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Research article

Identifying barriers for nature-based solutions in flood risk management: An interdisciplinary overview using expert community approach

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ABSTRACT

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The major event that hit Europe in summer 2021 reminds society that floods are recurrent and among the costliest and deadliest natural hazards. The long-term flood risk management (FRM) efforts preferring sole technical measures to prevent and mitigate floods have shown to be not sufficiently effective and sensitive to the environment. Nature-Based Solutions (NBS) mark a recent paradigm shift of FRM towards solutions that use nature-derived features, processes and management options to improve water retention and mitigate floods. Yet, the empirical evidence on the effects of NBS across various settings remains fragmented and their implementation faces a series of institutional barriers. In this paper, we adopt a community expert perspective drawing upon *LAND4FLOOD Natural flood retention on private land* network (https://www.land4flood.eu) in order to identify a set of barriers and their cascading and compound interactions relevant to individual NBS. The experts identified a comprehensive set of 17 barriers affecting the implementation of 12 groups of NBS in both urban and rural settings in five European regional environmental domains (i.e., Boreal, Atlantic, Continental, Alpine-Carpathian, and Mediterranean). Based on the results, we define avenues for further research, connecting hydrology and soil science, on the one hand, and land use planning, social geography and economics, on the other. Our suggestions ultimately call for a transdisciplinary turn in the research of NBS in FRM.

1. Introduction

The recent major flood that hit vast regions of Belgium, the Netherlands, Germany, and Austria reminds society that floods are recurrent and among the costliest natural hazards in Europe (Cornwall, 2021; MunichRe, 2021). Despite the existing flood risk management (FRM) strategies and initiatives implemented over the last decades, flood hazard is expected to increase in some European regions due to climate change (Blöschl et al., 2019; IPCC, 2021) and increasing human pressure on river systems (Hein et al., 2016; Ferreira et al., 2018; EEA, 2018).

The long-term FRM efforts relying on technical measures to prevent and mitigate floods have shown to be not sufficiently effective (Ellis et al., 2021) and to have some adverse environmental impacts (Xu et al., 2021). Indeed, the implementation of technical measures can cause unintended consequences that lead to increased exposure of societal assets, denoted as the safe development paradox (Haer et al., 2020), or may negatively affect floodplain connectivity and its ecological functions (Keesstra et al., 2020; Jakubínský et al., 2021). Therefore, FRM strategies have recently shifted towards solutions that use nature-derived features, processes and management options to improve water retention in catchments and floodplains (Jakubínský et al., 2021). Nature-Based Solutions (NBS; Kabisch et al., 2016; Hartmann et al., 2019a,b, for definitions of overlapping terms) are measures and actions that are inspired and supported by natural processes, although their implementation and maintenance may also require technical interventions. The intended function of these measures range from reducing runoff and instream flow by water storage, to de-synchronizing spatio-temporal patterns of peak flows during extreme hydrological events. For settings such as urban landscapes with limited availability of land to retain water, NBS are also combined with engineered infrastructure to form hybrid solutions (Alves et al., 2020). However, regardless of the setting, a catchment-wide perspective is essential to mobilise co-benefits of various NBS and to support water sensitive spatial planning (Hartmann, 2018; Albrecht and Hartmann, 2021).

While there is an increasing number of initiatives and projects implementing NBS worldwide and the reviews of NBS effects for enhancing ecosystem services are available (Jones et al., 2012; Kabisch et al., 2016; Keesstra et al., 2018), there is a persisting lack of empirical data documenting the effectiveness and efficacy of NBS in FRM at various spatiotemporal scales (Dadson et al., 2017; Ellis et al., 2021). In addition, the existing evidence from the implementation of NBS in FRM is rather fragmented and with contrasting results, leading to a lack in wider policy considerations (Wingfield et al., 2019). These factors limit our understanding of suitable design and implementation of different types of NBS in various environmental and institutional settings.

The research on effects and implementation barriers of NBS is mostly diverted in the two following avenues employing different concepts, epistemologies and methodologies. First, for hydrological processes, the evidence on effects related to NBS is mainly collected through ongoing field experiments and modelling (e.g., Ferreira et al., 2020; Nicholson et al., 2020). Second, for the policy domain, the research has mostly focused on developing new planning instruments, negotiation approaches and stakeholder engagement schemes (e.g., Bark et al., 2021; Zingraff-Hamed et al., 2021). This drives an urgent need to adopt an integrated approach for exploring the cascading and compound interactions among various implementation barriers related to NBS and their combinations. Moreover, as the empirical evidence is poorly validated and it will take considerable time to provide more robust results, expert-based approaches should be employed to inform policy- and decision-makers in using NBS for FRM.

This paper aims to identify the barriers of NBS for FRM based on an expert community approach, which has been successfully employed for understanding complex problems across fields (e.g., Elliot et al., 2020). More specifically, we identify experiences with the preferred NBS in European regions and document the spectre of barriers that impair their wider implementation. Based on this evidence, we identify knowledge gaps and formulate research directions to streamline and facilitate further studies of NBS for FRM. Adding up to the existing NBS in FRM reviews (e.g., Dadson et al., 2017; Wingfield et al., 2019; Keestra et al., 2020; Ellis et al., 2021), we extend our focus on both the urban and rural settings and their interactions, and on the implementation barriers emerging at the intersect of hydrology and soil sciences, on the one hand, and land use planning, social geography and economics, on the other. We draw upon the four years of the Cost Action initiative entitled *LAND4FLOOD Natural flood retention on private land* (https://www.land4flood.eu), which has established an interdisciplinary community of researchers and practitioners.

2. Data and methods

The research has been conducted in three phases (Fig. 1), allowing to refine the methodological design upon internal and external discussions and to ensure consistency in the contributions by experts involved in the survey.

The first phase involved establishing an interdisciplinary group of experts (https://www.land4flood.eu) based on academia and conducting collaborative research with practitioners. The expert community discussions conducted enabled drafting a research design for this study and to obtain preliminary empirical evidence on the use of NBS for FRM.

The second phase started with a workshop where we collected primary data through a peering framework based on open questionnaires. In total, 35 experts from 32 countries, including hydrologists, soil scientists, environmental engineers, water resources managers, spatial planners and geographers, participated in the workshop in Thessaloniki, Greece (June 2019). During the workshop, the experts were asked to list up to five NBS relevant for FRM. Each contribution was then commented on by another participant randomly selected, who was asked to identify possible barriers for the listed NBS. This resulted in the identification of

123 NBS. Along, a list of barriers relating to NBS was compiled and grouped in terms of their uncertain effects, dependence on environmental conditions, institutional capacity and availability of resources to implement the measures. The workshop results were summarized in a report, which was discussed and validated within the expert group. Ambiguous inputs were verified with contributors, and the preliminary results were presented outside the group (Session on Land for Flood Risk Management; PLPR Annual Conference, 2020).

During the last phase, feedback from the outside of the group enabled us to derive the final online data form to collect the information from contributors about perceived barriers impeding the implementation of NBS across different environmental settings in Europe.In order to distinguish regional variances in preferred NBS and possible barriers, the regional environmental domains (REDs) were delimited (Fig. 2) based on a literature review of hydro-climatic and land cover variations across Europe (Mitchell et al., 2004; Kottek et al., 2006; Finger et al., 2016; EEA, 2021). To achieve a similar distribution of contributors for all REDs, four additional experts were invited to fill an online questionnaire (the same as distributed during the Thessaloniki workshop). Similar to the methodology used in the workshop, the new obtained lists of NBS were sent among the mentioned four experts to identify the barriers. The initial 35 contributors from the workshop were also asked to verify and confirm online their previous list of NBS. The NBS identified by the 39 experts (during both workshop and additional online survey) were aggregated into 12 groups by iterative sorting and following the environmental and functional similarities among the listed NBS. The groups of NBS were compiled in an online form along with the types of barriers identified. All contributors were asked to list the major barriers for all NBS relevant for their RED, and to provide references to studies supporting their statements. We obtained 32 fully completed questionnaires, and the collected data were then processed and aggregated. Finally, all participants were invited to comment on and approve the final analysis and interpretation.

3. Results and discussion

3.1. Types of NBS

The list of NBS (Table 1) obtained during the initial expert workshop showed that there is no common understanding of whether NBS denote only physically-based nature-derived measures. The results indicate that NBS should be understood as a broader ensemble of measures and practices that would also include (i) artificial measures supporting nature-based processes as well as hybrid measures combining technical and green interventions, such as dry polders, and (ii) management approaches, such as traditional environment-sensitive agricultural practices. Additionally, the experts reported that procedural arrangements and certain stakeholder engagement techniques building on common mental models about what is natural, must be studied, supporting the findings of Langergraber et al. (2021).

The most-reported NBS differed among individual REDs (Fig. 3). These differences suggest distinct environmental conditions in each of the REDs, but they also indicate the different statuses of discourse on NBS and their implementation across Europe (Keesstra et al., 2018; Okruszko et al., 2019; Oral et al., 2020). In particular, there is a preference among the experts in Continental and Alpine-Carpathian Europe towards the land-use practices and catchment-scale retention measures located in the countryside (both listed most frequently from these REDs), whereas other REDs often reported NBS in urban settings as the important components of FRM. In addition, certain NBS were reported only in some REDs. These included institutional approaches, such as policies and planning frameworks, that were considered a specific type of NBS by six experts, mostly from the Atlantic region. Furthermore, NBS measures associated with the improvement of soil conditions were largely reported by experts from the Mediterranean, whereas NBS associated with coastal measures were reported mostly for the Atlantic region.

3.2. Barriers for implementation of NBS

The assessment of barriers for each NBS resulted in a matrix of frequency distribution for each NBS-barrier combination. Given the differences in the significance of NBS across the REDs, the original frequency distributions were grouped (Fig. 4) showing the frequency of the reported barriers and conceding with the qualitative nature of the expert community approach. In the following subsections, we summarize the main findings and provide examples for individual REDs. The barriers were aggregated into four Sections, including barriers related to (i)unknown effects of NBS, (ii) locational decisions on NBS, (iii) institutional settings, and (iv) the availability of (re)sources, land and physical capability. The individual barriers are referred to with letters within the text (see note in Fig. 4).

3.2.1. Barriers related to the unknown effect of NBS

The survey indicated that some NBS measures have rather uncertain effects at various scales and across environments, as their efficiency depends on topography, vegetation type, soils and spatial configuration and extent (barrier A). This mainly relates to nature-based river dams, where accurate calculations are absent for their effects on alleviation of peak discharges as well as for their effect on sediment budgets in case of sediment traps and log dams (Macura et al., 2016; Kidová et al., 2021). Moreover, uncertainties result from temporal instabilities of nature-based river dams, such as log dams, which may release a substantial volume of woody debris during peak discharges and affect flow direction and velocities (Wen Lo et al., 2021). The barriers of unknown effects are also related to NBS aiming to improve soil conditions, where basic considerations on what are good soil properties don't have a common understanding. Measures to be taken are vaguely defined mostly in mountainous environments across Europe, whereas they may pose implementation barriers in agricultural lowlands (see Section 3.3 and 3.4). Further examples of NBS with uncertain effects for FRM are interventions linked to land use management supporting water

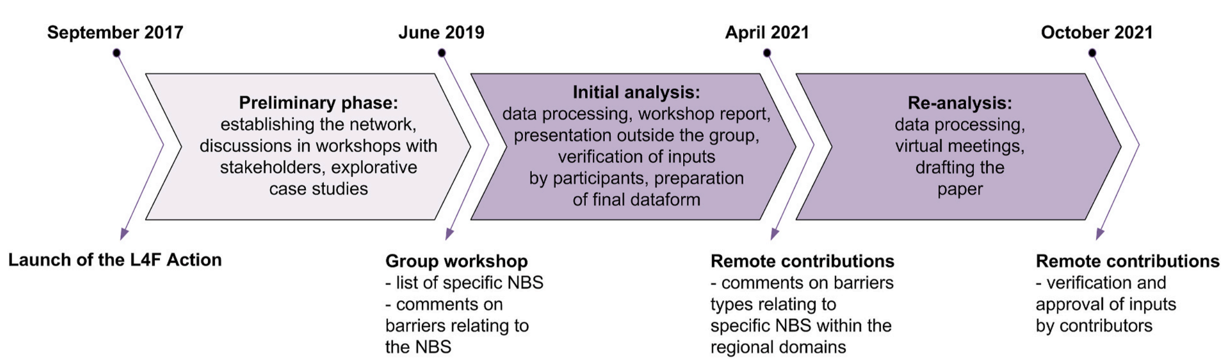

Fig. 1. Time framework of the data collection and processing.

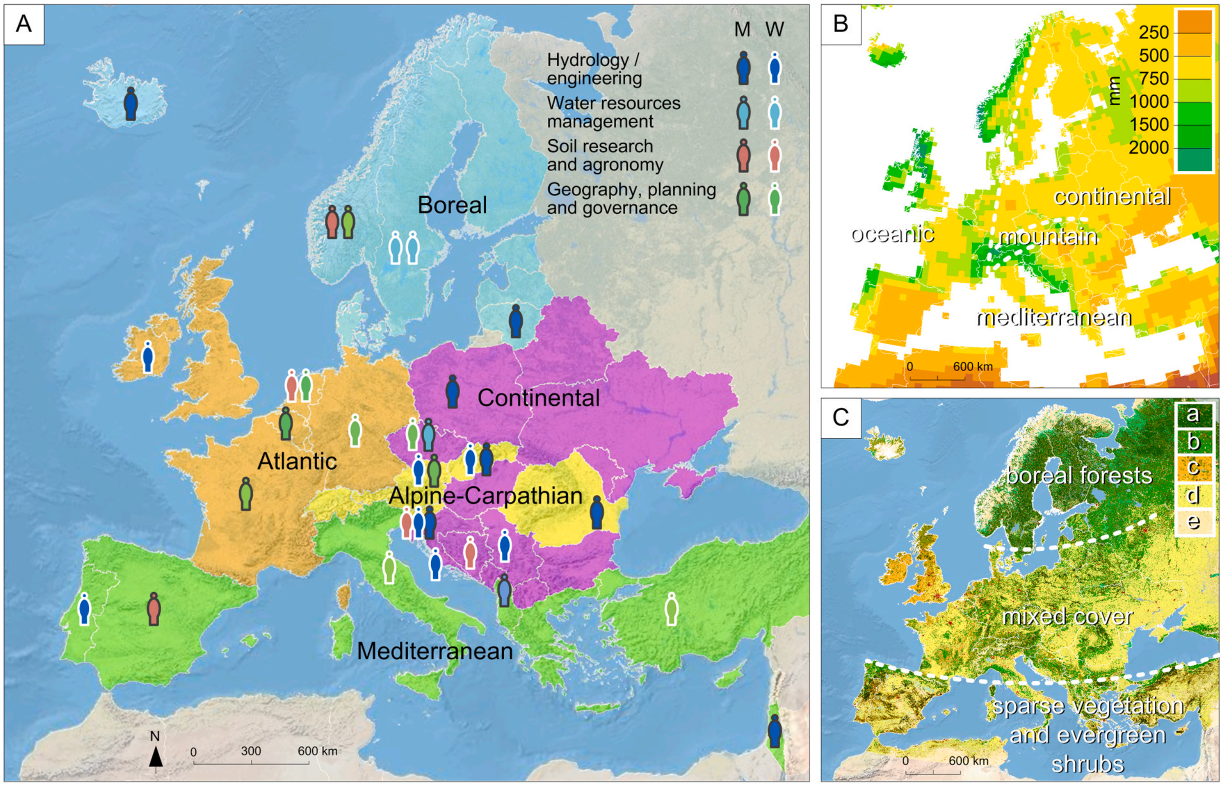

Fig. 2. (A) Aggregated regional environmental domains (REDs) are considered in this study. REDs are named and shown in different colours. Symbols of humans indicate the main self-reported research focus and gender structure of experts involved in this study. (B) Average annual precipitation (adapted from Mitchell et al., 2004). (C) CORINE Land cover: a – coniferous forests, b – mixed forests, c – grasslands, d – rainfed croplands and complex agricultural patterns, e – sparse vegetation (adapted from EEA, 2021). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

retention. Effects of forest on water retention and flood alleviation have been widely discussed (Calder, 2007). Using modelling approaches in a Slovenian watershed, Bezak et al. (2021) indicated a limited effect of afforestation on water retention and flood risk. This is in agreement with a review of contrasting evidence by Ellis et al. (2021). While afforestation is recommended for supporting water retention and decreasing surface runoff in some regions, in other cases (e.g. Danáčová et al., 2020) such effects are limited. Conversely, the expert community has shown a rather converging perspective of benefits for forest buffer zones along rivers. These are an important stabilization feature against erosional processes and also a buffer zone against overuse of agricultural land along water streams, thus limiting the alteration of soil infiltration capacity by heavy machinery or cattle trampling (Dunn et al., 2011). The effects of trees and forest stands are also conditioned by the selection of species given their differences in rainfall interception (Zabret and Šraj, 2015) and runoff generation (Ferreira et al., 2016). Finally, uncertain and limited effects were reported for small retention pools, ponds and lakes, where water detention in restored pools is negatively balanced by draining the surrounding land, an increase in evaporation, mineralization of organic soil compounds where banks are left without vegetation, and where the effects on groundwater recharge may be limited (barrier C; Wilkinson, 2019). These uncertain effects affect location decisions about land use management and the establishment of nature-based river dams and small water surfaces (see barriers E and F in Section 3.2.2 below).

3.2.2. Barriers related to locational decisions on NBS

Many of the uncertainties reported in Section 3.2.1 manifest themselves in locational decisions (barrier E) and the unknown extent of land (barrier F) that is necessary for the effective implementation of the individual NBS. These barriers mainly result from the expected variability of the effects of NBS across spatial and temporal scales. Examples from Czechia and Slovenia show that small retention pools and ponds may locally support water retention and biodiversity, but even if employing a large number of small retention ponds in the catchment, their upscaling potential is limited even in countries where these measures are among the preferred NBS (Nester et al., 2017; Wilkinson, 2019). On the other hand, based on modelling approaches, Ferreira et al. (2020) reported that a network of small water retention areas implemented at the catchment scale is more effective for flood mitigation than larger isolated areas. The role of water retention areas in significantly reducing surface runoff and alleviating flood peaks downstream, however, has not been clearly evinced. Similarly, the locational decisions and upscaling potential of river restoration efforts are limited because individual interventions which are often fragmented due to the limited availability of private-owned land (barrier N). Consensus on the design of the restoration projects is absent and the approaches differ from sole channel restorations in agricultural areas of the Continental Eastern-European countries and Mediterranean region to spatially extensive design including restored buffer zones along the water streams in countries of the Atlantic RED.

Along with uncertain effects there are limits to applicability and transfer of NBS to other settings (barrier G). Such barriers are rooted in multi-scalar factors involving both the local geological and hydro-climatic conditions and the variable effects of global environmental change on, e.g., annual rainfall, humidity and average air temperatures. Typically, such variances affect suitability of regions and sites for restoring various types of wetlands (Acreman and Holden, 2013), diverging flows by channel alterations and establishing forest stands to retain water. The transferability of certain NBS, such as stone terracing to reduce runoff velocity during extreme events, is also limited by locally adopted agricultural systems (barrier H). Such NBS may necessitate certain management practices, and these cannot be easily implemented, e.g., in large-scale autonomous ploughing in Continental lowlands. The

Table 1
Groups and types of NBS identified during the expert survey.

Group of NBS	Type of NBS (the most frequently reported NBS are shown)	References
Floodplain retention and polders	floodplain restoration, restoring fluid connectivity, retention basins, polders	Macura et al. (2016); Glavan et al. (2020); Bezak et al. (2021); Jakubínský et al. (2021)
Wetlands	wetland construction, restoration and preservation (the actions refer to various wetland types including mainly wet woodlands, peat bogs and marshes)	Acreman and Holden (2013); Potočki et al. (2022); Oral et al. (2020)
River restoration	channel restoration, re-meandering, riverbanks restoration, supporting riparian vegetation, preserving natural buffer zones along rivers	Mondal and Patel (2018); Nilsson et al. (2018); Jakubínský et al. (2021)
Nature-based river dams	wattlets, log dams, wood check dams, leaky dams, sediment traps	Thomas and Nisbet (2012); Wen Lo et al. (2021); Kuriqi and Hysa (2021)
Small retention ponds, pools and lakes	small-scale pools on agricultural land, stormwater retention pools and ponds, dry ponds	Bezak et al. (2021); Glavan et al. (2020); Wilkinskon et al. (2019) Oral et al. (2020)
Channel alterations and diverging flows	flood moulds in forests and agricultural land, channel restoration, supporting natural levees, biodrainage, bioswales	Mondal and Patel (2018); O'Donnel et al. (2020); Oral et al. (2020); Kidová et al. (2021)
Coastal measures	restoration of coastal vegetation, sand motor/sand replenishment	Temmerman et al. (2013); Bennett and Karunarathna (2019)
Land use changes	(re-)forestation, grassing, vegetation filter strips, supporting woodland buffer zones and riparian forests, delimiting agricultural floodable land, multifunctional agriculture	Leyer et al. (2012); Hlavčová et al. (2012); Kapović Solomun et al. (2018); Halbac-Cotoara-Zamfir et al. (2019); Finger et al. (2019a,b); Danáčová et al. (2020)
Improving soil conditions	increasing soil organic matter, supporting deep infiltration, reducing soil erosion by vegetation cover	Hlavčová et al. (2012); Ristić et al. (2021); Halbac-Cotoara-Zamfir et al. (2019); Finger et al. (2019a,b)
Spatial water retention in urban areas	inner city green areas, rainwater basins and polders, river and channel restoration	Banasik et al. (2009); Uzelac et al. (2012); Kabisch et al. (2016); Macura et al. (2016); Šrajdohar et al. (2016); Macháč and Louda (2019); Oral et al. (2020)
Urban water sensitive buildings	bunds, green walls, roofs and permeable pavings, NBS retrofitting, sustainable urban drainage systems	Keestra et al. (2016); Kabisch et al. (2016); Oral et al. (2020)
Improving policies for NBS coordination and planning	spatial displacement, limiting reconstructions after major floods, low impact development, linking NbS with climate change adaptation policies	Zingraff-Hamed et al. (2021); Kapović Solomun et al. (2020)

applicability and transferability of NBS may, however, involve complex links among forest management, agricultural practices, artificial drainage, and terracing, as reported, e.g. by Rogger et al. (2017), and require an approach integrating processes across temporal, spatial and institutional scales.

3.2.3. Barriers related to institutional settings

The ability to prove the positive effects of NBS is a legal requirement for enforcing its implementation on private land (Albrecht and Hartmann, 2020). Restrictions and land-use adjustments cannot be realized if the effects are unknown or vague. This means that cooperation of stakeholders becomes more imperative (Warner and Damm, 2019). However, limited information on the effects of specific NBS in a particular environmental setting may result in lack of stakeholders' trust to such measures (barrier I). This was especially reported for water-sensitive urban design, especially if responsibilities for implementing measures are vague (Snel et al., 2021). Also, the epistemic lock-ins resulting from maintaining historical practices may undermine trust in new FRM approaches as shown by Solín (2020) for Slovakia. This may occur despite existing studies documenting positive effects of these measures (Keestra et al., 2016). However, the lack of trust can also represent a mimicry to a generally low willingness to implement these efforts, e.g. due to their costs. This negative effect can be increased by financial flood recovery schemes that do not support adaptive measures (Slavikova et al., 2021). Since 2007, the Czech legislation requires all new individual housing developments to implement rainfall infiltration measures, yet recent research shows that the motivation of home-owners is often to save the money for water use rather than to be based on the real trust in the effects of such measures (Slavíková and Macháč, 2017). Similar effects have been observed in Germany (Hartmann and Scheibel, 2016), the Netherlands (Snel et al., 2020), Austria and Belgium (Attems et al., 2020). In addition, such measures are perceived by the public as water retention solutions to avoid droughts, but considerations on large-scale effects to reduce extremely high discharges downstream are not trusted. Importantly, such measures should be presented and argued for in an integrative plan comprising various measures and their combined effects (The 'Ekostaden Augustenborg', 2021). Based on experiences and mental models, the trust can also be differentially distributed among stakeholders which impede their coordination towards implementation of NBS (Barrier J; Goulden et al., 2018).

Distrust can be overcome by including both community members and stakeholders with formal roles in the co-design and co-implementation of NBS (Almoradie et al., 2020; Han and Kuhlicke, 2019; Finger et al., 2019a,b). In this regard, studies have found that wider stakeholder participation can contribute to mainstreaming NBS while fulfilling the project's ecological aim (Wamsler et al., 2015). Nevertheless, as Zingraff-Hamed et al. (2020) showed for Germany, existing co-creation efforts are rather targeted at large-scale restoration efforts, where municipalities already owned part of necessary lands. Contrarily, the experts indicated that stakeholders' coordination is most challenging in urban projects, where many public and private land- and homeowners and initiatives interact, and also in river restoration efforts. The latter is often based on specific ownership models, where rivers and small water streams are legally designated as a property and subject to management of other bodies than those which own the surrounding land. Conflicts then emerge both at the intersection of private landowners and public institutions (Hartmann et al., 2018), as well as on different administrative bodies (e.g. municipalities and water management authorities; Slavíková et al., 2018). Hlavčová et al. (2019) reports a case from Slovakia, where complex and combined measures including NBS were designed to reduce the flood risk, but their implementation was impeded by land fragmentation among too many landowners.

Along with local interactions of stakeholders, higher-level institutional settings and a lack of financial (barrier K) and institutional (barrier L) supporting mechanisms are reported as the most frequent barriers hindering the implementation of NBS. These were the only barriers that were referred to for all groups of NBS. The key perceived gap is in the lack of distribution of responsibilities to design, incentivize, and implement NBS (Johnson and Priest, 2008; Snel et al., 2020). In countries such as the Netherlands, supporting mechanisms do exist, but the water management authorities may hesitate to incentivize NBS (e.g.,

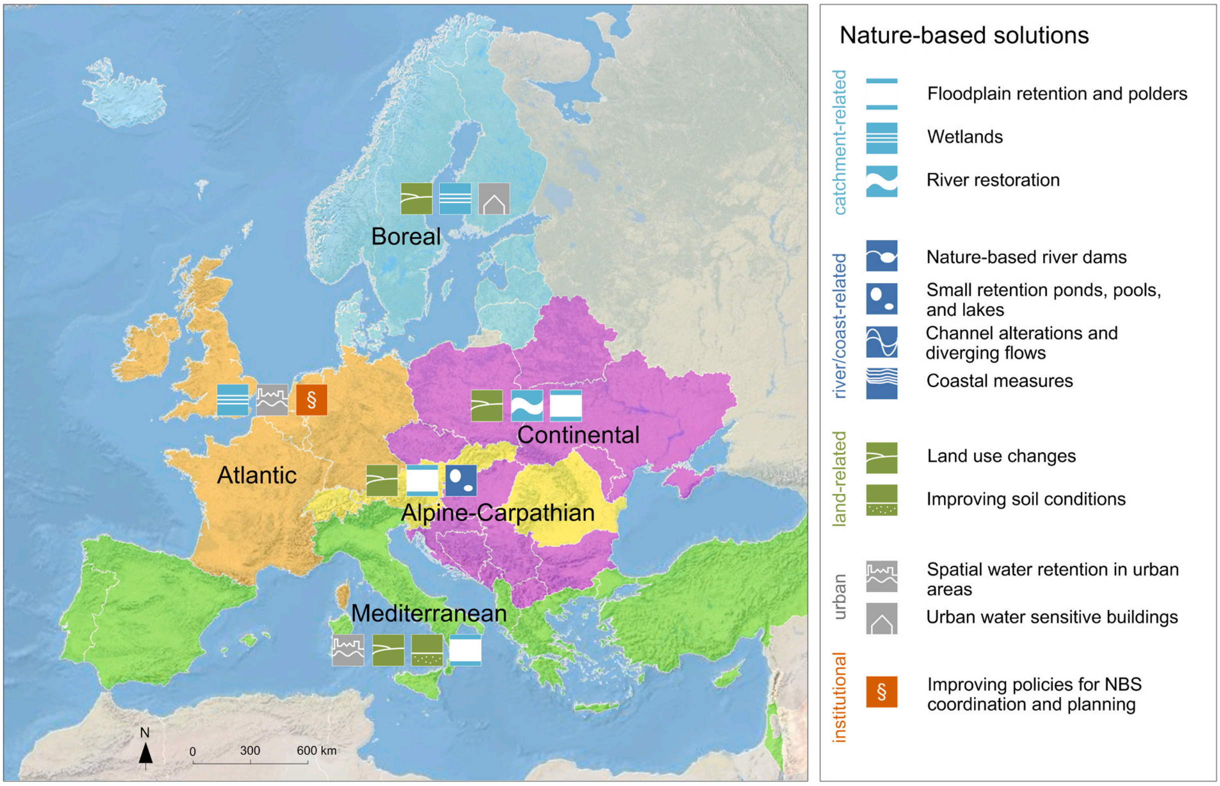

Fig. 3. The three most reported NBS for aggregated regional environmental domains (REDs). (Note: two groups of NBS in Mediterranean were reported with equal frequency).

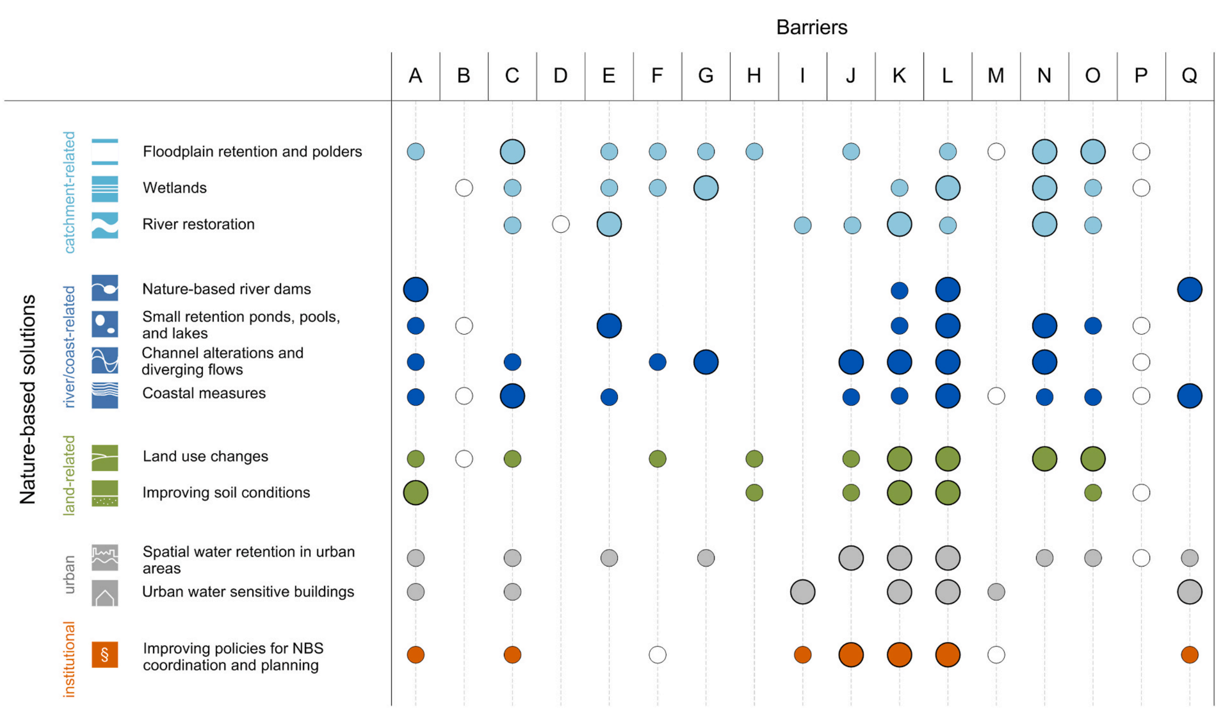

Fig. 4. The most reported barriers for NBS. Note: the barriers with the three highest scores are indicated in large coloured circles; the barriers with above average scores within the particular NBS are in small coloured circles; the barriers that have not been reported for the particular NBS are in small white circles. Absent circles indicate barriers below average scores. Barriers: A – Limited/uncertain/unknown effects, B – adverse effects for FRM, C – Involve relevant trade-offs, D – Disincentivises resilient practices, E – Locational decisions are too difficult, F – Extent of necessary land is unknown, G – Broad applicability/transferability is limited, H – Limited in certain agricultural systems, I – Lack of stakeholders' trust in the measure, J – Stakeholders' coordination too challenging, K – Lacking financial incentives and political will, L – Lacking institutional frameworks (also responsibility), M – Too expensive compared with benefits, N – Difficulty in acquiring the land, O – Landowner compensation is not clear, P – Lack of labour capacities, Q – Lack of information on design and technical details.

implementing riparian and in-channel vegetation) because of their uncertain effects (Kaufmann et al., 2017). Goulden et al. (2018) recommend using incentives rather than punitive measures to encourage NBS implementation for stormwater management.

Besides trust, the legal system and the constitution of property rights influence how homeowners respond to floods (Hartmann et al., 2019). Hence, risk communication is not just about informing citizens, but also clarifying public and private responsibilities (Davids et al., 2019), and the implementation of NBS requires strategic land policy.

3.2.4. Barriers related to availability of (re)sources, land and physical capability

Even with empirical evidence for the positive effects of NBS on flood risk reduction, and after gaining trust among the landowners, difficulty in acquiring the land (barrier N) remains a key barrier as reported by experts. This holds especially for large scale measures aiming at floodplain, wetland and river restoration, and for changes in land-use management practices. The reasoning is that the land-owners will lose productive land space, which is considerable in countries with low share of agricultural land (e.g., only 3.5% in Norway) and small average size of plots (e.g., in Central and Eastern Europe; van Dijk, 2003). The loss of agricultural land then requires compensation schemes. These were successfully implemented in the Netherlands, for example, where voluntary agreements were achieved by poldering [the Dutch culture of cooperation based on compromise and consensus] (Kaufmann and Wiering, 2019). The difficulties to calculate the value of land for compensation (barrier O) for upstream-downstream effects of the implemented measures must be considered (Macháč et al., 2018).

Besides the uncertain effect of some NBS and their low social acceptance, the lack of institutional and financial mechanisms is rooted in a lack of information on appropriate design and technical guidelines to implement these measures (barrier Q). Typically, nature-based river dams require different materials, design and consideration on the degree of stabilization in mountainous and lowland water streams (Macura et al., 2017). Coastal measures, such as 'sand motor' in the Netherlands, to replenish sand and reduce erosion during the rainstorms and floods, were only recently experimentally implemented (Kaufmann et al., 2022). In an urban setting, the availability of land for spatial water retention measures is limited, so the current research and field experiments focus on hybrid measures (Alves et al., 2020). The guidelines to design these measures are yet missing in most countries, resulting from both their technical complexity and necessary considerations on costs and benefits in urban settings with high land prices (Macháč and Louda, 2019).

3.3. Cascading and compound barriers

Here, we adopt the concepts of cascading and compound interactions to show how individual barriers may line up and amplify each other, finally resulting in FRM decisions that need complex and transdisciplinary approaches to be effectively managed. The concepts of cascading and compound interactions are well established in disaster risk reduction studies (Cutter, 2018; de Brito, 2021), yet they were mostly applied to underlying hazards and their effects rather than to barriers to risk management options. We understand cascading barriers as a situation where a certain barrier directly or indirectly amplifies spatially and temporarily related barriers. This may go beyond the simple linear causal chain as the effect of a primary barrier may diverge to induce multiple barriers (Fig. 5A). Typically, the lacking or fragmented evidence on flood mitigating effects of a particular NBS may lead to a lack of trust in such measures and low willingness for its funding and implementation. The compound interaction then characterizes situations where implementation of the intended NBS is impeded by multiple amplifying feedbacks among barriers (Fig. 5B). For instance, the lack of guidelines for designing a particular NBS may act together with unclear evidence of its effects to amplify the questions over the extent of private

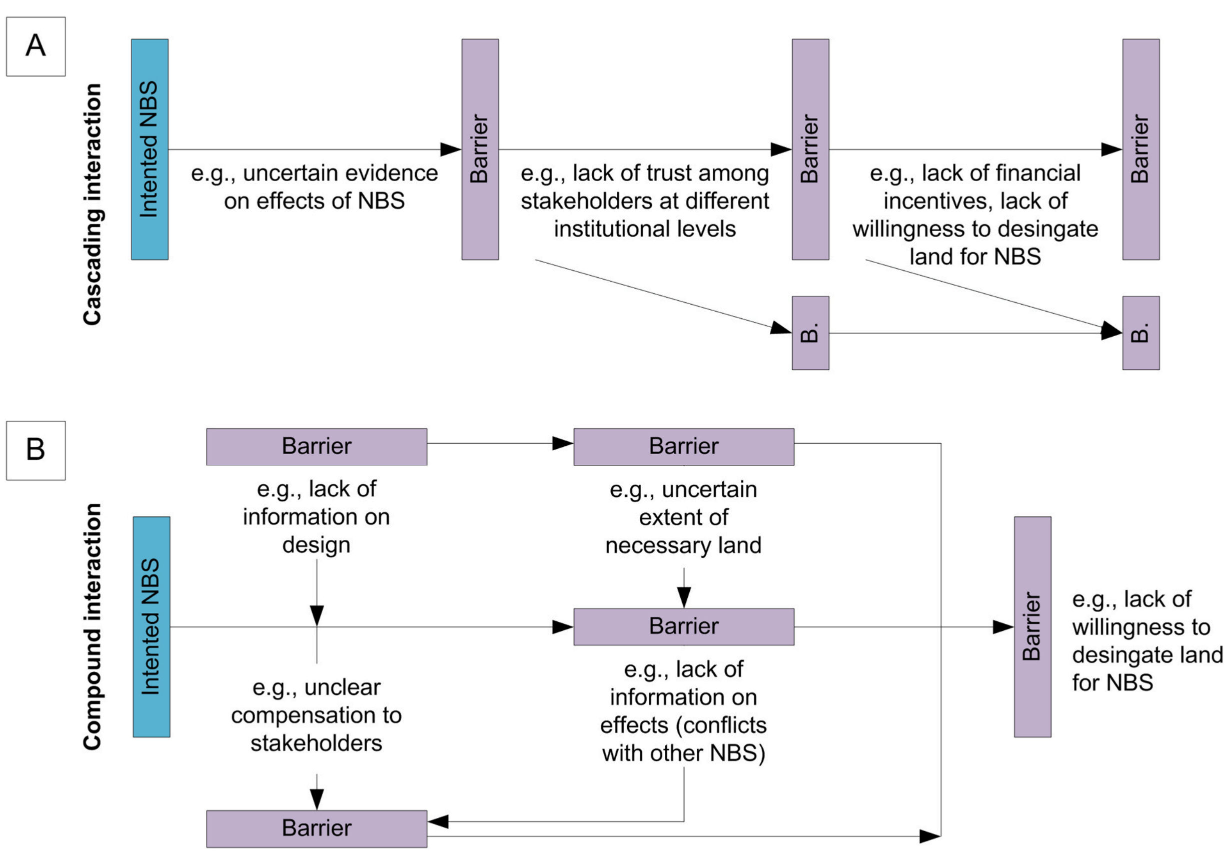

Fig. 5. The concept and examples of (A) cascading and (B) compound interactions among the implementation barriers for NBS in FRM.

land necessary to implement a measure that would have effects at a catchment scale. All these barriers, in turn, pose a challenge for compensation measures to private land-owners.

The suggested approach allows tracing out the interactions of barriers in complex FRM situations, and stimulates further research. Table 2 provides examples of such research problems, using the NBS groups for which most barriers were reported. The formulated problems may be applied across various NBS, while their research requires further operationalization.

Addressing these questions (Table 2) requires a transdisciplinary approach that will bring together different axiomatics, and allow for integrating the perspectives on natural and societal processes that occur at various spatial, temporal and institutional scales (Raška et al., 2019; Vanelli et al., 2021).

3.4. Potential study limitations

While the study provided interdisciplinary insights on barriers to implementation of NBS for FRM, it has some limitations related to the expert community approach employed. First, there is bias caused by a limited number of experts resulting in a different composition of expert groups representing each RED in terms of field of expertise (e.g., hydrologists, planners), types of NBS under study (e.g., floodplain restoration, nature-based river dams, urban NBS), and collaborative experiences with stakeholders (ranging from providing the modelling and simulations to conducting the social inquiry and preparing spatial plans). Second, the diversity of empirical evidence and expert insights does not allow us to infer functional and causal links among all NBS and barriers for each RED independently. Therefore, cascading and compound effects of implementation barriers are drawn upon the combined experience from various RED and must be considered as indicative. This necessitates further research and validation of the cascading and compound effects specifically for individual NBS and particular REDs. Third, we must reiterate that the expert community approach is a provisional substitute for empirical evidence and its major role is to define avenues stimulating future research. While some experts' claims are empirically-grounded and refer to previous studies, any further inferences must be yet supported by field experiments and applied studies.

4. Conclusions

Current policies and strategies increasingly highlight NBS as suitable approaches to FRM. This paradigm shift is supported by empirical evidence that remains rather fragmented. In addition, an increasing number of studies point out NBS limitations to effectively enhance water retention and reduce flood risk, and report various implementation barriers for NBS across Europe and beyond. In this paper, we scrutinized the research devoted to implementation barriers of NBS by conducting discussions among experts from various fields and regions. This allowed us to compile a comprehensive set of 17 barriers relevant to NBS in FRM. The most-reported barriers include a lack of financial incentives and political will to implement NBS, a lack of institutional frameworks assigning responsibilities for specific actions regarding NBS, difficulties in acquiring a sufficient extent of the land for NBS, and unknown effects of particular NBS. It is suggested that the implementation barriers may line up into the cascading and compound sequences, creating fundamental challenges for practitioners employing NBS in FRM. The lack of trust among stakeholders was shown as a fundamental amplifier of the cascading and compound barriers. This calls for broader evidence of practice that would support drafting guidelines for implementing NBS at a catchment scale. The NBS that were associated with the highest number of barriers included river restoration, supporting functions of wetlands, floodplain retention and polders, land-use changes such as a/re-forestation, grassing, and change in agricultural practices. Notably, the barriers were differentially reported by experts from various fields of expertise and representing different regions. This urges a transdisciplinary turn in the approach to design and implement NBS for FRM.

Table 2
Examples of research questions formulated using the cascading and compound interaction approach.

Group of NBS	Example of research problems
Floodplain retention and polders	*Given the designation of land for floodplains (or floodable land in general) involves some relevant environmental and socioeconomic trade-offs, what compensation schemes and mechanisms do land-owners perceive as suitable for specific trade-offs?*
Wetlands	*Considering the regions with similar environmental settings and similar wetland types, which institutional frameworks (e.g., environmental law, property rights and land tenure schemes) limit the transferability of wetland restoration approaches?*
River restoration	*Given the limited availability of financial resources, how can empirically-informed locational decisions reduce the extent of necessary land and facilitate its acquisition (i.e. willingness of land-owners) for river restoration programmes?*
Water retention in urban areas	*Given the challenging stakeholders' coordination, how does the spatially fragmented implementation and dis-connectivity of urban water retention measures affect their flood mitigating effects?*

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Author contributions statement

P. Raška, N. Bezak, C.S.S. Ferreira and Z. Kalantari: research design, data curation, drafting the paper. All authors contributed to data collection, commented on and approved the final paper. All authors understand that the Corresponding Author is the sole contact for the Editorial process.

Declaration of competing interest

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

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