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Integrating Nature-Based Solutions (NbS) for Enhanced Flood Resilience under a Changing Climate: The Case of the Cologne District, Germany

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Abstract. The Cologne District in western Germany has frequently experienced flooding from the Rhine River and its tributaries. Current protection measures consist of a combination of engineered, green, blue and soft infrastructure. The district was affected by the catastrophic floods in Europe in July 2021, and climate models predict an increased risk of heavy summer rainfall, which could lead to severe flooding, especially of the tributaries of the Rhine. Nature-based solutions (NbS) are recommended to enhance flood resilience. However, there is no publicly available systematic register of existing and planned NbS. This study addresses this gap by mapping, categorising and evaluating existing and planned NbS for flood risk mitigation. We have created maps and assessment tables for both existing and planned NbS, as well as identified potential areas for future interventions using various databases. The results demonstrate that multiple NbS have been implemented and are planned along the Rhine, but additional efforts are needed in the Erft and Wupper tributaries, despite several planned and implemented river restoration projects. NbS in these catchments focus on floodplains, while slopes and riparian areas, suitable for the existing urban and agricultural land uses, have not been systematically assessed for their effectiveness. With the predicted increase in extreme climate events with intense summer rainfall and drought periods, surface runoff may rise due to dried and hardened soils, increasing flash flood risks. We therefore recommend targeted NbS interventions on slopes. Additionally, cites such as Cologne should develop further infiltration areas to mitigate the risk of pluvial flooding.

Keywords: Nature-based solutions, flood mitigation, climate change adaptation, Cologne District, heavy rainfall events.

1 Introduction

The Cologne District, located in North Rhine-Westphalia in the western part of Germany, is a dynamic and historically rich area that combines urban centres, such as Cologne, Bonn and Leverkusen in the Lower Rhine Plain with the rural low mountain ranges of the Eifel in the west, the Bergisches Land in the east and the Siebengebirge in the south. The region benefits from its strategic position along the Rhine River, which has historically facilitated trade and commerce. Today, it is characterized

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by a diverse economy that includes strong industrial, technological, and service sectors. Despite its many strengths, the Cologne District faces significant challenges, particularly related to a comprehensive structural change of the Rhenish lignite mining area in the western part of the region and climate change impacts.

The Rhine River is the major hydrological influence in the region with a discharge comparable to any large river in Europe and a history of major floods, usually the result of snow-melt in the upper reaches, saturated soils and rainfall in the larger tributaries (Disse & Engel, 2001). In recent years, the region has experienced a noticeable increase in the frequency and intensity of extreme weather events such as heavy rainfall (Tradowsky et al., 2023), heatwaves (Eingrüber et al., 2022), and droughts (Rousi et al., 2023). These events not only pose direct threats to human health and safety (Sandholz et al., 2021), they also have far-reaching effects on the local economy, infrastructure, and environment (Nick et al., 2023). In particular, the catastrophic floods of July 2021 underscored the region's vulnerability to severe hydrological events, resulting in human losses as well as extensive damage to property, critical infrastructure, and significant disruptions to daily life (Fekete & Sandholz, 2021).

Climate change is expected to have a significant impact on flood risk in North Rhine-Westphalia (NRW), including the Cologne District (Holsten et al., 2013; Thomas & Knüppe, 2016). It is likely to result in more intense and frequent heavy rainfall events (Thieken et al., 2023). This can lead to river floods, flash floods and pluvial floods, as the increased volume of water exceeds the capacity of natural and man-made drainage systems (Bosseler et al., 2021). Furthermore, settlements, often with historic town plans, built around smaller watercourses face the prospect of severe and more frequent flash floods (Alobid et al., 2024). Figure 1 shows the case study area which is a sub-area of the administrative district of Cologne including the municipalities of the Rhein-Erft-Kreis, the Rheinisch-Bergischer Kreis and the cities of Cologne and Leverkusen, which are exposed to the hydrological hazards' river floods, flash floods, agricultural drought and forest drought. Pluvial floods are not shown on this map for scaling reasons.

Summer droughts can also have complex and varied impacts on flood risk. While droughts typically reduce soil moisture and river flow, which might intuitively lower the risk of flooding, they can also exacerbate certain factors that contribute to flooding. This can result in hardened soil surfaces, reducing the ability of the soil to absorb water when rain does occur (Barendrecht et al., 2024). Consequently, instead of infiltrating into the soil, rainwater runs off more quickly, increasing surface runoff and the risk of flash flooding. Moreover, drought stress can weaken vegetation and ecosystems, leading to reduced canopy cover and root systems (Zölch et al., 2017). This diminishes the stabilizing effect of vegetation, increasing the likelihood of soil erosion and landslides when heavy rainfall eventually does occur (Panagos et al., 2015). Vegetation loss can also lead to increased sedimentation in rivers and streams, potentially exacerbating flooding (Kretz et al., 2021).

In addition to the increase in extreme climatic events, increased urbanization and changes in land use can exacerbate flood risks (Mustafa et al., 2018). Impervious surfaces like concrete and asphalt prevent water from being absorbed into the ground, leading to higher surface runoff and increased flood risk (Feng et al., 2021). Outdated infrastructure and inadequate drainage systems can fail to cope with the increased volume and intensity of water, leading to more frequent and severe flooding

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(Wüthrich et al., 2025). The dense population and extensive infrastructure make the area vulnerable to all types of flooding. Overcoming these challenges is crucial for the sustainable development and resilience of the region.

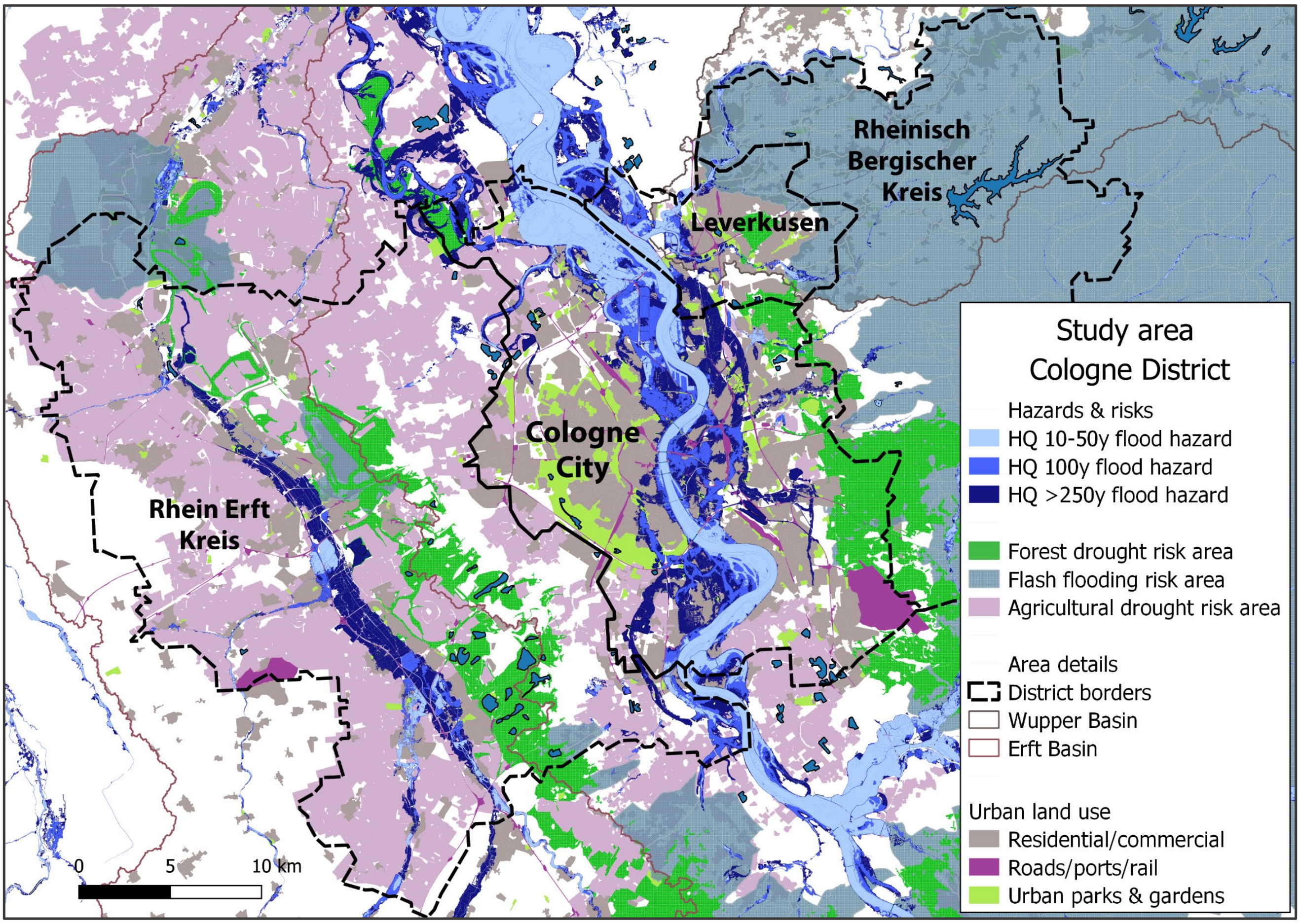

Figure 1: Hydrological hazards and risks occurring in the Cologne District study area
Data sources: BKG, 2021; Diva-GIS, n.d.; NASA, 2013; OpenGeodata.NRW, n.d.; Region Köln Bonn, 2019; USGS, 2014. Processed in QGIS 3.6.2.

In response to these challenges, the communities and water authorities in the Cologne District have been working on various adaptation strategies to mitigate flood risk, including (a) improved flood protection measures such as dikes, dams and flood barriers (StEB, 2025c) (b) improved early warning systems (Fekete & Sandholz, 2021), (c) community engagement and education (StEB, 2025c) and (d) ecosystem-based measures such as the creation of retention and detention areas, river restoration projects and urban green-blue infrastructures (StEB, 2025a). All the ecosystem-based measures aim to improve flood peak management, water absorption and reduce runoff and can be summarized under the umbrella term nature-based solutions (NbS).

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Sudmeier-Rieux et al. (2021) were able to demonstrate in a meta-study that there is evidence for ecosystem-based disaster risk reduction (Eco-DRR), including flooding. This applies to urban landscapes as well as to forests and river landscapes, all of which are found in the Cologne District. Nehren et al. (2023) developed a typology of nature-based solutions (NbS) for disaster risk reduction (DRR) and found, among other things, that Eco-DRR is the approach under the umbrella term NbS that aims to mitigate all types of natural hazards through ecosystems. However, there are numerous other approaches that include DRR as a co-benefit or secondary objective. These include for instance ecosystem-based adaptation (EbA) as well as various sectoral approaches (e.g., green-blue, infrastructure, bioengineering, building with nature) and various conservation and restoration approaches. This is important for the evaluation of existing NbS for flood mitigation in the Cologne District, as not all measures have the primary objective of flood protection but also include for instance measures under the European Water Framework Directive, which primarily aim to achieve a good ecological status of the watercourse and include flood protection only a co-benefit.

With regard to the creation of flood-resilient landscapes, it is important to first record and categorize existing and planned NbS interventions in order to obtain an overview of the various measures implemented by different actors at different times and at different spatial scales. It should be noted in particular that the term NbS is still relatively new and the individual measures are known in Germany under other terms such as green or blue infrastructures or simply as retention areas, while the term sponge city (German: Schwammstadt) is becoming increasingly important for urban areas.

Geographically, we focus on NbS measures along the Rhine River and the sub-catchments of the Wupper and Erft Rivers, which were strongly affected by the 2021 European floods. Within the context of Cologne as a City Lab under the NBSINFRA project, funded by Horizon Europe, we are also taking a closer look at the urban areas of Cologne and Leverkusen as examples and investigating which NbS for flood and storm water management have already been implemented there. The aims of the NBSINFRA project include demonstrating the viability of NbS to protect critical infrastructure and human lives from natural hazards, therefore our first research objective is derived from this context:

(1) Recording, categorising and presenting in a GIS the different types of existing and planned NbS for flood protection (a) along the Upper to Lower Rhine (river floods) that may impact Cologne City downstream, (b) along the Wupper River that can impact the city of Leverkusen and the Erft (river floods and flash floods) that can impact multiple small cities in Rhine Erft Kreis and (c) for the city of Cologne (river floods and pluvial floods).

In a second step, we identify areas where additional interventions could be focussed to increase flood resilience from a landscape perspective, taking into account climate projections and the resulting changes in hydrological and geomorphological process dynamics. However, factors such as land tenure and legal aspects remain unconsidered. Our second research objective is accordingly:

(2) Identifying, categorizing and evaluating potential areas to implement further NbS to increase flood resilience in the study area based on an indicator system.

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With our results, we inform scientists, planners and political decision-makers about the current status of NbS interventions for flood and storm water protection in the Cologne District and also identify further needs. In addition, we contribute to sharpening the concept of NbS in the context of flood risk mitigation. This is of fundamental importance for flood management in the region and can also serve as an example for other cities and agglomerations in Europe and beyond.

2 Methodology

2.1 Data sourcing and layer creation

Nature-based solutions (NbS) is a term applied to the broad and varied approaches that work by either protecting, enhancing or mimicking natural functions to improve natural, societal or economic resilience, including reducing the impact of natural hazards (Nehren et al., 2023). The broad and varying character and different scale of NbS means that identifying existing NbS is often not a priority for district administrations or emergency planners. However, as the need for strategically planned NbS intensifies along with the impacts of natural hazards, the need for recognizing, categorizing and documenting existing and planned NbS becomes more apparent.

In order to identify existing and planned NbS we conducted a search of online information provided by historical archives, the city of Cologne (Stadt Köln), the International Commission for the Protection of the Rhine (ICPR) and water resource managers, the "Stadtentwässerungsbetriebe Köln" (StEB; Cologne Municipal Drainage Operations), and the two catchment associations "Wupperverband" and "Erftverband". We also consulted online maps and maps provided by federal and state government bodies in Germany. Our aim is to identify near-natural to hybrid NbS (existing and planned) that function in a way that reduces the impact of flood hazards through flood peak reduction or water retention. All data sets used and the respective references are listed in Table 1.

We used spatial data available through state and federal German government bodies to identify the spatial extent of hazards, land cover, protected areas and designated floodplains. We also used the Copernicus permeability layer of the European Commission to illustrate the impermeable areas in Cologne City. Using the information available from the ICPR, Cologne city and the water resource managers, we created new layers to display the existing and planned NbS. NbS identified for flood mitigation includes retained floodplain, existing and planned retention/detention basins, renatured meanders and associated re-connected floodplains across Cologne City (and downstream along the Rhine), and in the Cologne Region of the Wupper and Erft catchments. For pluvial/stormwater floods in Cologne City we created a layer to show the measures planned to increase urban green areas and to implement the pilot multifunction retention areas. We also categorised the NbS through assessment of the NbS type, degree of engineering or naturalness, flood reduction capacity, co-benefits and potential risks. This recognises the uniqueness of each NbS feature and also allows for comparison, further assessment and monitoring to preserve the flood protection capacity and co-benefits that they provide, into the future.

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Table 1: Data sets used in this study

Data source	Dataset	Dataset available at:
BKG	Land cover/ land use	https://gdz.bkg.bund.de/index.php/default/open-data/corine-land-cover-5-ha-stand-2018-clc5-2018.html
Copernicus	Permeability	https://land.copernicus.eu/en/products/high-resolution-layer-imperviousness/impervious-built-up-2018
Erftverband	Location of flood infrastructure, Erft basin	https://www.erftverband.de/fluesse-und-seen/
ICPR	Location of flood infrastructure Upper Rhine	https://www.iksr.org/en/
OpenGeodata	Flood limits Designated floodplains	https://www.opengeodata.nrw.de/produkte/ HQhaeufig/HQ100/HQextreme Ueberschwemmungsgrenzen Überschwemmungsgebiete NRW
Region Köln Bonn e.V.	Hydrological risks	https://www.klimawandelvorsorge.de/home/ KWVS_Koelnbonn_20190930_DPhkategorien_S1-3 KWVS_Koelnbonn_20190930_DPhkategorien_A1-2 KWVS_Koelnbonn_20190930_DPhkategorien_W1-2
Stadt Köln	Green Master Plan Location of Urban forest Location of Nature reserves	https://www.stadt-koeln.de/artikel/73108/index.html https://www.stadt-koeln.de/leben-in-koeln/freizeit-natur-sport/wald/naturwaldentwicklungsflaechen-im-staedtischen-wald https://www.stadt-koeln.de/leben-in-koeln/klima-umwelt-tiere/naturschutzgebiete
StEB	Location of flood infrastructure, Cologne City	https://steb-koeln.de/hochwasser-und-ueberflutungsschutz/starkregen-und-sturzfluten/starkregen-und-sturzfluten.jsp
Wupperverband	Location of flood infrastructure, Wupper basin	https://www.wupperverband.de/unsere-aufgaben/hochwassermanagement

2.2 GIS-analyses of slope, topographic wetness index (TWI) and riparian land use

All spatial analysis was carried out in QGIS version 3.6.2. QGIS is an open-source geographic information system. Basin delineation, elevation and slope analyses were carried out using the USGS (2014) and NASA (2013) Digital Elevation Model (DEM). The DEM is a digital elevation topography dataset taken from the Shuttle Radar Topography Mission (SRTM) in 2000 and has a 1-arc-second resolution. Slope percentages were extracted using the DEM in Raster Analysis which was reclassified by table via the Toolbox Raster Analysis to generate slope at 6-15%, 15-25%, 25% and greater. The raster was then converted to vector format using the Raster Conversion tool to obtain more display options.

The Topographic Wetness Index (TWI) was calculated using the reprojected and filled DEM (USGS, 2014; Weng et al., 2009). The tan of the slopes was calculated in the Processing Toolbox, using the slope, aspect, curvature tool, creating a new layer. The DEM and slope in radians were then used as the input layers to the Saga, Topographic Wetness Index in the Processing toolbox. The standard method was used to process the TWI layer. TWI values ranged from 4.1 to 16.4. The TWI layer was then further processed to show only TWI cells ≥9 (highest 50%) and ≥11 (highest 70%) which were polygonised to aid display purposes.

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Riparian land use maps are based on Corine landcover maps (BKG, 2021). River lines from Region Köln Bonn (2019) were modified and a buffer zone of 10 m either side were created using the Buffer Geoprocessing tool. A 10 m buffer zone was chosen as a minimum to cover the legislated 5 m of riparian buffer strip zone either side of the river (Umweltbundesamt, 2012). The Vector Intersection tool was then used to create intersections with Corine ldcover (BKG, 2021) clc cass 2 (agricultural land use) and clc class 1 (urban land use) to indicate areas where little to no riparian woody vegetation exists in the riparian zone. The lack of woody vegetation was verified using the Google satellite view in QGIS.

3 Results

3.1 Geomorphologic-hydrological conditions as a basis for NbS interventions

As an essential basis for NbS interventions, we first consider the geomorphological and hydrological conditions of the water catchment areas and urban areas investigated. Figure 2 illustrates the differences in elevation and slope between the city of Cologne and the Wupper and Erft basins. While Cologne is situated in the Rhine floodplains and on the low-lying Rhine terraces in the Cologne Bay, the Erft and in particular the Wupper basin have higher topography, and greater slopes with higher occurrence. This has implications for the type of flood hazard likely to occur and the suitability of specific NbS.

Cologne is primarily subject to the major flood events of the Rhine, which have included historically devastating events, as well as to pluvial flooding. However, Rhine flood events occur relatively slowly due to the large catchment area and Cologne's location on the lower reaches of the Rhine, so that there is sufficient warning time to enact protective measures. In addition, many flood infrastructures that reduce the risk of flooding, such as mobile walls, have been implemented, particularly in the last few decades. However, due to the high and still increasing level of urban development, which is accompanied by the loss of open soils and ecosystems, there is an increased risk of storm water flooding, as less water is stored in urban soils and green spaces (Gramaglia et al., 2024; Senes et al., 2021).

In contrast the Cologne District areas in both the Erft and the Wupper basins are at the downstream end of higher relief and highly sloping land. For the Rhein-Erft-Kreis (municipality) in the Erft basin, this means the concentration of fast-moving water flow in a highly straightened and restricted channel. For the Rheinisch-Bergischer Kreis (municipality) in the Wupper Basin it means the rise of a very large number of small streams supplied and accelerated by runoff from the slopes and for the city of Leverkusen the confluence of these streams.

As previously mentioned, the differences in landscape and flood hazard also mean differences in suitability for NbS. Areas with low slope such as the city of Cologne and much of the lower Erft basin in the Cologne District are more suitable for retention/detention basins, secondary channels, floodplain reconnection or meander renaturation (Mubeen et al., 2021). However, they are also subject to restrictions due to more intensive land use, urbanization processes and more fragmented land ownership. Vegetation-based NbS are mostly more suitable in the middle part of the Wupper basin, with its higher sloping

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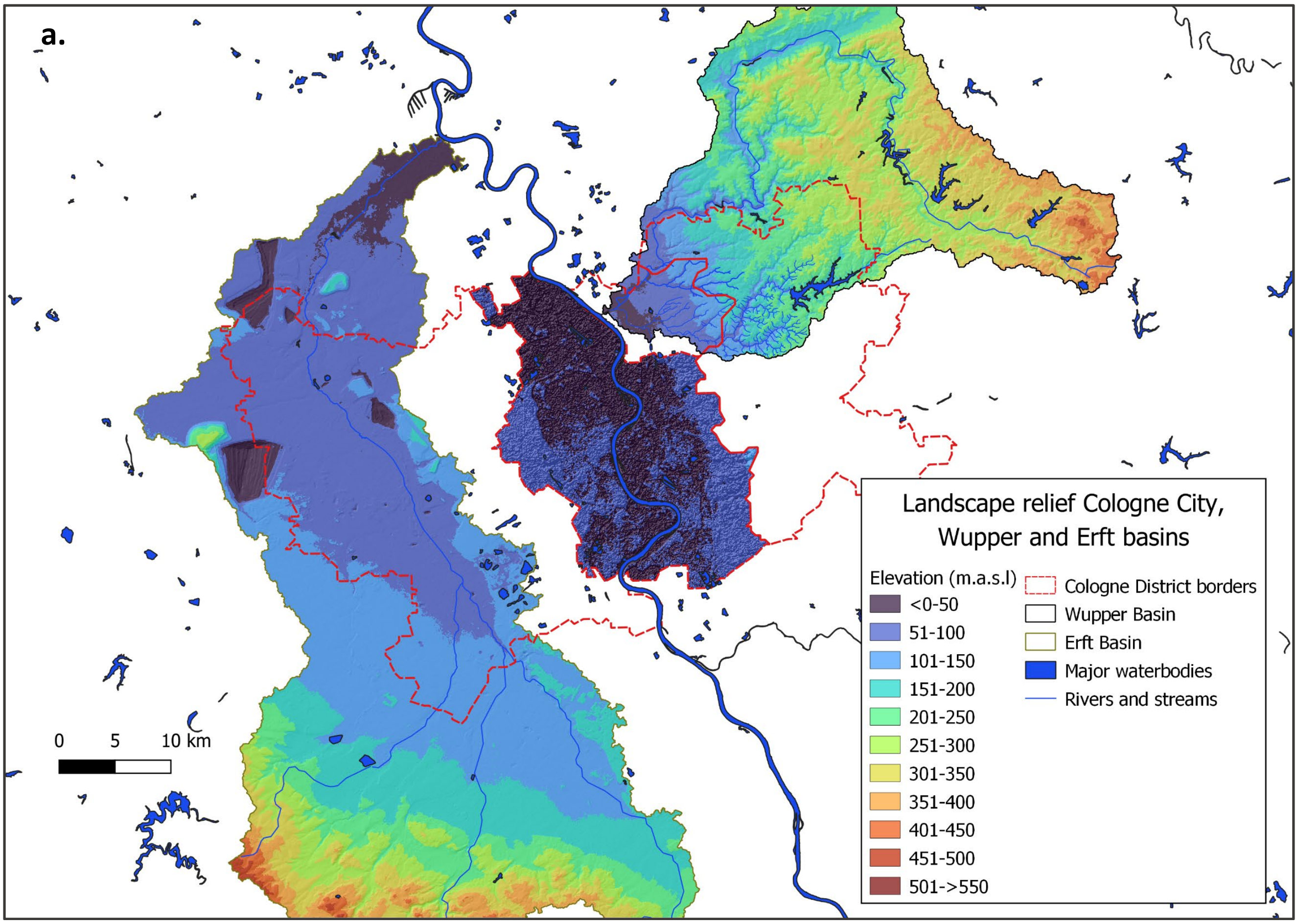
relief, as these provide the required stability to the soils and reduce the volume and velocity of runoff (Cooper et al., 2021). Vegetation selected for this purpose should be drought-tolerant, and native tree species should be given priority for nature conservation reasons. Implementation of NbS at these sites, however, are also subject to restrictions due to factors such as fragmented land ownership and nature conservation areas, while the lower, highly urbanized part of the catchment area with the city of Leverkusen is subject to the same restrictions as in the city of Cologne and the lower Erft area.



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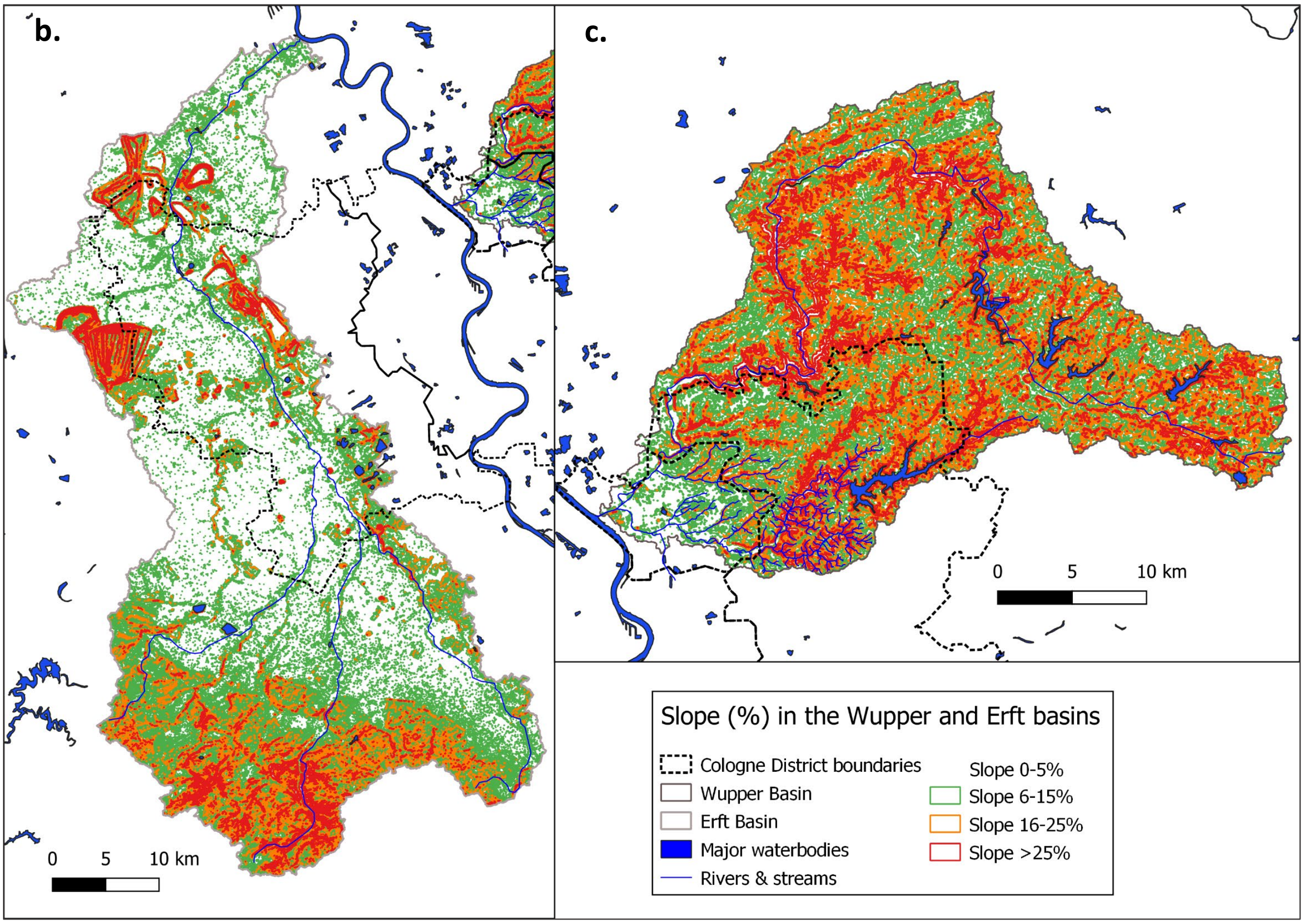

Figure 2: (a) Elevation in meters above sea level (M.A.S.L) of the three study regions in the Cologne District; (b) slope classes in the Erft Basin; (c) slope classes in the Wupper Basin. Data sources: BKG, 2021; Diva-GIS, n.d.; NASA, 2013; USGS, 2014. Processed in QGIS 3.6.2.

3.2 NbS for Rhine flood mitigation

Flood water retention/detention and reinstatement of floodplain capacities where possible along the Rhine, have been the focus of flood management for the International Commission for the Protection of the Rhine (ICPR) since the major floods in 1993 and 1995 (ICPR, 2021). The Upper Rhine, upstream of Cologne, currently has a total flood water retention capacity of 157.1 million m3 in the form of hybrid and blue-green retention polders and due to an ongoing dike relocation strategy, the closest fifteen (from Strasbourg) are shown in Figure 3. The addition of the current retention capacity in the city of Cologne brings this to 161.6 million m3. Including the planned retention area Worringer Bruch (29.5 million m3) and others in the Upper

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Rhine. Flood retention/detention from the Upper Rhine to (and including) Cologne is expected to total around 339.7 million m3 by 2027 (ICPR, 2021).

The extent to which flood infrastructure, such as retention polders, located upstream of Cologne reduce the impacts of flooding in Cologne City are not precisely quantifiable. This is because floods in such large river basins can vary based on rainfall in different tributaries, local channel characteristics and management decisions on the operation of flood reduction infrastructure. While retention/detention basins have a greater local impact on floodwaters, the detention or retention of water upstream has the effect of reducing, to some extent, the flood peak downstream, especially given larger capacities.

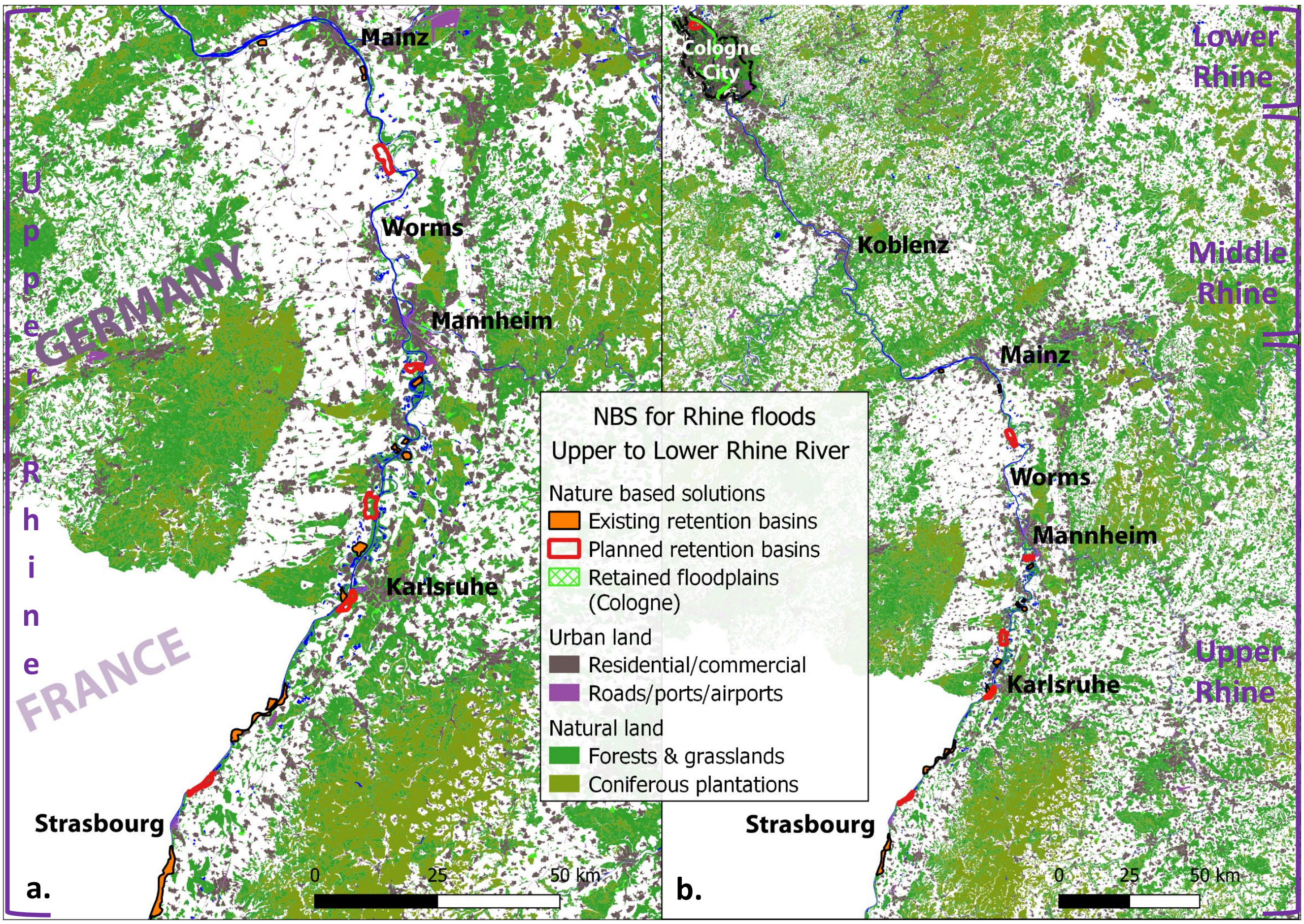

Figure 3: NbS for Rhine floods (left) Strasbourg to Mainz (Upper Rhine) and (right) Strasbourg (Upper Rhine) to Cologne City (Lower Rhine). Data sources: BKG, 2021; ICPR, 2021; OpenGeodata. NRW, n.d. Prepared in QGIS 3.6.2

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The city of Cologne is a historic city on the Rhine, which was founded around 50 AD by the Roman Empire and, due to its narrow radial structure in the inner, flood-prone urban area along the Rhine, has only a few undeveloped areas in the center. As a result, flood defences in the inner city include a combination of engineered retaining walls (mobile), dykes, and pumping stations. NbS are comprised of flood retention polders (one established and one planned), which are located in the very south and north of the city, and retained floodplains. Figure 4 illustrates the NbS in Cologne City that have the primary purpose of protecting the city from Rhine floods.

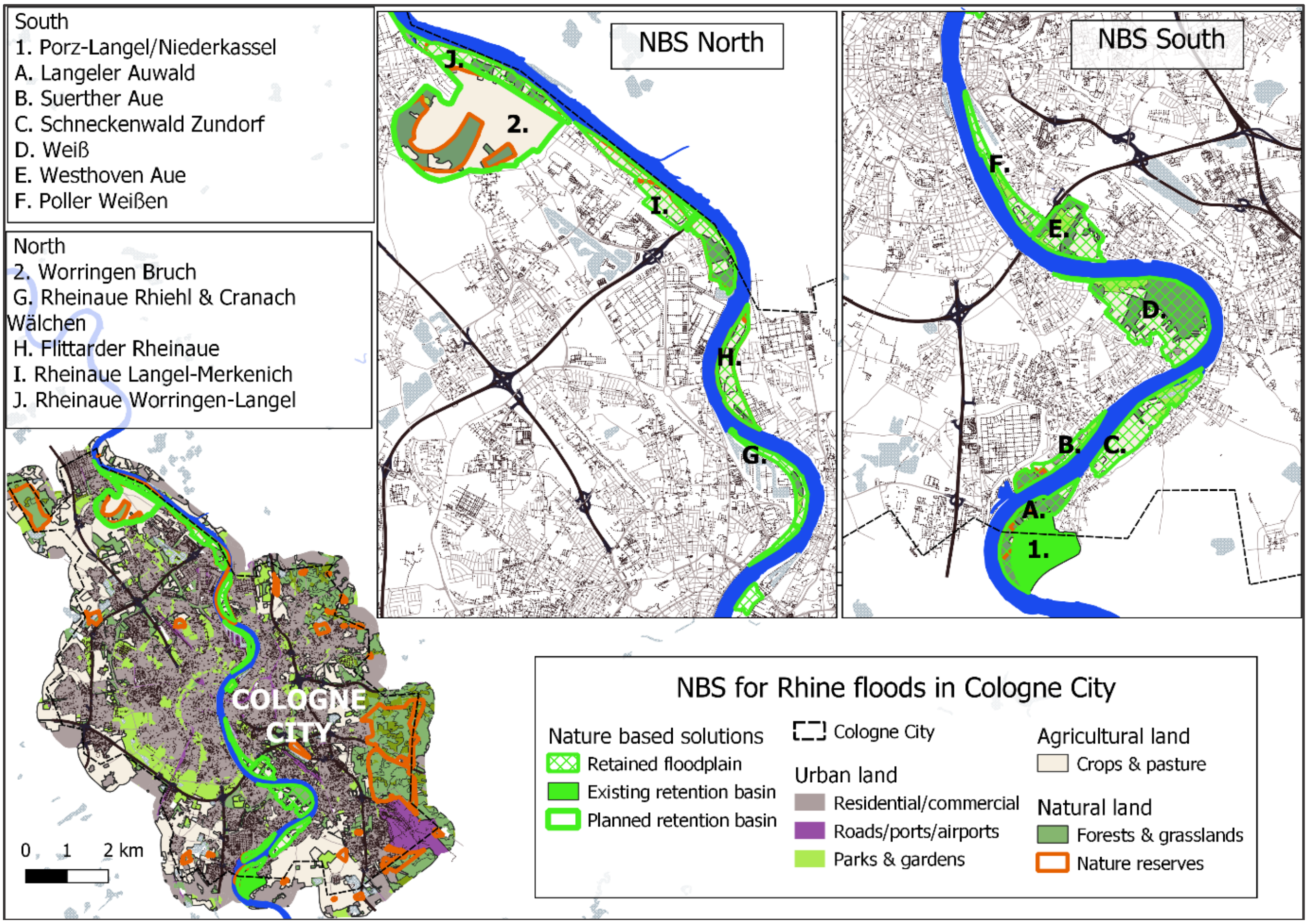

Figure 4: NbS for Rhine floods in Cologne City. Data sources: BKG, 2021; Diva-GIS, n.d.; OpenGeodata.NRW, n.d.; © OpenStreetMap contributors 2015. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.; StEB, 2025a, 2025b. Processed in QGIS 3.6.2.

NbS can vary in regards to the degree of naturalness and with regards to how it is combined with engineered structures, as a result, different NbS can offer varying levels of flood protection and also different co-benefits in form of ecosystem services (Nehren et al. 2023). In Table 2, the NbS are categorised and described in terms of their feature(s), type, degree of naturalness,

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water retention capacity (cubic meters or hectares) and/or modelled flood peak reduction (if available), co-benefits (ecosystem services) and potential risk to the local environment.

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Table 2: NbS for Rhine River flood mitigation Cologne city.

NbS feature	NbS type	Degree of Naturalness	Water retention capacity	Co-benefits in form of ecosystem services[1]	Risks and challenges
Flood retention basin Cologne-Porz-Langel / Niederkassel-Lülsdorf (ICPR, 2021; StEB, 2025a)	Hybrid (blue-green & grey)	Cultural: engineered levees with secondary land use of agriculture	Across an area of 160 ha this retention basin can reduce the flood wave height in Cologne by up to 5 cm	Food production (agricultural land), habitat provision, soil formation, carbon sequestration, recreation	Water pollution, soil pollution
Planned flood retention basin Worringer Bruch (ICPR, 2021; StEB, 2025b)	Hybrid (blue-green & grey)	Semi-natural: engineered levee with mix of natural wetland, forest and agriculture as secondary land use	Planned flood retention basin (670 ha) will reduce flood height by up to 17 cm and extend the emergency response time by 14 hours	Climate regulation, habitat provision, carbon sequestration, recreation, landscape aesthetics	Water pollution, soil pollution, carbon emissions
Retained floodplain Langeler Auwald (Stadt Köln, n.db; Stadt Köln, 2021)	Blue-green	Near-natural: natural succession riparian vegetation that has been undisturbed from at least 1828	More than 57 ha for the spread of floodwater	Climate regulation, habitat provision (breeding site for native bird and bat species), carbon sequestration, recreation, landscape aesthetics	Limited flood control infrastructure may pose risks during extreme events, sensitive to sudden climate shifts
Retained floodplain Sürther Aue (Stadt Köln, n.db; Stadt Köln, 2021)	Blue-green	Semi-natural: historically used as a port, dredging dump and farmland, now preserved and includes a nature reserve	34.4 ha for the spread of floodwater.	Climate regulation, habitat provision, carbon sequestration, recreation, landscape aesthetics	Altered soil profile, legacy contamination from prior port, soil disturbance and compaction
Retained floodplain Rheinaue Worringen-Langel (Stadt Köln, n.db)	Blue-green	Near-natural: grassland, remnants of both softwood and hardwood forests and areas converted to agricultural meadowlands; protected species and an oxbow lake	204 ha for the spread of floodwater	Climate regulation, habitat provision, carbon sequestration, recreation, landscape aesthetics	Carbon emissions from wet areas, soil compaction from grazing, habitat fragmentation
Retained floodplain Weiß (Stadt Köln, n.dc)	Blue-green	Semi-natural: used as agricultural land and vineyards since at least 1130; now a mix of agriculture and forest	335 ha for the spread of floodwater	Food production (agricultural land), habitat provision, climate regulation, soil formation, carbon sequestration, recreation	Agricultural runoff, habitat fragmentation, reduced biodiversity, conflicting land uses, invasive species,

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					maintenance burden
Retained floodplain Westhovener Aue (Stadt Köln, n.dc; 1995; n.da)	Blue-green	Semi-natural and cultural: mix of parkland, sporting and camping facilities, restored forest and garden allotments	140 ha for the spread of floodwater (Archivgruppe Bürgervereinigung Ensen-Westhoven, 2022)	Food production (agricultural land), habitat provision, climate regulation, soil formation, carbon sequestration, recreation	Habitat fragmentation, reduced biodiversity, conflicting land uses, invasive species, maintenance burden
Retained floodplain Poller Wiesen (Stadt Köln, n.dc)	Blue-green	Semi-natural and cultural: mix of green urban areas and grazing	Up to 77 ha for the spread of floodwater	Habitat provision (semi-natural and cultural land use), climate regulation, soil formation, carbon sequestration, recreation, landscape aesthetics	Unprotected floodplain, land use conflicts, invasive species, limited water retention capacity
Retained floodplains Schneckwald Zündorf (Cityinfo-koeln.de, n.d; Porz Am Rhein, 2003)	Blue-green	Semi-natural and Cultural: mix of green urban area, recreation facilities and farmland	Provides up to 155 ha for the spread of floodwater	Habitat provision (semi-natural and cultural land use), climate regulation, soil formation, carbon sequestration, recreation, landscape aesthetics	Unprotected floodplain, land use conflicts, invasive species, soil compaction, limited water retention capacity
Retained floodplains Rheinaue Riehl and Cranach Wäldchen (Brokmeier, n.d.; Brüggermann, 2014)	Blue-green	Semi-natural: mix of successional forest and parklands	Allows for the spread of floodwater across 70 ha	Habitat provision (promotes successional forest development and ecological connectivity), climate regulation, soil formation, carbon sequestration, recreation, landscape aesthetics	Altered soil profile, legacy pollutants
Retained floodplain Flittarder Rheinaue (Stadt Köln, n.d-b)	Blue-green	Semi-natural: mix of replanted forest and open grasslands with oxbow lake wetland	Provides up to 180 ha for the spread of floodwater	Habitat provision (wetland and oxbow lake), climate regulation, soil formation, carbon sequestration, recreation, landscape aesthetics	Vegetation management challenges, lacks formal flood control structures, mosquito breeding
Retained floodplain Rheinaue Langel-Merkenich (Stadt Köln, n.d-b)	Blue-green	Near-natural: succession fragments with softwood/hardwood biotopes	Allows floodwater to spread across 460 ha	Habitat provision, climate regulation, soil formation, carbon sequestration, recreation, landscape aesthetics	Maintenance burden, limited infrastructure, sensitive to sudden climate shifts

[1] The catalogue includes important provisioning, regulatory and cultural services in accordance with the descriptions of the measures, but does not claim to be exhaustive

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3.3 NbS for stormwater inundation mitigation in the city of Cologne

Stormwater inundation is a problem for cities worldwide, due to the high prevalence of surface sealing and the replacement of natural landscapes with the hard, impervious construction associated with the built environment (Feng et al., 2021). Both the municipal water managers StEB and the City of Cologne are working on NbS related plans to reduce the risk of stormwater inundation and flash floods as a result of heavy rainfall episodes. The StEB (2025c) have plans to pilot "multifunctional retention areas" for stormwater retention, which include the use of public green areas and open spaces including that of car parks and public squares, to contain stormwater. The two pilot areas will be in open areas in Eil-Süd in the Southeast of the city. The Stadt Koeln (2023) strategy is to ensure conservation of the existing green areas in the green-belt/green corridors concept in which two concentric green area bands circle the city, and where possible complete the green-belt in areas of minimum coverage. On a broad scale these green rings around the city act to soak-up excess rain and stormwater. These measures are the starting point for a larger program for climate change adaptation in the city of Cologne which also includes modifications to grey infrastructure to hold more stormwater runoff and support for unsealing and green roof installation which also play a role in the prevention of stormwater flooding at the local scale (StEB, 2025c).

Figure 5 shows the location of NbS that can reduce the impacts of stormwater overflow and flash floods. These NbS include existing forests, grasslands, parks and gardens, and also the planned extension of the green belt and pilot multifunctional retention areas (Table 3). The figure also shows the potential for unsealing, green roofs and further expansion of the green belt/green corridor concept due to the concentration and extent of impermeable land cover, especially in central and southeast Cologne.

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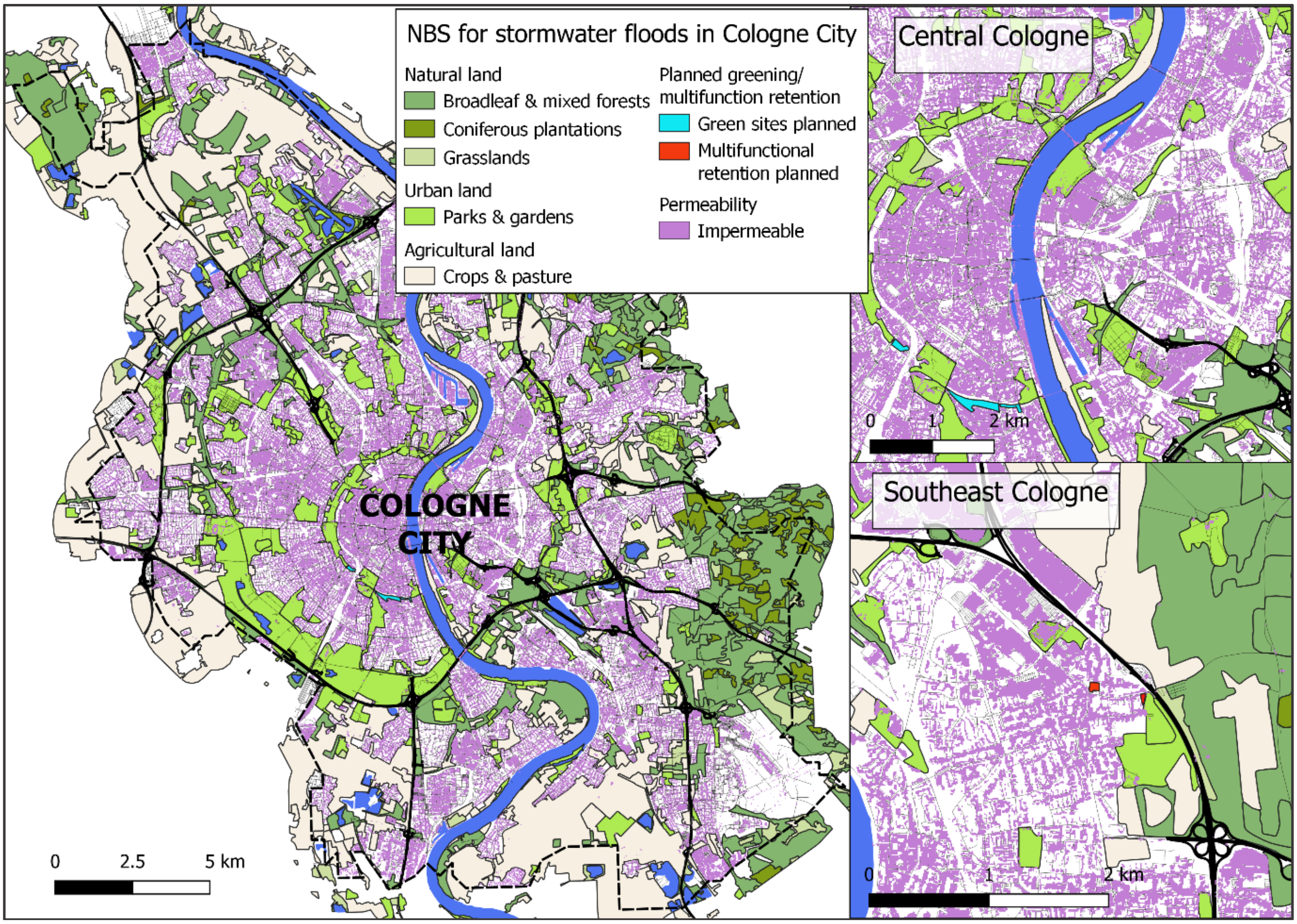

265 **Figure 5: NbS for stormwater floods in Cologne City. Data sources: BKG, 2021; Copernicus,2018; Diva-GIS, n.d.; © OpenStreetMap contributors 2015. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.; StEB, 2025, Stadt Koeln, 2023. Processed in QGIS 3.6.2.**

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Table 3: NbS for pluvial/stormwater flood mitigation in Cologne City.

NbS feature	NbS type	Degree of Naturalness	Water retention capacity	Co-benefits in form of ecosystem services[1]	Risks and challenges
Existing forest and natural grassland area	Green	Natural	Up to 10,900 ha	Habitat provision, climate regulation, soil formation, carbon sequestration, recreation, landscape aesthetics	Wildfire, habitat fragmentation, maintenance burden
Existing parks & gardens (Green belt/ corridors)	Green	Semi-natural to cultural: constructed but areas varying between cultivated grassed, maintained and non-maintained trees and areas set aside for nature	Up to 4,279 ha	Habitat provision, climate regulation, soil formation, carbon sequestration, recreation, landscape aesthetics	Habitat fragmentation, maintenance burden, land use conflicts, invasive species
Planned extension to green belt	Green	Semi-natural to cultural:	32 ha	Habitat provision, climate regulation, soil formation, carbon sequestration, recreation, landscape aesthetics	Habitat fragmentation, maintenance burden, land use conflicts, invasive species
Pilot multifunctional retention areas	Hybrid (grey-green)	Semi-natural to cultural: areas vary between parks, parking lots and public squares	Not disclosed	Recreation	Limited flood control infrastructure may pose risks during extreme events, pollution runoff and concentration, risks for unaware residents during flooding

[1] The catalogue includes important provisioning, regulatory and cultural services in accordance with the descriptions of the measures, but does not claim to be exhaustive. The NbS features are based on Masterplan Stadtgruen, 2023

3.4 NbS for flood mitigation in the Wupper Basin

The Wupper Basin within the administrative district of Cologne is comprised of the undulating and predominantly rural pastoral landscape of Rheinisch Bergischer Kreis, where many small tributaries of the Wupper originate, and the industrial city of Leverkusen, where the many small streams along with the Wupper and the Dhün converge before discharging to the Rhine. NbS in the Cologne District part of the Wupper catchment include small retention basins, two existing and one planned and sections of renatured stream, one existing and several sites identified for potential restoration and renaturation. Many areas of natural riparian vegetation in the catchment are protected and these, as well as the scattered broadleaf forests act as natural NbS retaining water in the landscape and reducing rainfall runoff. Figure 6 shows the location of existing and planned NbS in the city of Leverkusen and the Rheinisch Bergischer Kreis.

The Wupperverband (Wupper Association) has been a public corporation since 1930 and is one of the largest water management associations in North Rhine-Westphalia. It is responsible for water management in the Wupper catchment area

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and operates 26 flood retention basins within the wider Wupper Basin. Most of the retention basins have a limited capacity and are located on the Wupper and its tributaries in the upper reaches of the catchment area outside the Cologne district, e.g., in the municipalities of Wuppertal and Wermelskirchen. Small retention basins in these locations are useful for local urban areas but would have little impact on the downstream locations such as Leverkusen and Solingen (ICPR, 2020). Several large dams are located in the upper reaches of the basin and on the Dhünn River. While these are grey or engineered infrastructure used for water supply and drinking water supplies, some have a large capacity such as the Great Dhünn Dam and are also used to reduce the impact of flooding on downstream locations such as Leverkusen. These dams also provide environmental releases into the river when water is low water to maintain river ecology (Wupperverband, n.dc). Within the administrative district of Cologne, Rheinisch-Bergischer Kreis and in the city of Leverkusen, there are a total of three nature-based retention basins (existing and planned) and one restored river section. The existing and planned NbS are illustrated in Figure 6 and described and categorised in Table 4.

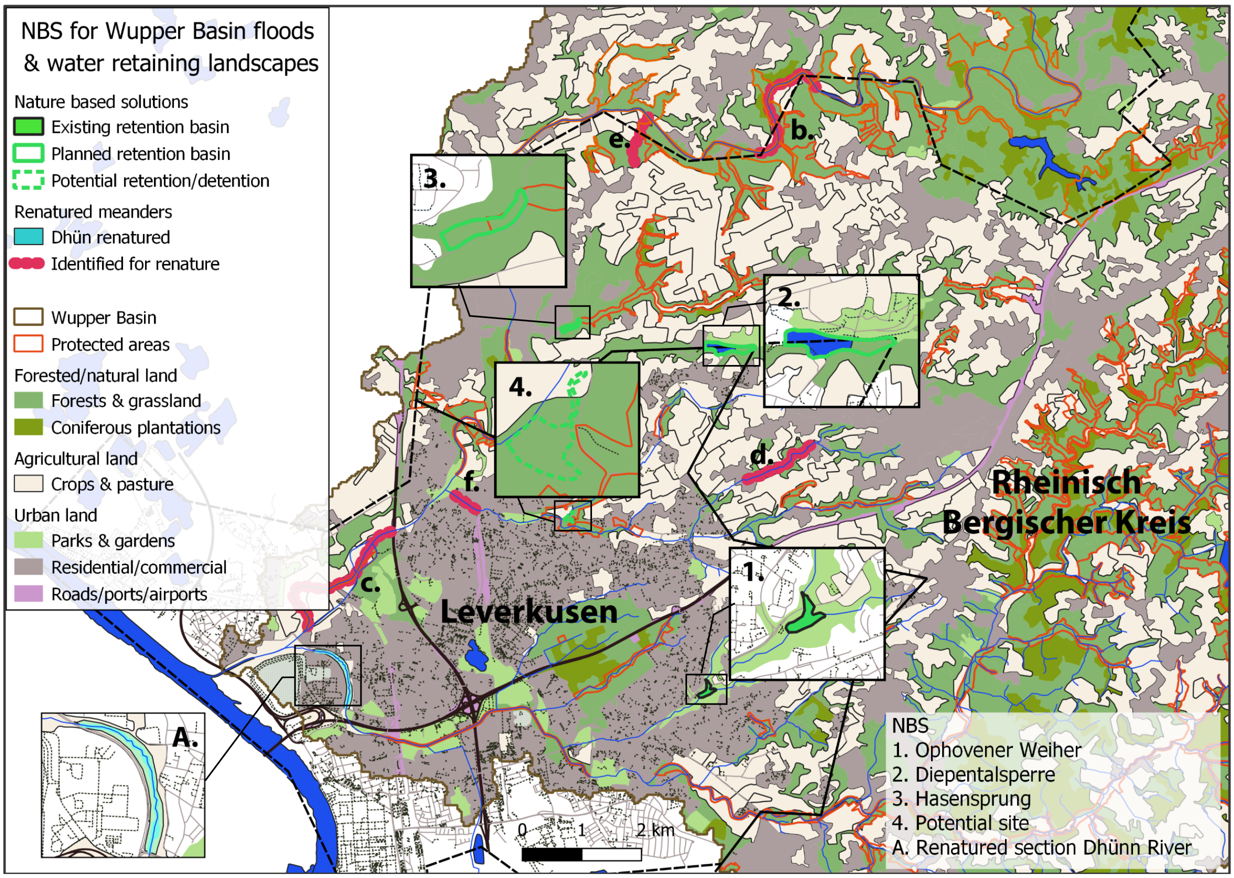

Figure 6: Flood NbS and water retaining landscapes in Leverkusen and Rheinisch-Bergischer Kreis. Data sources: BKG, 2021; Diva-GIS, n.d.; OpenGeodata. NRW, n.d.; © OpenStreetMap contributors 2015. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.; Stadt Leverkusen, 2025; USGS, 2014; Wupperverband, n.da, n.db. Processed in QGIS 3.6.2

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Table 4: NbS for river flood mitigation in the Wupper.

NBS feature	NbS type	Degree of naturalness	Water retention capacity	Co-benefits in form of ecosystem services[1]	Risks and challenges
Flood retention basin Ophovener Weiher (Leverkusen) (Wupperverband, 2022)	Hybrid (blue & grey)	Cultural (recreational green space with engineered retention)	Year-round water retention up to 30,000 m³; expansion planned to enhance flood and operational capacity	Habitat provision, climate regulation, soil formation, carbon sequestration, recreation (parkland), landscape aesthetics	Limited ecological function; infrastructure dependence; space constraints for expansion
Planned flood retention basin Diepantal (Rheinisch Bergischer Kreis) (Wupperverband, 2022; 2023)	Hybrid (blue-green & grey)	Semi-natural (mix of planned naturalization with habitat creation)	Floodwater capacity not disclosed. Conversion from a dam into a flood retention basin with renatured stream and habitat for local species	Habitat provision, climate regulation, soil formation, carbon sequestration, stream connectivity	Uncertain ecological success, construction-phase disturbance, delayed implementation
Planned flood retention basin Hasensprung (Rheinisch Bergischer Kreis) (Wupperverband, 2022)	Hybrid (blue-green & grey)	Cultural (mix of existing grassed strip and planned retention adaptation)	Floodwater capacity not disclosed. Planned designation of low-lying area with pond as formal flood retention basin	Potential for integrated green infrastructure, landscape enhancement, local flood control	May offer limited capacity without a redesign; risk of underperformance
Renatured river section Dhünn River (Leverkusen) (Wupperverband, 2004)	Blue-green	Near-natural (former channelized section with restored meanders)	Provides natural water storage and potential for slowing of floodwaters; limited impact on flood risk due to small scale	Aquatic habitat restoration, riparian vegetation recovery, biodiversity refuge, improves habitat quality and supports riparian regeneration;	Minimal flood protection value, potential for unmanaged vegetation spread

[1] The catalogue includes important provisioning, regulatory and cultural services in accordance with the descriptions of the measures, but does not claim to be exhaustive.

In addition to the already restored river section, the Wupper Association is also reportedly planning to restore and renaturalize the floodplain connectivity in certain sections of the Wupper and some of its tributaries. A number of these are within the Rheinisch-Bergischer Kreis and Leverkusen regions. This includes the Wupper from Auer Kotten to behind Untenrüden in Solingen (b. in Figure 5) and the Wupper below Opladen (c. in Figure 6). The sections of the Bornheimer Bach / Großhamberg at Burscheid (d. in Figure 6) and the Leysiefen in Leichlingen (e. in Figure 6) are also marked for restoration and renaturation (Wupperverband, n.db). Such measures can work to increase the area available for the river to spill during floods, enable runoff collection for dry periods and increase habitat and species diversity.

During the heavy rainfall event in July 2021, inundation caused by the Wupper and the Wiembach, a stream that flows into the Wupper in Opladen, resulted in major property damage in the Leverkusen district of Opladen (Stadt Leverkusen, 2025). The city of Leverkusen is currently working on a feasibility study to identify possible blue, green and grey infrastructures to reduce the impact of flooding and increase natural areas and has identified two potential sites. The first area Pintsch-

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Oelgelaende (4. in Figure 6) located at the conjunction of the Wiembach and the Oelbach, was identified for a retention basin (although due to the site being a nature reserve and required removal of trees and potential for contamination from the soil, this is unlikely to be developed). The second potential is for the widening of the Wiembach Allee (f. in Figure 6), which would lower the flow by up to 17cm, however, this would also mean that around 300 trees would be removed (Stadt Leverkusen, 2025).

3.5 NbS for flood mitigation in the Erft Basin

In terms of landscape hydrology, the Erft basin has a higher relief energy in the south, in the low mountain range of the Eifel, where the river originates, while the relief in the Cologne urban area is undulating to flat and a number of small towns have settled along the river, surrounded by predominantly agricultural land. However, the landscape of the Erft basin in the Cologne District is extensively reshaped as a result of lignite coal mining in the region, which has also significantly changed the hydrology. Above all, the groundwater was pumped out for the large-scale open-cast mining and discharged into the Erft, so that the river carries significantly more water downstream than it would do naturally. In addition, large sections of the river were straightened and embanked and parts of it were relocated.

Across the Erft catchment, the Erftverband (Erft Association) operates 23 retention/detention basins that can store approximately 7.73 million m3 floodwater in total. Three of the largest are found near to or within Rhein-Erft-Kreis, where the large basins are designed to retain floodwaters for a HQ 100 year flood (Erftverband, 2022). Compared to the Wupper Basin, there is little remaining natural vegetation along the Erft waterways with only small fragments of remaining and of protected riparian vegetation. However, several small sections of the Erft River and its tributaries have been restored and re-natured, where bank protection and levees have been removed and meanders or instream islands have been recreated. Renaturing acts to increase the ecological status of the waterways and to provide natural water retention by slowing the flow of the river and providing the space for water storage in the floodplains and wetlands. Figure 7 shows the location of existing and planned NbS for floods in Rhein Erft Kreis, and Table 5 provides a brief characterization of the interventions.

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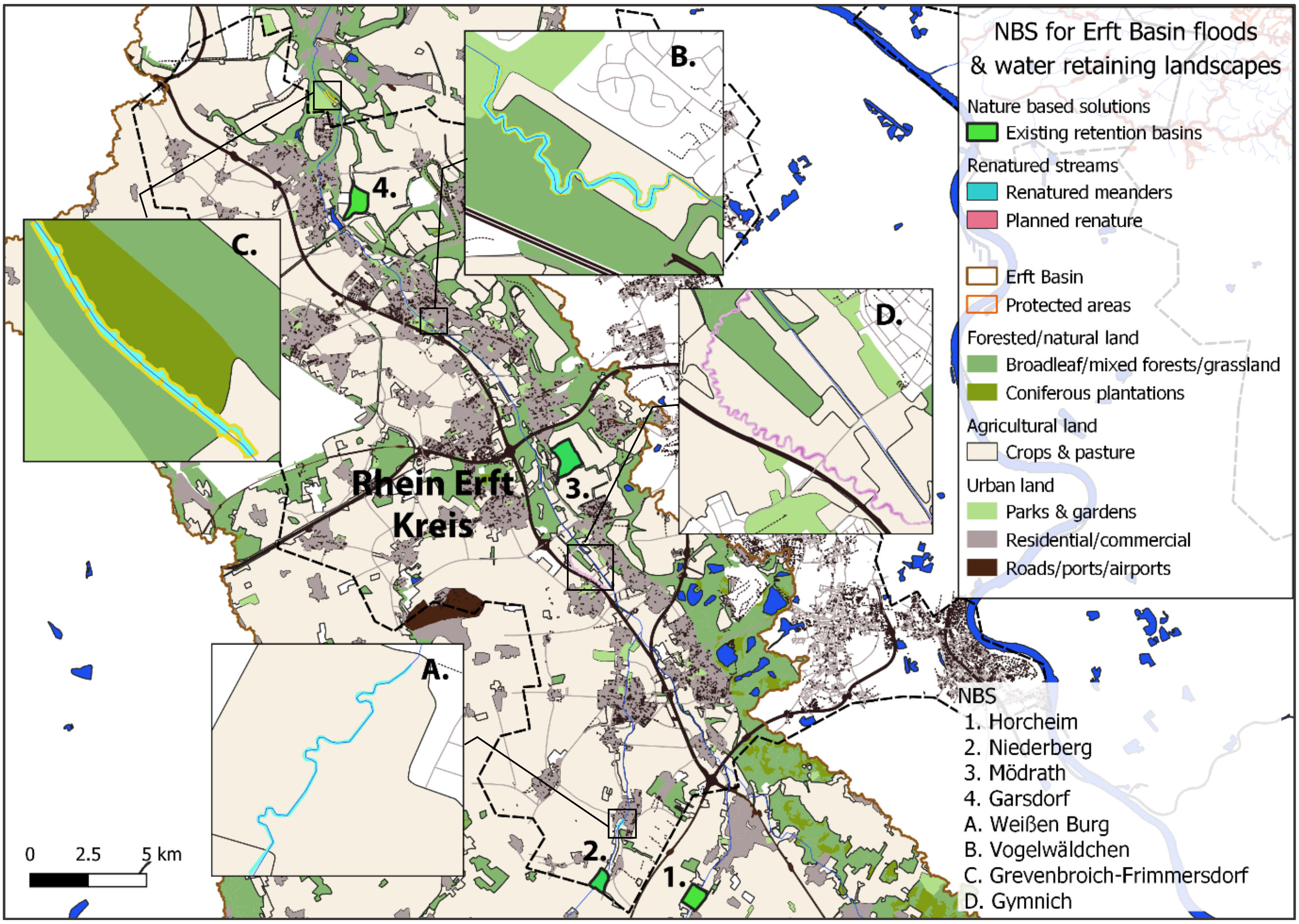

345 **Figure 7: Flood NbS and water retaining landscapes in Rhein Erft Kreis. Data sources: BKG, 2021; Diva-GIS, n.d.; Erftverband, n.da, n.db; OpenGeodata. NRW, n.d.; © OpenStreetMap contributors 2015. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.; NASA, 2013. Processed in QGIS 3.6.2**

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Table 5: NbS for river flood mitigation in the Erft.

NbS feature	NbS type	Degree of naturalness	Water retention capacity	Co-benefits in form of ecosystem services[1]	Risks and challenges
Flood retention basin Horcheim (Erftverband, 2022)	Hybrid (blue-green & grey)	Cultural (agriculture and flood control infrastructure)	Holds 1.072 million m³ of floodwater with controlled release on the Erft River	Food production (agricultural land), habitat provision, soil formation, carbon sequestration, recreation	Ecological limitations, land-use conflict during flood events
Flood retention basin Niederberg (Erftverband, 2022; 2006)	Hybrid (blue-green & grey)	Semi-natural (mix of pastureland, riparian planting)	Contains up to 0.930 million m³ capacity for floodwater to protect Erftstadt	Riparian habitat creation, pastureland use, minor wetland formation	Seasonal ecological function, limited biodiversity value outside flood events
Flood retention basin Mödrath (Erftverband, 2022; 2024; 2009)	Hybrid (blue-green & grey)	Semi-natural (mix of former mine, forested green space and pasture)	Holds 1.44 million m³ of floodwater to protect the city of Bergheim from flooding	Recreational and mixed land use (green space, pasture), biodiversity support, forest habitat	Habitat fragmentation, legacy land disturbance
Flood retention basin Garsdorf (Erftverband, 2022; 2024; 2008)	Hybrid (blue-green & grey)	Semi-natural former coal mining site and now a series of small lakes and woodland	Protects the city of Bedburg from flooding through storage capacity of 1.032 million m³	Recreational and mixed land use (green space, pasture), biodiversity support, forest habitat	Habitat fragmentation, legacy land disturbance
Renatured river section An der Weißen Burg (Erftverband, 2023)	Blue-green	Semi-natural (renatured meanders and floodplain reconnection surrounded by pastureland)	Extension of the river flow path to 170 m and added 1.2 ha of connected floodplain	Flow velocity reduction, aquatic habitat,	Limited capacity for major floods, sediment buildup, vegetation overgrowth
Renatured river section Vogelwäldchen (Erftverband, 2021)	Blue-green	Near-natural (meander recreation and floodplain reconnection with beginnings of natural vegetation succession)	1.3 km of meanders added and 25 ha floodplain reconnected, can act to store water naturally and potentially slow the flow of floodwater	Habitat diversity, flow velocity reduction, aquatic habitat	Limited capacity for major floods, sediment buildup, vegetation overgrowth, invasive species
Renatured river section Grevenbroich-Frimmersdorf (Grevenbroich) (Erftverband, 2018)	Blue-green	Near-natural (renatured bank structures provide diverse flow and habitat via islands and groynes)	May slow the flow of floodwaters as bank was protection removed and islands and groynes added to flow diversify	Flow diversity, improved aquatic and riparian ecosystems	Maintenance needs for dynamic features; variable sedimentation
Planned renaturation of river section Gymnich (Erftverband, 2018)	Blue-green	Semi-natural (planned renaturation of meanders and connection with floodplain with highly urban surrounds)	Extension of the flow of the river by 3 km to 5.5km creates water storage and may slow floodwaters	Habitat diversity, flow velocity reduction, aquatic habitat	Limited capacity for floods, sediment buildup, vegetation overgrowth

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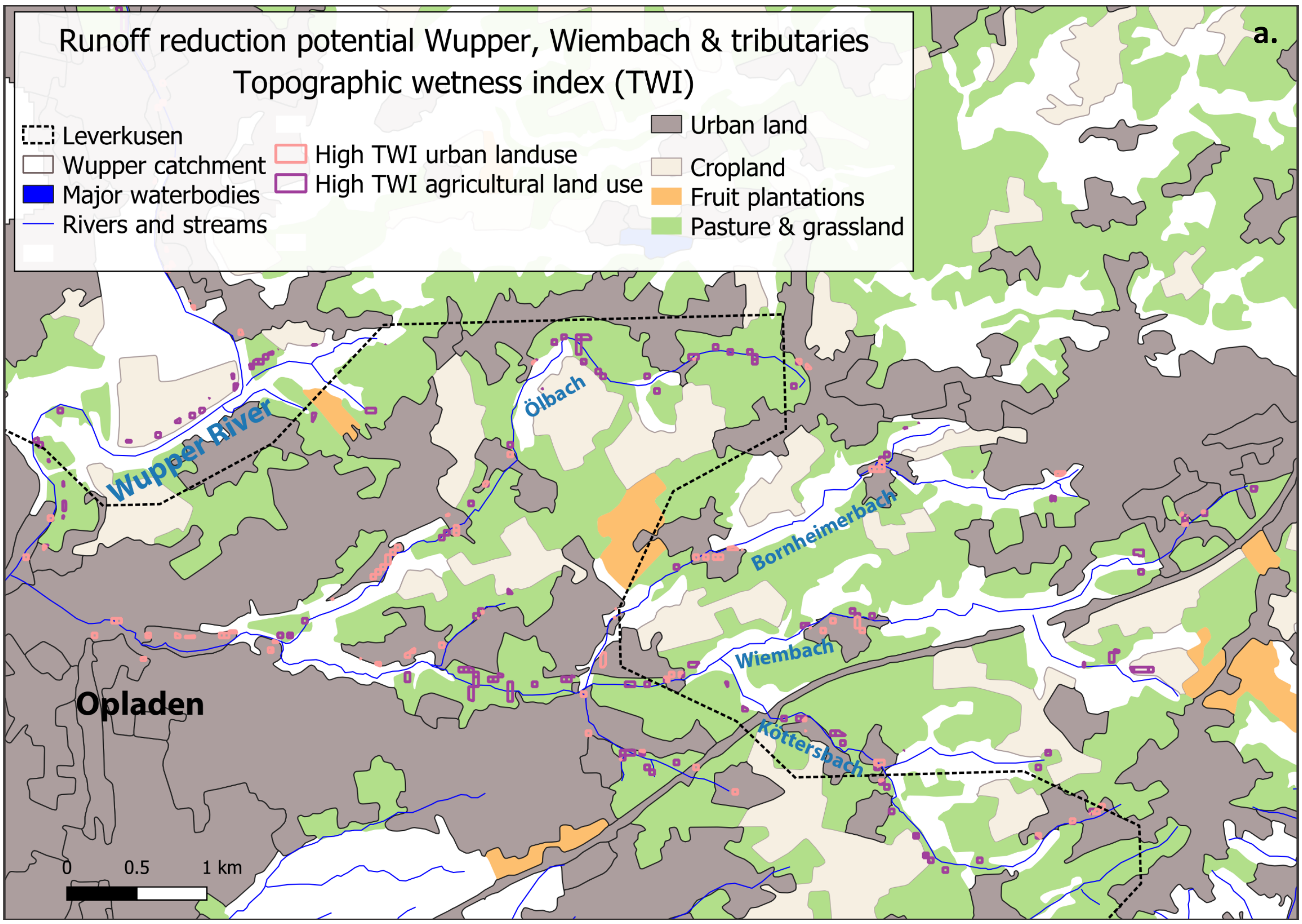
3.6 Identification of additional sites for NbS interventions in the Erft and Wupper basins

Based on landscape GIS analysis (see Figures 2a, b & c) and the hazard reduction needs identified by the outcomes of the July 2021 floods, sites in the Erft and Wupper basins are deemed suitable for a broad range of additional NbS interventions. The twin hazards of pluvial and fluvial flooding were features of the July 2021 floods in Germany (Fekete & Sandholz, 2021; Kron et al., 2022). These floods were the result of the high precipitation amounts from the stationary storm Bernd, and runoff induced by antecedent soil moisture that was moderate, but high enough to lead to rapid runoff which was intensified in the highly sloping areas (Mohr et al., 2023).

Depending on the existing land cover, these sites would be suitable for a range of NbS including unsealing with permeable pavements, increasing water retention with vegetated swales, infiltration trenches, rain gardens, filter strips and various rainwater storage NbS. Indicators, land use/ land cover and suitable NbS are listed in Table 6.



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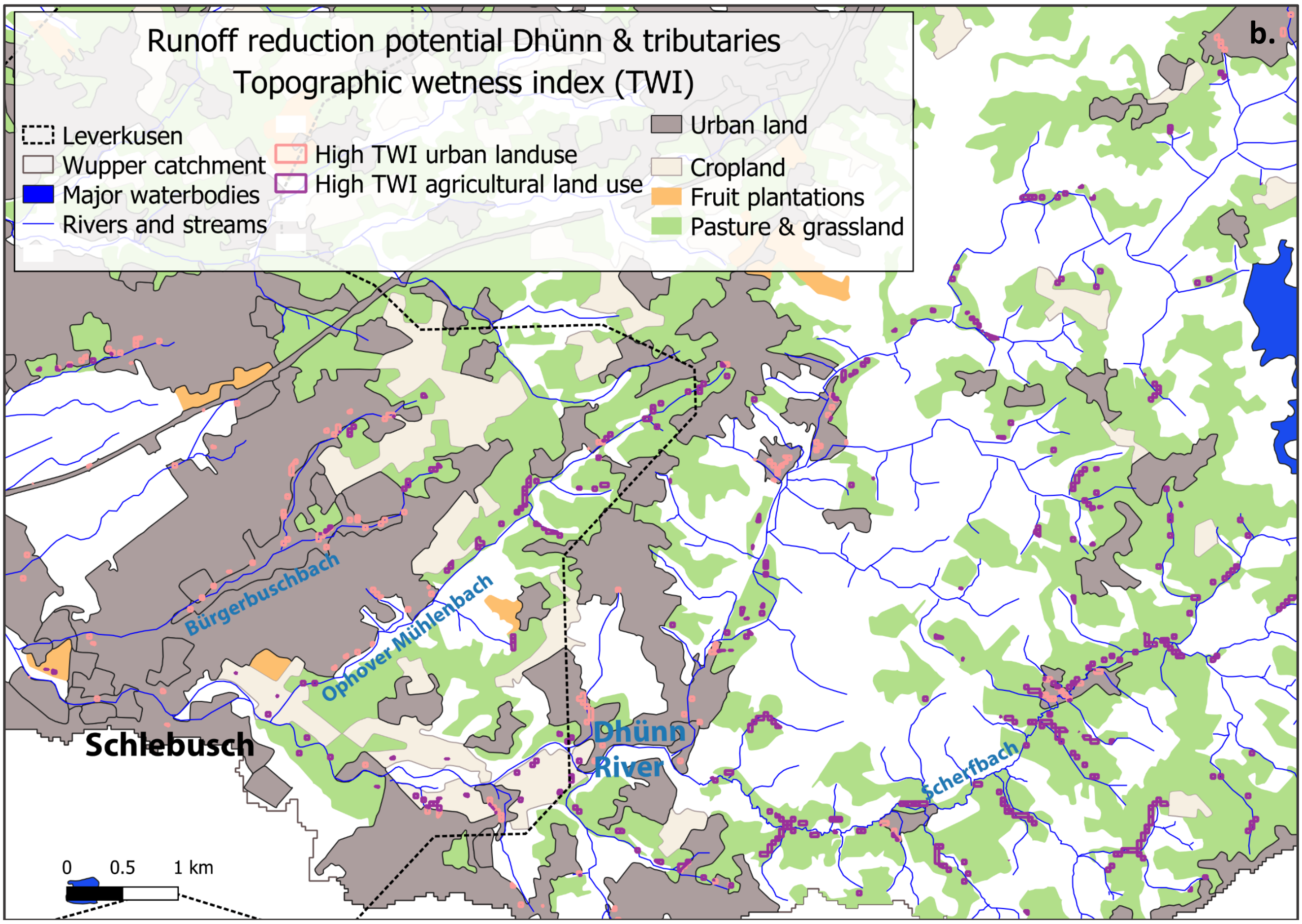

Figure 8: Sites of high TWI on agricultural and urban land affecting (a) Opladen and (b) Schlebusch. Data sources: BKG, 2021; Diva-GIS, n.d.; NASA, 2013; USGS, 2014. Processed in QGIS 3.6.2.

GIS-analyses were carried out to demonstrate the potential of methods available for designing NbS interventions. Across Leverkusen and Rheinisch-Bergischer-Kreis in the Wupper basin many small waterways rise bringing a high flood risk to the settlements after heavy rainfall. An analysis of the topographic wetness index was carried out to identify the areas where runoff is generated or more likely to occur due to higher soil moisture based on topographic controls. These sites shown as white boxes in Figure 8a and 8b indicate suitability for vegetation based NbS on agricultural land. This includes buffer strips, hedgerows and tree rows (planted across the slope) that act to increase soil water retention, reduce rainfall runoff (Borin et al., 2010; Marshall et al., 2014; Nerlich et al., 2013). plantings can also reduce instances of agricultural residues leaching into the waterways (Borin et al., 2010; Nerlich et al., 2013). Sites indicated by the pink boxes on Figure 9 are location of high TWI in urban areas and as such are suitable for NbS measures such as swales, vegetated ditches, infiltration trenches, rain gardens, permeable pavements etc. depending on the specific current urban land use.

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In the Erft basin, the risk of soil erosion is high due to the soil type and fast floods moving through the plains from the higher elevations in the south of the basin. Loess soils are prolific through the Erft basin, much of which is also cleared for agriculture and urban uses. Riparian vegetation supports riverbank cohesion against erosion, provides natural runoff reduction and also provides roughness to slow overbank flows during flooding (Cooper et al., 2021; Murphy et al., 2021). Figure 9 illustrates the Erft River below the planned restoration site of Gymnich to the junction of the Erft and Swist rivers in the very south of Rhein-Erft-Kreis. During the 2021 floods major erosion occurred just to the north of the village of Blessem. The erosion started in a flooded gravel pit, cut back into agricultural floodplain sediments, and eventually joined the river as it overflowed into the site. The erosion resulted in gullies from 6 to 12 meters in depth across 7 hectares (Lehmkuhl et al., 2018).

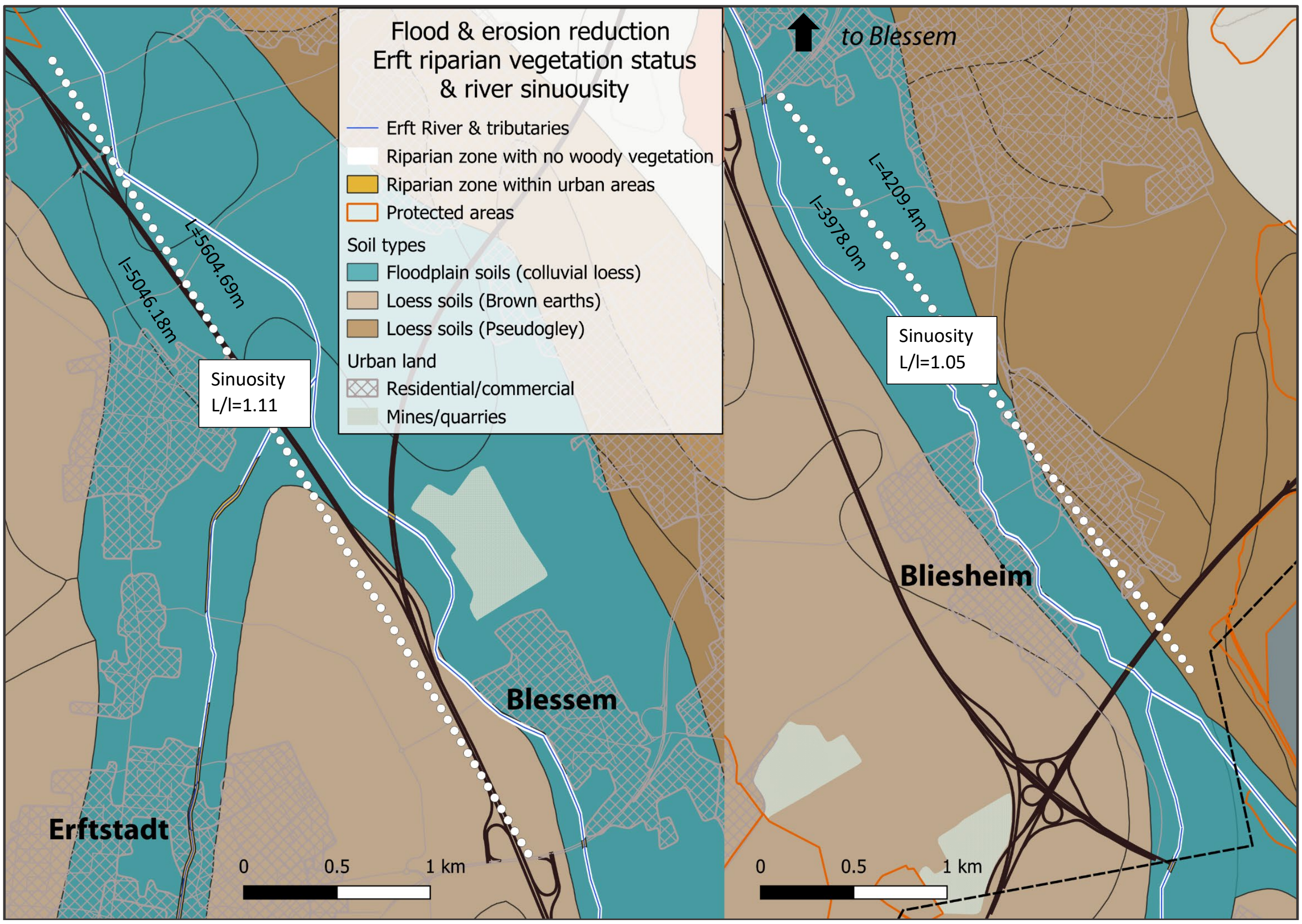

Figure 9: Riparian zones on the Erft devoid of woody vegetation & measure of river sinuosity; Data sources: BKG, 2021; OpenGeodata. NRW, n.d; © OpenStreetMap contributors 2015. Distributed under the Open Data Commons Open Database License (ODbL) v1.0. Processed in QGIS 3.6.2.

Analysis of riparian vegetation, shown with the white buffer line, indicates that this stretch of river is lacking substantial woody riparian vegetation. This lack of riparian vegetation means that the river bank and beyond are vulnerable to erosion, especially because the soils (as shown in Figure 9) are formed from highly fertile, but erodible loess sediments. Loess soils in Germany are derived from fine-grained aeolian deposited sediments, which are highly vulnerable to structure loss and erosion (FAO, 2015; Lehmkuhl et al., 2018). Furthermore, the sinuosity of the river from Gymnich to Blessem and from Blessem to Bliesheim is very low at 1.11 and 1.05 respectively, this indicates that these river stretches are not meandering (S=>1.05) or even mildly sinuous (S=>1.3) according to the river sinuosity index (Hohensinner et al., 2018). This analysis supports further efforts of meander renaturation at locations along this stretch that are suitable with regards to land ownership and zoning.

4. Discussion

The Rhine, an important historical waterway in Western Europe, has long posed a flood risk to the communities along its banks, including the administrative district of Cologne with the metropolis of Cologne and several other large cities, such as Bonn and Leverkusen. Throughout history, Cologne has experienced several severe floods, in which are documented from the Middle Ages and more recently in 1993 and 1995, when floodwaters reached critical levels and caused extensive damage. In response to these recurring threats, comprehensive flood protection measures have been implemented in the region to mitigate potential impacts. The city of Cologne has developed a robust flood protection system that includes elevated flood walls, mobile barriers, pumping stations, and improved drainage systems. In addition, outside the densely built-up inner city, natural floodplains are also being used and old river branches reactivated and used as nature-based solutions (NbS) or hybrids combined with engineered infrastructure.

NbS and hybrid NbS offer a promising approach to enhancing flood resilience by utilizing natural processes and ecosystem services (Debele et al., 2023). In the city of Cologne, for example, the Westhovener Aue floodplain in the south of Cologne not only helps to reduce flooding, but also promotes biodiversity and offers recreational opportunities (Archivgruppe Bürgervereinigung Ensen-Westhoven, 2022). This will also be the case with the Worringer Bruch project currently under construction in the north of Cologne (StEB, 2025b). These multifunctional landscapes underscore the importance of NbS in balancing flood management with ecosystem and social benefits. In the Netherlands, similar measures have been successfully implemented along the Waal and Meuse rivers as part of the Room for the River Project (Dutch Water Sector, 2019), and other European countries, such as the United Kingdom with the Thames Estuary 2100 Plan (UK Government, 2019) are also taking steps to combine flood protection with nature conservation and recreation.

While the city of Cologne is protected for Rhine floods up to a 1 in 200 year statistical return period thanks to a combination of engineered infrastructure, NbS, early warning systems, and evacuation plans, the flood disaster of summer 2021 showed that this was not the case in other parts of the Cologne administrative district. Although the greatest loss of life and material damage occurred in the Ahr Valley in the state of Rhineland-Palatinate south of the study area, the Erft and Wupper river basins in the Cologne administrative district, were also severely affected (Fekete & Sandholz, 2021; Mohr, et al., 2023 Neitzke et al., 2025). This was also the case for the city of Leverkusen, which lies at the confluence of the Wupper and the Rhine, as well as smaller streams and rivers that flow into the Wupper, and was therefore severely affected by flooding. Our investigations show that the smaller tributary catchments of the Erft and Wupper to the west and east of Cologne city provide different challenges. Heavy rainfall over short time periods can overwhelm natural and man-made drainage in these catchments, producing highly damaging, fast-moving floods. River floods in the smaller tributary catchments of the Wupper and Erft operate on a different scale and time-frame to the multi-landscape traversing Rhine River. As such these river systems are subject to fast floods as occurred in July 2021 and even flash floods (see Figure 1), which are often the result of climate change enhanced convective rainfall (Tradowsky et al., 2023), and high risk for inhabitants based on exposure or vulnerability. Both the Wupper and the Erft basins contain a large percentage of agricultural lands on the periphery of the rivers and streams, and small cities along the waterways, which provide a range of challenges but also opportunities in particular for runoff reduction. In terms of geomorphology however, the two basins are quite different. With some simple GIS analysis of geomorphology, streamflow and runoff controls, we illustrate how additional NbS interventions can be designed. In the Wupper Basin slope characteristics used to calculate the topographic wetness index (TWI), where runoff flow paths are inferred by topography, illustrate suitable sites for NbS. In the Erft Basin the status of river sinuosity and riparian zone land use is analysed to inform NbS design. While we do not suggest that they are the only NbS suitable for flood mitigation, our analyses based on landscape and land use characteristics suggest that slope revegetation in the form of buffer strips, hedgerows, tree rows are suitable in the Wupper Basin while meander renaturation and riparian zone revegetation would be highly suited in the analysed section of the Erft Basin. Looking at climate models and the study area located in western Germany, it can be assumed that extreme climatic events with stationary heavy rainfall events in summer and longer periods of drought will continue to increase (Tradowsky et al., 2023), which will further increase the risk of rapidly forming floods and even flash floods in the side valleys of the Rhine (Laux et al., 2025). The risk is exacerbated by the fact that, due to the droughts, bark beetle infections and wind throws of recent years, many conifers, especially spruce (Picea abies) and, in some cases also deciduous trees have died, and young secondary forests are currently forming in many places (Ministerium für Landwirtschaft und Verbraucherschutz des Landes Nordrhein-Westfalen, 2024). As a result, some slopes are only sparsely vegetated and are susceptible to erosion and rapid slope runoff. In addition, the soil has become crusted after the long summer droughts, which also increases slope runoff (Doerr et al., 2000).

Considering these rapid climatic and ecological changes, there is a need for more integrated flood protection measures at the landscape level, which include not only river floodplains but also hillside areas in flood protection (Stein et al., 2024), where measures like afforestation, terracing and soil stabilization could significantly reduce runoff and delay flood peaks. The current concentration of NbS in floodplain areas within the Cologne District highlights a prevalent focus on managing the floodplains of major rivers and their tributaries. These interventions, such as floodplain restoration, retention basins, and river restoration are vital for mitigating large-scale riverine flood events by leveraging the natural capacity of floodplains to absorb excess water and reduce flood peaks. However, they neglect flood risks associated with runoff and flash floods from larger slopes, which pose a high risk, particularly in the Wupper catchment area.

Floodplains naturally attract attention due to their visibility and historical impact on urban centers like Cologne. These areas are traditionally prone to significant flooding events, making them logical targets for initial flood mitigation efforts. Furthermore, floodplains provide immediate gains in flood management through interventions that can often coincide with existing land use, cultivated agricultural areas, or protected natural habitats. But gaining and retaining floodplains is also often in conflict with other demands for urban development or agriculture. For example, creating a flood retention area south of Cologne after the floods in 1993 and 1995, at an area called Langeler Bogen, resulted in conflicts over compensation for farmers that took some time to solve (StEB, 2025a). Also, regarding recent planning of a new Rhine crossing, nature-related interests of protection of species often clashes with planning or agricultural use (BUND, 2016). This is another argument to also consider other types of NbS solutions rather than floodplains. The systematic evaluation and implementation of NbS in slope areas could, therefore, represent a significant enhancement of regional comprehensive flood risk management.

Slope areas are critical in the hydrological cycle, particularly in triggering rapid runoff and flash floods. When heavy rainfall events occur—often exacerbated by climate change—the swift movement of water down slopes can lead to severe flash floods and contribute substantially to flooding in downstream areas. Implementing NbS in slope areas, has therefore the potential to drastically reduce the speed and volume of runoff (Santos, 2025; Xiong et al., 2018). These interventions could enhance soil stability and increase water infiltration, thus mitigating erosion and reducing the frequency and impact of flash flooding. Additionally, they can improve the overall landscape resilience to climate impacts including drought events, supporting biodiversity, carbon sequestration, and soil fertility.

The absence of a publicly available, systematic evaluation of NbS in these areas can be attributed to several reasons, including technical and administrative challenges. Land ownership fragmentation, diverse stakeholder interests, and regulatory constraints may hinder the implementation of landscape-scale interventions. Moreover, there might be a lack of awareness or understanding of the benefits and feasibility of such measures in slope regions, leading to a bias toward more visible, established projects in floodplains. To bridge this gap, a further strategic shift toward integrated watershed management is essential. This shift would involve mapping and assessing slope areas for their potential to support NbS interventions, accompanied by pilot projects to demonstrate their effectiveness. Engaging local communities and stakeholders in these areas is also crucial, creating opportunities for collaboration and fostering ownership of NbS initiatives. And while we focus on macroscopic slope areas here (also Table 6), also at finer scales erosion and run-off processes within urban areas can be mitigated. While the city of Cologne has guidelines for water-sensitive planning or programs supporting urban greening at finer scales (StEB, 2023), such measures and overviews at the broader scale we analyse here, are less available.

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Table 6: Potential NbS interventions to decrease flood risk at catchment scale

Suitable intervention	Landscape typology	Paper or literature	Potential NbS	River section
Reforestation / afforestation	Terrestrial (forest upland)	Geng et al. (2024); Panagos et al. (2015); Sudmeier-Rieux et al. (2021)	Reduces slope runoff and erosion; increases infiltration and forest ecosystem resilience	Upper
Contour farming / strip cropping	Agroecosystem (sloping fields)	Panagos et al. (2015); Albrecht & Hartmann (2021)	Slows surface runoff; conserves soil and improves infiltration on slopes	Upper / Middle
Vegetated buffer strips	Agroecosystem (field edges)	Kretz et al. (2021); Nehren et al. (2023)	Intercepts slope runoff; filters sediments; protects streambanks	Upper / Middle
Grassed swales / vegetated ditches	Built-environment (fringe)	Zölch et al. (2017); Mustafa et al. (2018)	Manages concentrated runoff on slopes near settlements; improves percolation	Middle
Terracing	Agroecosystem (steep farmland)	Sudmeier-Rieux et al. (2021); Alobid et al. (2024)	Prevents slope erosion; slows runoff velocity; retains water for crops	Upper
Agroforestry systems	Agroecosystem (mixed cropland)	Nehren et al. (2023)	Reduces slope runoff; promotes biodiversity and carbon sinks on agricultural land	Upper / Middle
Infiltration trenches / micro-basins	Built-environment (fringe)	Mustafa et al. (2018);	Captures flash runoff from adjacent slopes; delays and reduces flood peaks	Middle / Lower
Green roofs & permeable pavements	Built-environment (urban slopes)	Zölch et al. (2018); Eingrüber et al. (2022)	Reduces impervious runoff in hilly urban zones; promotes urban infiltration	Lower
Woody debris / check dams	Riverine (gullies / ravines)	Sudmeier-Rieux et al. (2021); Panagos et al. (2015)	Slows runoff from forested slopes; traps sediment before reaching floodplains	Upper
Grassland restoration	Terrestrial (degraded pasture)	Nehren et al. (2023); Cao et al. (2023)	Rebuilds soil sponge function on slopes; slows runoff and reduces erosion	Upper

While NbS provide essential benefits, the study highlights several challenges in their implementation. Land use constraints, fragmented ownership, and the perception of NbS as secondary to grey infrastructure pose significant hurdles. Additionally, conflicts with existing forestry and agricultural practices can arise, as these sectors may prioritize economic yields over ecological benefits (Henle et al., 2008). Administrative issues and responsibilities in water management further complicate the adoption of NbS, as jurisdictional overlaps and fragmented governance can impede cohesive action (Janssen, 2008; Pahl-Wostl, 2015; Kirshke et al., 2017). As noted, areas suitable for intervention are often limited by existing land use, legal frameworks, and the need for stakeholder consensus. Addressing these challenges requires integrated planning approaches that consider land-use compatibilities, resolve conflicts, and foster cooperation among diverse stakeholders.

Moreover, the study underscores the need for improved data collection and systematic recording of NbS interventions. NbS encompass a wide range of activities of different sizes, varying from retention basins to river restoration and even smaller scope implementation of revegetation and individual urban runoff reduction measures. Therefore, a comprehensive database could facilitate better planning and resource allocation, ensuring that interventions are strategically targeted and effectively integrated into broader flood management strategies.

Given the projected increase in extreme weather events due to climate change, expanding the scope and scale of NbS in the Cologne District is imperative. This study provides a foundation for identifying potential areas for new interventions, particularly in the Wupper and Erft basins, where flash floods pose significant risks. Enhancing NbS upstream, especially in slope areas, could complement existing downstream efforts and provide a holistic approach to flood risk reduction. To advance this, future research could focus on the long-term monitoring and quantification of the effectiveness of NbS interventions. Moreover, developing tools for modelling and predicting flood events with NbS integration would support adaptive management strategies, allowing for real-time adjustments to intervention plans. Additionally, integrating community engagement into NbS planning could foster local stewardship and enhance the social acceptance of such measures. Educational initiatives and inclusive planning processes could empower communities to contribute to flood resilience, leveraging local knowledge and facilitating sustainable management practices.

5. Conclusions

The integration of Nature-Based Solutions (NbS) for enhanced flood resilience in the Cologne District exemplifies a proactive response to the escalating challenges of climate change-induced flooding. This study has identified and mapped existing and potential NbS interventions, highlighting the importance of reconnecting floodplains, enhancing riverine habitats, and implementing green-blue infrastructures to mitigate flood risks. While the use of engineered, nature-based and hybrid solutions together with early warning systems has provided a robust framework for flood protection, the increasing frequency of extreme weather events necessitates a broader and more integrated approach. By focusing on the geomorphological and hydrological dynamics of the region, particularly in areas prone to rapid runoff and erosion, this research underscores the need for strategic NbS implementations on slopes and upstream areas. These efforts not only aim to reduce flood peaks and improve water retention but also contribute to biodiversity conservation and provisioning ecosystem services.

The varied implementation of NbS across different administrative and catchment levels, involving numerous stakeholders, highlights the absence of a unified framework and standard NbS terminology, complicating comprehensive planning and evaluation. While the use of open GIS tools and publicly available data offers the advantage of transferability, limitations persist in data resolution and accessibility. A defining feature of this case study is the diverse mix of NbS employed, set against a backdrop of mixed flood and drought hazards and varying landscape types. Germany's cultural readiness for green solutions is evident; however, issues such as land ownership conflicts and competing demands from agriculture, traffic, and urban development remain significant barriers. To advance flood resilience, a strategic shift toward comprehensive, catchment-wide approaches is essential. This includes greater emphasis on addressing flash floods and the synergistic impacts of drought, alongside enhanced cooperation and clarity among all parties involved in NbS deployment.

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Author contributions

UN contributed to the conceptualization of the study, conducted the literature review, and took the lead on writing the manuscript. ACB contributed to the literature review, writing, and performed GIS processing. PSQ assisted with the literature review and prepared the tables. AF carried out the internal review and made revisions and adjustments to the text.

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