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Research paper

RESILIENT WATERSHEDS FOR SUSTAINABLE SOCIETIES

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Abstract

Climate change, land-use change, environmental degradation and increasing competition for water are placing growing pressure on river basins and the communities that depend on them. Addressing these pressures requires moving beyond isolated measures towards an integrated watershed perspective that recognizes the interactions between hydrological processes, ecosystems, land use, infrastructure and governance. This paper discusses a conceptual pathway to resilience linking watershed resilience with spatial planning, green infrastructure (GI) and nature-based solutions (NBS). Watersheds are considered as social-ecological-technological systems in which natural storage, connectivity and water regulation provide the physical basis for resilience. GI and NBS can strengthen these functions across forests, agricultural areas, wetlands, floodplains, rivers and urban areas, while providing multiple hydrological, ecological and socio-economic benefits. However, their wider implementation is constrained by institutional, regulatory, political, financial and knowledge-related barriers. These barriers interact and may reinforce each other, requiring interventions that address the most influential constraints within a particular governance context. The paper therefore emphasizes the integration of NBS and GI into watershed-scale spatial planning and infrastructure development, supported by coordinated governance, technical capacity and long-term institutional commitment. Such an approach can strengthen both rural and urban resilience as it provides a link between climate adaptation, water security and sustainable development.

Key words: *watershed resilience; nature-based solutions; green infrastructure; integrated governance; spatial planning*

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1. INTRODUCTION

River watersheds are among the most important natural systems. They provide water, food, energy, biodiversity, and livelihoods to people globally. However, growing climatic, environmental, and socio-economic pressures increasingly threaten their ability to deliver these essential services. Climate change, interacting with other challenges such as land degradation, biodiversity loss, pollution, river fragmentation, and growing competition for water resources create complex and interconnected risks across entire river basins.

Climate warming is altering the hydrological cycle and increasing the intensity and frequency of extreme events, including heavy rainfall, floods, droughts, or heatwaves [1]. Warmer air can hold more moisture, leading to more intense precipitation events and greater flood risk in many watersheds. At the same time, rising temperatures increase evaporation from soils, rivers, lakes, and reservoirs, contributing to more frequent and severe droughts. Both flood and drought risks are projected to increase under all scenarios of global warming [2]. Heat also places additional stress on river ecosystems by raising water temperatures, reducing dissolved oxygen levels, and increasing water demand from cities and agriculture.

Land-use change and land degradation considerably affect the hydrological cycle and amplify hydrological extremes. Urbanization, deforestation, and intensifying agricultural practices reduce the landscape's ability to absorb and store water. As a result, rainfall is converted into surface runoff more rapidly, increasing flood peaks and erosion. At the same time, degraded soils are less able to retain moisture and recharge groundwater, making watersheds more vulnerable during dry periods. The Food and Agriculture Organization [3] identifies land degradation, water scarcity, and climate change as closely linked challenges that threaten the sustainability of land and water resources.

Another major concern is the rapid loss of freshwater biodiversity, which is declining rapidly because of multiple human pressures accumulated across entire watershed systems [4]. Rivers, wetlands, floodplains, and riparian forests provide critical ecosystem services, including flood regulation, water purification, groundwater recharge, and habitat for countless species. Yet freshwater ecosystems are among the most threatened ones due to pollution, water abstraction, dam construction, and climate change. With degrading ecosystems, watersheds lose part of their natural capacity to buffer floods, sustain water quality, and remain resilient during droughts.

Increasing competition for water resources adds further pressure. Agriculture, which accounts for more than 70% of global freshwater withdrawals [3], competes with growing municipal, industrial, energy, and environmental water needs. During drought periods, these competing demands become particularly acute, often leading to difficult trade-offs between economic development and ecosystem protection. Water scarcity limits water supply, reduces agricultural productivity, threatens energy generation, damages ecosystems, and increases the potential for social and political tensions, especially in transboundary river basins shared by several countries.

The greatest challenge for watersheds is therefore the interaction of multiple pressures rather than any single issue taken alone. Addressing these interconnected

challenges requires integrated river basin management that simultaneously considers water, land, ecosystems, climate adaptation, and governance across the whole catchment. Despite this, many current responses remain fragmented and sectoral in nature. Water resource management, flood and drought risk management, urban development, agricultural policy, and biodiversity conservation are often addressed through separate institutional and planning processes, limiting their ability to deliver integrated outcomes.

Water security and hence the community resilience in urban and rural areas is therefore closely linked to the health of upstream watersheds or the watershed from which they are supplied with water. Disturbed hydrological and ecological processes in a watershed directly influence the quantity, quality, and timing of water reaching downstream areas. With growing pressures on both land and water resources and the intensification of hydrological extremes due to climate change, there is a need to strengthen watersheds' health by moving beyond separated interventions towards a more integrated systems perspective. Such an approach must recognize watersheds as complex systems shaped by interdependencies among biophysical processes, human settlements, infrastructure, ecosystems, and governance arrangements across multiple spatial and temporal scales.

In response to this need and building on a synthesis of current research and the most recent European policies [5], this paper discusses a conceptual pathway to resilience that integrates watershed processes, ecosystem services, green infrastructure, spatial planning, and governance. The aim is to demonstrate how decision- making that is both integrated and synergistic can enhance the capacity of watersheds and communities to adapt to and manage increasingly complex environmental and societal risks.

2. WATERSHEDS AS SOCIAL-ECOLOGICAL SYSTEMS

Watersheds are not merely hydrological units but complex social-ecological-technological systems in which the water cycle is tightly interconnected with ecological processes and human socio-economic activities [5][7]. Resilience of the communities is closely linked to the health of upstream watersheds because the ecological and hydrological processes occurring across a watershed directly influence the quantity, quality, and timing of water reaching downstream areas (see Figure 1).

Healthy watersheds are characterized by natural land cover, functioning headwater streams, riparian corridors, connected floodplains, wetlands, and intact hydrological and geomorphological processes that operate within their natural range of variation [8]. These elements function as natural infrastructure [9], regulating the movement and storage of water across the landscape. They intercept, store and gradually release water, facilitate infiltration and groundwater recharge, regulate sediment transport, filter pollutants, and sustain water quality and ecological integrity. For example, groundwater storage maintains streamflow during drought, while large soil storage reduces rapid runoff generation and floodplain storage attenuates flood peaks. Natural ecosystems like forests and wetlands purify water, regulate flow regimes, and sustain

biodiversity, which directly underpins public water supplies, agriculture, and power generation [5][10].

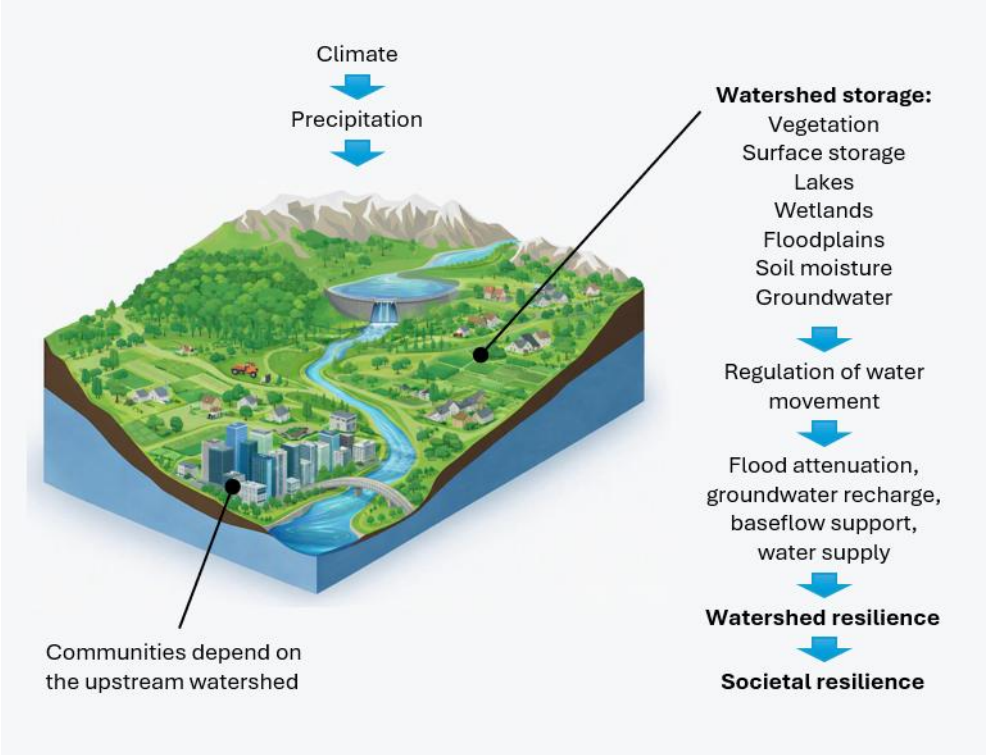


Figure 1. Watershed as an interconnected social-ecological system.

Human systems are embedded within and dependent on these biophysical processes. Anthropogenic interventions, such as intensive water abstraction and environmental degradation disrupt water cycle by deteriorating both water quality and water quantity, also intensifying risks like droughts and floods, which all threaten socio-economic stability [5][11]. Land-use conversion, deforestation, and intensive irrigation and artificial drainage accelerate runoff, increase sediment and pollution loads, reduce groundwater recharge, and diminish the natural capacity of landscapes to buffer climatic extremes, thereby amplifying downstream flood, drought, and water-quality risks. Cumulative degradation can push a watershed past critical ecological thresholds, triggering a regime shift into a permanently degraded, alternative state (such as persistent lake eutrophication or land subsidence) that is difficult or impossible to reverse [5].

Therefore, sustainable human societies, public health, water and food security, and economic development depend fundamentally on healthy, resilient watersheds [5] [12]. Building watershed resilience requires integrated, multi-benefit actions across scales and sectors [5] [13]. These actions should be grounded in integrated water resources management, spatial planning that safeguards landscape functions and reconnects storage elements, and measures that preserve natural water retention and recharge, such as nature-based solutions or managed aquifer recharge [11]. Agricultural and

forest practices that enhance infiltration and reduce erosion are equally vital. Combining green and grey infrastructure also creates a diversified and redundant portfolio that buffers communities against climate variability, protects aquatic biodiversity, and secures a resilient water future.

3. GREEN INFRASTRUCTURE AS THE BACKBONE OF WATERSHED RESILIENCE

Green infrastructure (GI) and nature-based solutions (NBS) are fundamentally landscape-scale approaches [14], although they are often perceived primarily as urban tools. While much research focuses on their role in addressing urban flooding, heat and pollution [15] [16], their application extends throughout entire river catchments across forests, agricultural landscapes, wetlands, rivers and floodplains. By using and restoring natural processes, NBS and GI can regulate water, reduce hazards, improve water quality and support biodiversity, creating a connected network of natural and semi natural areas from headwaters to the sea [5][14]. To be effective, these measures must be planned and managed with a broad landscape perspective that recognizes the interlinked dynamics of whole watersheds.

The appropriate measures depend on the biophysical characteristics and land uses within each part of the watershed. Forests in headwater areas can increase interception and soil storage, slow runoff, reduce erosion and sediment transport, and regulate water availability. Sustainable forest management, afforestation, forest preservation and continuous-cover forestry can therefore contribute to both flood and drought resilience [14]. Floodplain restoration and reconnection, including levee setbacks and removal of obsolete embankments, restore lateral river-floodplain connectivity and provide space for temporary flood storage, reducing downstream flood levels. Wetland restoration and rewetting, including peatlands, can increase landscape water storage, regulate runoff and improve water quality [5] [16]. River restoration, through re-meandering, natural bank stabilization, removal of barriers and the use of woody structures or permeable barriers, can restore channel complexity, slow flow and improve longitudinal and ecological connectivity weirs [16].

In agricultural landscapes, conservation tillage, cover crops, contour farming, agroforestry, vegetated buffer strips and farm ponds can increase soil water retention, reduce erosion and intercept nutrients and sediments. These measures can simultaneously reduce rapid runoff during wet periods and retain water for use during dry periods. In cities, where soil sealing has disrupted natural water pathways, GI and sustainable urban drainage systems translate these principles into space-efficient interventions such as green roofs, permeable surfaces, swales and rain gardens. By retaining and infiltrating rainfall close to where it falls, they reduce pressure on drainage systems while providing additional environmental and social benefits.

The importance of NBS and GI lies in their multifunctionality. By restoring the storage and regulatory capacity of landscapes, they can attenuate flood peaks, retain water during wet periods, support groundwater recharge and sustain baseflows during droughts. At the same time, they create and reconnect habitats, improve water quality, support carbon storage and enhance ecological connectivity [18]. These ecological

functions generate socio-economic benefits, including more reliable water supplies, protection of agricultural productivity and infrastructure, reduced exposure to hazards, recreational opportunities and improved human wellbeing.

Thus, NBS and GI should not be considered alternatives to conventional infrastructure in a simple "green versus grey" distinction. Rather, they form a complementary layer of natural and semi-natural infrastructure that works across spatial and temporal scales. At watershed scale, their combined effect is to strengthen the capacity of landscapes to store, regulate, filter and redistribute water while maintaining ecological functions. This makes NBS and GI a central means of translating the concept of watershed resilience into practical spatial planning and climate adaptation.

4. GOVERNANCE: FROM FRAGMENTATION TO RESILIENCE

The effectiveness of watershed-scale GI and NBS depends not only on their technical performance, but also on the conditions under which they are planned, implemented and maintained. Watersheds cross administrative boundaries, while the responsibilities for water management, spatial planning, forestry, environmental protection, agriculture, infrastructure and economic development are distributed among different authorities. Decisions are therefore frequently made according to different objectives and regulatory frameworks, so the measures are planned for individual sectors or locations rather than as parts of an integrated watershed management.

Although there is increasing support to GI and NBS in strategic policies, their implementation and mainstreaming into governance remain fragmented and context-specific [19]. This "implementation gap" (as coined by [19]) is driven by a combination of institutional, legal, technical, financial, and knowledge-related barriers, including unclear responsibilities, fragmented regulations, insufficient funding, limited technical expertise and evidence of NBS performance, difficulties in assessing their multiple benefits, and stakeholder conflicts. Additionally, conventional grey infrastructure is often favoured because its design standards, costs, and performance are more familiar to decision-makers.

However, the barriers to NBS implementation are not independent problems; they are interconnected through feedback mechanisms among knowledge and awareness, political will and financial resources, institutional fragmentation, and implementation challenges [20]. These interactions can create self-reinforcing cycles in which one barrier strengthens other ones. Conversely, actions directed at overcoming strategically important barriers (i.e., those strongly affecting the emergence of other barriers) can produce positive spillover effects beyond overcoming the individual problem being addressed. Evidence from two Serbian pilot cases [20] illustrates these interactions: although funding was identified as a major barrier, its availability alone would have limited effect without adequate regulation, spatial planning, implementation procedures and qualified personnel. The analysis therefore points to education and raising awareness, stronger regulatory and planning frameworks, political commitment,

and better evidence on the costs and wider ecological and societal benefits of NBS as potentially more transformative intervention points.

Based on these findings, the first step in improving the GI/NBS uptake and watershed resilience should be to identify the dominant constraints and their interactions within a particular watershed. For example, floodplain or wetland restoration may conflict with economic development objectives, creating pressure on spatial plans to allocate land for housing, infrastructure, agriculture, or industry rather than retain it for flood storage and ecological functions. Loss of these natural functions can subsequently increase flood risk and the need for costly engineered protection, creating feedback in which short-term development benefits contribute to higher long-term risk.

The second requirement is to move from individual projects towards their systematic integration into watershed-scale spatial planning and infrastructure development. Spatial planning, river basin management, climate adaptation, flood-risk management, biodiversity conservation and rural development should not be treated as separate activities when they affect the same watershed processes. Planning at the watershed scale can identify where natural storage, infiltration, flood conveyance and ecological connectivity should be protected or restored, and where NBS can complement conventional infrastructure. Landscape architecture is also an important component of NBS design, closely linked to spatial planning in translating ecological and hydrological objectives into spatial interventions [21].

For watershed resilience, governance should consequently provide three basic functions: coordination, capacity and continuity. Coordination is needed to align decisions across sectors, administrative levels and upstream-downstream interests. Capacity includes technical knowledge, reliable evidence on NBS performance, appropriate design and maintenance practices, and methods for assessing multiple benefits. Continuity requires stable regulations, financing and institutional responsibilities that extend beyond individual projects and political cycles. Many of these factors (dedicated funding, polycentric governance, cross-sector coordination and alignment among governance levels, evidence, expertise, and stakeholder engagement) are identified in [22] and [19] as important enablers of NBS implementation.

Effective governance should therefore be seen as a part of the infrastructure required for watershed-scale resilience. Its role is to create conditions for individual GI/NBS measures to function as a connected system: integrated through spatial planning, supported by appropriate institutions and financing, monitored for performance, and adapted as knowledge and climate conditions evolve. In this way, governance is the mechanism through which watershed resilience can lead to long-term societal resilience.

5. AN INTEGRATED PATHWAY TO SOCIETAL RESILIENCE

The preceding sections show that watershed resilience cannot be achieved through separate interventions or within administrative boundaries. It requires an integrated approach in which: (i) the watershed is considered as a connected social-ecological-

technological system, (ii) spatial planning determines how land, water and people interact, and (iii) GI/NBS measures strengthen the natural processes that regulate water and support ecosystems. In this way, resilience should not be a single function of flood protection or water supply, but an outcome of interactions among hydrological, ecological and socio-economic functions.

A watershed resilience pathway can therefore be understood through four interconnected elements (Figure 2). First, watershed processes provide the physical foundation of resilience. The capacity of forests, soil, groundwater, rivers, wetlands, and floodplains to store, regulate, redistribute and purify water determines how the watershed responds to climatic extremes. Maintaining connectivity among these components, while restoring it where it has been lost, is essential for reducing both flood and drought risks.

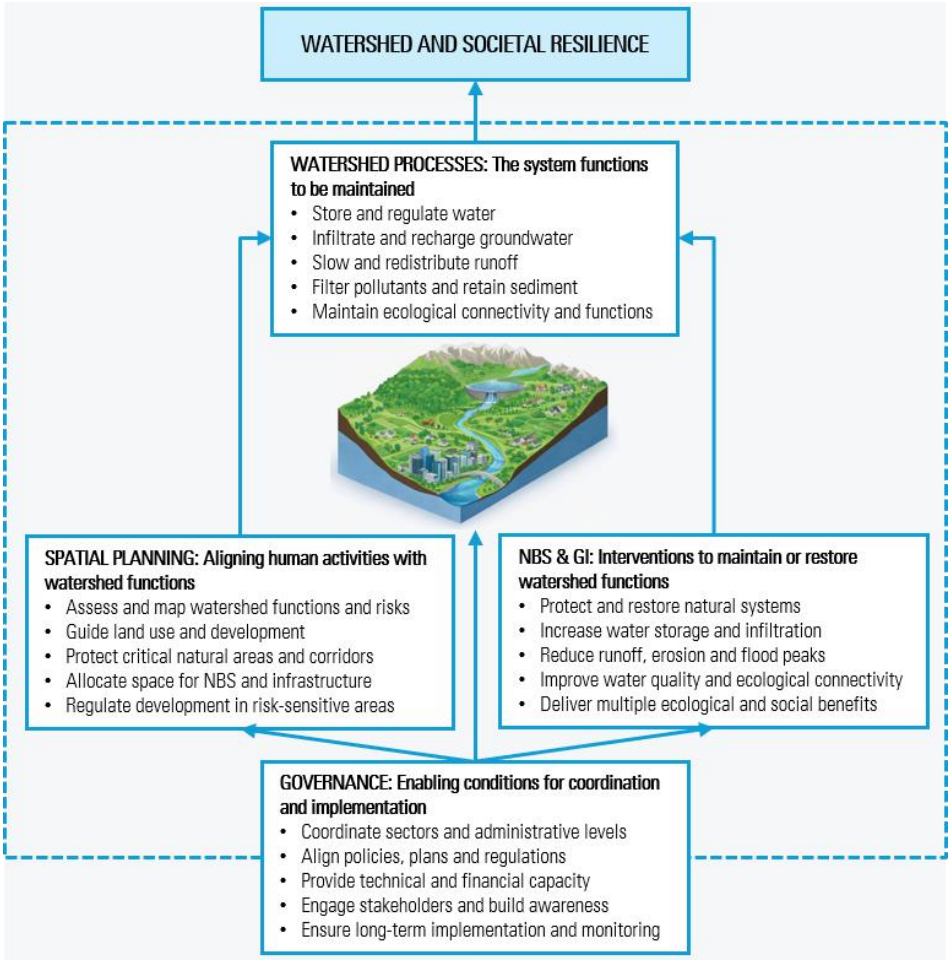


Figure 2. Integrated pathway towards watershed resilience.

Second, spatial planning provides the means to protect and enhance these functions. Decisions on land use, urban development, agriculture, forestry and infrastructure directly influence runoff, infiltration, storage and water quality. Planning should therefore recognize the watershed as a functional unit and identify where natural

processes should be protected, restored or complemented by engineered infrastructure. This includes identifying areas where interventions such as headwater forest protection, floodplain restoration or urban green infrastructure can provide significant risk reduction benefits, as well as strategically locating appropriate measures that reduce downstream risks using knowledge of hydrological and hydrogeological pathways. Spatial planning can incorporate connected networks of strategically located landscape elements, including ecological and freshwater corridors, into territorial plans. Spatially distributed but coordinated interventions can provide multiple simultaneous benefits (including flood attenuation, groundwater recharge, water-quality improvement, heat mitigation, carbon storage and recreational opportunities) and can further increase the robustness of the overall system by avoiding excessive dependence on individual locations or interventions. This also implies moving beyond the conventional separation between urban and rural planning and considering upstream-downstream relationships explicitly.

Third, GI and NBS provide practical measures for translating these principles into action. Their value lies not only in reducing individual hazards but also in generating multiple ecological, social and economic benefits from the same intervention. For example, restoring a floodplain can reduce flood risk while improving biodiversity, water quality, habitat connectivity and recreational opportunities; improving agricultural soil management can reduce runoff and erosion while increasing soil moisture, productivity and soil health; and protecting headwater forests can support water regulation, water quality, biodiversity and carbon storage. Across the watershed, connected GI/NBS can contribute to groundwater recharge, ecosystem functioning, climate regulation, landscape quality and human wellbeing, while also reducing damage to settlements, infrastructure and productive activities. Such multifunctionality can increase the overall efficiency and societal value of resilience investments. However, the evidence that these benefits are achieved simultaneously or without adverse effects is still limited, and therefore potential disbenefits, conflicts and trade-offs should be identified and assessed during the planning stage.

Fourth, governance determines whether these opportunities can be realized at the required scale. Effective watershed resilience requires coordination across administrative levels, sectors and stakeholder groups, supported by coherent policies, appropriate financial mechanisms and long-term institutional commitment. Financial mechanisms may include public investment programmes, dedicated climate-adaptation funds, green bonds, payments for ecosystem services, and emerging instruments such as flood credits that can reward or finance measures providing verified flood-risk reduction. Governance should also enable learning and adaptation, since the performance of NBS and GI depends on local conditions and may change under future climatic and socio-economic conditions. This requires systematic monitoring of hydrological, ecological and socio-economic performance, regular assessment of whether measures deliver their intended benefits, and mechanisms for adjusting their design, operation, maintenance or spatial distribution as conditions and knowledge evolve.

These elements form a reinforcing system rather than a linear sequence. Healthy landscapes improve hydrological regulation and generate visible environmental and socio-economic benefits; these benefits can strengthen public support and political commitment for further investment and protection. Conversely, fragmented planning, weak institutions or inappropriate land-use decisions can undermine natural regulation and increase risks, creating further pressure on infrastructure and public resources.

The ultimate objective is therefore not simply watershed resilience, but the capacity of society to remain secure and functional under changing environmental conditions. A resilient watershed supports reliable water resources, reduces exposure to floods and droughts, sustains ecosystems and livelihoods, and provides healthier and more liveable settlements. In this sense, watershed resilience provides a bridge between climate adaptation and sustainable development: protecting and restoring the functions of the watershed becomes an investment in the resilience and sustainability of society as a whole.

6. CONCLUSIONS

Climate change and increasing pressures on land and water resources require a shift from fragmented responses towards a watershed-scale approach to resilience. This paper has argued that the watershed provides an appropriate framework for connecting hydrological processes, ecosystems, human settlements and infrastructure. Its capacity to store, regulate, filter and redistribute water is a fundamental component of resilience to both floods and droughts.

Green infrastructure and nature-based solutions can strengthen these natural functions across the watershed, from headwater forests and agricultural landscapes to wetlands, floodplains, rivers and urban areas. Their main advantage is their multifunctionality: the same measures can reduce hydrological risks while improving water quality, biodiversity, ecosystem services and human wellbeing. Their value is therefore greater when they are considered as a connected network rather than as individual projects.

However, achieving watershed-scale resilience is not only a technical challenge. Spatial planning and infrastructure decisions determine whether natural storage and connectivity are protected or lost, while governance determines whether individual measures can be coordinated, implemented and maintained at the required scale. Institutional fragmentation, lack of political will, competing land-use objectives, limited capacity, inadequate evidence and financing can reinforce each other and constrain implementation. Identifying these interactions and addressing strategically important constraints is therefore essential.

The proposed pathway links watershed processes, spatial planning, GI/NBS and governance within a common resilience perspective. Its central message is that resilient societies depend on resilient watersheds. Protecting and restoring watershed functions should therefore be considered not only as an environmental objective, but as a long-term investment in water security, climate adaptation, economic stability and societal sustainability.

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