Harmonizing Erosion Control and Flood Prevention with Restoration of Biodiversity through Ecological Engineering Used for Co-Benefits Nature-Based Solutions

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Opinion

Harmonizing Erosion Control and Flood Prevention with Restoration of Biodiversity through Ecological Engineering Used for Co-Benefits Nature-Based Solutions

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Abstract: Reconciling erosion control and flood prevention with restoration of diversity is an important challenge for our societies today. However, examples of applications remain rare because practitioners and engineers are searching for more integrated solutions for this kind of situation. New considerations should, therefore, refocus attention on developing innovative actions by raising the question of how best to accommodate the two components. Moreover, little attention has been paid to erosion processes and their control for decreasing floods, although this can largely contribute to this purpose. Merging security with ecology, turning to co-benefits nature-based solutions at the catchment scale, based on the use of local ecological engineering, especially soil and water bioengineering combined with civil engineering, can provide adapted practices for harmonizing flood prevention and erosion control with restoration of biodiversity at the water catchment scale. This kind of approach should be accompanied by proposals for coherent and adapted governance for application of co-benefits nature-based solutions at the catchment and territory scales.

Keywords: nature-based solutions; ecological engineering; soil and water bioengineering; erosion; natural risks; ecological restoration

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1. Introduction on Concepts

Facing increasingly pronounced degradation of the environment and its biodiversity in today's society, a common concern more than ever remains the conservation or restoration of its quality. Repairing degraded environments is all the more urgent because they often contribute to increasing natural risks, particularly flooding [1]. How can we achieve these objectives and optimize our actions? Linking these two aspects of water and biodiversity management is an important step. However, examples of applications remain too rare. One explanation is that for obvious security reasons, the flood prevention aspect is the primary focus of attention. That is why civil engineering, used to constructing containment systems, dams, and overflow ponds, or even contributing to the morphological restoration of rivers, is primarily used as an effective solution to protect infrastructures and people against floods. However, given the absence or paucity of biodiversity in these works, or the features of such structures that interrupt the continuity of rivers, in general, they depreciate the local ecology [2]. Moreover, by accelerating water flow and cutting a river from its natural expansion areas, dikes can accentuate floods downstream and result in an imbalance in the transport of solid material. Within an integrated management context, we are now seeking to consider all of these preoccupations early in a project's conception phase, which requires that it becomes multidisciplinary [3]. To this end, the aquatic and terrestrial environment management aspect, such as ecological restoration of degraded lands (actions seen as assisting and speeding the repairing and recovery of an ecosystem that has been degraded, according to [4,5], should be considered as facilitating flood prevention. New considerations should, therefore, refocus attention on developing innovative actions by raising the question of how best to accommodate the two components.

Current challenges in policies for environmental management try to merge security with ecology, considering co-benefits approaches. In particular, harmonizing erosion control and flood prevention with restoration of biodiversity appear crucial. To this end, turning to nature-based solutions (NBS) at the catchment scale can be advantageous. They correspond to actions aiming to sustainably protect, restore, and manage natural or modified ecosystems, to effectively and adaptively address societal issues directly, while ensuring the well-being of humans and the advantages for biodiversity at the landscape scale and over the long term [6,7]. Societal issues and benefits for biodiversity appear inseparable here, even if the actions are based on the use or development of natural environments for benefits that can be other than preservation of biodiversity. Therefore, they are co-benefits solutions; thus, like any NBS, they should provide a gain for biodiversity and respond to a societal challenge, among which mitigation of natural risks [8,9]. International experience with NBS is growing and the European Union is seeking scientific projects that will encourage their development.

Ecological engineering (EE) proposes a panel of existing local technical tools serving NBS (Figure 1). It is precisely defined as "the design of sustainable systems, consistent with ecological principles, which integrate human society with its natural environment for the benefit of both" [10]. Benefits that natural habitats and populations derive from EE actions are natural hazard mitigation, biodiversity and soil conservation, ecological restoration of degraded lands, soil and water depollution, and management of natural lands. For example, one of the EE activities used for NBS is removing invasive species to maintain ecosystem services, such as carbon sequestration, and reduce transpiration as a way of water conservation, while enhancing biodiversity. This was demonstrated by [11,12], who found that removal of juniper trees (invasive species) resulted in significant hydrological improvements and potential water savings while maintaining the potential for ecosystem carbon sequestration.

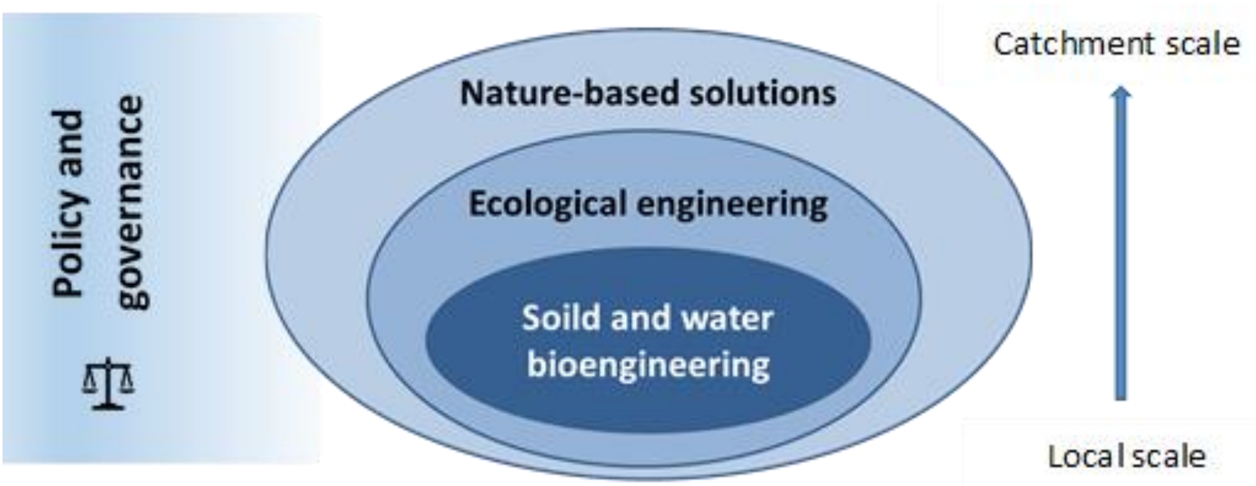

Figure 1. Links between soil and water bioengineering, ecological engineering, and nature-based solutions, from local to global (for example catchment) scales, calling to specific and adapted policy and governance. All these concepts are closely linked and should be mutually inspired.

These benefits belong to several ecosystem services, defined as the gains ecosystems provide to humankind [13,14]. An important issue for the actors in the field of NBS remains highlighting all the benefits and ecosystem services related to their use, by showing the multiple gains of these kinds of projects. Such new approaches ask questions for researchers and require innovation on the part of practitioners, with the need to design EE actions combining approaches by and for life [15].

Among the existing EE techniques, we find soil and water bioengineering (SWB), which involves practices covering all the techniques using living organisms, animal as well as plant organisms, and more globally natural means and processes, to preserve, restore, or manage ecosystems so as to respond effectively to a variety of ecological, economic, and social objectives, among which: (i) natural hazard control, such as soil erosion, torrential floods, and landslides [16], and (ii) ecological restoration, rehabilitation, or re-introduction of species on degraded lands, river embankments, and other disturbed environments [17] (Figure 1). They are well-known and well-developed practices, and they have demonstrated their effectiveness for local projects (part of a riverbank, for example), aiming at (re-)vegetating bare or degraded terrains [18–20].

2. Exploring the Use of Local Ecological Measures Combined with Civil Engineering, for Either Erosion Control, Flood Prevention, or Restoration of Biodiversity

For EE and SWB, best practice guidelines, handbooks, and models (software) can be used to choose appropriate species at a local site (taking both above- and below-ground plant characteristics into account) and design structures, regardless of the objective of the project. These tools currently range from illustrative catalogues of techniques or plant species, technical guidelines for the construction of structures, decision-making schemes to diagnose potential instability or degradation causes and plans for adequate mitigation strategies, and models for simulating actions [21,22]. They are applied mainly to riverbanks and slopes [23–25] and take into account the dynamic nature of the EE and SWB measures and the systems involved.

Practitioners need know-how and knowledge on the appropriateness of one or the other structure depending on their wish to control erosion, prevent floods, or restore biodiversity (Figure 2). Therefore, guidelines for choosing and designing bioengineering structures, depending on the precise objective of the project, are important. Their use for erosion control or restoration of biodiversity are common. They are composed of technical recommendations for their design and construction, based on a review of the knowledge in response to practitioners' needs, such as selection of plant species, and selection and design of SWB structures and EE works [19,26]. On the contrary, concerning flood prevention, EE in general and SWB more particularly are more rarely involved, although they may, in certain well-defined situations and with adapted structures, contribute to this end.

Figure 2. SWB structures using plants of different species and with a strong soil stabilization power thanks to their root development. These works help protect the bank from erosion.

Processes of flood and erosion are linked. However, little attention is currently paid to erosion processes and their control for decreasing floods, although this can largely contribute to this purpose. Erosion is a natural phenomenon with worrying consequences in many parts of the world, where socio-economic and ecological issues exist [27]. The latter are understood here as the infrastructures, people, and environments threatened by this hazard. Surface erosion involves all processes that affect soils and/or the geological substratum at a shallow depth. It is, thus, mainly due to the action of water, which encompasses forms of runoff and small muddy flows from a few centimeters to a depth of a few decimeters, but that excludes all major ground movements that can have depths of several meters [28]. It consists of two successive phases. The first corresponds to the removal and the transport of eroded materials. The second phase corresponds to the deposit of eroded materials, corresponding to sedimentation. Erosion occurs in semi-natural environments (torrential watersheds, banks of rivers and lakes) as well as in human environments (agricultural areas, slopes, ski runs). It is particularly present in mountainous and Mediterranean climates. These eroded soils are often characterized by a very low or even an absence of biodiversity. They are also responsible for a significant production of fine sediment, which causes multiple threats. This fine sedimentation, which takes place mainly in the bottom of rivers, causes various damages, such as a scarcity of fish breeding grounds, a disturbed functioning of hydroelectric dams, an upwelling of the river bed, and increased flooding [29–31]. For several years, practitioners have been seeking effective, inexpensive and sustainable solutions to these problems. Erosion control or slope protection and the resulting decrease of fine sedimentation in the rivers then appear as a challenge to be met [19,32].

3. NBS for Harmonizing Erosion Control and Flood Prevention with Restoration of Biodiversity

NBS can be used particularly for flood prevention [14]. Experience has been reported from several European countries, such as Slovenia [33], the UK [34], and Germany [35], and across the world, such as in Africa [36]. NBS can also be utilized for restoration of biodiversity [37], especially in aquatic environments [38,39]. To go further, we can consider that NBS, seen as multi-benefit actions based on the use of EE, especially SWB combined with civil engineering, can reconcile erosion control and flood prevention with restoration of biodiversity. This allows one to act on ecosystems and to expand the services rendered by these ecosystems and increase their numbers. EE in general and SWB more particularly can also, in certain well-defined situations, complement civil engineering for flood prevention. In such situations, it is actually less expensive to install and manage than a civil engineering structure, and it is better integrated into the landscape [40]. The benefits induced must also be considered because, in contrast to civil engineering works, EE and SWB structures are multi-functional in terms of the benefits procured beyond their protective role. In particular, they procure evident gains for biodiversity. One must not forget, however, that optimized operation of any system founded on nature requires maintenance given that it evolves continually. This involves a cost that must be integrated into the economic analysis. The benefits induced must also be considered because, in contrast to civil engineering works, ecological and vegetation engineering works are multifunctional in terms of the benefits procured beyond their protective role. For example, floodplains acquire a large proportion of the nutrients and pollutants that are then bio-transformed, producing biomass and biodiversity and reducing pollution.

Consequently, technical structures using vegetation are the base tools for designing an NBS project aiming at both preventing floods (while controlling erosion) and restoring biodiversity. Knowing which structures can be used and how effective they are for both practical goals is lacking today, although it appears essential for a future vision of integrated strategies deployed at the catchment scale. Yet, by combining these different types of approaches within a catchment, NBS can be envisaged, founded on nature and conjugating flood prevention with integrated management of aquatic environments at this scale. Based on worldwide experiments and references, and allied with recent scientific innovations in this domain, the following types of action can be proposed (Figure 3):

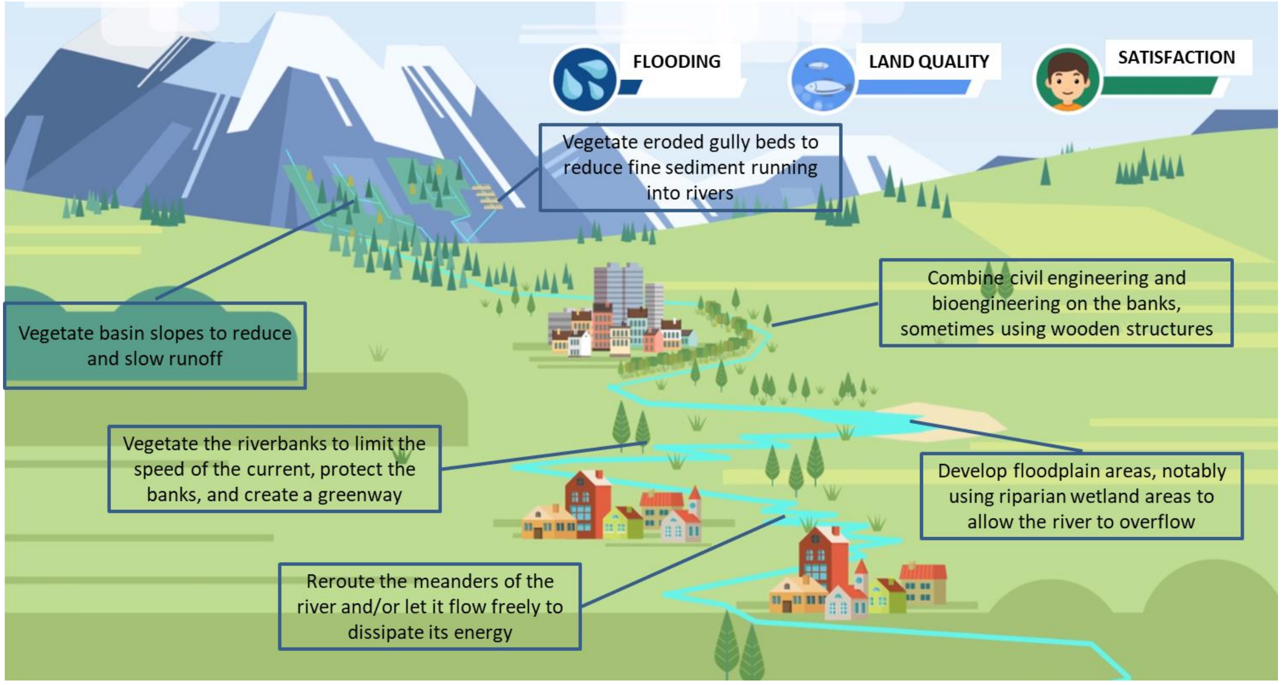

Figure 3. From local ecological engineering and bioengineering actions combined with civil engineering, to a global NBS at the catchment scale for harmonizing flood prevention and erosion control with restoration of biodiversity.

Reroute the meanders of the river and/or let it flow freely to dissipate its energy;

Develop floodplain areas, notably using riparian wetland areas to allow the river to overflow;

Combine civil engineering and bioengineering on the banks, sometimes using wooden structures (e.g., vegetated crib-walls), taking care that the large root systems of ligneous species do not destabilize any nearby protection structures (e.g., a dike at the top of a riverbank);

Vegetate the riverbanks to limit the speed of the current, protect the banks against erosion, and create a greenway;

Vegetate basin slopes to reduce and slow runoff, while controlling erosion and protecting slopes;

Leave rivers the possibility of eroding their banks in the areas least vulnerable to flooding;

Vegetate eroded gully beds (with wooden sills, cuttings, and plants) to reduce fine sediment running into rivers.

In particular, the last four types of actions are dealing with erosion processes and allow better control of floods. For example, building dynamic plant barriers to retain fine sediments, with results obtained from the first year and in a sustainable way, allows to derive multiple benefits: plant diversity is restored on eroded slopes, fish can lay eggs again in the river bed, aquatic lands are cleaner and fish are more numerous, hydroelectric dams are working better, and some floods are being mitigated [19].

4. Defining Effective NBS Actions at the Catchment Scale

Reconciling erosion control and flood prevention with restoration of biodiversity remains difficult because solutions have to be considered at the water catchment scale, with upstream to downstream interactions (physical, ecological, social, political), and with interdisciplinary (geosciences, ecology, social sciences) and transdisciplinary overviews. Indeed, EE and SWB techniques are usually targeted at limited areas. Technical difficulties may be involved in the application of these solutions from a hydrological point of view, an environmental perspective, and a project management angle. Consequently, practitioners and engineers are searching for more integrated solutions based on nature to reconcile flood prevention with restoration of biodiversity at the catchment scale, so that the objective of this kind of project is too rarely achieved. We need a truly novel scientific and applied approach to the design of integrated co-benefits NBS, based on a cumulative effect of several EE and SWB structures, considering changing spatial scales.

Precisely defining the combined effect of structures within a single catchment for both objectives remains difficult. In particular, in engineering projects that study several structures, the evaluation remains based on a specific high-water event, as observed in the catchment, with high-water events that will, of course, never return in identical form [41]. Moreover, in terms of engineering, moving from a flood prevention to an aquatic environment management mindset leads to technical problems, notably related to different types of intervention, each raising specific modeling difficulties, dispersed over the catchment but requiring assessment as a catchment-scale system [42]. Truly reasoning within a multi-criteria context, at the appropriate spatial scale, to assess and prioritize the proposals and, if possible, encourage multidisciplinary design, remains a problem. Research and development committed to innovatively designing and carrying out projects reconciling aquatic environment management and flood prevention need to be able to draw on validated methods so that they can make ecological diagnoses of environments, evaluate the performance of flood protection and restoration structures, and carry out multicriteria and cost–benefit analyses. These tools should make it possible to proceed from the initial diagnosis to the possible intervention modes, passing through the socioeconomic assessment of the actions envisioned [43,44].

Nevertheless, the water catchment scale remains the best adapted scale for designing NBS for both flood prevention and restoration of biodiversity, based on consideration of cumulating the use and effects of several local structures, especially from EE and SWB (Figure 3). However, the absence of a generic approach at this scale is the principal obstacle to the implementation of this type of NBS. Consequently, developing a new approach for elaborating this kind of framework is the core of this idea of "better acting at the local scale for better designing at the global (catchment) scale". An interdisciplinary approach, at the frontier of geosciences and ecology, is crucial to this goal.

Therefore, the grand challenge for future is to propose a new framework for designing NBS capable of reconciling erosion control and flood prevention with restoration of biodiversity at the water catchment scale. This framework should be able to envisage global NBS conception from the use of local EE and SWB structures, combined with civil engineering. Its originality is to consider the multi-benefits character of NBS for designing actions to protect people against floods while restoring biodiversity at the catchment scale.

For this, it is necessary to identify optimal NBS that are effective for reconciling erosion control and flood prevention with restoration of biodiversity at the catchment scale. The objective is to deduce the types of local actions (EE and SWB actions combined with civil engineering) that local authorities can conduct within an integrative approach. The latter should be considered at the spatial scale of catchments of surface areas around 100–10,000 km^2 (or more). Indeed, envisaging integrated management of the catchment means that flood prevention begins at catchment headwaters, using the catchment's wetland and vegetated areas, and then draws on containment systems or limiting structures in the bed of the main streams as well as on the ecological characteristics of the catchment. This, therefore, means considering, at the catchment scale, the interactions between structural developments (floodplain areas, dikes, etc.), the plant cover, and high water and flood processes, as well as erosion- and runoff-related processes. Moreover, using EE and SWB for natural hazard mitigation at the catchment scale implies taking into account the connectivity between upstream and downstream parts of the catchment [32].

Globally, the challenge for science is to be able to: (i) quantify the efficiency of different NBS strategies in preventing floods from a hydrological point of view; (ii) evaluate the performance of different NBS strategies in restoring biodiversity from an ecological point of view; (iii) define the best NBS strategy at the catchment scale for both domains; (iv) recommend optimized NBS actions reconciling flood prevention and erosion control with restoration of biodiversity, at each step of a project, according to practitioners' needs and the final aim of defining actions at the catchment scale.

Then, we need a methodological framework, allowing designing and evaluating the efficacy of optimal NBS for both flood prevention and restoration of biodiversity at the catchment scale, corresponding to actions decreasing the waterline during floods while increasing biodiversity. This approach could be inspired from the experimental and applied works of [45], who developed a general framework to appraise the success of projects in ecological restoration and EE (called ASPIRE). The method involves three levels of information: the variables, the objectives, and the project. The outputs are detailed scores for each of the different objectives of the project considered, contributing to their values as well as their assessment. The ultimate score of the project is a weighted mean of objectives scores; the objectives scores are weighted means of their variables scores and the variables scores are calculated through a utility function based on the variables values relative to their references. Thus, an adapted tool to build should (i) supply a global assessment of an NBS project, (ii) favor appreciating the various points of view of various actors (what is a 'success'?), (iii) define objectives which can be measured and evaluated, (iv) allow comparisons between different projects, and (v) provide an easy-to-use tool. This would be a pioneering approach to the application of co-benefits NBS in the case of flood prevention, erosion control, and restoration of biodiversity.

5. Considering an Interdisciplinary and Transdisciplinary Approach for NBS Projects Dedicated to Erosion Control and Flood Prevention with Restoration of Biodiversity

If a vision at the catchment scale makes it possible to plan for integrated management of natural hazards related to water and combined with environmental considerations, it should ask all the relevant questions concerning the area under the responsibility of the contracting authority, as well as on the entire area impacted: protection of property and people, environmental objectives, all potential uses, both economic and recreational, and upstream and downstream dependencies, most particularly concerning hazards [46]. When designing an EE work or a SWB structure, many different areas of expertise are required. It is necessary to collect diverse types of information concerning climatic conditions, pedological and geological parameters, geomorphology, hydrological data, as well as environmental and urban regulation. Therefore, the development of NBS actions requires interdisciplinary and transdisciplinary approaches to design an effective and sustainable construction [47], and propose dedicated frameworks [48]. Indeed, such an integrated approach needs to consider: (i) engineering: finding technical solutions, (ii) economics: justifying the construction cost and priorities with specific budgets, (iii) social aspects: specifying health, aesthetic, and safety measures for operators and residents, and (iv) environment: including climatic, soil, and vegetation constraints [19,20].

Although considering the design of NBS at the water catchment scale appears to be the coherent scaling approach, political decisions are in general taken at the scale of administrative areas, which do not correspond to the catchment limits. A shift between the two approaches can be responsible for problems applying the best technical NBS for both flood prevention and restoration of biodiversity. That is why defining the coherent and adapted governance for application of this kind of NBS at the catchment scale, from interdisciplinary (geosciences, ecology, and social sciences) and transdisciplinary (researchers, practitioners, and decision makers) approaches is of prime importance, to ensure the best application of a potential future generic framework [49]. Their application requires adapted policy and governance [50]. For this, an analysis of the actor's system of territories related to catchments where both flood prevention and restoration of biodiversity are applied is necessary. It corresponds to actors and their decision factors, as well as the modalities of governance of NBS in different European countries, crossing considerations at the catchment level (scale of NBS application for preventing floods and restoring biodiversity, through ecological measures) and at the level of administrative or project territories (decision scale) (Figure 4). The interventions to reduce erosion and floods must benefit biodiversity, and monitoring programs must evaluate that such interventions to ensure that they do not act as ecological traps. In other words, it should be demonstrated that the intervention effectively improves habitat for example, and does not have negative effects on reproductive success or survival [51].

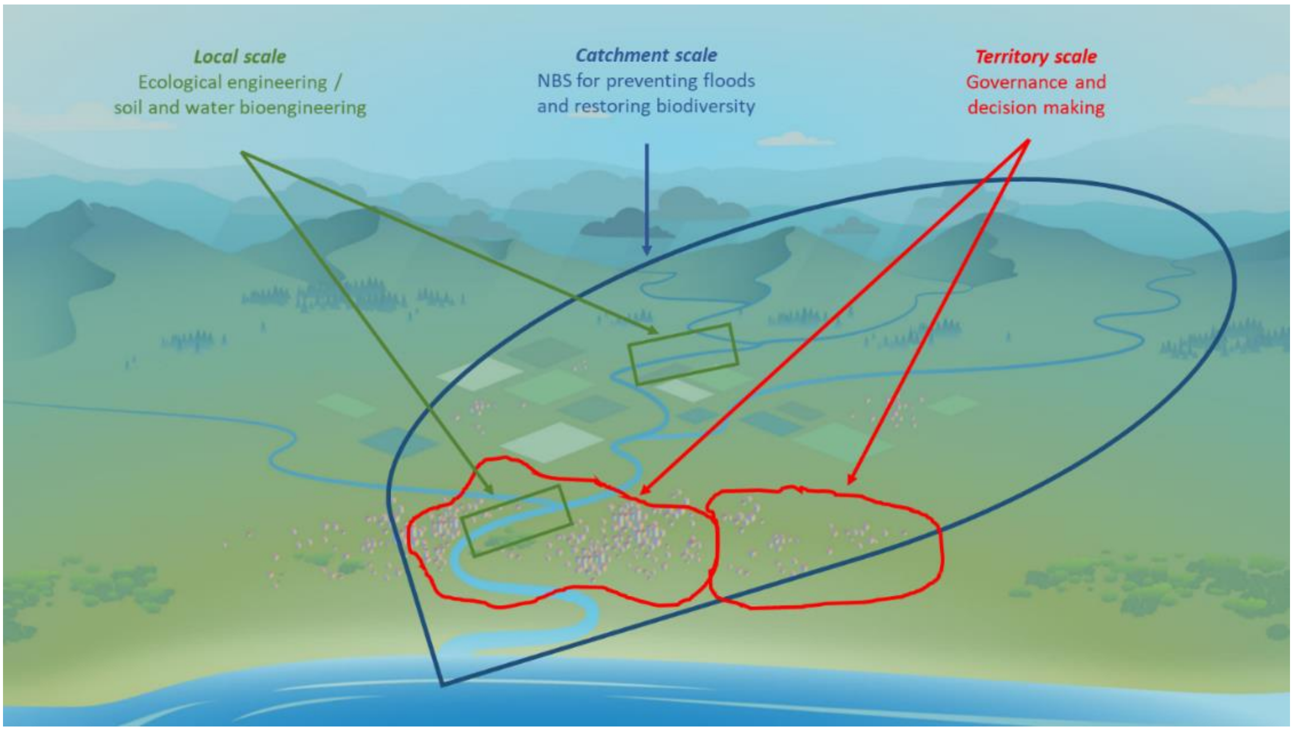

Figure 4. Crossing spatial scales for defining coherent and adapted governance and application of NBS projects dedicated to erosion control, flood mitigation, and restoration of biodiversity.

A stronger decision-making system should ensure that the solutions proposed are feasible and that all the objectives of co-benefits projects are compatible. In particular, ecosystem services are linked to benefits to humans, and environmental goods can be monetized. Therefore, they can be used for cost–benefit analysis. This kind of system should facilitate surpassing the step of accommodating different objectives, such as the reduction of damage and the preservation of biodiversity, which require multicriteria analyses so that the key challenge of integrating aquatic environment management and flood prevention can be met [52]. An expected outcome could be a proposal of coherent and adapted governance for application of co-benefits NBS at the catchment and territory scales. It should be accompanied by proposals of possible new European and national laws for reaching the objective to allow practitioners and engineers to find truly integrated solutions based on nature for reconciling flood prevention with restoration of biodiversity at the catchment and territory scales. They could take the form of recommendations for improving territorial organization, providing increasing resilience to flooding and more broadly to natural hazards related to water (erosion, runoff, floods), improving multi-stakeholders participation, and combining city and inter-city (community) management [53].

6. Challenges for Research in Engineering Ecology and Geosciences

These reflections could be sources of further disciplinary, interdisciplinary, and transdisciplinary research, since they combine approaches in several scientific disciplines, and involve different kinds of actors. NBS, seen as multi-benefits actions, can allow envisioning more integrated management of natural and local hazards, and notably attune flood prevention with aquatic environment management. However, the development of the NBS concept already calls for new, much more global research, whose results should become the knowledge base of engineers, managers, and decision-makers. Below, we propose a few key issues for further exploration that should better demonstrate the possible contributions of NBS for aquatic environment management, flood prevention, and erosion control:

What role is played by vegetation engineering structures and vegetation in flooding in the catchment, integrating the complexity of the processes at the plant and structure scales, especially erosion control?

How can protection and ecology be reconciled for integrated management of ecosystems, water, and local areas? For example, how can SWB contribute solutions in grouping the functions of bank protection and ecological corridors?

How can the security of structural works be ensured while optimizing the ecosystemic services of vegetation?

What restoration methods should be implemented to limit the long-term impacts of development on rivers?

Within the range of river management possibilities compatible with flood control, what management scenarios would be capable of preserving ecosystems associated with the river's natural dynamics?

How can a (truly) integrated approach to the design of river/catchment development accommodating both aquatic environment management and flood prevention be elaborated? More specifically, how can we make sure that flood prevention does not systematically "dominate" aquatic environment management needs? Moreover, more globally, how can all the physical and biological processes be integrated at the catchment scale?

In addition, sharing feedback will always be advantageous, with each new project and experimental field, with specific constraints (areas/structures vulnerable to flooding, available land, ecosystem health, acceptation, pollution threatening the effectiveness of the restoration work, compensation possibilities) calling for specific adjustments.

7. Conclusions

Novel approaches and frameworks for designing and simulating the use and efficiency of NBS for multiple purposes should provide larger scientific impacts. Dedicated to considering flood prevention and erosion control in addition to restoration of biodiversity, this kind of approaches is intended to be adapted for other societal challenges, such as public health [54], water security [55], or climate change [56,57]. The innovative use of NBS presented in this paper makes it possible to respond in part to the search for a reconciliation between the restoration of environments and the prevention of floods. More broadly, the results of future research are intended to help scientists make improved assessments of the links between practices, ecosystem structures and functions, and ultimately services, and to foster evaluations of ecosystem management approaches.

From the practical, political, and societal points of view, they will help project designers improve the appropriateness of their action to the specified targets of their projects, as well as practitioners. It should also facilitate public institutions and private companies establishing the specifications of the ecosystem management adapted to their objective through the application of multi-benefits NBS. More broadly, it should (i) improve ecological coherence and integrity within water catchments, including cities and at the peri-urban and urban/rural interfaces, (ii) provide ecosystem services and human well-being (flood prevention, land restoration and preservation, making cities resilient to flood risks), (iii) strengthen business development through the green economy and private investment, by developing innovative NBS related to new knowledge on their effectiveness, and (iv) contribute to the objectives of regulatory frameworks, i.e., the European Water Framework Directive and Floods Directive, but also the European Green Infrastructure Strategy and the EU 2020 Biodiversity Strategy. Finally, this reflection should be the basis for further considerations on NBS, for defining sound techniques and strategies that reconcile erosion control and flood protection with restoration of biodiversity.

8. Highlights

Ecological engineering meets nature-based solutions with common principles and objectives.

They both respond to current challenges in policies for environmental management, considering co-benefits approaches.

Applications for harmonizing erosion control and flood prevention with restoration of biodiversity are relevant.

They call for new approaches in governance, practice, and research.

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