fig. 8 Schematic representation of two types of temporary flood barrier in left and the right, a picture is showing implementation in practice (Source: https://www.bbc.com/news/uk-25929644)

Fig. 9 Leaky barriers structure applied in the torrential river, after Hankin et al. [19]

Structural measures can be found at different typology, applicable at different scale within the river basin, and target different typology of floods. For instance, leaky barriers (Fig. 9) are mostly applicable in the torrential river and take place in the upland part of the river basin.

Hybrid or combined structural mitigation solution such as tree planting in combination with dykes is also very often applied in practice (Fig. 10).

Such solutions are cost-effective because they can quickly absorb the flooding wave energy and therefore reduce the construction cost of a dyke while in the meantime, increasing the reliability of Dykes [62].

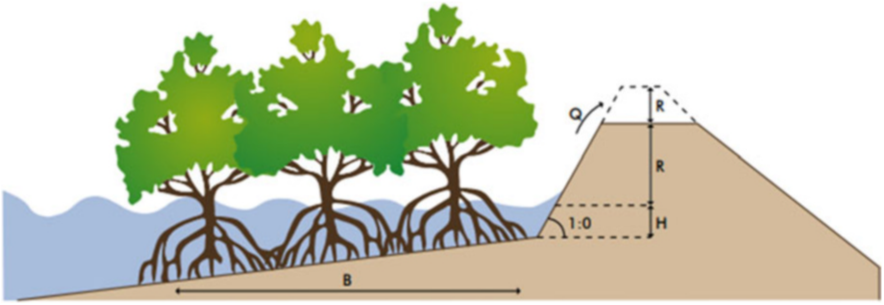

Fig. 10 Schematic representation of a hybrid solution. Mangrove trees can absorb the flood wave energy. As a result, it reduces the dike height that is needed to meet the safety standards after K. van Wesenbeeck et al. [61]

3.3 The Ecosystem Conservation Aspects of Nature-Based Mitigation Measures

Particularly in urban areas, large impermeable pavement areas, as well as the roofs of buildings direct rainwater to be collected straight into drainage systems which can quickly become overwhelmed. Therefore, new sustainable approaches such as the "Sponge Cities" [63], Integrated Water Resource Management (IWRM) [64], or the Sustainable Urban Drainage System (SuDS) are receiving considerable interest [65]. According to these new eco-friendly concepts, runoff water coming from impermeable surfaces should seep into the ground or be collected in detention basis and small ponds rather than flushing way through the sewerage system (Fig. 11). So, the collected rainwater can be released in a controlled way, or it can even be used for irrigation or other purposes after validating its quality [66].

Such solutions have huge potential in reducing global warming and in helping people and also ecosystems adapting to a warmer planet. The NBS solutions, namely SuDS and "Sponge Cities", have great potential to sequestering CO_2, and also improve resilience, especially of the urban area, to guarantee sustainable food supplies, to increase biodiversity, and to generate healthier, greener living environments for people and biota [67]. Concerning the biota, particularly the one related to fluvial ecosystems, it is significantly affected by the habitat conditions; degradation of habitat conditions leads to the decline of the aquatic biodiversity [68]. Therefore, flood mitigation measures to take place in the river reach scale must also consider preservation and/or improvement of habitat suitability conditions. In this regard, such measures should guarantee lateral and longitudinal connectivity, spatially and temporally heterogeneous areas with related water bodies, dynamics of water exchanges between surface waters and groundwater, and water quality among others [14, 68]. Figure 12 shows flood mitigation measures in the semi-natural and quasi-natural channel while in the meantime, intending to improve and preserve the habitat conditions.

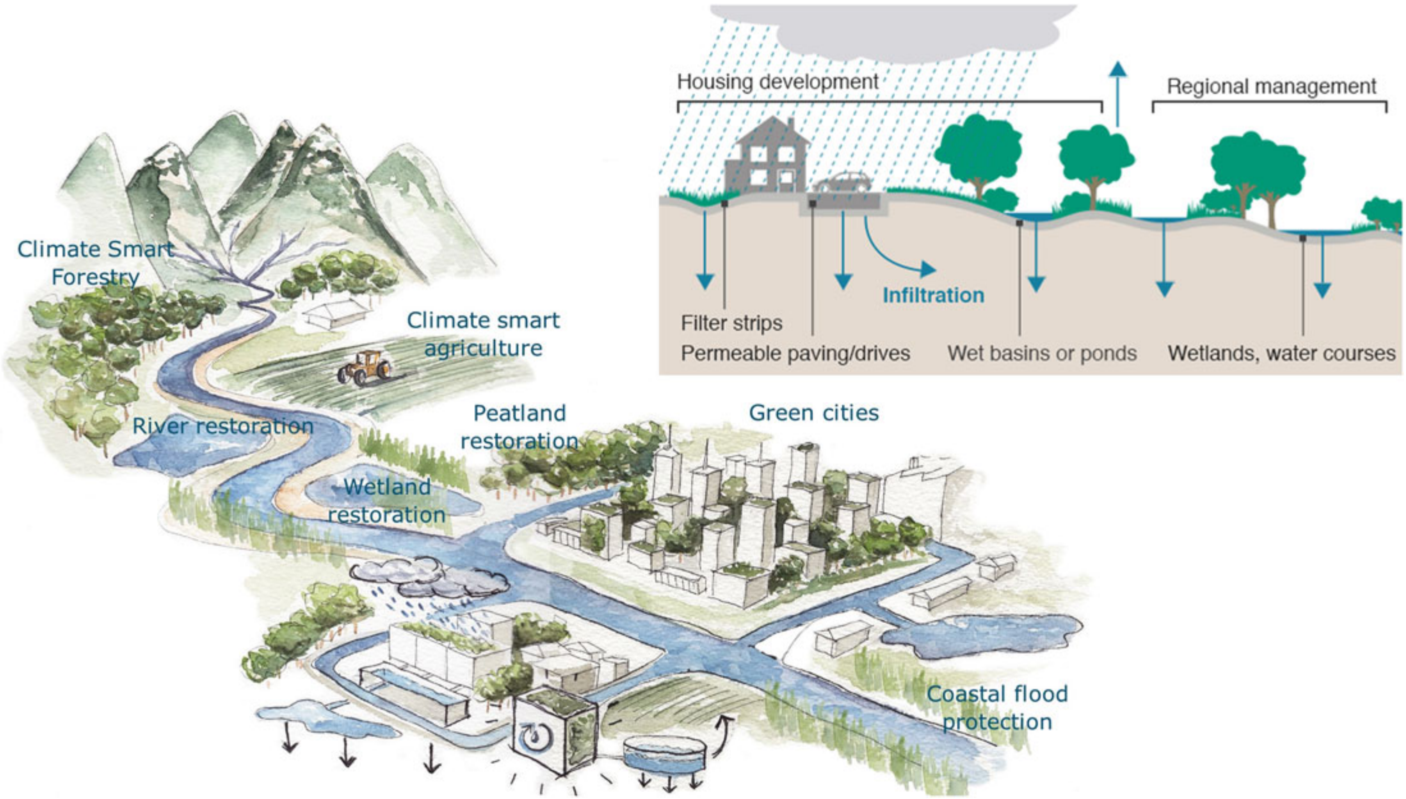

Fig. 11 The upper-right picture shows a cross-section view of SuDS (Source: https://www.susdrain.org), the lower-left picture schematically shows the "Sponge Cities" concept, adapted from Hattum, Blauw [65] (Credits: Natasha de Sena)

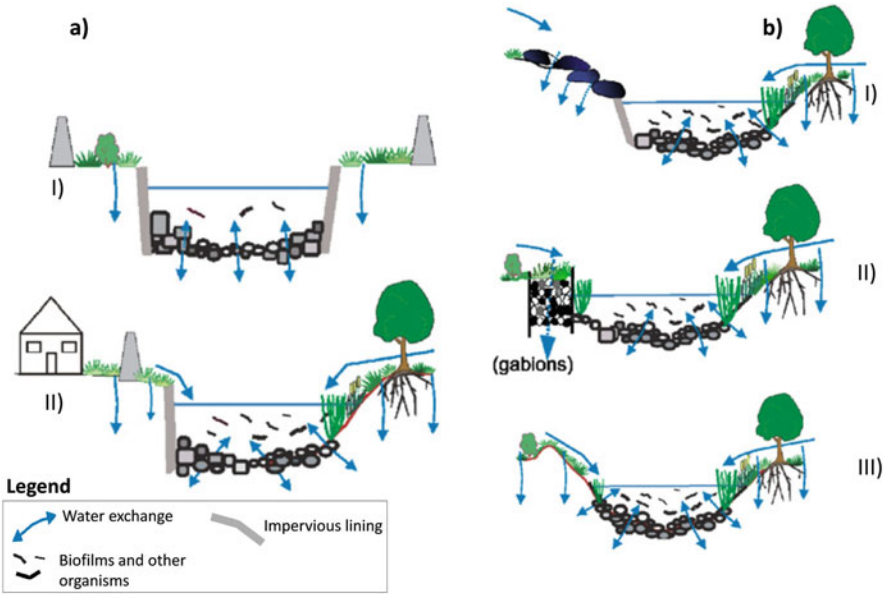

Fig. 12 Schematic representation of the habitat improvement: (**a**) semi-natural channel and (**b**) quasi-natural channel, adapted from Poulard et al. [14]

In the case of the semi-natural channel (Fig. 12a, I), about 50% of the bed is artificial. At the same time, the surface and groundwater connectivity are possible only through the bed. In contrast, in the second scenario (Fig. 12a, II) only about 30% of the bed is artificial; therefore, surface and groundwater connectivity are possible through the bed as well as the riverbank. In the case of the quasi-natural channel (Fig. 12b), almost all types of habitat might be preserved. Nevertheless, the presence of the artificial elements, particularly in the case of Fig. 12b, I), may restrict three-dimensional water connectivity and may also influence the water quality. Overall, the best strategy in such and other types of flood mitigation measures would be the eco-friendly usage design as well as materials [57, 69].

4 Future Research Needs and Recommendations for Improvement of Floods Mitigation Measures

One of the essential aspects in the enhancement of flood risk management strategies is an investment in sciences and communications, which provides a prospect for further improvement and expansion of the context of NBS utility in flood mitigation measures. In this regard, real-time localisation of the most vulnerable areas is an essential task to be considered for further advancement of computer modelling to provide possible accurate information about high-risk flooding areas. Zonation and flood mapping of the flood-prone areas should be done on priority basis [3], in this particular context attention should be given to lower-latitude areas where flood frequency and population are both projected to increase in the future [9]. Many countries fail in providing effective flood mitigation solution due to the lack of information on the flood typology. Therefore, it is essential to define the flood typology at the regional and country scale [10].

Expansion and modernisation of the existing hydrometeorological system are particularly significant for real-time storm tracking. Multidimensional aspects improvement of the structural and non-structural measures is tremendously imperative to enhance the efficacy of the flood management system. In this regard, further research is needed to improve the eco-friendliness related to the design and type of strategies and materials used in flood mitigation solutions [68]. Fostering interdisciplinary research involving different stakeholders is critical in providing sustainable flood mitigation solution with a twofold function; reducing flooding risk but in the meantime, preserving the natural conditions of the riverscape corridor as well as the fluvial ecosystem [14]. Effective flood risk management requires monitoring of mitigation solution with regard to their functionality and eco-friendliness. Data collected through monitoring campaign is essential for decision-makers in the improvement of the existing mitigation measures and developing the new ones [16].

Further research is needed in flood risk perception, to achieve a more inclusive understanding of how risk perceptions affect the vulnerability, capacity, and resilience of individuals and communities facing flooding [13]. The term "resilience" has arisen as the dominant model in flood risk management, mainly related to NBS, which implies the need to plan and design cities that can absorb water during flooding and reproduce natural processes more thoroughly [65]. A better understanding of the flood risk perception is particularly important in urban areas by facilitating the cost-effective and safe expansion of such areas. Finally, further research is also needed to assess the synergistic effects of multiple flood mitigation strategies on protecting community properties [20]. Last but not least, additional research is also needed in terms of policies concerning insurance and jurisdictions aspects related to damage compensation, which might contribute towards enhancement of management practices and governance provisions.

5 Concluding Remarks

This chapter delivered a summary of the existing flood mitigation and protective measures at a cross-scalar context from reach to the basin area. Furthermore, it identified the main natural factors within the context that affects the flooding regimes. It must be considered in flood risk management. This was realised by thoroughly reviewing the ongoing scholarly discourse on the topic. The main focus was given to novel approaches that are based on the principles of NBS. These are advocated to inspire not only cost-effective solutions but also sustainable proposals that are in harmony with the natural environment and native landscapes. We identified four major aspects that have direct implications on the flood regimes, which are LULC, topography, hydrometeorology, and hydraulics of the river. These factors have been discussed in detail to clarify their cross-spatial influence on flood events.

On the other hand, novel concepts such as "Sponge Cities", IWRM, and the SuDS have been reviewed and discussed as examples of mitigation practices that combine cost-effective non-structural and structural mitigation measures. These agendas aim to integrate the social, geophysical, and ecological aspects and provide a comprehensive frame while dealing with urban flooding. Community engagement and activation are crucial dimensions of these approaches, as well as the ecological conservation of existing habitats. Nevertheless, we realised that the importance of the cross-scalar character of flooding phenomena is not considered enough.

In conclusion, this chapter highlights two recommendations. First, the flood risk reduction agendas must adopt a cross-scale approach while considering flood events. The mitigation measures downstream and upstream must complement each other and must be designed in a spatially comprehensive manner. Second, natural properties of the context (i.e. at both basin and reach scale) such as LULC, topography, hydrometeorology, and hydraulics must be considered to utilise the full native capacity in flood risk mitigation. Finally, flood risk reduction agendas must integrate social, geophysical, and ecological properties of the study area while drafting practical nature-based flood risk mitigation measurements.

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References

1. Haque AN, Bithell M, Richards KS (2020) Adaptation to flooding in low-income urban settlements in the least developed countries: a systems approach. Geogr J. https://doi.org/10.1111/geoj.12348
2. Lawford RG, Prowse TD, Hogg WD et al (1995) Hydrometeorological aspects of flood hazards in Canada. Atmosphere-Ocean 33(2):303–328. https://doi.org/10.1080/07055900.1995.9649535
3. Tariq MAUR, van de Giesen N (2012) Floods and flood management in Pakistan. Phys Chem Earth Parts A/B/C 47-48:11–20. https://doi.org/10.1016/j.pce.2011.08.014
4. Ardıçlıoğlu M, Kuriqi A (2019) Calibration of channel roughness in intermittent rivers using HEC-RAS model: case of Sarimsakli creek, Turkey. S.N. Appl Sci 1(9). https://doi.org/10.1007/s42452-019-1141-9
5. Kuriqi A, Koçileri G, Ardiçlioğlu M (2019) Potential of Meyer-Peter and Müller approach for estimation of bed-load sediment transport under different hydraulic regimes. Model Earth Syst Environ 6(1):129–137. https://doi.org/10.1007/s40808-019-00665-0
6. Carolyn A, Hollis A, Leon AB et al (1998) Stream corridors: processes and characteristics. In: Stream corridor restoration: principles, processes, and practices, vol 1. vol A 57.6/2:EN3/PT.653. 15 Federal agencies of the U.S. Gov't, USA, pp 1–89

7. Schismenos S, Stevens GJ, Emmanouloudis D et al (2020) Humanitarian engineering and vulnerable communities: hydropower applications in localised flood response and sustainable development. Int J Sustain Energy. https://doi.org/10.1080/14786451.2020.1779274
8. Dettinger M (2011) Climate change, atmospheric Rivers, and floods in California – a multimodel analysis of storm frequency and magnitude Changes1. JAWRA J Am Water Resour Assoc 47(3):514–523. https://doi.org/10.1111/j.1752-1688.2011.00546.x
9. Hirabayashi Y, Mahendran R, Koirala S et al (2013) Global flood risk under climate change. Nat Clim Chang 3(9):816–821. https://doi.org/10.1038/nclimate1911
10. Blöschl G, Hall J, Parajka J et al (2017) Changing climate shifts timing of European floods. Science 357(6351):588–590. https://doi.org/10.1126/science.aan2506
11. Kundzewicz ZW, Hegger DLT, Matczak P et al (2018) Opinion: flood-risk reduction: structural measures and diverse strategies. Proc Natl Acad Sci U S A 115(49):12321–12325. https://doi.org/10.1073/pnas.1818227115
12. Plate EJ (2002) Flood risk and flood management. J Hydrol 267(1–2):2–11. https://doi.org/10.1016/S0022-1694(02)00135-X
13. Birkholz S, Muro M, Jeffrey P et al (2014) Rethinking the relationship between flood risk perception and flood management. Sci Total Environ 478:12–20. https://doi.org/10.1016/j.scitotenv.2014.01.061
14. Poulard C, Lafont M, Lenar-Matyas A et al (2010) Flood mitigation designs with respect to river ecosystem functions – a problem oriented conceptual approach. Ecol Eng 36(1):69–77. https://doi.org/10.1016/j.ecoleng.2009.09.013
15. Wingfield T, Macdonald N, Peters K et al (2019) Natural flood management: beyond the evidence debate. Area 51(4):743–751. https://doi.org/10.1111/area.12535
16. Short C, Clarke L, Carnelli F et al (2019) Capturing the multiple benefits associated with nature-based solutions: lessons from a natural flood management project in the Cotswolds, U.K. Land Degrad Dev 30(3):241–252. https://doi.org/10.1002/ldr.3205
17. Bokhove O, Kelmanson MA, Kent T et al (2020) Communicating (nature-based) flood-mitigation schemes using flood-excess volume. River Res Appl 35(9):1402–1414
18. Bokhove O, Kelmanson MA, Kent T et al (2019) Communicating (nature-based) flood-mitigation schemes using flood-excess volume. River Res Appl 35(9):1402–1414
19. Hankin B, Hewitt I, Sander G et al (2020) A risk-based, network analysis of distributed in-stream leaky barriers for flood risk management. Nat Hazards Earth Syst Sci. https://doi.org/10.5194/nhess-2019-394
20. Brody SD, Highfield WE (2013) Open space protection and flood mitigation: a national study. Land Use Policy 32:89–95. https://doi.org/10.1016/j.landusepol.2012.10.017
21. Kuriqi A, Ardiçlioglu M, Muceku Y (2016) Investigation of seepage effect on river dike's stability under steady state and transient conditions. Pollack Periodica 11(2):87–104. https://doi.org/10.1556/606.2016.11.2.8
22. Meyer V, Priest S, Kuhlicke C (2011) Economic evaluation of structural and non-structural flood risk management measures: examples from the Mulde River. Nat Hazards 62(2):301–324. https://doi.org/10.1007/s11069-011-9997-z
23. Brody SD, Zahran S, Highfield WE et al (2009) Policy learning for flood mitigation: a longitudinal assessment of the community rating system in Florida. Risk Anal 29 (6):912–929. https://doi.org/10.1111/j.1539-6924.2009.01210.x
24. Poff NL, Zimmerman JKH (2010) Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows. Freshw Biol 55 (1):194–205. https://doi.org/10.1111/j.1365-2427.2009.02272.x
25. Janssen P, Piegay H, Pont B et al (2019) How maintenance and restoration measures mediate the response of riparian plant functional composition to environmental gradients on channel margins: insights from a highly degraded large river. Sci Total Environ 656:1312–1325. https://doi.org/10.1016/j.scitotenv.2018.11.434

26. Januschke K, Brunzel S, Haase P et al (2011) Effects of stream restorations on riparian mesohabitats, vegetation and carabid beetles. Biodivers Conserv 20(13):3147–3164. https://doi.org/10.1007/s10531-011-0119-8
27. Khosravi K, Shahabi H, Pham BT et al (2019) A comparative assessment of flood susceptibility modeling using multi-criteria decision-making analysis and machine learning methods. J Hydrol 573:311–323. https://doi.org/10.1016/j.jhydrol.2019.03.073
28. Comiti F, Da Canal M, Surian N et al (2011) Channel adjustments and vegetation cover dynamics in a large gravel bed river over the last 200years. Geomorphology 125(1):147–159. https://doi.org/10.1016/j.geomorph.2010.09.011
29. Shields FD, Nunnally NR (1984) Environmental aspects of clearing and snagging. 110 (1):152–165. https://doi.org/10.1061/(ASCE)0733-9372(1984)110:1(152)
30. Darby SE (1999) Effect of riparian vegetation on flow resistance and flood potential. 125 (5):443–454. https://doi.org/10.1061/(ASCE)0733-9429(1999)125:5(443)
31. Anderson BG, Rutherfurd ID, Western AW (2006) An analysis of the influence of riparian vegetation on the propagation of flood waves. Environ Model Softw 21(9):1290–1296. https://doi.org/10.1016/j.envsoft.2005.04.027
32. Acreman M, Holden J (2013) How wetlands affect floods. Wetlands 33(5):773–786. https://doi.org/10.1007/s13157-013-0473-2
33. Hysa A, Başkaya FAT (2018) Revealing the transversal continuum of natural landscapes in coastal zones – case of the Turkish Mediterranean coast. Ocean Coastal Manag 158:103–115. https://doi.org/10.1016/j.ocecoaman.2018.03.011
34. Hysa A (2021) Introducing transversal connectivity index (TCI) as a method to evaluate the effectiveness of the blue-green infrastructure at metropolitan scale. Ecol Indic 124:107432. https://doi.org/10.1016/j.ecolind.2021.107432
35. Hysa A, Baskaya FAT (2018) A GIS-based method for revealing the transversal continuum of natural landscapes in the coastal zone. MethodsX 5:514–523. https://doi.org/10.1016/j.mex.2018.05.012
36. Smith SV, Renwick WH, Bartley JD et al (2002) Distribution and significance of small, artificial water bodies across the United States landscape. Sci Total Environ 299(1):21–36. https://doi.org/10.1016/S0048-9697(02)00222-X
37. Merz R, Blöschl G (2003) A process typology of regional floods. Water Resour Res 39(12). https://doi.org/10.1029/2002wr001952
38. Yang W, Yang H, Yang D (2020) Classifying floods by quantifying driver contributions in the eastern monsoon region of China. J Hydrol 585. https://doi.org/10.1016/j.jhydrol.2020.124767
39. Cecchini MA, Silva Dias MAF, Machado LAT et al (2020) Macrophysical and microphysical characteristics of convective rain cells observed during SOS-CHUVA. J Geophys Res Atmos 125(13). https://doi.org/10.1029/2019jd031187
40. Kale VS, Ely LL, Enzel Y et al (1994) Geomorphic and hydrologic aspects of monsoon floods on the Narmada and Tapi Rivers in Central India. In: Geomorphology and natural hazards, pp 157–168
41. Li D, Lettenmaier DP, Margulis SA et al (2019) The role of rain-on-snow in flooding over the conterminous United States. Water Resour Res 55(11):8492–8513. https://doi.org/10.1029/2019wr024950
42. Mateo-Lázaro J, Castillo-Mateo J, Sánchez-Navarro J et al (2019) Assessment of the role of snowmelt in a flood event in a gauged catchment. Water 11(3). https://doi.org/10.3390/w11030506
43. De Michele C (2003) A generalised Pareto intensity-duration model of storm rainfall exploiting 2-copulas. J Geophys Res 108(D2). https://doi.org/10.1029/2002jd002534
44. Rogers JD (2008) Development of the New Orleans flood protection system prior to hurricane Katrina. J Geotech Geoenviron 134(5):602–617. https://doi.org/10.1061/(asce)1090-0241(2008)134:5(602)

45. Kuriqi A, Ardiçlioğlu M (2018) Investigation of hydraulic regime at middle part of the Loire River in context of floods and low flow events. Pollack Periodica 13(1):145–156. https://doi.org/10.1556/606.2018.13.1.13
46. Kumar M, Kumari A, Kushwaha DP et al (2020) Estimation of daily stage–discharge relationship by using data-driven techniques of a Perennial River, India. Sustainability 12(19). https://doi.org/10.3390/su12197877
47. Mihu-Pintilie A, Cîmpianu CI, Stoleriu CC et al (2019) Using high-density LiDAR data and 2D streamflow hydraulic modeling to improve urban flood Hazard maps: a HEC-RAS multi-scenario approach. Water 11(9). https://doi.org/10.3390/w11091832
48. Helmiö T, Järvelä J (2004) Hydraulic aspects of environmental flood management in boreal conditions. Boreal Environ Res 9(3):227–241
49. McClain ME, Subalusky AL, Anderson EP et al (2014) Comparing flow regime, channel hydraulics, and biological communities to infer flow–ecology relationships in the Mara River of Kenya and Tanzania. Hydrol Sci J 59(3–4):801–819. https://doi.org/10.1080/02626667.2013.853121
50. Castelltort FX, Bladé E, Balasch JC et al (2020) The backwater effect as a tool to assess formative long-term flood regimes. Quat Int 538:29–43. https://doi.org/10.1016/j.quaint.2020.01.012
51. Christian F, Arturas R, Saulius G et al (2008) Hydraulic regime-based zonation scheme of the Curonian lagoon. Hydrobiologia 611(1):133–146. https://doi.org/10.1007/s10750-008-9454-5
52. Kuriqi A, Pinheiro AN, Sordo-Ward A et al (2020) Water-energy-ecosystem nexus: balancing competing interests at a run-of-river hydropower plant coupling a hydrologic–ecohydraulic approach. Energy Convers Manag 223. https://doi.org/10.1016/j.enconman.2020.113267
53. Pasternack GB, Bounrisavong MK, Parikh KK (2008) Backwater control on riffle–pool hydraulics, fish habitat quality, and sediment transport regime in gravel-bed rivers. J Hydrol 357(1–2):125–139. https://doi.org/10.1016/j.jhydrol.2008.05.014
54. Dawson RJ, Ball T, Werritty J et al (2011) Assessing the effectiveness of non-structural flood management measures in the Thames estuary under conditions of socio-economic and environmental change. Glob Environ Chang 21(2):628–646. https://doi.org/10.1016/j.gloenvcha.2011.01.013
55. Simonovic SP (2002) Two new non-structural measures for sustainable management of floods. Water Int 27(1):38–46. https://doi.org/10.1080/02508060208686976
56. Faisal IMM, Kabir R et al (1999) Non-structural flood mitigation measures for Dhaka City. Urban Water 1(2):145–153
57. Poussin JK, Bubeck P, Aerts JCJH et al (2012) Potential of semi-structural and non-structural adaptation strategies to reduce future flood risk: case study for the Meuse. Nat Hazards Earth Syst Sci 12(11):3455–3471. https://doi.org/10.5194/nhess-12-3455-2012
58. Kundzewicz ZW (2002) Non-structural flood protection and sustainability. Water Int 27(1):3–13. https://doi.org/10.1080/02508060208686972
59. Oliveri E, Mario S (2000) Estimation of urban structural flood damages: the case study of Palermo. Urban Water 2(3):223–234
60. Gilbuena Jr R, Kawamura A, Medina R et al (2013) Environmental impact assessment using a utility-based recursive evidential reasoning approach for structural flood mitigation measures in metro Manila, Philippines. J Environ Manag 131:92–102. https://doi.org/10.1016/j.jenvman.2013.09.020
61. van Wesenbeeck KB, IJff S, Jongman B et al (2017) Implementing naturebased flood protection. World Bank Group, Washington
62. Jongman B (2018) Effective adaptation to rising flood risk. Nat Commun 9(1):1986. https://doi.org/10.1038/s41467-018-04396-1
63. Jiang Y, Zevenbergen C, Ma Y (2018) Urban pluvial flooding and stormwater management: a contemporary review of China's challenges and "sponge cities" strategy. Environ Sci Pol 80:132–143. https://doi.org/10.1016/j.envsci.2017.11.016

64. Gain A, Mondal M, Rahman R (2017) From flood control to water management: a journey of Bangladesh towards integrated water resources management. Water 9(1). https://doi.org/10.3390/w9010055
65. Potter K, Vilcan T (2020) Managing urban flood resilience through the English planning system: insights from the 'SuDS-face'. Philos Trans A Math Phys Eng Sci 378 (2168):20190206. https://doi.org/10.1098/rsta.2019.0206
66. Musz-Pomorska A, Widomski MK, Gołębiowska J (2020) Financial sustainability of selected rain water harvesting systems for single-family house under conditions of eastern Poland. Sustainability 12(12). https://doi.org/10.3390/su12124853
67. Hattum TV, Blauw M, Bergen Jensen M et al (2016) Climate adaptation is a huge opportunity to improve the quality of life in cities. Towards Water Smart Cities Wageningen Environmental Research Gelderland, Belgium
68. Kail J, Guse B, Radinger J et al (2015) A modelling framework to assess the effect of pressures on river abiotic habitat conditions and biota. PLoS One 10(6):e0130228. https://doi.org/10.1371/journal.pone.0130228
69. Masi F, Rizzo A, Regelsberger M (2018) The role of constructed wetlands in a new circular economy, resource oriented, and ecosystem services paradigm. J Environ Manag 216:275–284. https://doi.org/10.1016/j.jenvman.2017.11.086