



Research Article

Flood Risk Management Driven by Naturebased Solutions: From Watershed Ecosystem Services to Resilience Enhancement under Climate Change

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Abstract: Climate warming is increasing levels of flood risk worldwide because it increases heavy precipitation, runoff and floodplain encroaching accelerates land use change, and concentrates people and assets in flood prone areas. Due to the creation of nonstationary hazard regimes due to the process of climate change, flood governance can no longer be based only on the statistics of events in the past or predetermined design criteria. Traditional grey-only techniques of flood control, such as levees, channelization and hard shorelines structures can provide temporary risk alleviation, but frequently take a toll on river structure, decouple floodplains, shift risk along stream or through time and can lock societies into unbending infrastructural courses that can destroy ecosystems and reduce adaptive capacity.

As proposed by the IUCN and gaining growing root in the UN policy processes, as well as regional level policy, Nature-based Solutions (NbS) demonstrate another avenue of flood risk management, which consists in protecting, restoring or sustainably managing ecosystems to sustain societal needs and deliver ecosystem services, biodiversity benefits and co-benefits to human well-being. In a synthesis of NbS-based flood risk management synthesized in a watershed-to-resilience perspective, this paper integrates (i) hydrological and ecological processes operating, respectively, along the catchment continuum



(headwaters to river corridors to floodplains to deltas/coasts to urban systems), (ii) watershed risk-reduction pathways, which operate on hazard, exposure, and vulnerability, and (iii) assessment approaches, which convert ecosystem service delivery into decision-relevant measures, such as ecosystem accounting frameworks (e.g. On the whole, the evidence suggests that NbS can offset flooding and improve resilience, yet the influence depends on conditions and may be insignificant in extreme cases; thus, hybrid green-grey portfolios, stress testing at scenarios under non-stationary conditions, and strict monitoring are needed to match the implementation with the Sendai Framework on Disaster Risk Reduction and the IUCN Global Standard on NbS.

Keywords: Nature-based solutions, Flood risk management, Watershed, Ecosystem services, Floodplain reconnection, Wetlands, Urban blue-green infrastructure, Coastal protection, Climate adaptation, Resilience, Ecosystem accounting, GEP

1. Introduction: Flood risk under nonstationary and ecological constraints

The combination of the intensifying hydroclimatic extremes, quick land use transformation, and the growth in socioeconomic exposure are increasingly influencing flood risk. The physical fundamentals behind increased precipitation extremes in warmer conditions are well solidified, but the linkage of rainfall extremes to flood peaks is regionally diverse since evapotranspiration, antecedent moisture, soils, storage and river network interactions moderate runoff production and flood propagation. This means that stationary planning assumptions, that the past is a reliable predictor of the future, will not be reliable, especially where there are compound drivers (e.g. heavy rainfalls with soak saturated soil, storm surge or infrastructure failure cascades). Simultaneously, the floodplain development and the urban growth managed carelessly only raise the number of people at risk and the value of the exposed properties and the vulnerability is not evenly distributed because of inequality, lack of infrastructure, and broken institutions (Acreman & Holden, 2013).

In such framework, flood risk management no longer revolves around a relatively limited paradigm of flood control but rather a risk governance paradigm that is more explicit in its approach to hazard, exposure and vulnerability. The popularity of NbS is due to their ecosystem procedures: retention, infiltration, roughness, sediment stabilization and coastal wave suppression coupled with the creation of cobenefits akin (biodiversity, water quality, recreation, heat radiating) which can bolster social legitimacy and lifelong stewardship. Nevertheless, the growing policy vocabulary of NbS also brings about the worries of the conceptual vagueness and greenwashing, inspiring the quality assurance models, most notably the IUCN Global



Standard of NbS, and compliance with the norms of disaster risk reduction, including the Sendai Framework (Dadson et al., 2017).

In this paper, I develop a synthesis of watershed to resilience: NbS performance should be determined by the ability of interventions to recover or reorganize watershed ecosystem services, notably the performance of regulating services, including flood regulation, and the capacity of these regulating services to produce measurably reduced risks and resilience to climate change.

2. Conceptual foundations: Risk, ecosystem services, and resilience as an integrated system

2.1 Flood risk as a coupled social–ecological problem

The risk of flooding can be conceptualized as a consequence of hazard (e.g., the height, duration and intensity of discharge), exposure (people and assets at risk areas), and vulnerability (susceptibility and ability to foresee and respond, recover and adjust). NbS has the ability to affect all of them, however, through various causal mechanisms (Debele et al., 2019). The three measures of reducing the hazard correspondingly include increasing storage and infiltration, reducing flow speed, and restoring floodplain connections; the three factors of exposure reduction include land use planning, floodplain preservation/restoration of space to water, and diminishing vulnerability to NbS; and improvement of livelihoods, ecosystem dependent economies, and redundancy of essential services (IUCN, 2020). This is the sort of integration that ecosystem-based disaster risk reduction (EcoDRR) stresses, but in practice implementation of it is usually disjointed between water management, land use regulation, conservation, and social policy an institutional failure that is more materialized when there is nonstationary hazard.

2.2 Ecosystem services across the watershed continuum

The frameworks of ecosystem services (best known as the Millennium Ecosystem Assessment) categorize the ecosystem service into provisioning, regulating, cultural, and supporting service types, with flood regulation being explicitly identified as a regulating service. In the case of flood governance, watershed location is important since the generation and absorption of floods are distributed: headwaters can modify the runoff distribution; riparian strips can modify the attenuation, roughness and sediment; flood plains and deltas can store and dissipate floods; and coastal ecosystems may alleviate wave energy and surge whilst interacting with river backwater influence (IPCC, 2021). Functional ecological floodplains rely upon hydrologic connectivity, fluctuating flow regimes, and adequate spatial scale, which are directly compatible with floodplain reconnection and room for the river floodplain



designs.

2.3 Resilience as measurable system performance under extremes

Flood governance does not only entail quick recovery; it also entails the ability to foresee, internalize, adapt and when necessary, change with the changing risk drivers. NbS can be able to build resilience through spreading retention (modularity), restoring ecological redundancy (Multiple storage and flow pathways) and the creation of cobenefits that facilitate long-term political and communal backing. However, resilience claims should be made measurably, in performance in terms of hydrological (reduction of peaked runoff, lags, extent/duration of inundation), ecosystem (condition of habitat, connectivity, sediment) and social (equity of benefits and burden, recovery time) performance (Menéndez et al., 2020).

3. Scope and approach

This article entails a systematized concept synthesis based on peer reviewed pieces of evidence syntheses, policy guidelines, and examples. It emphasizes hydrological responses on a watershed scale by concentrating on riverine, pluvial flooding and integrates urban and coastal NbS with a hydrological connection. The results are analyzed in terms of ecosystem services and associated with decision support using the ecosystem accounting (SEEAEA) and aggregated ecosystem service valuation concepts including GEP (Millennium Ecosystem Assessment, 2005).

4. Mechanisms: How NbS reduce flood risk through watershed ecosystem services

4.1 Headwaters and uplands: runoff generation control through infiltration and storage

NbS (forest restoration, soil conservation, and peatland rewetting) are designed to add infiltration capacity, soil water storage and complication of the runoff path, thus slowing down runoff and may disynch the tributary peaks in uplands. But these effects are highly context-dependent: once the intensity of rainfall becomes greater than the infiltration capacity or the soils are saturated, then the attenuation of hazards will reduce, particularly during infrequent large-scale events. Besides, different wetlands will have varying impacts dictating which conditions are favorable and which are unfavorable (such as the flood generating potential of some wetlands), and



therefore it is not necessarily the case that restoring any wetland will be identical to the mitigation of floods. Therefore, upland NbS should be approached as part of a larger portfolio as opposed to be seen as an independent response to extreme flood management (Narayan et al., 2016).

4.2 River corridors and riparian zones: roughness, conveyance moderation, and sediment stabilization

Corridor restoration, remaining and riparian vegetation change flood hydraulics by making it rough and increasing channel-floodplain exchange. Vegetation has the ability to slow down the flow velocity and the energy capability of erosion, facilitate the deposition of sediments and stabilize the banks, which produces cobenefits on the quality of water and habitat. However, the mechanism of the same roughness can elevate the local water levels, given some circumstances, which means that the mechanisms of coaring in corridor NbS must be assessed locally and given upfront tradeoff management (Opperman et al., 2010). Notably, such actions usually have multiservice benefits such as flood control, erosion control, purification, biodiversity, which makes them value-enhancing and hard to assess when decision frameworks simply monetize destruction of unwanted flood damages (Ruangpan et al., 2020).

4.3 Floodplains: reconnection and “room for the river” as direct flood regulation services

Floodplain offers one of the most explicit NbS opportunities of reducing riverine flood risk since it has the capacity to retention and slow discharge of floodwaters, reducing the downstream peaks whilst having high biodiversity and cycling of nutrients. These interventions consist of levy retreat, establishment of side channels, depreciation of floodplain and eradication or alteration of obstacles that obstruct links between rivers and floodplains. The so-called Room to River model is an excellent example of a new way of thinking about flows that can be summarized as the replacement of flows with space to manage controlled inundation, often supported not just by their safety advantages, but also by the quality of space, ecological, and recreational amenities. Reconnection in floodplain may also interplay with sediment processes and delta resilience in which sediment supply and deposition facilitates land construction, although again results are related to local hydraulics and management goals (Seddon et al., 2020).

4.4 Urban NbS: distributed retention and source control for pluvial



flooding

The use of extreme rainfall of relatively brief duration, elevated levels of imperviousness, and a scarcity of drainage capacity often dominate in the determination of urban flood risk. Raising a green roof, a rain garden or bioswales, permeable pavements, a detention basin, a multifunctional blue-green open space are examples of Urban NbS that use retains infiltrate evapotranspiration logic on runoff at its source. Planted scale approaches to sponge cities help demonstrate how to recreating infiltration and storage capacity of dense urban structure as well as to integrate flood management with the urban livability outcomes (heat reduction, recreation, air quality). Since urban NbS activity is grounded in design, maintenance, and network effects, standards, long-term management of asset, and monitoring are necessary as ways to implement green infrastructure as a service-delivering infrastructure instead of landscape decoration (UNDRR, 2015).

4.5 Deltas and coasts: ecosystems as surge and wave buffers within layered protection

Coastal floods are due to storm surge, waves, sea-level rise and combination of rivers discharge with sea-level rise. Mangroves, salt marshes and reef associated habitats mitigate risk (wave energy) by dissipating it, stabilizing the sediments, and facilitating vertical accretion, which can somewhat counter the sea-level rise. It is shown that coastal systems may produce substantial avoided losses and safeguard significant populations, yet it is contingent on the width of the habitat, health, water level, NbS tend to perform best in most settings as components of layered or hybrid defense systems that reduce design loads and extend the service life of engineered structures, while also delivering co-benefits for biodiversity and fisheries.

5. Evidence, limits, and the case for hybrid portfolios

Evidence base of NbS in hydrometeorological risk management has continued to grow, which records numerous types of interventions and effects; however, three shortcomings always remain relevant to flood management. First, scaling and attribution is problematic: the results of NbS under small catchments or frequent events might not be relevant to basin scale extremes, and the separation between the NbS effects and climate variability and land use change could only be done with the strong designs and long time series. Second, the performance of things over time: forests grow, wetlands change with sedimentation and transition of plants and vegetation, and green parks in cities are vulnerable to urban decay. Third, the space of benefits is redistributed: the recovery of the flood plain areas may decrease



downstream peaks and increase local inundational frequency, which creates the questions of recompense, land ownership, and social legitimacy (UN Statistics Division, 2021).

They do not prescribe NbS as unworthy; instead, these aspects suggest that in safety critical flood governance, (i) systemic green-grey portfolios that incorporate ecosystems processes with engineered reliability, (ii) stress testing scenarios in non-stationary climate, and (iii) adaptive governance should be based on monitoring to the standards of NbS.

6. From ecosystem services to decision metrics: Evaluation, accounting, and finance

6.1 Why conventional appraisal undercounts NbS

NbS have many advantages that are lightly priced or not visible in the markets and traditional infrastructure appraisal can tend to favor direct, short term risk reduction at the expense of more indirect, long-term benefits like water quality enhancement, carbon capture, biodiversity and human health. This bias may underinvest systematically in the restoration where the avoided damages to the ecosystem and the social gains are massive.

6.2 Ecosystem accounting and GEP style metrics

Ecosystem accounting systems such as SEEA Ecosystem Accounting provide a standardized way of measuring ecosystem extent and condition, monitoring ecosystem service networks and bridging the biophysical records of nature with economic activity and policy assessment, enhancing the visibility of the service nature provides in decision-making. Simultaneously, GEP-type methods attempt to estimate the overall worth of terminal ecosystem final goods and/or services supplied to the population, as a supplementary measure to GDP-based systems and to attempt to correctly address endemic under-acknowledgment of regulating services. In NbS-based flood risk management, the three tools can be operationalized in three closely associated ways, first, by developing flood regulation service accounts which convert biophysical functions (e.g., temporary storage capacity, peak attenuation) into estimates of avoided-damage, second, by facilitating portfolio appraisal through multi-criteria comparison of NbS, grey, and hybrid options, and third, by enabling the management of protective ecosystem assets, whereby wetlands, floodplains, and mangroves are managed as infrastructure-like protective assets with explicit condition, performance, and long.



6.3 Monitoring for credibility and learning

NbS programs will need monitoring to connect the interventions with outcomes, which is hydrological performance (peaks, lag times, extent/duration of inundation), ecosystem condition (connectivity, vegetation structure, sediment processes), and distributional effects (who benefits, who pays costs, recovery and wellbeing). The focus of the IUCN Global Standard on measurable outcomes and adaptive management forms and accountability foundation and the EcoDRR advice points to the chronic disconnect between ecosystems understanding and sectoral planning activity.

7. Governance and equity: enabling conditions for NbS at scale

Watersheds scale NbS necessitate administrative coordination since hydrological systems do not appertain to jurisdictions most of the time. Multilevel governance arrangements that connect water administration, land use coordinators, conservation teams, and neighborhoods and the policy-disaster risk reduction directions (e.g., Sendai Framework) are likely to be essential to effective implementation. Central to the consideration of equity is the fact that NbS are typically land intensive and they can change property values and access to resources, as well as introduce local costs to downstream benefits. The concept of participatory design, transparent variety of compensation, protection of maladaptation, and rights sensitive planning are then not the optional features, but the essential qualities that determine legitimate and enduring quality.

Institutional innovation is also needed when it comes to financing. Sustainable NbS portfolios may also be based on blended public funding of public goods, focused private investment associated with cobenefits and where risk reduction can be assessed, insurance linked instruments or resilience financing packages. The benefits may be made legible to the budget processes and performance tracking may be made through ecosystem accounting that will make the financing stronger.

8. Practical roadmap for NbSdriven flood risk management

An actual implementation journey on NbS-driven flood risk management which is practical and compliant with NbS standards can be stated as an integrated process which starts with risk-ecosystem diagnosis (plotting riverine/pluvial/coastal flood pathways, exposure hotspots, vulnerability and ecosystem service deficits, e.g. lost floodplain storage, degraded wetlands and urban imperviousness), then an option-design based on mechanisms which adapts interventions to the dominant



processes and watershed locations (e.g. floodplain reconnection to recreate lost storage, urban This in turn advocates hybrid portfolio development involving NbS and engineered actions to address the safety requirements and increase the redundancy across scales with scenario stress testing on climate and land use futures involving compound extremes. The implementation ought to be justified based on benefit and equity evaluation quantifying flood regulation services and cobenefits, and distributional impacts using ecosystem accounting or GEPstyle measures where possible, and facilitated by institutionalization and finance cross jurisdiction governance, secured funding, explicit maintenance accountability, and inclusion in asset management which leads to monitoring processes and adaptive management re-quantifying hydrological, ecological, and social indicators and reiterating the designs and operations in response to changes in system conditions.

9. Conclusion

Nature based Solutions offer a scientifically based and policy-approved way to reframe the flood risk management based on watershed processes and ecosystem services instead of structural control per se. A watershed to resilience framing explains how NbS can foster flood risk reduction in various ways: hazard attenuation, exposure management, and vulnerability reduction, and provide cobenefits, which can enhance long-term adaptive capacity. There are grounds to make meaningful contributions but also note the dependence on the situation, scaling ambiguity, and the use of hybrid green-grey portfolios, scenario testing in nonstationary settings, and believable monitoring in tandem with NbS standards and disaster risk governance policies. NbS can be further mainstreamed using ecosystem accounting and GEP style metrics that can convert the flows of ecosystem services into the decision-relevant evidences to be used in the planning, budgeting, and investment of flood resilience plans to design safer and more ecologically sustainable strategies.

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