MASTER THESIS – Integrated Water Resources Management

TH Köln (University of Applied Sciences)
ITT- Institute for Technology and Resources Management in the Tropics and Subtropics
Faculty of Spatial Development and Infrastructure Systems

Assessing potential locations for green-blue interventions to reduce hydrometeorological hazards in the Wupper Catchment, Germany

Ali Cara Barrett
2023

ITT
Institute for Technology and
Resources Management in
the Tropics and Subtropics

Faculty of
Spatial Development and
Infrastructure Systems

Technology
Arts Sciences
TH Köln

Integrated Water Resources Management

TH Köln (University of Applied Sciences)
Faculty of Spatial Development and Infrastructure Systems
ITT - Institute for Technology and Resources Management
in the Tropics and Subtropics

Assessing potential locations for green-blue interventions to reduce hydrometeorological hazards in the Wupper Catchment, Germany

Thesis to Obtain the Degree of

MASTER OF SCIENCE
Integrated Water Resources Management
DEGREE AWARDED BY COLOGNE UNIVERSITY OF APPLIED SCIENCES

PRESENTS:
Ali Cara Barrett
SUPERVISOR OF THESIS (FACULTY)
Prof. Dr. Udo Nehren
SUPERVISOR:
Prof. Dr. Alexander Fekete

DATE OF SUBMISSION
05.05.2023

presented by
Ali Cara Barrett Student no.: 11149441 Email: ali_cara.barrett@smail.th-koeln.de

Abstract:

Aim: European cities are facing heighten hydrological risks as a result of climate change at the same time as ecological degradation has reduced the environmental capacity to absorb and regulate such fluctuations. Climate forecasts predict more intense convective rainfall and winter flood events in the Wupper Basin in Germany, against a background trend of reduced mean rainfall during the summer months. On 14 July 2021 intense convective rainfall fell at points across Western Germany and led to flash floods in the Wupper Basin, many sites were inundated and the Wupper and Dhünn rivers rose to new record highs. Green-blue infrastructure offers strategies to reduce the impacts of hazards at the same time as providing a range of co-benefits. A study was undertaken to find which green-blue interventions will be most effective at reducing the impacts of hydrometeorological hazards for a study area in the west of the Wupper basin. Furthermore, as landscape features are highly influential in hydrology, the study sought to establish which sites within the landscape can provide maximum results from green-blue interventions, with a minimum of change to current land uses.

Region: Europe, peri-urban and rural, undulating, low mountainous landscapes

Methods: Literature findings on observed and projected climate data are summarised and long-term rainfall data from the study area is analysed to confirm rainfall trends. A state-of-the-art review is conducted and summarised to form a toolbox of potential interventions. The most recent hazardous hydrometeorological event is analysed to inform the locational priorities of potential interventions. Landscape features that have the most influence on basin hydrology are identified from the literature. These sites are paired with green-blue interventions that are shown to have the highest potential impact on interception, infiltration, runoff and flooding. A series of spatial analyses are carried out to produce maps detailing location and intervention with high potential to reduce the impact of hydrometeorological hazards in the study area. All of the evidence gathered from the literature analysis is combined in an implementation guide for green-blue interventions in the Wupper Basin.

Results: The hazards caused by the hydrometeorological extremes of flooding and drought are addressed or minimised through the green-blue interventions that increase interception and infiltration and reduce runoff and flooding. Priority locations are identified as the riparian zone with slope ≤15%, hilltop, lower slope and toe slope, all locations with a slope ≥30% and areas with a high topographic wetness index (TWI). A series of spatial analyses were carried out and suggestions made including potential locations for retention or detention areas and ponds, sites for revegetation and potential locations for implementation of shelterbelts/hedgerows, buffer strips, conservation tillage or strip tillage, reduced mowing intensity or frequency and biochar additions. An implementation guide is created that provides a summary of the highest potential green-blue interventions and landscape locations, and a description of the mechanisms involved in addressing the hydrometeorological hazards.

Keywords: *Green-blue interventions, hydrometeorological hazard reduction, Wupper Basin hydrology*

Acknowledgements

I would like to thank my supervisors Prof. Dr. Udo Nehren and Prof. Dr. Alexander Fekete for assisting me with the direction of this thesis and for providing very helpful feedback and assistance.

Also, a big thanks to my mother Fay Barrett in Australia and Thomas Cüper in Germany.

List of tables

List of Figures

Abbreviations

Abbreviation	**Long name**
CAP	Common Agricultural Policy
EC	European Commission
EU	European Union
FAO	Food and Agricultural Organisation of the United Nations
GHG	Greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
NbS	Nature based solutions
NRW	North Rhein Westphalia
QGIS	Quantum Geographic Information System
RCP4.5	IPCC Representative Concentration Pathways (CO_2 peaks at 2040)
RCP8.5	IPCC Representative Concentration Pathways (CO_2 peaks after 2100)
SPI	Standard Precipitation Index
SSI	Standard Streamflow Index
TWI	Topographic wetness index

Table of Contents

1. Introduction

1.1. Study justification and gap analysis

European cities are facing increasing hydrometeorological hazards as a result of climate change at the same time as ecological degradation has reduced environmental capacity to absorb and regulate fluctuations in the hydrological cycle. In Germany land pressures also mean that large urban centres and agricultural zones are close neighbours and that natural forests have been removed or replaced by plantations in many areas. In 2022 the IPCC stated that “numerous examples of extreme hydrometeorological events, including heavy precipitation, flooding, drought and wildfire events causing deaths, high levels of economic damage and extensive ecological impacts, have been shown to have been made more likely by human influence on climate through increased GHG concentrations in the atmosphere” (Caretta, 2022). Mean rainfall has increased across Europe and with that fluvial floods have also become more common across Western Europe (IPCC, 2021). Climate forecasts also predict increased flooding and more widespread and intense convective rainfall across Western Europe (Purr et al., 2021; IPCC, 2021). Hydrometeorological hazards such as storms, floods and heatwaves have cost Europe up to half a trillion euros over the twenty years from 1980 to 2020. Within the European Union (EU) the country that incurred the highest cost was Germany at 450 billion euros (EEA, 2022). All of these issues indicate that there is an increasing need to reinstate ecological functions by employing natural solutions which offer multiple ecosystem benefits, including that of hydrometeorological hazard management. Hence, solutions to natural hazards such as these are now sought from natural processes.

In the early 2000s, eminent scientists Falkenmark and Roström (2006; 2010) wrote about the need to broaden the focus of water management from purely “blue water” to “green-blue water”. Blue water is the runoff that collects in rivers, dams and aquifers, and green water the water that is held in the soil and available for use by terrestrial biomass including forests, grassland and agricultural crops. Falkenmark and Roström (2010) reasoned that by broadening the concept of water in water resource planning to green-blue water that it would enhance understanding of the significance of water in the environment, and its ability to sustain not only cropping and forestry but also the ecological cycle and biodiversity which promote resilience to flooding and drought, just in a different way to conventional water resource management. At the same time the concept of nature-based solutions (NbS) was being developed and refined by international organisations, NGOs and researchers (Nehren et al., 2023). The current NbS definition, from the United Nations Environment Assembly “actions to protect, conserve, restore, sustainably use and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems, which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services and resilience and biodiversity benefits” is accepted as the most all-encompassing (Nehren et al. 2023; UNEP, 2022).

The concept of green and blue infrastructure is considered to be one of the many sub-categories of NbS (Nehren et al., 2023). Green and blue infrastructure specifically describes land zones and water bodies that can be managed to provide ecosystem services, including that of hydrometeorological hazard management (EC, 2019). Green and blue infrastructure is defined by the European Commission (EC, 2019) as the natural and semi natural elements of the terrestrial and aquatic landscape that can be enhanced or reinstated to provide environmental, economic, and social benefits. These infrastructure elements can be further broken down into local, regional and EU wide scale features. Local scale green and blue features include green-roofs, hedgerows, ponds and woods, regional scale includes river basins, forests, agricultural areas, and EU wide features cover transboundary river basins, lakes or forests (EC, 2019). Green and blue infrastructure can be used as either an alternative to, or in combination with, grey or engineered infrastructure. Furthermore, green-blue infrastructure describes different structures that exist on a spectrum of natural to semi-natural such as forests, floodplains, restored wetlands, retention areas, green urban spaces and stormwater management systems. However, there is also more that can be done in terms of land management to address hydrometeorological risks, including soil, cropland and grassland management. While these are not usually prominent themes within NbS, they can make a large difference in reducing runoff and retaining water in the landscape, which is key to addressing the hydrological extremes of flood and drought (Collentine and Futter, 2018; EC, 2012;2019; Murphy et al., 2021). This study reviews both green and blue infrastructure and agricultural management methods in order to identify interventions which can minimise hydrometeorological hazards.

The literature refers to green and blue infrastructure interventions by a number of different terms including, green and blue infrastructure, green-blue infrastructure, blue-green infrastructure, green-blue strategies, blue-green infrastructure interventions, green and blue spaces and more. Some academic papers apply the concept either in association with NbS (Debele et al., 2019) or the ‘sponge city’ concept from China (Xia et al., 2017) but the majority of research is based on urban and peri-urban locations and measures. There are a range of green-blue measures that can be applied to reduce the impact of hydrometeorological hazards. In order to select the best measure for a given site or location multicriteria analyses have been applied (Ferreira et al., 2020; Pacetti et al., 2022), and multiple screening tools and best practice management documents exist to help with selection (Albert et al., 2021; Alves et al., 2018). While their information is sound and often backed by case studies, they are largely generalised, providing no information on landscape characteristics or climate, whereas these variables should inform the measures that are implemented. This paper attempts to address this gap by reviewing the effectiveness of green-blue interventions for various land uses and the landscape characteristics that have the most influence hydrology, and applying the results to a particular study area that is experiencing a range of hydrometeorological hazards.

This paper seeks to identify the highest potential, local scale, green-blue interventions and locations for green-blue interventions for the peri-urban and rural locations of Leverkusen, Rheinisch-Bergischer Kreis and Solingen in the Wupper Basin, Germany. The Wupper Catchment is a sub-catchment of the major Rhine River and is a catchment that features a high percentage of urban and also agricultural land use. Observed data indicates that intense convective rainfall events have been increasing across the basin, against a background trend of reduced mean rainfall during the summer months (BINGO, 2016; Lorza-Villegas et al., 2021). Most recently the Wupper Basin experienced damaging flash floods incurred by the Bernd weather system in July of 2021 (KARL, 2021; Kreienkamp et al., 2021). During high rainfall events Leverkusen with the lowest relief and high proportion of urban/industrial-impervious land cover, receives both localised rainfall and water draining out of the higher relief areas to the east before it flows to the Rhine (see *Figure 2*). Because of the low relief and high proportion of impervious surfaces, water is unable to drain away quickly which can also prolong the duration of flood inundation. This creates a high risk in terms of lives, infrastructure and financial impact. Had the July 2021 floods also led to Rhine flooding, the situation could have been disastrous for the entire city of Leverkusen.

1.2. Objectives of the study

The objectives of this study are to 1. Identify which hydrometeorological hazards are affecting Leverkusen, Rheinisch-Bergischer Kreis and Solingen in the Wupper Basin, now and into the future. 2. Determine which green-blue interventions will be most effective at reducing the impacts of those hydrometeorological hazards. 3. Determine which landscape locations will afford maximum results from green-blue interventions with a minimum of change to current land uses. This study does not focus on urban interventions, there are already many reports written on the design, implementation and effectiveness of green-blue infrastructure in urban settings. Furthermore, green and blue infrastructure can also describe the large-scale engineering projects that aim to re-establish or mimic natural river hydro-geomorphology in highly modified basins, such as the works undertaken in the successful Netherlands ‘Room for the River’ program. These works included large scale changes including land buy-back schemes, levee lowering and re-establishment of once disconnected floodplains. These types of engineering projects are not appropriate in the Wupper Basin.

This thesis instead focuses on working with basin landscapes and current landcover and land usages. This study focuses on green-blue interventions for peri-urban, rural and agricultural areas and attempts to identify specific interventions that increase rainfall interception and rainfall infiltration and reduce runoff and flooding. Furthermore, certain landscape characteristics have more influence on hydrology than others these factors are also examined and combined with landcover and land use characteristics to suggest the locations that can provide the highest impact for any given intervention. The hydrological extremes of flood and drought are both exacerbated by increased runoff, therefore retaining water in the landscape is a key (Collentine and Futter, 2018; Murphy et al. 2021). This study focuses on addressing the hazard only, not risk as it doesn't account for any differences in vulnerability or exposure of the population across the study site. This study is also realistic about what is possible in the real world, care is taken that the interventions recommended do not mean whole-scale change to current land usage.

1.3. Steps taken to meet the objectives

The objectives are met through the following steps:

1. The background to the study is provided including conceptual framework and problem framing, gap analysis, physical setting characteristics and scientific methods described.
2. Mapping analysis is carried out to confirm major landcover and land use patterns, topography and hydrology.
3. Literature on observed and projected climate data is summarised. Long-term rainfall data from the study area is analysed to confirm rainfall trends.
4. A state-of-the-art review is conducted from field trials and studies of potential interventions in similar climatic and topographical landscapes. Modelling studies are also used provided the input parameters are also suitable. Field trial/modelling study details and outcomes are summarised to form a toolbox of potential interventions.
5. The most recent hazardous hydrometeorological event is analysed to inform the locational priorities of potential interventions.
6. Landscape features that have the most influence on basin hydrology are identified from the literature. These sites are paired with green-blue interventions that are shown to have the highest potential impact on interception, infiltration, runoff and flooding.
7. A series of spatial analyses are carried out to produce maps detailing location and intervention with high potential to reduce the impact of hydrometeorological hazards in the study area.
8. All of the evidence gathered from the literature analysis is combined in an implementation guide for green-blue interventions. The guide includes suggesting potential interventions for the type of landcover and land use categories and landscape characteristics with a description of the mechanisms involved, species suggestions and co-benefits of the interventions.
9. Suggestions are made for the possible application of this study and further research that would extend the usefulness of this work.

2. Characterisation of the study area

2.1. Population and administration

The Wupper basin is located in the German state of North Rhine-Westphalia along the lower Rhine and is occupied in the west of the basin by the urban municipality of Leverkusen and the rural municipalities of Rheinisch-Bergischer Kreis and Solingen (see *Figure 1*). These three municipalities make up the study area for the purposes of this report. The Wupper basin extends across 813 km^2 with relief ranging from 35 to 499 meters above sea level (m.a.s.l.) (USGS, 2014; Wupperverband, n.d). The rivers that form the drainage boundaries of the basin, the Wupper and the Dhünn, merge within the city of Leverkusen before flowing to the Rhine. Leverkusen has a population of around 167,000 people and has predominately urban landcover at around 67% and around 21% agricultural land spread across 78.85 km^2 (BKG, 2021a; IT.NRW, 2021; Stadt Leverkusen 2023a). Rheinisch-Bergischer Kreis has a population of around 286,055 with landcover of just over 21% urban, 52.5% agricultural lands spread across 437,32 km^2 (BKG, 2021a; IT.NRW, 2021; 2022). The administrative capital of Rheinisch-Bergischer Kreis is Bergisch Gladbach which is located outside of the Wupper basin. Solingen has a population of 160,065 across 89.54 km^2 land area with land cover that is 42% urban with around 33% forest (BKG, 2021a; IT.NRW, 2021; 2022).

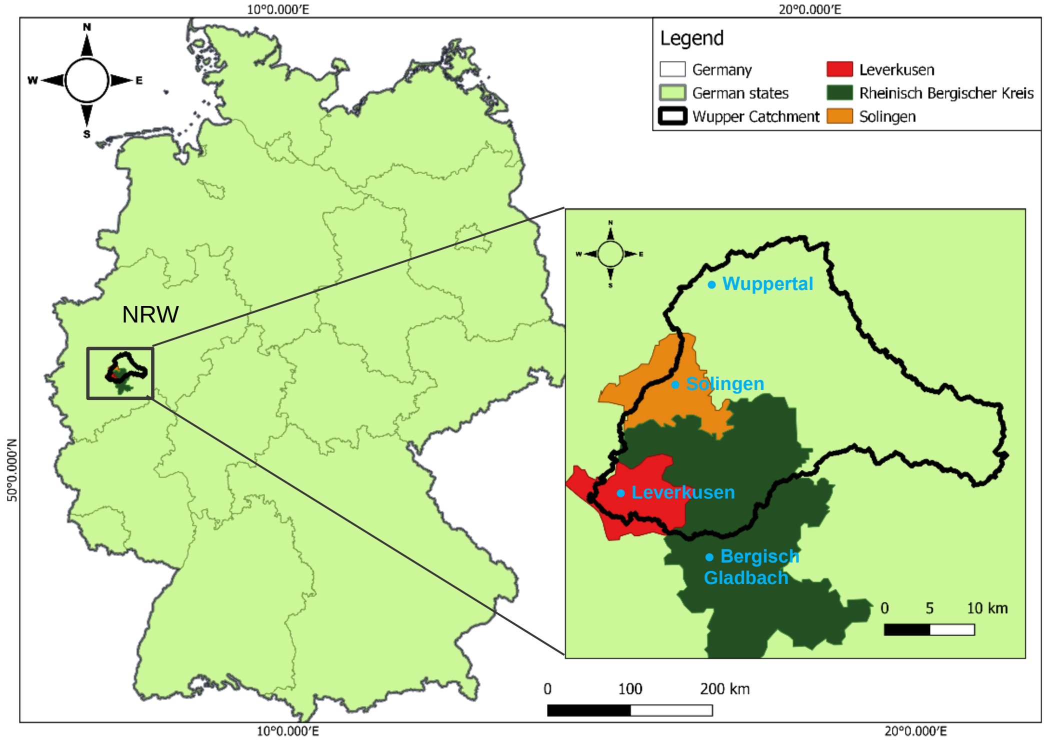


Figure 1: Location of the study area in the Wupper Basin, North Rhein Westphalia (NRW), Germany

(Data source: Diva-GIS n.d. Prepared in QGIS v3.18.0)

Surface water resources for each of the municipalities within the Wupper basin are managed by the Wupperverband, a public water resources management company who operate and maintain water supply and water detention infrastructure, and 2,300 km of waterways across the basin (Wupperverband n.d.). Both the Wupperverband and each of the municipalities participate in flood management activities under state-based coordination. The Wupperverband is responsible for monitoring water levels, dam operation and flood retention ponds while the municipalities take responsibility for structural flood protection within their own borders (Umwelt.nrw, 2022b; Wupperverband n.d.). Responsibility for flood risk planning, monitoring and warning is shared between the water managers, each individual municipality, sometimes the district government (Stadt Leverkusen, 2023b) and the state of NRW according to regulations under the Federal Water Resources Act, the North Rhine Westphalian Water Resources Act and according to the EU Flood Risk Management directive (Umwelt.nrw, 2022a). German states are responsible for developing flood risk management plans under the EU directive which also include flood risk and hazard maps (Umwelt.nrw, 2022a). The current flood risk management plans, however, do not include the smaller low mountain range tributaries such as those within the Wupper basin, which, as experienced in July 2021, carry a high risk for flash flooding events (Umwelt.nrw, 2022b).

Administration of activities such as land use planning are generally carried out by each individual local municipality along guidelines that are set by the states (OECD, 1997). Certain rules for the agriculture and the environment sectors are also covered by European Union (EU) regulation under what is termed 'common policy'. Countries such as Germany may also make their own regulation across these sectors providing the matters are not already covered by EU laws (EC, n.d.).

2.2. Hydromorphology

Figure 2 shows the location of rivers, streams and local drainage and relief in the three municipalities. The Wupper River rises in the very southeast of the basin at a height of around 431 m.a.s.l (Wupperverband, 2002). The river emerges from junction of the minor Wipper and Kerspe rivers. It makes its way northwest flowing through the Rheinische Slate Mountains and Devonian geological formations of sandstone, greywacke and quartzite, and then arcs around to flow west where the city of Wuppertal is established on its banks (Umwelt.nrw, 2022b; Wupperverband, 2002; 2012). As it leaves the Wuppertal municipality it changes direction again to the south as it flows into Solingen, where it makes another turn to the west and then again to the south where it flows into Rheinisch-Bergischer Kreis, here the rivers floodplains begin to widen as it flows into the lower Rhine plain at Leverkusen. Several tributaries meet the Wupper as it travels through Solingen including the Weinsbergerbach, and as it flows into Leverkusen local tributaries such as the Weltersbach, the Murbach, the Ölbach and the Wiembach merge with the larger river. In total the river flows for around 115 km, eventually falling 397 m from starting point to its discharge into the Rhine River at Leverkusen (Wupperverband, 2002). Within Leverkusen the Wupper is highly channelised as it has been straightened and rerouted around industrial development before it meets the Rhine (Wupperverband, 2002).

The Wupper river in the study area is classified as an upland river with fine to course siliceous substrate material (#9 River type according to the River Framework Directive (RFD)). Whereas the Weltersbach, Murbach and Wiembach are classified as low mountain streams with a substrate of fine carbonate material (#6 RFD). The Wupper is highly modified especially within city limits and former industrial sites, and is also highly constrained, with many urban areas bordering its banks (Wupperverband, 2012).

In comparison, the Dhünn River rises in the mid-south of the basin (starting out as the Groß Dhünn) and flows through the uplands of Rheinisch-Bergischer Kreis. Tributaries such as the Eifgenbach and the Scherfbach join the Dhünn as it makes its way into Leverkusen where the Leimbach also joins prior to the Dhünn merging with the Wupper before emptying into the Rhine. The Dhünn is also classified as a siliceous upland river (#9 RFD) and its tributaries Eifgenbach and the Scherfbach are classified as low mountain range streams with coarse carbonate substrate (#5 RFD) (Wupperverband, 2012). There are also a few local drainage streams of note including the Leimbach that flow towards the Dhünn within Leverkusen and because of the low relief in Leverkusen these also become a flood hazard after heavy rains. The Ophovener Weiher retention basin is located on the local drainage line just to the north of the Leimbach. There are current plans to expand this basin to address localised flooding (Wupperverband, 2022c).

Several dams are located in the headwaters of the Wupper and Dhünn rivers, including the Groß Dhünn Dam (see *Figure 2*). While parts of the Groß Dhünn River and the Groß Dhünn Dam are located within the borders of Rheinisch-Bergischer Kreis the majority of the catchment area of the dam is not, therefore this section of the Dhünn is not considered in this study. While some water from the dam is released into the Dhünn River, and the dam is used for flood reduction when managed capacity and limits permit, the majority of this water is captured in the dam and used for drinking water (Lorza-Villegas et al., 2021; Wupperverband, 2022a).

2.3. Soils

As illustrated in *Figure 3* the soils in the study area predominantly consist of Braunede (Cambisols) and Parabraunerde (Luvisols) with minor deposits of Vega (Fluvic Cambisols), Pseudogley (Stagnosols), Gley (Gleysols) and Podsol (Podzols) according to the German and FAO soil classifications (FAO classification in brackets). The Fluvic Cambisols, Stagnosol and Gleysol soils have been subject to water deposition or formation. These soils are distributed across the rivers and floodplains, such as the Fluvic Cambisol soils in the constricted floodplain areas of the Wupper and Dhünn rivers (BGR 88).

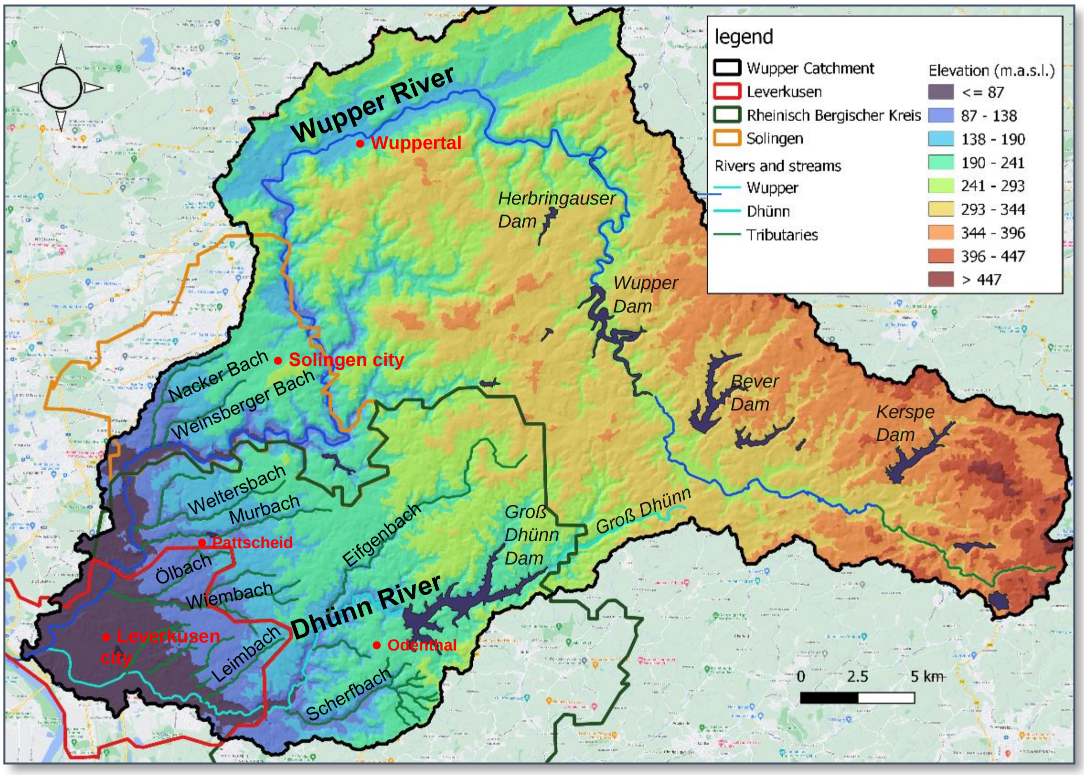


Figure 2: Location of Rivers and streams in the Wupper Catchment
(Data source: BKG, 2021a; Diva-GIS n.d; USGS, 2014; Wupperverband, n.d. Prepared in QGIS v3.18.0)

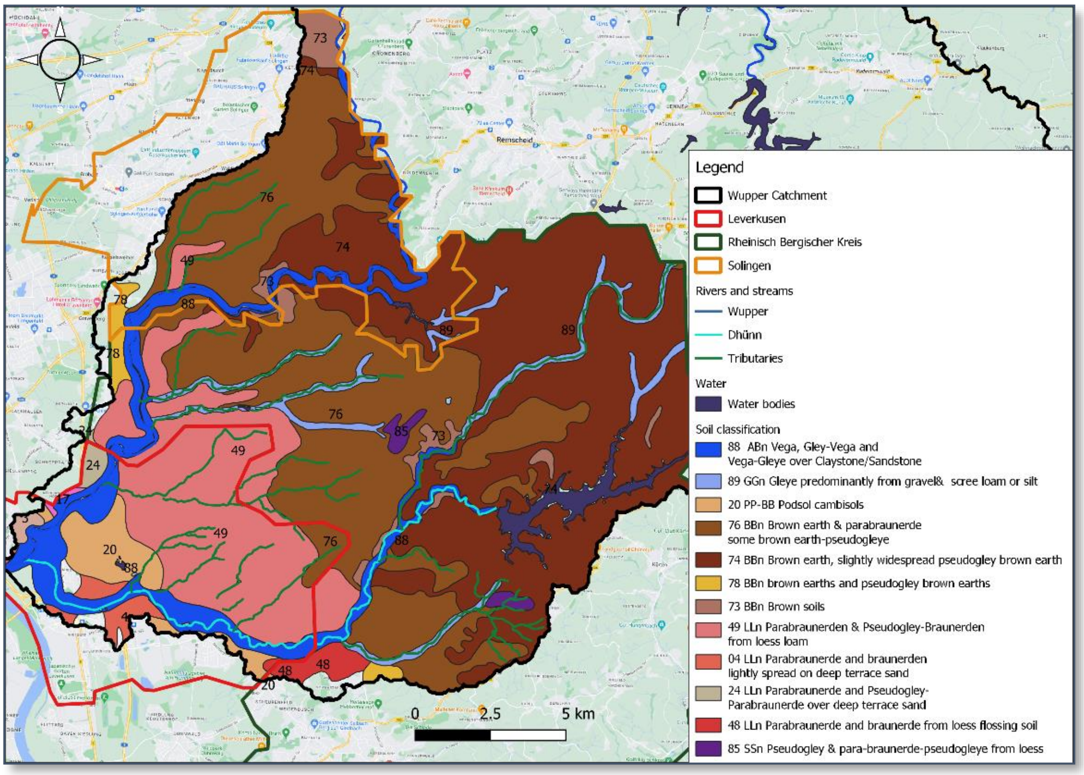


Figure 3: Soil type and distribution across Leverkusen, Rheinisch-Bergischer Kreis and Solingen
(Data source: BGR, 2020; BKG, 2021a; Diva-GIS n.d. Prepared in QGIS v3.18.0)

The Gley, groundwater effected soils are found across the riverbeds of the larger tributaries (BGR 89) (FAO, 2015; Wittman et al.,1997). Stagnosols are found concentrated in very small regions of the upland headwaters of the Scherfbach and Murbach and thinly distributed throughout the predominantly Cambisol soil areas. These soils are associated with perched water tables and are likely some of the spring sources of the streams in the region. These soils are usually too wet and often oxygen deficient for agricultural uses (FAO, 2015).

In comparison Cambisols, Luvisols and Podzols are the result of glacial, alluvial or aeolian erosion and deposition processes. The brown-earth (Braunede) Cambisols found across the majority of the study area (BGR 49, 76, 74,78 & 73) are developing, fertile and lightly weathered soils (FAO, 2015). These soils are used for agriculture in the study area, as is common worldwide, but they are vulnerable to erosion, and it is recommended that soils of this type should remain under forest cover on steep slopes (FAO, 2015). This is even more so the case with the Parabraunerde or Luvisol soils which are also found mixed with the brown-earth Cambisols in the wider soil distributions found in BGR 76 and 74 of the study area and concentrated across Leverkusen as BGR 49. Luvisol soils are often the result of aeolian deposition and as a result have highly mobile clay fractions, as is the case with the loess Luvisols in the study area. While these soils are often very fertile, if subject to intensive tillage or worked with heavy machinery when wet, these soils are highly vulnerable to structure loss and erosion (FAO, 2015).

Podzol soils which are found mainly at the downstream confluence of the Wupper and Dhünn rivers (BGR 20) are siliceous soils (FAO, 2015) and currently covered by urban land uses and not considered for any green-blue intervention. The majority of green-blue interventions investigated are situated on the Luvisol (BGR 49) and Cambsol soils (BGR 76 & 74).

2.4. Landcover, land use and relief

Leverkusen, Solingen and Rheinisch-Bergischer Kreis have very different relief and different proportions of land cover and land use within their borders, which means that the risks of hydrometeorological hazards for the people living in the municipalities differ in terms of exposure, and there are also different opportunities to address the hazards.

Leverkusen features a low relief of between 35m and 190m (see *Figure 2* above) as it extends across the floodplain where the Wupper empties into the Rhine River (USGS, 2014). Landcover and land use are highly modified and impermeable with urban areas making up around 67% of landcover including 4% industrial land use and up to 5.5% road and rail infrastructure. Agricultural land use is mainly grazing and permanent grassland (13%) and cropping (7.75%), while forest cover is mostly made up of broadleaf forests at just over 9% (BKG, 2021a).

Because of the low relief and high proportion of impervious surfaces, water is unable to drain away quickly which can also prolong the duration of flood inundation. This creates a high risk in terms of lives, infrastructure and financial impact. Had the July 2021 floods also led to Rhine flooding, the situation could have been disastrous for the entire Leverkusen region. *Figure 4* below shows landcover and land use categories and distribution across Leverkusen.

Rheinisch-Bergischer Kreis features higher relief reaching a low of 47m along the western border and max 359m in the east (USGS, 2014). Landcover in this municipality includes a higher proportion of rural landscapes to urban land cover. At just over 21% urban, this municipality has 52.5% agricultural land made up of almost 49% grazing and permanent grassland and large areas of forests which cover up to 25% of the land surface (BKG, 2021a). Rheinisch-Bergischer Kreis also has the largest proportion of coniferous forest cover at almost 5%, while the majority of forests within the municipality (15.7%) are classified as broadleaf forests. *Figure 5* illustrates the landcover and land uses and their distribution across Rheinisch-Bergischer Kreis.

Solingen also has a high proportion of urban landcover at around 42%, but has a larger area of forest cover close to the border with Rheinisch-Bergischer Kreis that makes up almost 34% of landcover. Solingen’s forest cover consists of mainly broadleaf (22%) with some mixed (7.9%) and coniferous (3.8%) (BKG, 2021a). The relief across Solingen is lowest along the Wupper floodplain (54 m.a.s.l) where the river turns south before entering Rheinisch-Bergischer Kreis, and reaches a maximum of 262 m.a.s.l in the north of the municipality (USGS, 2014). *Figure 6* shows landcover and land use and distribution across Solingen.

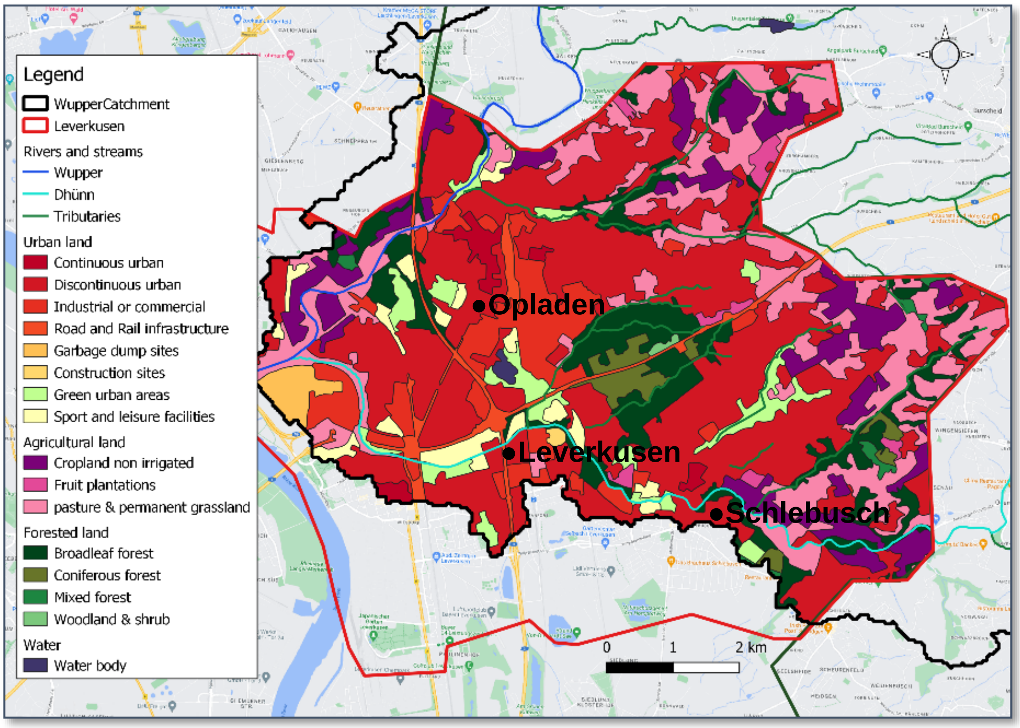


Figure 4: Leverkusen landcover and land use
(Data source: BKG, 2021a; Diva-GIS n.d. Prepared in QGIS v3.18.0)

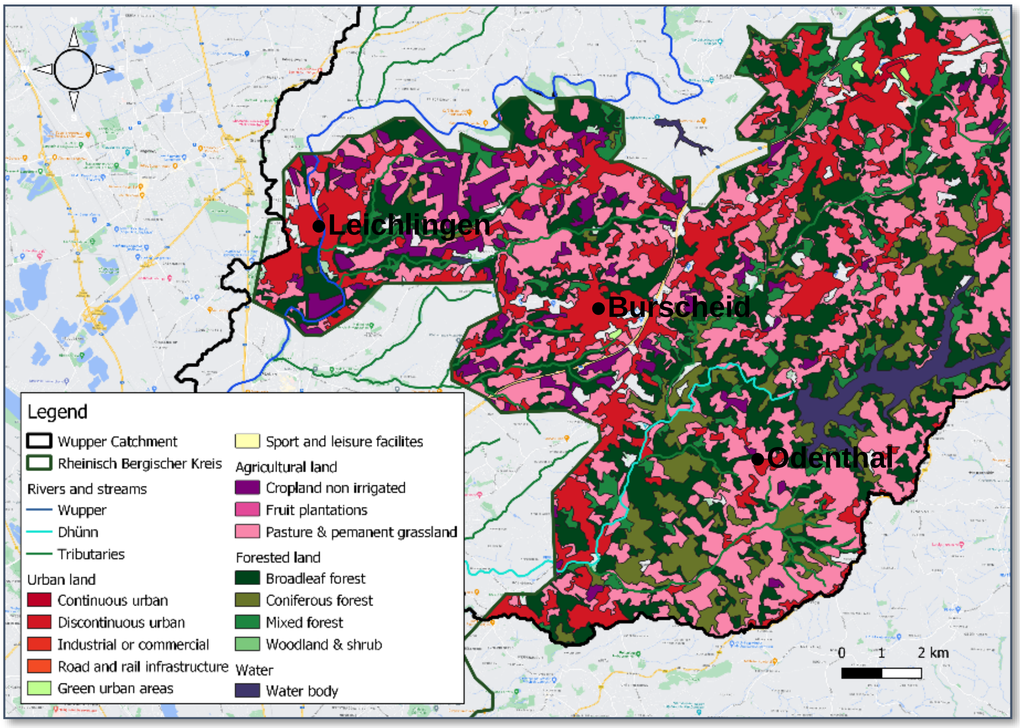


Figure 5: Rheinisch-Bergischer Kreis landcover and land use
(Data source: BKG, 2021a; Diva-GIS n.d. Prepared in QGIS v3.18.0)

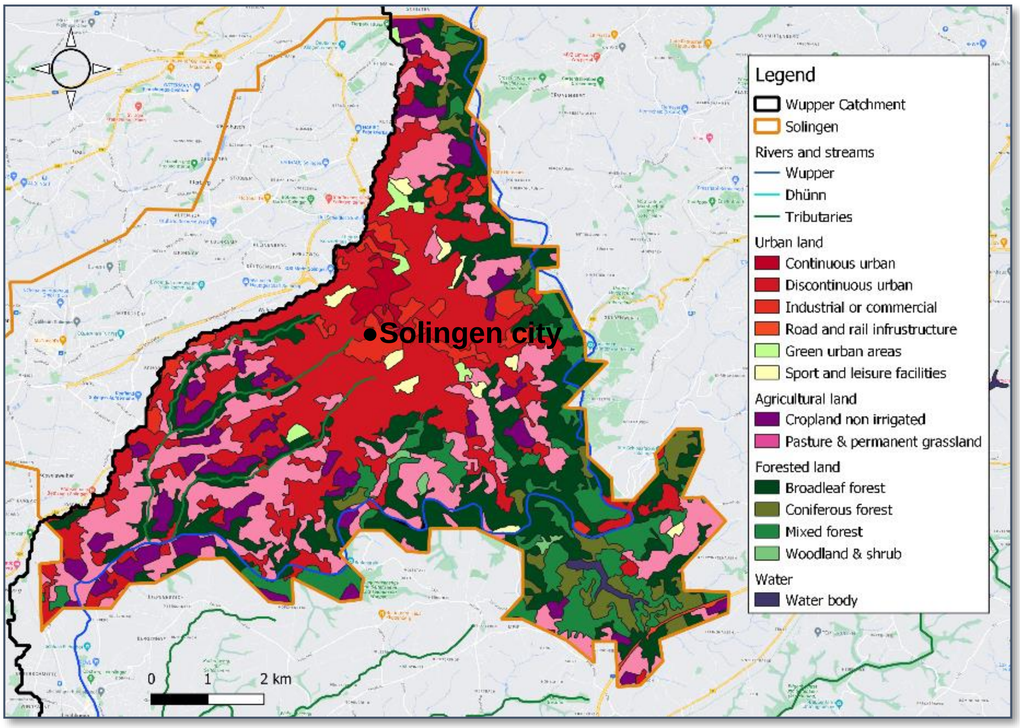


Figure 6: Solingen landcover and land use
(Data source: BKG, 2021a; Diva-GIS n.d. Prepared in QGIS v3.18.0)

2.5. Climate and hydrology

The Köppen-Geiger classification the Wupper Basin in North Rhine-Westphalia is that of a warm temperate European region (Cfb). Here summer and winter rainfall are not considered limited as a fully humid regime of precipitation occurs across both seasons. Summers are also classified as warm with at least four months of temperatures greater than or equal to 10 degrees Celsius (Kottek et al., 2006). In terms of the natural vegetation of the region, the basin is situated in the Western European broadleaf forest ecoregion, which is important for revegetation projects (Olson et al., 2001).

Annual average rainfall in the Wupper catchment ranges from 775 mm per annum in the lower reaches of Leverkusen, and up to 1425 mm in the southeast uplands of Solingen and the north and eastern extent of the basin (Lorza-Villegas et al., 2021). Average discharge for the Wupper is calculated at around 14m³/s (across years 1950-2021) as measured at Opladen, and 1.8m³/s for the Dhünn (across years 1987-2021) as measured at Manfort (LANUV, 2022a). Whereas the Wupperverband estimate the combined discharge of the Wupper and Dhünn as 17m³/s at the point where it enters the Rhine (Wupperverband, 2002).

The Wupper Basin has a long history of settlement and a long history of both flooding and water shortages. From the end of the 1800s dams were constructed to protect the population against flooding and to maintain a drinking water supply (Wupperverband, 2002).

2.5.1. Fluvial flooding hazard

Fluvial flooding hazard maps are available based on the NRW planning unit which are produced as a part of the EU's Flood Risk Management Directive. The maps show the extend of fluvial flooding in the basin for a given selection of flooding scenarios including HQ frequent for floods that are statistically likely to occur once in a 5 to 20 year period, HQ 100 statistically likely to occur once in a 100 year period and HQ Extreme, a flood with a return period likelihood of less than once in a 100 year period (Umwelt.nrw, 2022a). The official flood hazard maps are too large and detailed to show in this report and only available in Pdf format. *Figure 7* shows the flood hazard maps from the city of Rheinisch-Bergischer Kreis website which unfortunately does not include flood return periods in the legend. *Figure 8* shows the flood hazard maps for Leverkusen only, but also illustrates the difference between the frequent, 1 in 10- year and extreme flooding scenarios.

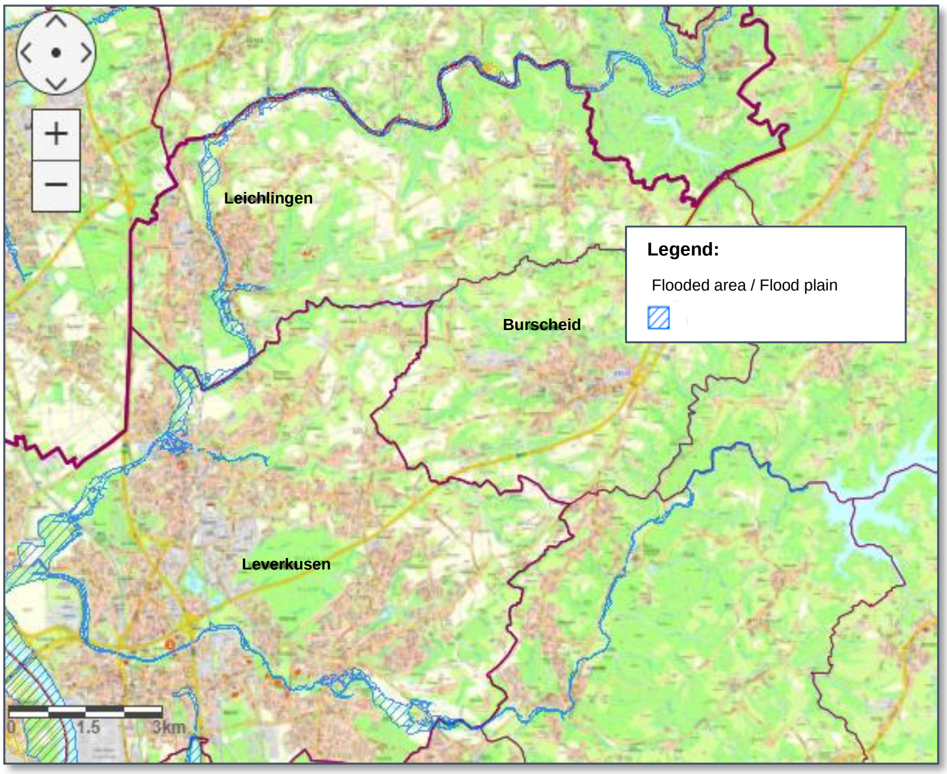


Figure 7: Flood hazard map of the study area (Stadt Rheinisch-Bergischer Kreis)

(Source: modified after RBK, 2021)

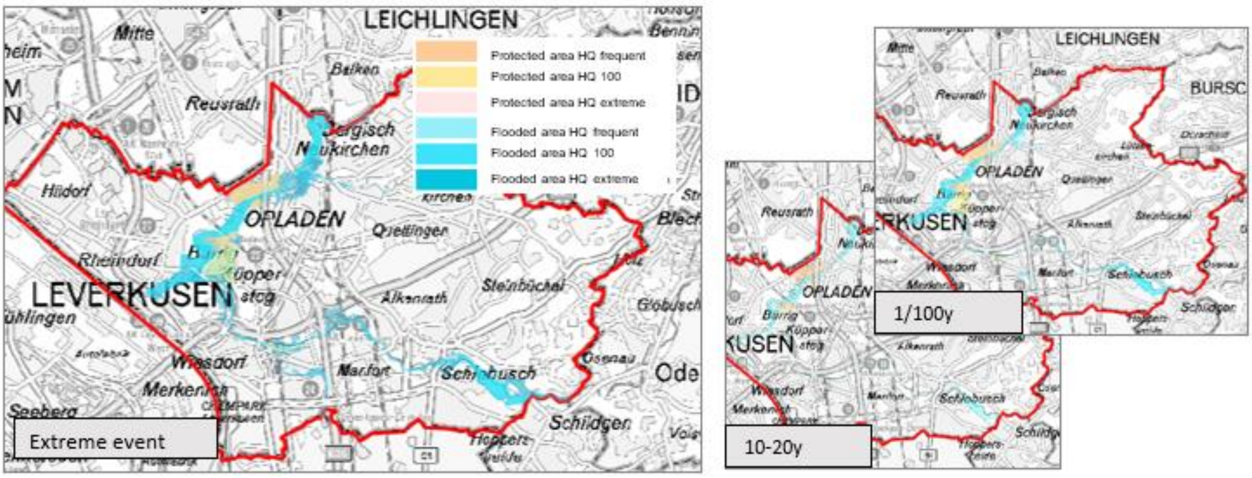


Figure 8: Flood hazard maps for Leverkusen

(Source: modified after Stadt Leverkusen, 2013)

2.5.2. Heavy rain flooding hazard

The heavy rainfall hazard map illustrates the difference between fluvial flooding and flash flooding across the study area. *Figure 9* shows the areas flooded in the study area under simulated heavy rain event for a rare and extreme event which are classified according to water height, rare event (1 in 100-year return period) and/or the water height of an extreme event (where equivalent rainfall is 90 mm/m² in 1 h) (BKG, 2021b). The difference between the fluvial flooding events and heavy rainfall or flash floods is evident in that the flash flooding events causes more widespread localised flooding which also leads to the overflow of minor and tributary streams in the basin. Whereas during a fluvial flood the Wupper and Dhünn rivers play a much larger role in delivering overbank water downstream. In the case of the floods of July 2021 both types of flooding occurred due to the spread of heavy rainfall across the basin, with the local streams, tributaries and both the Wupper and Dhünn rivers flooding.

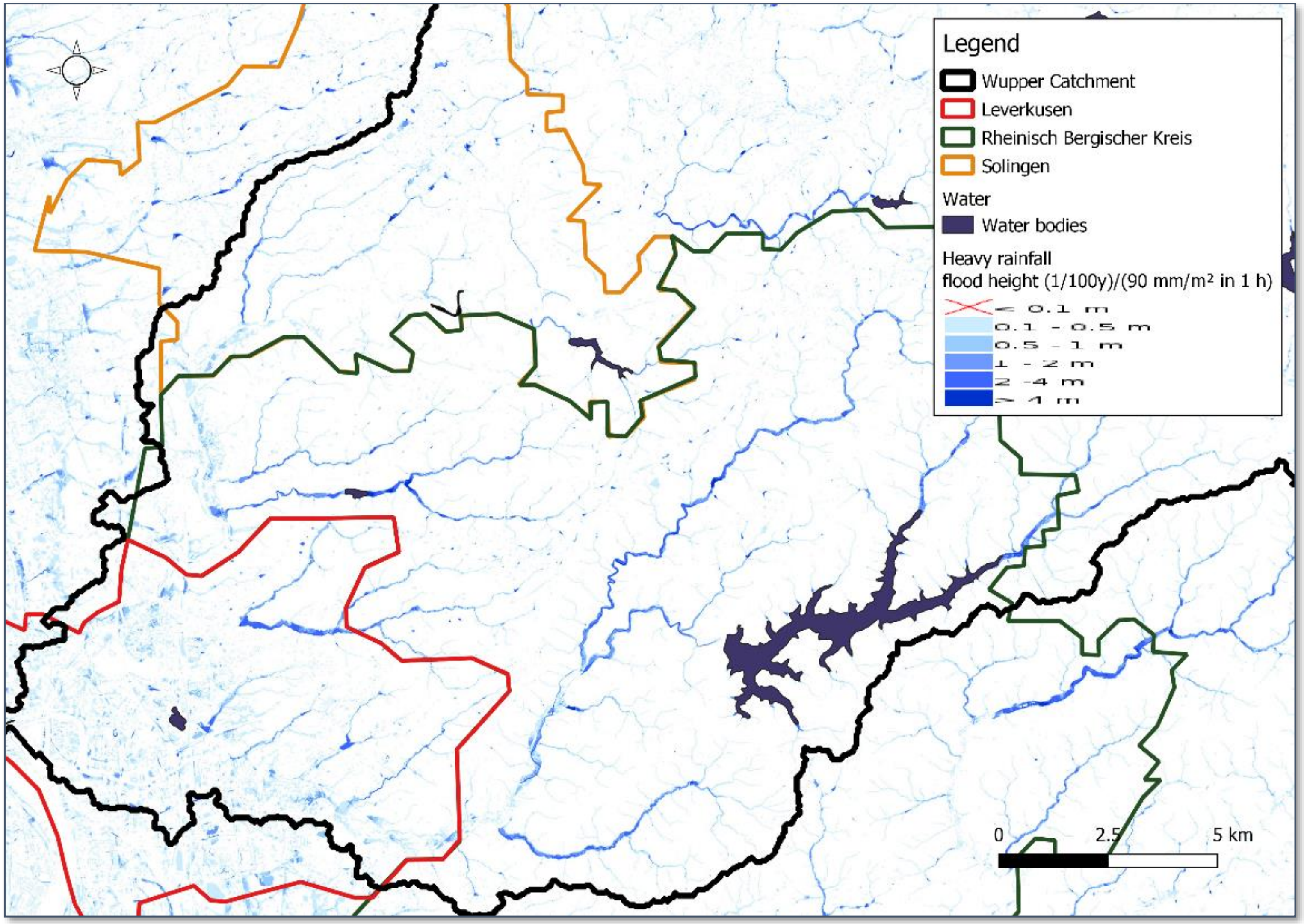


Figure 9: Heavy rainfall hazard map of the study area

(Data source: BKG, 2021b; Diva-GIS n.d.)

3. Methods

3.1. Literature review

Literature for the state-of-the-art reviews was sourced by searching the databases of Scopus and Google Scholar and via the bibliographies of literature sourced from those databases. In order to establish the likely baseline state of the basin given the landcover and land use categories searches including ‘landcover’ and ‘deforestation, reforestation and afforestation’ and ‘impact on runoff’, ‘impact on flooding’ were conducted. Similarly, the searches conducted for literature and field studies for each different category of intervention including forest interception, agroforestry in pastoral and cropping systems, grazing and grassland management, tillage, biochar and retention basins were conducted with the topic and ‘impact on interception’, ‘infiltration’, ‘runoff’ or ‘flooding’ as keywords. Once suitable papers were found and the intervention focus decide, additional searches were conducted to find alternative papers or field studies in Europe or other temperate climate regions. In order to seek state of the art knowledge on landscape characteristics and hydrology, searches were again carried out based on the categories for example riparian, slope position, slope form and gradient were carried out along with the keywords ‘impact on runoff’ and ‘impact on flooding’. For the observed and projected climate change impacts on Germany and the study area, the latest IPCC reports (2021/2022) were sought along with specific observed and projections relating to climate change impacts to the Wupper Basin.

3.2. Observed data on July 2021 floods

Rainfall data was obtained from two different sources, the Landesamt für Natur Umwelt und Verbraucherschutz (LANUV, 2022a), and Deutscher Wetterdeinst (DWD, 2022). Discharge and river height data was also sourced from the Landesamt für Natur Umwelt und Verbraucherschutz (LANUV, 2022b). This data was aggregated into monthly totals (if in daily format) and simple analysis such as averaging, calculating the extreme rainfall events (highest one percent according to USGCRP, 2022), and preparation for SPI and SSI carried out in Excel.

3.3. The Standard Precipitation Index (SPI)

The Standard Precipitation Index (SPI) method was developed by Mckee et al. (1993) to measure rainfall variation over a number of months (SPI-x).

SPI is calculated with monthly precipitation values. A sum is calculated for each three or twelve month period, the natural logarithm is calculated for each sum value and the size and shape of the gamma distribution are calculated (EDO, 2020).

$$G(x) = \int_0^x g(x)dx = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} \int_0^x x^{\alpha-1}e^{-x/\beta}dx$$

The equation is given as: by (Thom, 1966) where $\propto = \frac{1}{4A}\left(1 + \sqrt{1} + \frac{4A}{3}\right)$ and $A = \ln(\bar{x}) - \frac{\sum \ln(x)}{n}$ and $\beta = \frac{\bar{x}}{\alpha}$

n = number of precipitation observations and x = precipitation values.

The cumulative probability; $H(x) = q + (1 - q)G(x)$

Which is transformed into standard normal random variables Z;

$$Z = SPI = -\left(t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right)$$

$$Z = SPI = +\left(t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right)$$

And SPI;

$$Z = SPI = +\left(t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right) \quad for \quad 0.5 < H(x) \leq 1$$

Both SPI-12 and SPI-3 were calculated. SPI-12 allows for comparison of annual rainfall with the previous 12 months whilst SPI-3 was calculated to compare seasonal rainfall variation. Continuous historical rainfall data (1954 to 2021) is available for the station at Pattscheid which is located in the basin just to the northeast of Opladen. In order to gauge the relationship of rainfall to runoff in the basin and timeframes the Standardised Streamflow Index (SSI) was also calculated. SRI is calculated similarly to SPI but uses discharge data in the place of rainfall. The Standardised Streamflow Index (SSI) is calculated the same way as SPI (Shamshirband et al., 2020) and is used to verify a correlation between rainfall and stream discharge.

3.4. Spatial analysis

All spatial analysis was carried out in QGIS version 3.18.0. QGIS is an open-source geographic information system. In order to create the final intervention location maps for this report the following spatial analyses were carried out. Analysis was carried out using the CORINE landcover map CLC5-2018 (BKG, 2021a) and the USGS (2014) Digital Elevation Model (DEM). The CORINE landcover and land use maps have a resolution of 5 hectares and covers both landcover and in the more modified landscapes (urban and agricultural) land use, they are current to 2018 (BKG, 2021a). The USGS (2014) DEM is a digital elevation topography dataset taken from the Shuttle Radar Topography Mission (SRTM) in 2000 and has a 1-arc-second resolution.

Catchment delineation

The DEM from USGS (2014) was processed in QGIS using the following processing toolbox applications:

- Fill sinks (Wang and Liu)
- Strahler order
- Upslope area (Deterministic 8)

The raster was converted to polygon format using the Raster - Conversion tool.

Slope

Slope percentages were extracted using the DEM and Raster – Analysis – Slope tool. The raster was then converted to polygon format using the Raster - Conversion tool and slope percentages edited to generate layers of 15% and less and 30% and more slope.

Aspect

A layer of north facing slopes was created by using the processed DEM and Raster Calculator tool. North facing slopes were calculated using the equation: DEM ≤90 or DEM ≥270. The resulting raster was converted using the Raster – Conversion tool for further processing.

Contours

Contour lines were created from the processed DEM using the Raster – Extraction – Contour tool. Contours were created with 5m intervals.

Toe slope and hilltop

Toe slope and hilltop sites were selected and traced from the contour lines.

Buffers

Buffers were created to indicate the riparian zone from the traced river and streams layer. The buffer was created from the Vector – Geoprocessing tool – Buffer tool. Two buffer layers were created one with a distance of approximately 100m (0.001°) and the other with a distance of approximately 200m (0.025°) the former was used to delineate the riparian zone for retention/detention locations, and the latter for the TWI intersection to indicate locations for shelterbelts/hedgerows.

Rainfall maps

First delimited text layers were created for the location of the rainfall stations and containing the rainfall data in the attribute table. Rainfall maps were created using the Raster – Analysis – Inverse Distance to a Power function.

TWI

The Topographic Wetness Index (TWI) was calculated using the processed DEM. First the tan of the slopes was calculated in the Processing toolbox, using the Slope, aspect, curvature tool, this created a new layer. Next the DEM and slope in radans are used as the input layers to the Processing toolbox selection, Saga, Terrain analysis - Hydrology, Topographic Wetness Index. 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 for display and intersection purposes.

Intersections

The intersection tool from the Vector – Geoprocessing tools menu item was used to generate intersections of selected subcategories of landcover and land use distributions with the riparian buffer and slope of less than 15%, hilltop and toe slope contours, slope greater than 30% and north facing aspect. These were all used in the final intervention location maps.

4. State of the Art

4.1. Climate change impacts observed and forecast

The first step in planning for green and blue infrastructure intervention is to identify the hydrological risk (Martín et al., 2020). The literature indicates that the Wupper basin as a whole is facing increased risks of flooding and drought (Lorza- Villegas et al., 2021; Meredith et al., 2018). Drought is a slow onset weather phenomenon that can be partly offset by grey infrastructure such as dams. Around fourteen dams are already constructed within the Wupper basin, including the Große Dhünn-Talsperre which provides drinking water for the area (Wupperverband, 2022a). The dams are currently able to hold enough water to offset the effects of drought on the population for around two years (BINGO, 2016). Heavy rainfall and flooding events can also be partially offset by dams, depending on rainfall location. Floods, however, pose more immediate risk to communities and infrastructure as the nature of flash flooding can catch many people, including authorities, by surprise, leading to deaths and high damage costs (Cooper et al., 2021; Fekete and Sandholz, 2021; IPCC, 2022; Kreienkamp et al., 2021). The flooding rains such as that experienced across the Wupper basin and others on 14 and 15 July 2021 are considered to be an extreme event with a return period of 1 in 1000 years and are estimated to cost Germany between 4.5 and 5.5 billion euros (Kreienkamp et al., 2021; Wupperverbund, 2022a).

The green-blue interventions and infrastructure investigated as a part of this report aim to address both flooding and water shortages with the concept of “keeping the rain where it falls” (Collentine and Futter, 2018) and storage of the water in the soil and vegetation as “green water” (Falkenmark and Rockström, 2006; 2010). This can be achieved through green-blue interventions that act to increase interception, and infiltration and reduced runoff. These interventions are not the sole or ultimate solution, they will need to work with both engineered or ‘grey’ infrastructure and also urban green-blue infrastructure and interventions. The benefits to green-blue interventions, however, are multiple and timely as the impacts of biodiversity loss and climate change are being experienced in the form of natural hazards.

4.1.1. Observed hydrometeorological changes in Europe

CO_2 concentrations have increased 47% since 1750. With current CO_2 levels higher than any time over the last two million years, and CH_4 and N_2O higher than any time over the last 800,000 years, temperatures across the surface of the earth are now an average of 1.09 degrees warmer than 100 years ago (IPCC, 2021). Climate change is the likely cause of an observed increase in both the recurrence and intensity of high rainfall events across most continents since the 1950’s (IPCC, 2021). Across Europe there has been an increase in mean rainfall, and along with that fluvial flooding across western and central Europe has increased, and there is high confidence that this is caused by anthropogenic climate change. In addition, there is also medium confidence that pluvial flooding has increased, and that hydrological drought has increased across western and central Europe (IPCC, 2021).

4.1.2. Observed hydrometeorological changes in Germany

Petrow and Merz (2009) analysed 52 years of river gauge records across Germany to find that floods have indeed increased for the Rhine basin amongst others across western Germany, and that the trend was more pronounced for winter (fluvial) floods over pluvial or summer flooding. Furthermore, they found that the increase in flooding was more likely to be due to climatic changes rather than land use or river modification.

4.1.3. Observed hydrometeorological changes in the Wupper Basin

Analysis of the hydrometeorological situation in the Wupper Basin appear to mirror some of the larger scale trends of Germany and Western Europe. The Wupper catchment is impacted by hydrometeorological extremes in the form of winter fluvial floods caused by snow melt and rainfall, and summer localised flash floods from convective storms (Meredith et al. 2018; BINGO, 2016). Floods and major floods are recorded across the basin during 1890, 1909, 1925, 1946 prior to the establishment of the Wupperverband and their coordination and construction of flood protection measures, and also more recently in 2007, 2011, 2013 and 2021 (BINGO, 2016). In addition, extended dry periods have become more common across the basin in recent decades (Lorza-Villegas et al., 2021).

While average rainfall has been relatively stable, the BINGO project (2016) analysis of rainfall data from 1900 to 2010 in the basin indicates a reduction in spring (April) rainfall of around 25mm and an increase in late Autumn (November) rainfall of around 20mm from around the 1950-60s. In contrast to the German wide observations, BINGO (2016) also analysed flash floods in the Wupper Basin and found that flash flooding events caused by convective activity had increased by more than a factor of three since the 1970s. Lorza-Villegas et al. (2021) analysed rainfall and streamflow data for the hydro-meteorological station Neumühle located east of the Groß Dhünn River for the period 1961 to 2020. The authors used Standardised Precipitation Index (SPI), Standardised Precipitation-Evapotranspiration (SPEI) and Standardised Runoff Index (SRI) to demonstrate trends in rainfall and runoff (see *Figure 10*). The authors also found increased precipitation in the winter months but decreased rainfall and runoff during the autumn months. The authors also showed that while spring rainfall has reduced, higher evapotranspiration rates due to increasing temperatures are causing even less rainfall to reach the rivers and dams.

As there were no trend analyses found for the localities in the west of the Wupper Basin, SPI-3 was calculated (1960-1992/2021) for rainfall stations located at Pattscheid (between Wupper tributaries the Murbach and the Ölbach), and at Odenthal west of the Groß Dhünn dam. These locations can be considered to give a better indication of the local situation in terms of rainfall, unfortunately the data for Odenthal is only available until 1992 and there are no other rainfall gauges on the western side of the Groß Dhünn Dam (see *Figure 2* for station locations).

SPI-12 was calculated for Patscheid rainfall and SSI-12 calculated for streamflow at Opladen. These are graphed together (see *Figure 11*) to show that the rainfall data corresponds to streamflow as there is only some annual difference in the comparison between the peaks and troughs for both sets of data. The annual differences may be explained by the dams located in the upstream areas of the Wupper releasing additional water into the system, or higher upstream rainfall totals.

SPI results for the study area are shown in *Figure 12*. SPI is usually used as a drought indicator but can also be used to illustrate rainfall trends (Mckee et al.,1993). The SPI value classification at the centre of *Figure 12* shows that negative values mean reduced rainfall with -2 indicating an extremely dry period and positive values indicating higher rainfall with +2 indicating an extremely wet period. The SPI graphs from both Pattscheid and Odenthal station data indicate very clearly an increasing rainfall trend during the winter season and decreasing rainfall in the summer months. This trend correlates with the findings of BINGO (2016) and Lorza-Villegas et al. (2021). The SPI-3 results shown in *Figure 12* indicate that the spring and autumn seasons are when the highest frequency of rainfall deficits have occurred over the last 30 and 60 years. The autumn season rainfall at both Pattscheid and Odenthal also show a very slight increasing trend which is consistent with the BINGO (2016) analysis but not with that from Lorza-Villegas et al. (2021). However, the spring trend while similarly indicating a historic deficit in rainfall, also shows a slight upturn in the recent trend, which is not concurrent with the results from BINGO (2016) or Lorza-Villegas et al. (2021). These anomalies however, do not suggest any large deviation from the previously discussed findings, it is likely that they simply indicate micro climatic differences within the basin.

4.1.4. Forecast hydrometeorological changes across Germany

Under RCP8.5 there is high confidence that fluvial flooding will increase across western and central Europe (IPCC, 2021). In addition, Purr et al. (2021) analysed the connection between convective rain cell and temperature and humidity and ran the COSMO-CLM model for Germany to find that invective cells will be more intense and more widespread under RCP8.5. Pfeifer et al. (2015) used regional simulation ensembles and determined that average and high intensity rainfall in winter will increase across Germany for both RCP 4.5 and 8.5, with the largest increase under RCP 8.5.

4.1.5. Forecast hydrometeorological changes in the Wupper Catchment

There are large uncertainties involved in forecasting the impact of climate change across smaller areas such as the Wupper Basin. The BINGO project (2019) models only demonstrated clear signals on some aspects of the future climate including an increase in winter rainfall (similarly to German wide forecasts) in this case there were little differences between scenarios RCP 4.5 and 8.5. There is higher certainty that temperatures and evapotranspiration will increase across all months of the year within the basin area, with the highest increase in August under RCP 8.5. The authors predicted that these changes would lead to an increase in summer convective rainfall events, in both number and intensity (BINGO, 2019).

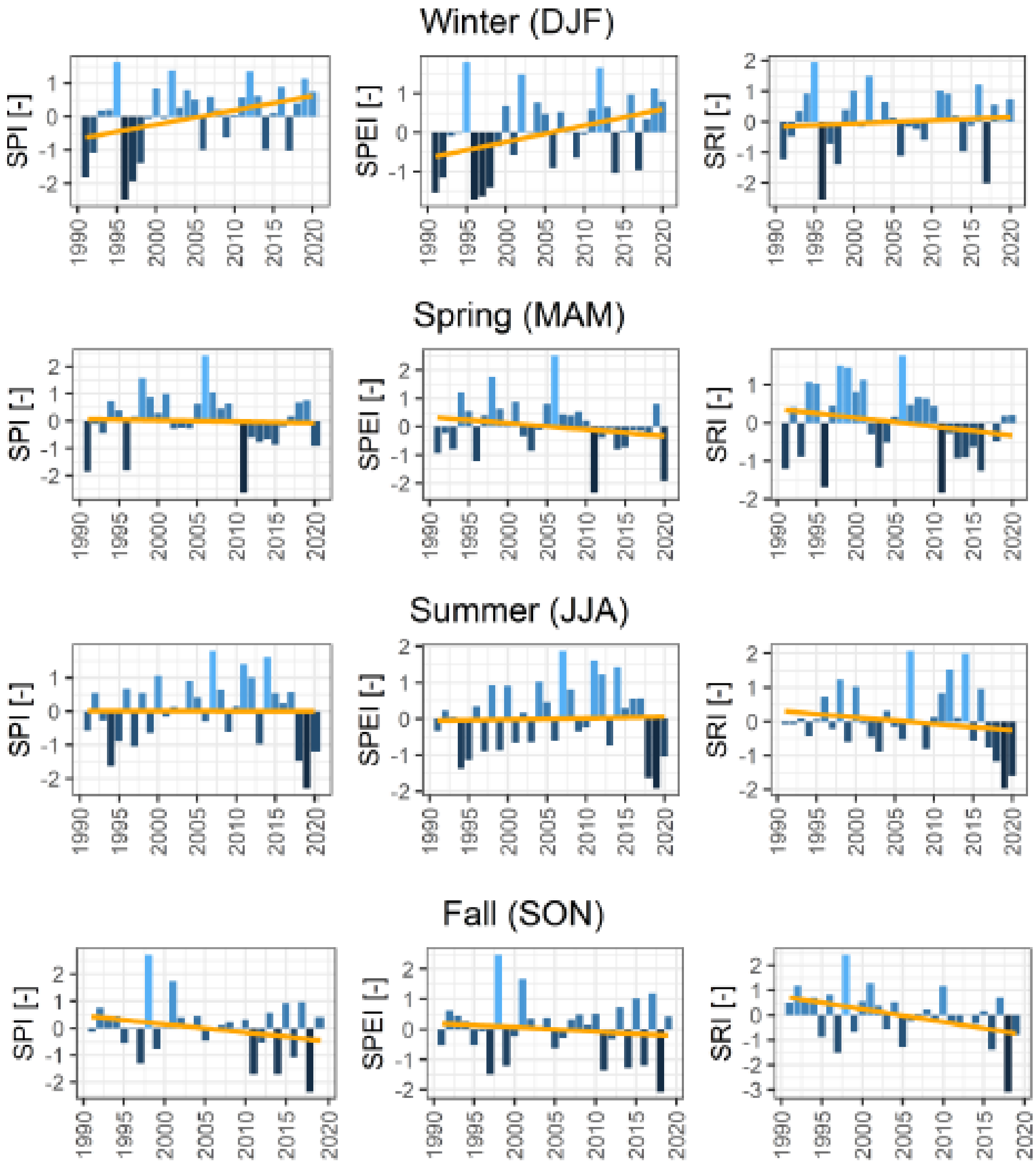


Figure 10: SPI, SPEI and SRI for Neumühle station (east of the Groß Dhünn Dam) from 1990 to 2020

(Source: Lorza-Villegas et al., 2021)

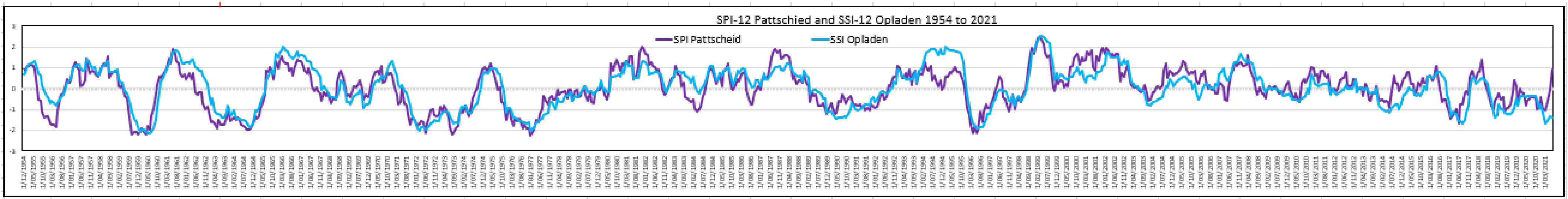
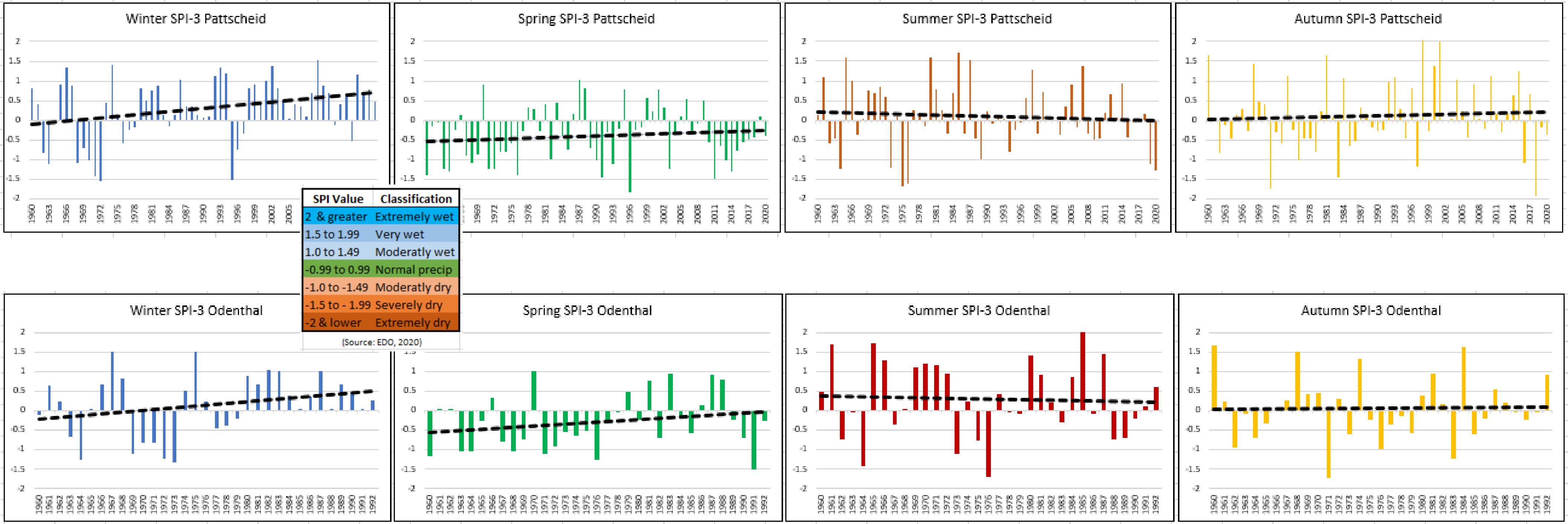


Figure 11: SPI-12 Pattschied and SSI-12 Wupper at Opladen from 1954 to 2021

(Data source: DWD, 2022; LANUV, 2023)



SPI Value	Classification
2 & greater	Extremely wet
1.5 to 1.99	Very wet
1.0 to 1.49	Moderatly wet
-0.99 to 0.99	Normal precip
-1.0 to -1.49	Moderatly dry
-1.5 to - 1.99	Severely dry
-2 & lower	Extremely dry

(Source: EDO, 2020)

Figure 12: SPI-3 for Pattscheid (Wupper) from 1960 to 2020 and Odenthal (Dhünn) from 1960 to 1992 as indicator of rainfall trends in the study area

(Data source: DWD, 2022 Prepared in Excel)

4.2. Identification of the most effective green-blue interventions for the Wupper Catchment

A meta-analysis of 1589 field trials by Xiong et al. (2018) on soil erosion and runoff concluded that biological solutions (afforestation and slope revegetation) were 11% more effective at reducing runoff than engineered methods (terraces, contour bunds etc.) and 7% more effective than soil conservation methods such as tillage and soil amendments. The authors also found that interventions were most effective on agricultural land with a slope of between 25 and 40 degrees. While taking this into account, this report attempts to identify green-blue infrastructure interventions with the highest potential impact on hydrometeorological extremes, with the least impact on productive land uses. Using the information obtained from climatic characterisation, landcover, land use and elevation maps, and analysis of the current and projected hydrometeorological hazards, suitable green-blue interventions were identified from the literature.

Ultimately, the hazards caused by the hydrometeorological extremes of flooding and drought are addressed or minimised through the green-blue interventions that increase interception, infiltration and reduce runoff and flooding. Literature measuring the impact of land cover or land use categories on rainfall infiltration, runoff and flooding, under similar climates and landscapes, was reviewed and summarised to determine the current situation or baseline within the basin. Using this information green-blue interventions for each of the land cover and land use categories were assessed, results from field trials, and model and laboratory analyses were compiled to produce a toolbox of potential interventions suitable for the climate, land uses and landscapes of the Wupper Basin along with research findings on the optimum layout or location for each intervention. *Figure 13* below illustrates the process.

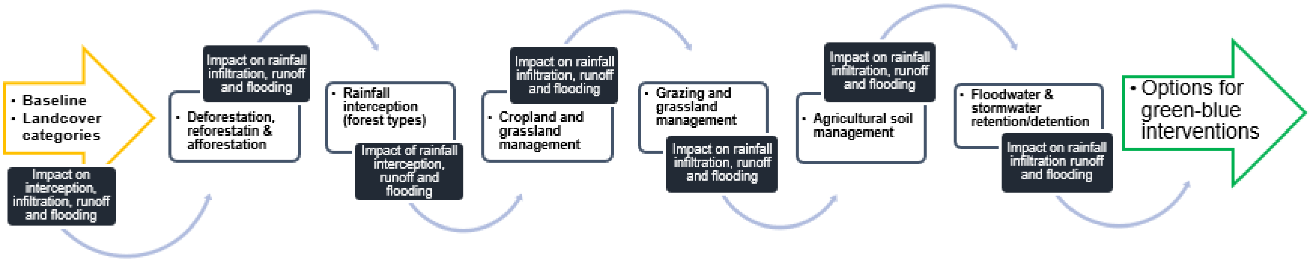


Figure 13: Process undertaken to identify optimum green-blue interventions

A state-of-the-art toolbox was produced for green-blue interventions in the temperature regions of peri-urban and rural Europe (see *Appendix 1*). Interventions such as such as floodplain restoration were not considered for several reasons, including cost and complexity, furthermore, extensive floodplains are not a large part of the landscape in the Wupper Catchment until the landscape flattens around Leverkusen (see limited extent of floodplains on *Figure 7*). The point where the floodplains are widest is almost at discharge to the Rhine, and here there is likely to be little impact as interventions only act to reduce the impact locally or downstream.

A range of themes were investigated within the published literature. The capability of the major landcover and land use categories to intercept rainfall, provide effective soil infiltration and reduce runoff and flooding, were first investigated to determine the current state (or baseline). Green-blue interventions that employ revegetation, soil, cropland and pasture/grassland management and floodwater retention techniques were investigated to determine their potential for increasing rainfall interception and soil infiltration and reducing runoff and flooding.

4.2.1. Landcover impact on infiltration, runoff and flooding

The literature reviewed all agreed that the soil under forests had the highest soil hydraulic conductivity and produced the lowest runoff rates, compared to all other land cover including cropland, pasture, grassland and orchards. The largest differences were between forest soils that of cropland and grazed pastures but also in forest clearings (Gonzalez-Sosa et al., 2010; Hümann et al., 2011; Maetens et al., 2012). There was no agreement on the type of forest that produce the best results, however. Archer et al. (2013) measured highest hydraulic conductivity under broadleaf forests (compared to a pine forest and willow floodplain forest), however it is possible that there was also subsurface flow under the broadleaf forests. Chandler et al. (2018) found the highest hydraulic conductivity under a Scots Pine dominated forest (compared to a Sycamore dominated forest and grazed forests). Gonzalez-Sosa et al. (2010) found the highest hydraulic conductivity under small woods (compared to broadleaf forest, permanent pasture, orchard and conifer forest). Hümann et al. (2011) found that the runoff coefficient was lowest for Douglas Fir forests (compared to Beech and Oak forests). Nordmann et al. (2009) found that mixed forests (Spruce and Beech) had the lowest runoff coefficients over three irrigation cycles (compared to broadleaf and spruce forests). Therefore, it is likely that there are other factors involved, including soil type and thickness, prior land use and slope characteristics.

4.2.2. Deforestation, reforestation and afforestation impact on infiltration, runoff and flooding

Parts of the Wupper Basin, particularly around the towns of Wuppertal, Remschied and Solingen, were completely deforested by the beginning of the 1800s. Forests were removed from the landscape and the only trees were found in town parks or orchards, the forests that grew on the hillsides were cut down and, in their place, only shrubs remained. Furthermore, people used the remnant woodlands to produce charcoal for heating (Laussmann, 2021). The history of the Wupper Basin is similar to many within Europe and while forests have been re-established (or remain) in some parts of the basin, even more land has since been cleared for farmland and cleared and sealed by urban development.

The literature found on deforestation, reforestation and afforestation in European hill-scapes all indicates that the loss of forest cover means increased rainfall runoff and increased flooding. Guillemette et al. (2005) found that the maximum impact that deforestation had on small to medium catchments was a 63% increase on peak flow when 61% of the forest catchment had been harvested. While the specific impact on different return period and peak flooding can differ depending on a wide range of factors including; precipitation volume and duration, forest size and location within the catchment, mechanism measured (soil storage, surface roughness or interception), forest species and flow type (overland, subsurface or baseflow), all studies suggest that to some degree deforestation increases flooding and reforestation or afforestation will act to inhibit flooding to different degrees.

Some studies found that during large flooding events and once the soil is saturated, forest cover or not has no further impact (Bathurst et al., 2020; Xiao et al., 2022). Although Bathurst et al. (2020) found that the frequency of return periods for small to medium floods is lower in forested catchments compared to cleared catchments in a review of several long-term studies in paired catchments. Ferguson and Fenner (2020) used a set of different models on a small catchment (48 km^2) and found that forest and woody debris reduced storm flood peak of 1 in 10 year storm by 57% and while the influenced reduced as storm return periods also reduced, the influence on a 1 in 100 year storm which was still a 15% reduction.

4.2.3. Rainfall interception - effectiveness of different forest types

The literature indicates that conifer species can intercept more rainfall of light to medium intensity than broadleaf varieties due to their highly fascicled leaf structure and leaf surface area (Barbier et al., 2009; Keim et al., 2006). Which might explain why earlier studies found that coniferous forests reduced runoff and flooding more effectively than broadleaf varieties. Broadleaf species can store more rainfall per biomass total and more at higher intensity rainfall levels than coniferous forests (Keim et al., 2006) however, broadleaf/deciduous species also recorded higher stemflow volumes than that of conifers which reduced as forest diversity increased (Barbier et al., 2009; Krämer and Hölscher, 2009). However, both Krämer and Hölscher (2009) and Pypker et al. (2005) found that throughfall was lowest in young coniferous forests because of uniformity and in broadleaf forests of low diversity, while interception was highest in old growth coniferous forests because of increased canopy and species diversity (Pypker et al., 2005). In terms of elevation Köhler et al. (2015) found that interception became less effective above 420 m.a.s.l as cloud water deposition provided additional moisture to biomass.

To sum up the evidence on interception, coniferous plantations intercept more water in general than broadleaf under light to medium rainfall intensity, broadleaf forests intercept more rainfall under high intensity conditions, broadleaf forests funnel more moisture from stemflow than coniferous forests, but this is offset by can be offset by higher diversity in broadleaf forests, however, throughfall may increase for light and medium intensity storms. In addition to interception properties some broadleaf trees such as the Beech in natural settings also have larger root systems which not only produce macropores for better soil water drainage but also use more water from the soil (Nordmann et al., 2009; Tembata et al., 2020). Elevations below 420 m.a.s.l are optimum for forest interception.

4.2.4. Shelterbelt/hedgerows and buffer strips - impact on infiltration and runoff

Studies on rainfall runoff consistently find cropland to be one of the highest runoff generating land uses compared to other vegetated landcover categories (Borin et al., 2010; Gonzalez-Sosa et al., 2010; Hümann et al., 2011; Nerlich et al., 2013). Monocropping and seasonal planting leave significant areas of bare soil and years of tilling and heavy machinery use result in soils with low organic matter, low saturated hydraulic conductivity and sorptivity and high bulk density (Gonzalez-Sosa et al., 2010; Hümann et al., 2011).

Grasslands, especially grazed pasture grasslands are also some of the highest runoff producing vegetated land covers due to poor soil hydraulic conductivity caused by livestock and machinery compaction (Archer et al., 2013; Chandler et al., 2018; Gonzalez-Sosa et al., 2010; Monger et al., 2022b). Soil under grazed forests also has reduced hydraulic conductivity similar to or sometimes in excess of grazed grasslands as grazing increases compaction and the span of bare soil within the forest (Chandler et al., 2018; Öllerer et al., 2019).

Significant improvements are reported in several studies on shelterbelt/hedgerow additions to grazed grasslands, and on agroforestry in the form of buffer strips and coppicing in croplands. Field studies in Italy and Germany have found that agroforestry which incorporates buffer strip tree or tree row planting and silvopasture along the borders of the crop field, in a form of agroforestry, can reduce overland flow by up to 79-90 per cent (Borin et al., 2010; Nerlich et al., 2013). The same studies also found that shelterbelts or tree rows also work to limit nitrogen and phosphorous losses. Other studies confirm that increased soil water storage capacity in forested strips can be attributed to the deeper reach of tree roots (Anderson et al., 2009). Agroforestry/ tree strips or shelterbelts and are not new concepts as European farmers throughout history practiced farming in agroforestry systems as it was the best way for them to maximise resources and income. However, agroforestry is no longer common throughout Germany as the practice is not compatible with modern machinery and farming methods (Nerlich et al., 2013).

Evidence from the literature suggests that grazing excluded shelterbelts can be particularly effective at reducing runoff from grassland pastures, especially on slopes. A long running study in the United Kingdom found that shelterbelts planted cross-slope were highly effective at reducing runoff. Field studies found that soil hydraulic conductivity and infiltration under the tree strip compared to soils under grazed grassland were up to 2.4 times and more than doubled respectively (Carroll et al., 2004; Marshall et al., 2009;2014). Marshall et al. (2014) measured an average 78 per cent runoff reduction under the slopes with shelterbelt plantings compared to the control pasture sites.

Management of trees in agroforestry and shelterbelt systems to ensure maximum crop and pasture growth will depend on whether the growth limiting factors at the site are predominantly light or water. Crop yield can be affected by shade and the influence of the shelterbelt, and this can be a problem in temperate climates such as that of the Wupper Basin (DBU, 2010; Nerlich et al., 2013). Studies on the impact of crop yield from shading and proximity to tree rows found that the results vary for different crop types. The DBU (2010) investigation on crop yield found that potato crops increased yield by 10% under light to medium shading and decreased only slightly under high shade. Maize and Winter Barley yields were only slightly reduced by light to medium shading but at heavy shading (50%) yields were reduced by 28-37% and grassland demonstrated a similar reduction in yield with increased shading. Whereas Borin et al. (2010) found that Maize and Soyabean yields were only reduced to within 4m of the shelterbelt and Sugarbeet was impacted by up to 50% yield reduction likely due to a shading effect by the tree shelterbelt. The differences in crop yield impact between studies will be due to the differences between experimental design and other growth requirements, but show that shading should be kept to a minimum if possible, except potentially for potato crops.

Nerlich et al. (2013) recommends a north-south configuration of shelterbelts surrounding cropland in order that the amount of shading is reduced. As this configuration will not always be possible given field location, shape and slope, trees can be managed to maintain a low canopy to reduce the shade effect on crops, such as short rotation poplar, sycamore or European cranberry bush for example (Borin et al., 2010; Eichorn et al., 2006; Nerlich et al., 2013). Established row trees can also be maintained with a high pruning regime (≥10m) to provide the soil benefits and let light through as leaf and stem are removed up to a 10m height (SAFE, 2003).

Water interactions may also need to be managed. It is clear that agroforestry buffer strips and shelterbelt systems are able to reduce rainfall runoff by retaining a greater portion of water in the soils and vegetation canopy (Borin et al., 2010; Marshall et al., 2014; Nerlich et al., 2013) which may at the very least delay a flood peak (Marshall et al., 2014). However, when water is a limiting factor for growth, some studies report that tree and crop or pasture interactions belowground may result in competition for water and yield reductions (Jose et al., 2004). Others report that because tree roots penetrate deeper than that of annual crops and grass, that there is little competition (Anderson et al., 2009). A more thorough explanation is that trees can draw from shallow or deeper layers depending on opportunity and need but can also increase soil moisture content for more shallow rooted species such as crops, by moving water from the deeper layers to dryer upper layers through the process of hydraulic lift (Bayala and Prieto, 2020). The authors also report that tree pruning has been shown to reduce the prevalence of shallow roots which works to limit competition between the tree and annual crops and in some cases increase hydraulic lift. Although, there is no indication of how this would impact the mechanisms involved in overland flow reduction.

4.2.5. Grazing and grassland management impact on infiltration and runoff

Pasture and permanent grasslands make up most of the agricultural land use throughout the study area. The landcover category is defined as ‘pastures, meadows and other permanent grassland under agricultural use’ (BKG, 2021a) which implies a wide range of different land use intensities that are, nevertheless, grouped together. As mentioned above, sown crops and grazing land are some of the highest runoff producing land covers due to compaction and reduced soil hydraulic conductivity. There is no indication that grazing pressure is high in general across the Wupper catchment, but there are livestock, in particular dairy and beef cows, and livestock have the effect of create greater compaction of the soil leading to increased runoff, particularly where they walk every day (Meijles et al., 2015).

While there has been plentiful research into the impact of grazing on soil erosion and water quality in Europe there are not so many investigations making the connection between grazing management and runoff and catchment hydrology (Minea et al., 2022). Cattle grazing has a much higher negative impact on grassland diversity than smaller grazing animals such as sheep (Socher et al., 2013) and because of their size place more weight on the ground that can cause compaction comparable to farm machinery (Minea et al., 2022). Meyles et al. (2006) showed that areas with heavier grazing propensity have higher soil bulk density and reduced water holding properties that reach saturation more quickly to initiate runoff. Furthermore, Pan et al. (2016) demonstrated that over 80% of surface resistance to overland flow in grasslands comes from the leaf and stem component of grasses and recommended that mowing/heavy grazing prior to heavy rainfall events may significantly contribute to rapid runoff. Meijles et al. (2015) further investigated the connection between grazing pressure and runoff to conclude that heavy grazing not only impacts soil properties which lead to faster soil saturation and runoff but the tracks of grazing animals are observed to contribute directly to stormwater runoff prior to runoff generation occurring from other areas. Finally, Monger et al. (2022a) investigated grazed woodlands and runoff generation. The authors found that runoff velocity can be reduced as long as good soil properties and undergrowth are maintained by reducing grazing pressure and ensuring an open tree canopy to allow for continued grass and understory growth

4.2.6. Soil management (conservation tillage / reduced tillage / strip tillage) impact on infiltration and runoff

The benefits of reduced tillage or no tillage to soil bulk density, soil moisture loss and erosion are well known (Soane et al, 2012; Klik and Rosner, 2020; Zikeli and Gruber., 2017). However, uptake of conservation tillage has been more successful in less humid climates than Germany due to a more pressing need to conserve soil water. Furthermore, German farmers stated that they use ploughing primarily for weed control between grass and crop rotations and to incorporate manure soil amendments, but increasing aridity of summers under climate change may also increase the need for conservation tillage (Zikeli and Gruber., 2017).

The benefits of reduced tillage on rainfall runoff in European conditions are also documented. Field trials carried out over 22 years in Austria show that no till can reduce rainfall runoff by 49-60% and mulch tillage (stubble retention) by 25-55% (Klik and Rosner, 2020). Runoff from conservation tillage (non-inversion with 30% of stubble retained) plots was reduced by an average of 75% compared to conventional tillage in a 16-year trial in Hungary (Madarasz et al., 2021). Strip tillage, where crops are sown into tilled strips with the stubble retained in between, is something that could work well for the study area, as weeds can pose problems under reduced tillage in the humid regions (Madarasz et al., 2021). Strip tillage was tested in Germany under sugar beet crops in luvisol soils similar to the study area and on slopes of around 8-13% and was found to reduce runoff by 92% compared to conventional tillage operations. In this study strip tillage also fared much better than conservation tillage for surface runoff, which resulted in a 55% reduction compared to the conventional control. Lastly, Haag et al. (2006) modelled rainfall from 1 in 2 year to 1 in 100 year return periods and found that a change in land use from conventional to 50% conservation tillage (across 37% of agricultural land area) could reduce the flood peak by 1.4% to 1.8%. They also found that changes to tillage in the basin had more impact on storms of high precipitation and short duration than long soaking rains.

4.2.7. Soil management (biochar additions) impact on infiltration and runoff

A review by Razzaghi et al. (2020) reports that water retention properties of fine textured soils (in high clay and tropical environments) have actually decreased with the addition of biochar. Although the authors acknowledge that there are such a large variety of biochar feedstocks and pyrolysis methods, that comparison of different trials can be problematic. Nevertheless, it appears that biochar has been used most successfully as a soil amendment in coarse sandy soils simply because these soils are most in need of improvements to water and nutrient holding capacities (Razzaghi et al., 2020; Xiao et al., 2016). Hence, the majority of studies on soil water properties and biochar have been carried out on coarse or sandy soils and as a result there are fewer trials to use as examples of what may occur in the field.

The major soils in the study area are defined as Cambisols and Luvisols which are derived from or at the least contain a proportion of fine-grained loess material so field trials on water holding properties using specifically Cambisols and Luvisols and loess soils were sourced and it appears that in certain circumstances the soils of the study area can be amended with biochar to increase water holding capacity. A biochar from charcoal residue and compost were added (20 Mg/ha) to a Dystric Cambisol under maize cropping in Brandenburg, Germany which led to doubling of the plant available water in the soils compared to the control. In addition, the nutrient content of Nitrogen and Potassium per kilogram of soil doubled (Liu et al., 2012). Similarly, a biochar of paper fibre sludge and grain husks (10 and 20 t/ha) was added to a Haplic Luvisol under maize, barley and wheat rotations in Slovakia which resulted in increased soil moisture and reduced bulk density compared to the control for each of the three application rates (Horak et al. 2019). The water holding properties of a Cumuli-Ustic Isohumosols loess soil under maize in China was also enhanced by the addition of a maize straw biochar. Biochar additions of 10, 20 and 30 t/ha all increased the water content of the soil and along with that soil permeability and water use efficiency of the crop and crop yields also increased compared to the control plot (Xiao et al. 2016).

Some studies on biochar applications to fine textured soils have found that the amendment can increased runoff and erosion on slopes (Li et al., 2020; Zhang et al., 2019) for that reason this study suggests that biochar could be added to hilltop sites only and only under conservation tillage. Furthermore, the application of biochar in any situation is cautioned due to the wide range of biochar available and potential non-compatibility with different soil types and potential German and EU regulations regarding soil amendments.

4.2.8. Floodwater and stormwater retention / detention areas and ponds

Floodwater retention/detention is a highly effective way of reducing the flood hazard risk to the community (ICPR, 2020; Krampl et al., 2016). While a few pieces of literature quite correctly refer to the temporary detainment of water as ‘detention’ as technically the water is not permanently retained but temporarily detained (Vieira et al, 2018), the vast majority refer to temporary and/or permanent detainment as retention because the effect is the same, to reduce the flood peak and so the term retention is used to describe this process. While there is a very real potential for temporarily detained floodwater to prolong the flood duration as water is released after the first flood peak, implementation of detention or retention areas requires engineering and modelling studies to determine prior to planning. Furthermore, actual flood retention whereby flood waters are separated from the system and not returned would be more often than not considered to be grey infrastructure, not necessarily green-blue infrastructure, as it requires a high degree of engineering.

Nevertheless, floodwater detention and/or retention acts to reduce or delay the flood peak by providing a larger area for floodwaters to spread across and in that way can reduce flood height and volume downstream. Flood retention can apply to a variety of different interventions and infrastructure, can be implemented through a range of structures from highly engineered (grey) infrastructure (as discussed above) to floodplain or meander restoration and utilisation of semi natural landscapes, and in various formats from pure dams to flooded woodlands, floodplains and occasional wetlands. While retention is used to describe the detention of water, Krampl et al. (2016) differentiate between retention basins and retention areas. The authors define the retention area as a near natural environment and the basin as an engineered structure. In light of this definition, this study assesses and identifies locations for detention/retention areas but also ponds as are mentioned in literature used in reviewing the state of the art, because as Krampl et al. (2016) also mention, there is often limited space for large scale retention areas, and ponds as a smaller version of a retention area are also assessed in the literature. Retention areas can be multi-purpose in that they are utilised as semi natural parkland areas for recreation or farmland year round, and also be used to hold back flood waters during times of flooding, in terms of green-blue interventions these are most beneficial as they also provide a range of co-benefits to the community, for biodiversity and when under agricultural land also an economic return. Förster et al. (2008) estimated a loss estimate of 40,000 euros per annum for the use of agricultural land for floodwater detention with a capacity of 40 million m^3 or a 1 in 100 y flood. This is quite cheap compared to the cost of engineering, construction and maintenance of a concrete dam, and not much for a city to pay to reduce the flood risk. The farmer benefits with an extra annual payment and so does the community as the hazard is minimised.

As discussed previously, there is high competition for space in urban and peri-urban areas so for planning purposes it is useful to assess the relative effectiveness of retention/detention basins and areas compared to other interventions. Bell et al. (2020) addresses this issue in reviewing the comparative effectiveness of modelled stormwater retention/detention and urban green-blue imperviousness measures. They found that retention/detention are more effective at reducing peak flow than increasing the imperviousness of the urban landscape. Giacomoni et al. (2014) also modelled the two measures for a small (370 km^2) catchment area to find that retention ponds are more effective at reducing the peak flow for 1 in 10 year and 1 in 100 year floods, however for the 1 in 2 year flood scenario imperviousness reduction measures are overall more effective. This information highlights the need for retention and detention basins are included in the mix of green-blue interventions for the Wupper Basin.

It is a given that taking water out of the system will reduce the flood peak downstream. However, depending on the layout and size of the basin and the flood event, retention areas can have greater impact on adjacent downstream sites and a lessor impact on sites further downstream (ICPR, 2020), particularly if there are additional tributaries further downstream or if the basin is large. Because of this it is imperative to assess the size, placement and arrangement of retention areas or ponds in order to achieve the greatest effectiveness. Nicholson et al. (2019) evaluated the effectiveness of temporary small-scale ponds constructed on pastureland at reducing flash flooding in a very small catchment (5.7 km^2) and showed that an upstream pond (400 m^3) could reduce a minor flash flood peak by approximately 12%, through basin modelling they also found that a network of small ponds of a combined total 20,000 m^3 storage, could reduce the impact of flash floods downstream by around 30%. Wilkinson et al. (2010) also found that a small-scale retention pond (<1000 m^3) set in the agricultural headwaters of a minor (6 km^2) catchment can reduce peak flow travel time by 15 minutes and a further four ponds (2800 m^3) set mid catchment could reduce downstream flooding during a 1 in 5 year event by 8%.

Salazar et al. (2012) also looked at small scale ponds to reduce flash flooding in rural mountainous regions and found that micro-ponds (100 m^3) were more effective than large reservoirs at reducing peak floods in medium sized catchments (954 km^2 and 621 km^2) but mostly for convective (flash flood) rainfall events. The magnitude of the impact varied between catchments, but it seems that smaller more distributed retention ponds can better capture rainfall in the headwaters which has a greater effect on convective rainfall runoff and potentially flash flooding events.

4.2.9. Location of intervention in catchment/ slope and impact on infiltration/runoff/flooding

It is extremely important for this study to identify the areas, both on a catchment-wide scale and in slope geomorphology, where green-blue interventions can be located to provide maximum impact. Not a lot of work has actually been carried out on the topic of potential placement of green-blue interventions on a catchment-wide scale, as Cooper et al. (2021) confirmed in their review. The authors reviewed the available literature to find that reforestation on a catchment basis reduces flood risk, but the location and percentage of reforestation that reduced flood risk the most, varied. The authors also reviewed papers on a) cross slope, b) flood plain and c) riparian reforestation. They found a) that there was a good deal of evidence that cross slope reforestation on agricultural lands (shelterbelts and hedgerows) reduced rainfall runoff and soil infiltration, b) that the main contribution to flood peaks by riparian reforestation was surface roughness slowing the flood peak, and c) only around 10% of Europe’s floodplain forests actually remain, modelling studies suggest that their re-instatement would reduce flooding but the magnitude of the impact varies.

Several authors investigated deforestation and reforestation or afforestation location within the catchment and the findings differed suggesting that there are more complex and interrelated factors occurring involved at the catchment scale. Wahren et al. (2012) found that reforestation/afforestation of headwater areas had the more impact on small to medium floods compared to downstream reforestation/afforestation. Conversely, Iacob et al. (2017) and Guillemette et al. (2005) found respectively that lowland afforestation had more impact on reducing peak flows and that deforestation of an upper catchment had no impact on peak flows. Cooper et al. (2021) also discussed the possibility that riparian vegetation had the most impact on water yield. Birkinshaw et al. (2014) measured an annual streamflow reduction of 250-300mm after upland afforestation of a small grassland catchment. The impact was estimated by the UK Environment Agency (UKEA, n.d.) to account for a 10-15% reduction of peak flows. While afforestation and reforestation can make a large impact on catchment runoff and flooding, water use by trees and forests during the summer months and during droughts must also be considered. The reduction in streamflow during dryer months should also be monitored and where possible species that are drought tolerant planted at sites exposed to more sun (Wupperverband, 2002) such as the south facing slopes or in the more freely draining soils.

There are several hillslope factors that influence runoff, so while there seem to be some simple generalisations that can be made, in reality the influences are complex and very difficult to measure and attribute to individual factors in the field. In general, a higher gradient will result in higher runoff and faster runoff velocities. Marapara et al. (2021) contends that in terms of runoff generation and flooding, a slope of greater than 30% will produce high velocity runoff and slopes 15-30% will generate medium to high velocity runoff hastening the occurrence of flash floods compared to lower angled slopes. A small number of studies were found on how slope characteristics (length and width), profile curvature (concave, convex, straight) and planform curvature affect subsurface runoff. Work by Aryal et al. (2005) suggests that divergent and concave hillslopes forms mean increased flow velocity. Similarly, Troch (2003) found that divergent slopes drain more quickly than convergent hillslopes. The authors acknowledging that there are also other complex factors influencing hillslope drainage in the field such as initial soil moisture, soil depth, hydraulic conductivity and bedrock. Sensitivity analysis of hillslope and landcover characteristics by Bachmair and Weiler (2012) found that soil hydraulic conductivity had the highest impact on subsurface flow followed by profile curvature, slope degree and plan curvature, while canopy cover and maximum throughfall percentages were the landcover characteristics with the highest impact on subsurface flows. Graham and Lin (2011) looked at preferential flows and found that the controls were initial soil moisture and that they were more likely to form on hilltops when soils were dry, hillslopes after long duration rainfall and toe slopes after rainfall of high intensity. Zhu et al. (2014) combined a simple classification of hillslope position and landcover. They found that soils on the hilltop, upper and mid points of the slope reflect rainfall volume and intensity regardless of landcover and that the lower and toe slope positions received both subsurface and overland flow during high intensity events only, when forested these locations received no flows at low and medium intensity.

Several authors ran models to assess the best layout of retention/detention basins within the basin to maximise flood peak reduction. Xing et al. (2016) found that maximum capture of rainfall runoff was achieved when retention/detention ponds were distributed across each of the headwater sub basins furthest from the main river channel and that the least reduction was achieved when detention/retention was concentrated in the lower sub-catchments. Smith et al. (2015) showed that placing retention basins on second order streams had the most impact on stormwater runoff and peak discharge (as opposed to first or third order streams) due to optimum coverage of spatially diverse rainfall. Birkinshaw and Krivtsov (2022) also found that retention/detention in the headwaters of a small (22.8 km^2) upland catchment is more effective than ponds lower in the catchment, providing that the size of the retention pond(s) in the headwaters allow for the flood wave to pass downstream urban areas prior to water being released. The authors also found that peak flow reduction was highest for the downstream urban location when retention/detention ponds were located in mid and upper catchment in addition to the headwaters. Similarly, Ayalew et al. (2015) found that retention/detention ponds of a higher capacity located in the headwaters achieve greater flood peak reduction for low and medium probability of exceedance floods and similar reductions for high exceedance floods than ponds located at downstream locations, unless the majority of rainfall fell in the lowlands. Furthermore, the authors also found that retention/detention ponds set parallel, or across-catchment in a small catchment (30 km^2), can better reduce low and medium probability of exceedance floods than those located linearly downstream because they capture a wider area of runoff to land area. The authors also cautioned that the impact reduces further downstream from the retention pond and also as catchment size increases and that the timing of the drainage of retention ponds is important to downstream impact.

In terms of identifying optimum locations for retention/detention basins on the basis of land use, geomorphology and relief, studies employed a multi-criteria approach. Bellu et al. (2016) used slope (0-5%), landuse (semi natural), minimised point source pollution (population density 1.7-3.3) as criteria. Ahmadisharaf et al. (2016) used a similar approach but with additional criteria including slope on a sliding scale (0 to >15%), distance to channels, distance to urban infrastructure (>5000m), soil permeability (CN 65-70) indicating some but not high permeability, and land acquisition favouring open land and public areas.

5. Assessing potential locations for green-blue interventions to reduce the impact of hydrometeorological hazards

5.1. Lessons from 14 July 2021 floods

On 14 July heavy rains fell across Western Europe including the Wupper Basin in Germany. These rains were the result of a stationary or cut-off low pressure system (Bernd) which was located over western Europe from around the 12 July (KARL, 2021; Kreienkamp et al., 2021). The low-pressure system was unable to move east because of a stable high pressure system that had become established across western Russia. Low pressure system Bernd remained in place across Western Europe for days drawing in warm moist air from the Mediterranean Sea. As it moved from southern to western Germany on the 14th the moisture laden air encountered the low mountain ranges of the Sauerland to the east of the Wupper and the Eifel to the west, the orographic lift resulted in intense convective rainfall which fell across Belgium, Luxemburg and Germany (KARL, 2021; Kreienkamp et al., 2021). Several catchments across western Germany were inundated as soils were already saturated from earlier rainfall and flash floods swept through the Ahr and the Erft valleys to the west of the Wupper and up to 184 people in Germany lost their lives (KARL, 2021; Kreienkamp et al., 2021). The cost of these flash floods in Germany is estimated at around 4.5 and 5.5 billion euros (Kreienkamp et al., 2021).

In the Wupper Basin the majority of the rainfall fell across the two days of the 13th and 14th of July (see *Figure 15*, Rainfall 13-14 July 2021). Many areas were inundated including both urban and rural sites as the water could not drain away through saturated soils and the rivers and streams also overflowed. Stadt Leverkusen (2022) reports that 135 L/m^2 fell across Leverkusen on the 14th July. Many sites including Opladen and Schlebusch in Leverkusen were inundated from rainfall and overbank waters from the Wupper, Weimbach and the Dhünn rivers (Wupperverband, 2022a). The rivers peaked in Leverkusen on the 15th and at the height of the flood the level of the Dhünn at Manfort was measured at 387 cm or 140 m^3/s. The Wupperverband report that this could have been worse as the Groß Dhünn Dam was used to retain up to 8 million m^3 of water throughout the event. Up until that point, an extreme flood (with return of 1/1000-years) in the Dhünn was estimated at the water level of 319 cm. The Wupper also reached new heights and was measured at 466 cm or greater than 500 m^3/s on the same day at Opladen, also exceeding extreme flood projections which were estimated at 398 cm or 375 m^3/s (Wupperverband 2022a).

Extreme rainfall events are defined as the highest one percent of rainfall occurring per days of rainfall (USGCRP, 2022). Analysis of long-term rainfall data (1931-2021) from Pattschied (located between Wupper tributaries Murbach and the Ölbach) shows three daily rainfall totals in the top one percent. 65.1mm occurring on 15 August 2015, 76.5mm from 17 April 1936, and by far the highest single daily rainfall of 115.1, which occurred on 14 July 2021.

The rainfall that occurred on the 13-14 July also created streamflow and river height peaks that were unprecedented across the Wupper Basin. The gauge on the Wupper at Glüder (Solingen) provides discharge data from 1950. Comparisons of the daily discharge totals since 1950 indicates that the Wupper Basin experienced two days of record discharge, with discharge of 151 m^3/s which was recorded on the 14th July being the fifth highest since 1950 and the 278 m^3/s flow recorded on the 15th July, one day after the heavy rainfall measuring as the highest flow recorded across the entire 70 year period, by a difference of 108 m^3/s. (DWD, 2022; LANUV, 2023).

The rainfall maps in *Figure 14* show the spatial differences between the average monthly rainfall across the Wupper Basin and the rainfall that fell between the 13 and 14th of July 2021. The 13-14 July rainfall was highly concentrated across the study area with totals of 143.3mm falling during the two days at Pattscheid in a rainband that stretched from Solingen Wald in the north to Stammheim just to the south of Leverkusen. This heavy rainfall created flash flooding in Leverkusen and other parts of the basin, and as the rainfall across the remainder of the Wupper Basin was only slightly lower, significant river floods occurred on the 15th across Leverkusen. Average rainfall totals follow a different pattern with the higher averages found in the east of the basin where the Wupper and Groß Dhünn Rivers rise, and averages gradually decreasing downstream towards the Rhine. Comparison of the two maps shows that there needs to be more emphasis on addressing hydrometeorological hazards within the study area, especially in terms of runoff and flash flood reduction.

The unprecedented rainfall and flooding that occurred in July 2021 has resulted in several plans and action at different levels of authority. The government of North Rhine-Westphalia has announced a ten-point plan for the Wupper Basin which involves updating flood forecasting, flood protection governance and funding, dam safety reviews and others along the lines of their jurisdiction. It also includes working with local agencies and landholders to increase the number of natural water retention measures including renaturation of channelised rivers, weir and levee removal and updates to risk management plans to include the smaller bodies of water, as currently this level of planning does not exist for the Wupper or tributaries (Umwelt.nrw, 2022b).

The Wupperverband and local municipalities are working together on a number of projects to examine what steps to take in urban areas and updating existing retention basins, expanding the Ophovener Wieher retention basin in Leverkusen and construction of new retention basins at Bornberg in Wuppertal and Diepental at Leichlingen and Mühlenteich at Remscheid (Wupperverband, 2022a; 2022c). There is more that can be done in terms of green-blue interventions however, that can work alongside the planned approaches. While no infrastructure or action can guarantee that flooding or droughts will never occur again, green-blue interventions provide a natural way of keeping the rain where it falls and enhancing landscape resilience to future hydrometeorological hazards while at the same time providing co-benefits for biodiversity, cost savings, aesthetic enjoyment and climate change.

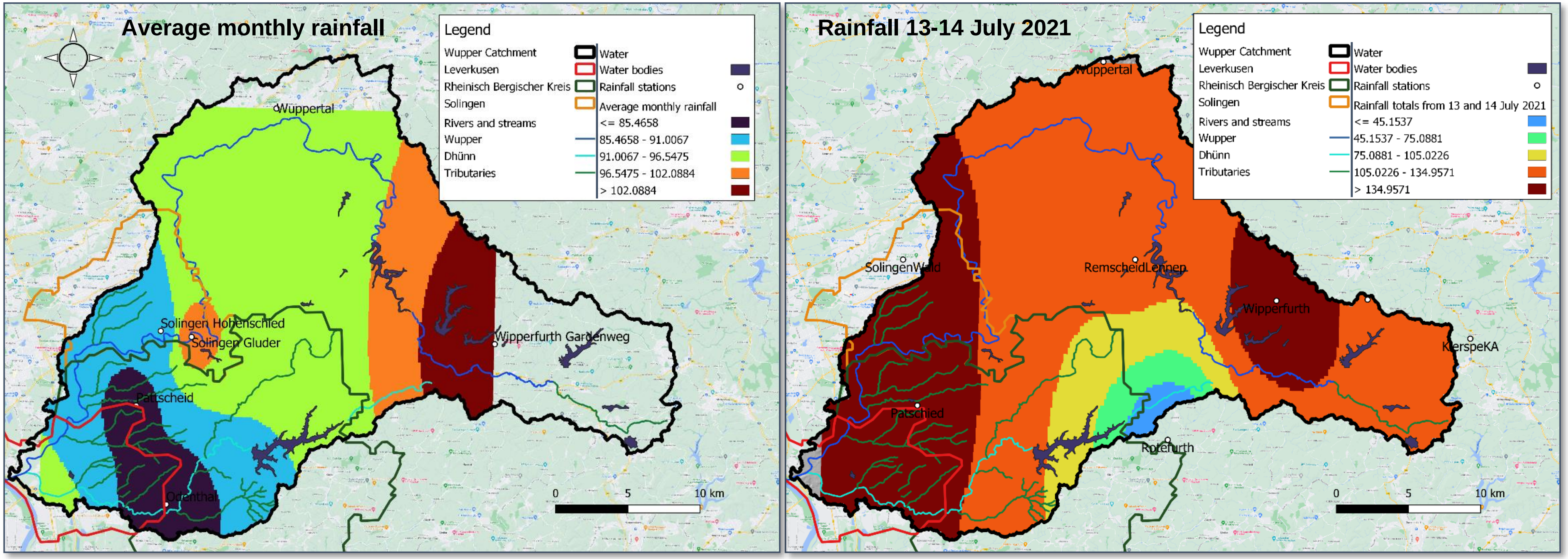


Figure 14: Comparison of average monthly rainfall totals across the Wupper Basin and rainfall totals that fell over the two days of July 13 and 14 2021

(Data source: DWD, 2022 LANUV, 2023. Prepared in QGIS v3.18.0)

5.2. Spatial assessment of potential locations for hydrometeorological hazard reduction

5.2.1. Identification of criteria

Certain landscape features have a greater, or lessor potential to influence basin hydrology. Before spatial analysis can be carried out to show the most promising location of green-blue interventions in the study area, the impact that different landscape features have on hydrology needs to be assessed. The starting point for the analysis is land cover and land use. Land cover and use categories are the starting point for analysis because they dictate the type of intervention that can be implemented. Landcover and land use categories were assigned simple priority rankings for green-blue interventions based on the evidence gathered from the state-of-the-art information. *Table 1* at the end of this section presents a summary of the evidence and the priority rankings (low to high) assigned to each landcover/land use category based on the evidence presented. As mentioned previously this report offers suggestions for interventions that may modify land management, but the aim is to do so in a realistic way, without suggesting any wholescale changes to the current land use, unless there is overwhelming evidence that the current land use is not feasible into the future. While the change suggested by interventions is kept to a minimum, so too is the land area affected. This is achieved by analysing landscape characteristics and pairing the sites with high potential to influence basin hydrology with green-blue interventions that are shown to have the highest potential impact on interception, infiltration, runoff and flooding.

5.2.1.1. Priority land cover and land use categories

As mentioned previously urban uses classified in the land cover maps as continuous and discontinuous urban, industrial, facilities or road and rail infrastructure are not considered in this study. There are many reports reporting or investigating the best use and placement of green-blue, and nature-based solutions in urban locations with highly impervious landcover, so this report does not focus on these areas. There is one exception however, green urban areas are considered for retention/detention ponds if located in the riparian zone. This is justified because they are not normally areas that are protected from flooding and may serve as useful detention areas to reduce the impact on sensitive urban locations if the landscape characteristics allow and it is safe to do so.

Land categorised as agricultural land is a priority for green-blue interventions within the study area. There are a number of reasons for this, firstly the large percentage of land that agriculture covers in the study area. Across Leverkusen and Solingen agriculture makes up around 21-24% of land use and in Rheinisch-Bergischer Kreis the percentage is even larger at 52% (BKG, 2021a). Also because agricultural land is often located alongside the rivers and streams in the study area, and also because of the opportunities that exist to improve infiltration and reduce runoff on agricultural lands (see *Figures 4, 5 and 6* for an illustration of landcover categories across the study area). Thirdly agricultural soils are generally associated with low infiltration properties indicated by low hydraulic conductivity, high bulk density and high runoff and erosion because of tillage and compaction (Gonzalez-Sosa et al. 2010; Haag et al., 2006; Hümann et al. 2011; Laufer et al. 2016; Maetens et al. 2012; Meijles et al. 2015; Meyles et al. 2006) this means that there is considerable room for improvement. With cropland in particular there are a range of management improvements that can be made to reduce runoff and improve water retention (Borin et al. 2010; Haag et al. 2006; Laufer et al. 2016; Nerlich et al. 2013).

Similarly, there are opportunities to improve infiltration and runoff under grazed pasture (Jackson et al., 2008; Marshall et al., 2014) and with different methods for grassland crops and permanent grasslands, however, as mentioned in *Section 4.2.5* it is impossible to separate out the more intensively managed sown grasslands and agricultural pastures from permanent grasslands in the current land use mapping categories. There are strict rules applying to grasslands classified as ‘permanent grassland’ for the purposes of EU Common Agriculture Policy (CAP) and German ‘Greening’ policy where a permit is required before ploughing can occur, and in areas designated Natura 2000 (FFH Habitats directive or bird sanctuaries) ploughing and/or conversion is effectively banned (BfN, 2014; UBA, 2021). From 2018 this restriction also included the ploughing of permanent grassland for pasture renewal and if a permit is allocated ploughing can only occur once every five years (Landberatung, 2023). These rules appear to apply to crops of ryegrass and timothy grass but not to crops of clover or alfalfa or maize, barley, triticale or oats (EC, 2015). The majority of grassland in the study area appears to be sown grassland or grassland and crop rotations, (see *Figure 15* photos of grasslands taken from within the study area in April 2023). This grass is used for the purposes of making hay for livestock, which is the case for around 30% of agricultural land in Germany (Socher et al., 2013).

Figure 15: Photos taken of sown grass crops within the study area

(Source: Photos taken by author)

This type of grassland is managed similarly to cropland although with potentially less ploughing but fertilising and mowing certainly does occur (Socher et al., 2013) and with that also the effects of compaction and perhaps also fallow which leaves land bare creating the perfect environment for additional runoff.

Although reduced tillage is effectively enforced for ‘permanent grassland’, there is no indication in Corine landcover maps which grassland is considered permanent grassland for CAP purposes, as there is also the classification natural grassland (321) of which none occur in the study area. The discussion is necessary because, tillage or ploughing is a deeply ingrained feature of German crop management. The 2015/16 Statistiches Bundesamt (2023) reported that conventional ploughing (as opposed to reduced tillage or no tillage) was the main sowing process for 53% of arable land. Conservation tillage techniques are also reportedly much more likely to be employed by larger farm holdings and the average farm size in western Germany being 52 ha compared to the average of 234 ha in the east in 2019 (Statistiches Bundesamt, 2023). For these reasons reduced tillage has been included as a potential green-blue intervention for grassland management in addition to arable land or crop management. Unfortunately, there is no way to differentiate between grazed pasture, cropped grassland or permanent grassland with the spatial data available so different interventions are suggested for each subcategory of land use.

Forested land is also considered for green-blue intervention. In the study area coniferous plantations have experienced high level of die-back in recent years due to bark beetle infestation (Chambers, 2021; Wald und Holz NRW, 2020). In many plantation areas these trees have been felled and are now devoid of extensive vegetation cover as illustrated in the photos in *Figure 16*, which were taken in the study area during 2022. As found by Gonzalez-Sosa et al. (2010) cleared forests can exhibit extremely low hydraulic conductivity and high bulk density potentially from heavy machinery compaction or erosion. Therefore, these areas would also generate high runoff and it is important that these forest areas are reforested, as they cover over up to 5% of land across the study area. The Wupperverband have a plan for the reforestation of the coniferous plantations managed by the corporation (see *Section 5.3.2*). Plantations owned by private entities, however, may replanted with alternative coniferous trees, as investors are looking for the quickest economic return, while there is also economic value in broadleaf plantations (DBU, 2010) their maturation period tends to be relatively longer than that of coniferous species.

Figure 16: Photos of cleared coniferous (likely spruce) plantations in the study area

(Source: Photos taken by author)

Revegetation for natural retention/detention areas is also suggested for coniferous plantations that are in close proximity to rivers or streams. There also aren’t necessarily generously wide floodplains under coniferous plantations in the Wupper Basin due to constriction by relief and urban development, and evidence of only a few small renaturing projects on the Wupper and Dhünn, although there is evidence that reinstatement of floodplains as use for natural flood retention has worked well along the Rhine (Redeker, 2018; Trémolières et al., 2008). Nevertheless, periodic flooding of the forested riparian sections along the Wupper would be a natural occurrence and can even be beneficial for the natural succession of forest species (Schnitzler, 1994; Trémolières et al., 2008). Existing broadleaf forests and mixed forests are not considered for any intervention. Such forests are already providing ongoing hydrological risk mitigation in the form of rainfall interception and soil water retention (Chandler et al. 2018; Keim et al., 2006; Krämer and Hölscher, 2009; Nordman et al., 2009) especially for low to medium sized rainfall events (Bathurst et al., 2020) and should be retained for this and other ongoing services.

Similarly with woodland and shrub, there is no recommendation for any changes to this land cover. This kind of landcover already provides benefits in relation to infiltration (Gonzalez-Sosa et al., 2010), surface roughness and slowing runoff (Monger et al., 2022a) and if located in the riparian zone, slowing the flow of water (Makaske et al., 2011) which can also be of benefit to delay the flood peak downstream. Of course, delaying a flood peak is not always the desirable outcome in terms of flood management, but can be as long as it means that a lower flood peak is reached.

Table 1: Priority rankings for green-blue intervention potential for each landcover/land use category

Landscape / feature type	Feature Characteristics	Priority for green-blue intervention in Wupper Basin	Justification
Land use and land cover	Urban areas	Low	Suitable for urban modification measures (permeable pavements, green roofs, rainwater harvesting etc.) (Alves et al. 2018).
	Coniferous forest	High	In Germany coniferous plantations have experienced high level of die-back in recent years due to bark beetle infestation (Chambers, 2021; Wald und Holz NRW, 2020). In many areas these trees have been felled and present an opportunity for strategic reforestation especially for state forests. Constraints in private forests, but many broadleaf trees also have high economic value (DBU, 2010), not just coniferous.
	Broadleaf and mixed forests	Ongoing therefore no need for additional intervention	Existing forests provide ongoing hydrological risk mitigation in the form of rainfall interception and soil water retention (Chandler et al., 2018; Nordman et al., 2009) especially for low to medium sized rainfall events (Bathurst et al., 2020) and should be maintained for this ongoing service.
	Arable cropland	Medium-High	Usually associated with soils of low hydraulic conductivity and high bulk density (Gonzalez-Sosa et al. 2010; Hümann et al. 2011). There are a number of improvements that can be made to reduce runoff and improve water retention in cropland (Borin et al. 2010; Klik and Rosner 2020; Laufer et al. 2016; Nerlich et al. 2013). Constraints include land ownership and economics.
	Pasture and permanent grasslands	Medium-High	Soils also associated with low hydraulic conductivity and high bulk density (Archer et al. 2013). There are a range of green-blue treatments that can increase water retention and runoff in grazed grasslands and sown grasslands (Carroll et al., 2004; Marshall et al., 2014; Jackson et al., 2008; Meijles et al., 2015; Pan et al., 2016). Constraints include land ownership and economics.

5.2.2. Assessment of landscape characteristics

The criteria used to identify high potential locations for green-blue interventions begins with an analysis of landscape features. The landscape features which provide the highest opportunity to increase interception and infiltration, or reduce runoff and flooding, are identified from the literature. Attributes that make sites more prone to flooding, more likely to generate runoff instead of infiltration or more likely to generate increased runoff than the surrounding sites are identified from landscape characteristics including location to river, location in the catchment, location along the slope and topographic wetness index (TWI) as illustrated in *Figure 17*.

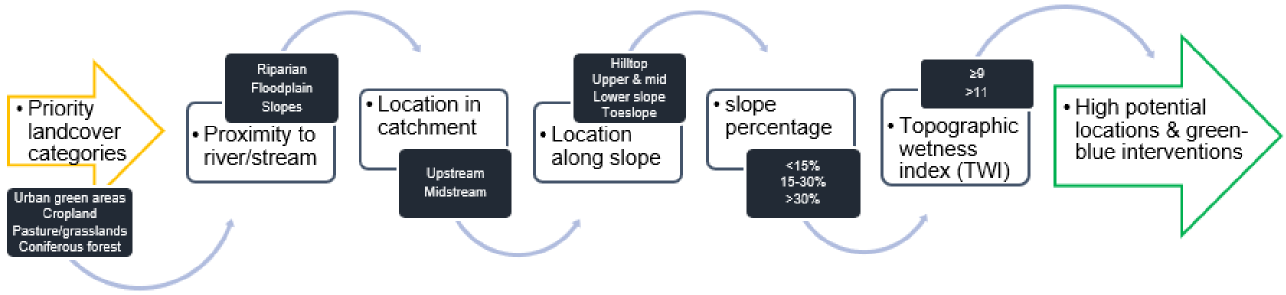


Figure 17: Landscape characteristics analysed to determine priority locations for green-blue interventions

Similar to the landcover and land use categories, landscape characteristics were assigned simple potential rankings according to hydrological impact based on the evidence gathered from the state-of-the-art review. *Table 2* at the end of this section presents a summary of the evidence and the rankings of potential (low to high) assigned to landscape characteristics based on the evidence presented

Once the landscape characteristics with highest opportunity to increase interception and infiltration, or reduce runoff and flooding, are identified, spatial analysis is used to illustrate the most promising locations for green-blue interventions. A number of spatial analyses are conducted including creation of buffer zones and contour lines, percentage slope and a topographic wetness index (TWI) evaluation in order to isolate the landscape characteristics. These are intersected with the priority landcover and land use categories to illustrate the locations and options for green-blue interventions with the best potential to minimise hydrometeorological hazards in the study area. The spatial distribution of the suggested green-blue interventions is shown on a series of figures with the heavy rainfall maps showing water heights in rare (1 in 100 year return) and extreme rainfall events (90 mm/m² in 1 hour).

5.2.2.1. Proximity to the river or stream

There is a high propensity for hydrological hazards such as flooding to occur on land situated closer to the river, therefore, there is also high potential to use the land in that area to reduce the risk (Englund et al., 2021; Krampl et al., 2016). Land is defined riparian, floodplain or slopes. Sites located within the riparian and floodplain zone are categorised as having high potential to be used for retention/detention of water. *Section 4.2* details the effectiveness of providing additional space for the water to spread into, thus reducing the flood peak downstream. Bell et al. (2020) found that based on equal implemented, retention/detention of floodwaters can reduce the peak flow by a larger percent than the runoff reduction mechanisms, due to the limitations of filtration and storage. Giacomoni et al. (2014) found that retention/detention ponds were 10 and 19% more effective at reducing peak flow for 1 in 10 and 1 in 100 year storms than urban permeability improvements. While the area of riparian zone exists continuously along the rivers and streams there is limited extent of floodplain in the study area except for within Leverkusen, due to urban encroachment and relief. Along the slopes there is no simple mechanism for retention or detention.

Scoping studies use a number of factors to identify the best potential sites for retention/detention basins and areas. Slightly different combinations of criteria are used in individual studies which often depend on local factors (soils and geology) and differences in intended basin configurations (large, small or used for water harvesting). Land use and low slope are the most common factors employed, however. Ahmadisharaf et al. (2016) and Bellu et al. (2016) both specify low slope (<5%), Pawattana and Tripathi (2008) also used a sliding scale of slope (0-2% up to >35%) with the highest weighting on the lowest slope and Krampl et al. (2016) also name distance to river, slope and land use as key components within their list of location criteria.

This study uses a slope of less than 15% along a 100m riparian zone either side of the river or stream to identify potential retention/detention basin locations. The intersection of the landcover and land uses including green urban, agricultural (cropping and pasture/grasslands), and coniferous forests and the 100m riparian zones with slope less than 15% are then processed in QGIS to identify priority locations for flood retention/detention.

While 15% is a large slope in relation to that chosen by some of the scoping studies discussed the reasons for this are fourfold. Firstly, there are many other factors that need to be scoped in preparation for locating retention basins including distance to critical infrastructure, engineering factors and cost, how potential basins or areas work together land ownership and sharing or acquisition possibilities, and desirable soil permeability (Ahmadisharaf et al., 2016; Bellu et al., 2016; Krampl et al., 2016). Secondly the landscape relief and propensity for flash floods in the study area lends itself to multiple small retention areas and basins in the headwaters, not fewer large basins. Multiple smaller retention/detention basins or areas located in the upper catchment or headwaters was found by several authors to be more effective at attenuating flash flooding (Nicholson et al., 2019; Salazar et al., 2012; Smith et al. 2015). Thirdly the high percentage of urban landcover downstream in Leverkusen also lends itself to the placement of multiple small-medium retention basins leading into the floodplains where space allows, to take advantage of the local impact on flood reduction. Choosing a slope of less than 15% and width of 100m keeps all of these options open. *Figure 18* and *Figure 19* illustrate the location of potential retention/detention across the study area based on the criteria discussed. Retention/detention is suggested on the landcover green urban areas, cropland and pasture and permanent grasslands. Potential locations for natural retention/detention areas, which would be situated on revegetated former coniferous plantations, are illustrated in *Figure 24*.

There are a number of locations along the riparian zones that are protected. These are indicated on the mapping legends as the Natur2000 which designates protected areas under EU law for threatened species and habitats, and Naturschutzgebiet which designates areas with national park status. These protected areas overlay the analysis in the mapping and override any suggested changes to land use within their boundaries except for the former coniferous plantations which will be reforested in protected areas such as the Wupperverband managed forests.

5.2.2.2. Location in catchment

The study area covers the midstream sections of the Wupper and Dhünn. The study area also coves the entirety of the tributary streams, upstream, midstream and downstream. However, on a technically catchment basis, the study focuses on the midstream. There are a number of interventions for which the literature recommends specific placement in the catchment such as retention/detention basins and areas. The majority of literature reviewed on retention/detention of floodwater recommend the upstream or headwaters of the catchment for basin/area location (Ayalew et al., 2015; Birkinshaw and Krivtsov, 2022; Bellu et al. 2016). While this works well in theory to capture the most runoff if runoff were evenly distributed across the basin, the flash floods of July 2021 demonstrated that not all heavy rainfall will occur in the headwaters, or where the heaviest falls occur on average. As illustrated in *Figure 14* convective rainfall can fall at any location within the basin and the areas with highest risk (hazard x vulnerability x exposure) which are most often urban areas also need to be protected, in this case retention/detention basins are most effective when located (where safe) close to the affected area to take advantage of the local effect (ICPR, 2020). *Figure 26* illustrates where potential retention/detention basins could be located to take advantage of the local impact and where headwater location would enable wider catchment coverage. As mentioned above this is simply a preliminary judgement, the placement of floodwater retention/detention must be modelled and must consider many more factors than simply relying on simple spatial assessment such as this, in order to evaluate the full impacts and risks.

5.2.2.3. Location along slope

The location of a site along a slope has important implications for the hydrology of the site (FAO, 2006; Graham and Lin, 2011; Zhu et al., 2014). FAO (2006) designates slope positions for undulating and mountainous topography as bottom, toe slope, lower slope, middle slope, upper slope and crest (hilltop). These categories are used to differentiate the sites critical for green-blue interventions from those that are either not as influential to slope hydrology, or influential but not in a way that can can't be addressed by green-blue interventions.

From the literature that there are a few factors that stand out in terms of how the hillslope position influences runoff including overland flow and subsurface flow. Graham and Lin (2011) found that preferential flows, rainwater runoff through conduits and large pores that bypass soil infiltration and instead feed flash flooding through increased runoff generation, occurred mostly on hilltop sites due to dry soils and high temperatures which caused hydrophobicity and cracks in the soils due to the loss of moisture. The dominant factor in the creating of preferential flows on the lower slopes was found to be initially wet soils conditions and higher intensity rainfall, while at the mid-slope positions the duration of rainfall was found to be the dominating factor in creating preferential flows. This information can be cross-checked with the mechanisms of green-blue interventions to find the best options for intervention. Green-blue interventions can influence soil condition which in turn affects soil infiltration and runoff, and the green water cycle of biomass uptake and evapotranspiration, but green-blue interventions cannot affect rainfall duration. Therefore, green-blue interventions will be effective on hilltops and lower to toe slope locations but not on the mid-slopes. Furthermore, Zhu et al. (2014) analysed the soil moisture response to rainfall and rainfall intensities along with vegetation cover. They found that total soil moisture at the hilltop, upper and middle slopes under pine forest and tea shrub vegetation cover, reflected the rainfall intensity and volume regardless of vegetation cover, while soil moisture at the lower slope and toe slope under clover and pine/magnolia forest cover, reflected rainfall intensity in a cumulative manner. The lower and toe slope positions received runoff from the upper slopes in addition to rainfall that falls across the site, and this propensity increases under high intensity precipitation or rainfall that is more likely to lead to flash flooding. In addition, the toe slope position receives subsurface flow in addition to cumulative rainfall volumes when initial soil conditions are saturated, even under forest cover. All combined, this information sets a priority for the lower to toe slope and hilltop positions, as it is these location along a hillslope that will contribute to both runoff and subsurface flow contributing to flash flooding when rainfall is heavy, which can be addressed by green-blue interventions as discussed in *Section 4*.

There are a few constraints in defining these areas, however, for the spatial analysis. The hilltop location can be identified easily using relief contour lines, it’s more difficult to accurately identify the lower and toe slope locations over an extended area such as the study area. For that reason, the toe slope but not the lower slope is used in the mapping analysis, as the toe slope can be identified approximately with the use of the river valley contour lines, but the width of the lower slope is much more difficult to estimate given the range of slope lengths and elevations throughout the study area. Therefore, the hilltop and toe slope positions which are identified as the priority slope locations for increasing interception and soil infiltration and reducing runoff and flooding. The landcover and land uses that apply to green-blue interventions along these slope locations are cropping and pasture or permanent grasslands.

There are several green-blue intervention options that can apply to these sites, so a range of suggestions are given. The intervention along hilltop sites with the highest potential impact would be for the sites to be revegetated or reforested with native species, this would lead to better soil condition, interception and runoff prevention as per comparisons of forested and agricultural land in the literature. However, it is understood that this would involve a drastic change of land management and loss of production for the owner so other options are also provided. For cropland on hilltops the application of biochar is an option, this is proven to increase the water holding capacity of the soil, a second option is a management change to reduced tillage and/or strip tillage, these have both been found to reduce rainfall runoff and increase plant available water (Horak et al., 2019; Laufer et al., Liu et al., 2012; Madarasz et al., 2021), these management options could also be combined. Another potential intervention would be to plant tree or hedge buffer strips around cropping locations on the hilltop, this is a traditional cropping strategy which can work as a windbreak to reduce the drying of soils, reduce runoff and the loss of key nutrients and also improve the microclimate (Borin et al. 2010; DBU, 2010; Nerlich et al., 2013). For grazing and permanent grassland there are also several options, including reduced stocking rates for grazing land, application of biochar and reduced tillage or strip tillage where grass crops are grown and silvopasture for permanent grasslands. These interventions also work to increase soil water holding capacity and reduce runoff (Meijles et al. 2015; Nerlich et al., 2013). See *Figure 18* and *Figure 19* for hilltop distribution and potential interventions for the study area.

Runoff attenuation along the lower slope and toeslope positions would also benefit most from revegetation to take up some of the subsurface flow through root systems, provide soil conditioning benefits. However, there are a number of factors to balance. These locations are likely to be prime land for cropping and grassland because of the extra nutrients in the soil from overbank flows, and a land use transition is highly unlikely without land acquisition. Furthermore, these locations are also likely to be the source of river baseflow in dryer times. The impact of deforestation and reforestation on baseflow is complex and can vary from basin to basin and study to study (Xiao et al., 2022) however, baseflow sources should be studied before any wholesale land use change is recommended in these areas. To strike a balance the range of green-blue intervention options for the toe slopes includes reduced mowing height and/or frequency for grasslands to increase surface roughness and reduce overland flow (Pan et al., 2016) reduced grazing pressure (Meijles et al., 2015; Monger et al., 2022b) and grazed woodlands, providing groundcover can be maintained which also acts to slow overland flow velocities (Monger et al. 2022a). For cropland there are also a range of interventions that can be implemented. Buffer strips and coppice intercropping could be introduced at the toe slope location for cropland as this management intervention can reduce overland flow and also reduce loss of vital crop nutrients. See *Figure 18* and *Figure 19* for the distribution of toe slope and potential interventions for these locations across the study area.

In fact, low height, cross slope shelterbelts/hedgerows for grassland and buffer strips for cropland have a high potential to reduce overland flow at the toe slope position, especially if there are high TWI lines that lead downslope (see *Section 5.2.2.5* for TWI explanation) as these areas are critical for runoff reduction. During the summer months reduced tillage or strip tillage which acts to maintain water held in the soil and reduce rainfall runoff is also recommended for cropland (Laufer et al., 2016; Klik and Rosner, 2020) this may also make some contribution to baseflow management during especially dry summers, at the very least soil water losses are reduced through impeded evaporation. See *Figures 20 to 23* for the locations of high TWI across the study area.

5.2.2.4. Slope gradient

The slope gradient as an indicator for the potential location of retention/detention basins and areas is discussed above in *Section 4.2.2.1*.

While there is some disagreement in the literature on when the slope gradient becomes significant for runoff, there is general agreement that the slope gradient is one of the most important factors influencing runoff generation (Bachmair and Weiler, 2012; Marapara et al., 2021). Zhu and Lin (2011) found that soil moisture variation was dominated by the slope gradient over soil type or vegetation type from a slope gradient at just over 8%. While Marapara et al. (2021) suggested that gradient of slope alone becomes a significant factor for runoff when approaching more than 15% and highly significant when more than 30% as this is when runoff velocity is highest and contribution to flash floods most likely. For this reason the optional green-blue intervention options for agricultural land use at these sites is simply for revegetation in order to maximise the reduction of runoff and also to reinforce the soil on the slope to avoid soil erosion. Revegetation does not have to be in the form of reforestation, as forest trees (with some exceptions such as *Fagus sylvatica* L. (Bolte et al., 2007) do not usually grow well across highly sloping gradients (Marapara et al., 2021). In these locations low growing shrubs and undisturbed grasslands cover can reduce runoff and also slow overland flow with increased roughness (Llorens & Domingo 2007; Maetens et al. 2012; Makaske et al, 2011; Monger et al., 2022a), perhaps better than total reforestation can achieve as this can sometimes lead to reduced groundcover. *Figure 17* and *Figure 18* illustrate the distribution of agricultural areas with slope greater than 30% at riparian and toe slope locations and potential green-blue interventions.

Similar to agricultural areas, the green-blue intervention suggested for former coniferous plantations across riparian zones at 30% and greater slope is also revegetation with low growing shrubs rather than with large forest trees. This is for three reasons, as mentioned previously it is thought that the main contribution to flood reduction from riparian vegetation is that of surface roughness slowing the flood peak (Cooper et al., 2021; Murphy et al., 2021). Makaske (2011) found that soft and hardwood shrubs provide double the amount of hydraulic roughness and therefore delay of the flood peak, to that of mature forest species. Furthermore, large woody debris was a problem for safety and infrastructure in the July 2021 floods in the study area (Wupperverband, 2022a), so establishment of shrubs, reeds and grasses rather than forest species in the riparian zone, especially at areas of high velocity flow and close to urban or sensitive infrastructure, goes some way to reducing this risk. *Figure 23* illustrates the former coniferous plantation sites recommended for this green-blue intervention.

5.2.2.5. Topographic Wetness Index (TWI)

The topographic wetness index (TWI) uses the landscape feature measurements of slope, contour length and upslope area to calculate preferential pathways of water accumulation and flow (Sørensen et al., 2006). These pathways can be used for green-blue intervention planning purposes. Where there is high TWI that leads down to the waterway, it can be assumed that during rainfall there is likely to be preferential runoff along the pathway due to the characteristics of the slope and local soil moisture increases (Sørensen et al., 2006). TWI is used as the concavity or divergence of each of the multiple slopes in the study area cannot be measured. TWI is a good indicator of wetness along slopes but does not work well to differentiate runoff paths in areas of extensive low relief such as the highly urbanised areas.

High TWI (≥9) is frequently evident on the agricultural land located along the slopes and down to rivers and streams in the study area (see *Figure 19* and *Figure 21*). As discussed in *Section 4* there are many studies demonstrating the effectiveness of shelterbelts or hedgerows in pasture and grassland, buffer strips in cropland and woodlands, planted cross-slope, in reducing rainfall runoff (Borin et al. 2010; Carroll et al. 2004; Cooper et al. 2021; Jackson et al. 2008; Marshall et al. 2014; Nerlich et al. 2013). This intervention could be combined with conservation tillage as discussed in *Section 4* which also acts to reduce runoff (Klik and Rosner 2020; Laufer et al. 2016; Haag et al. 2006) and cross slope cultivation.

In the study area there is sometimes riparian forest located between the agricultural fields and the rivers or streams at some sites, but often there is no forest buffer in the riparian zone. *Figure 21* and *Figure 23* are provided to illustrated where there is no riparian forest between potentially high runoff flowing from agricultural fields and the waterways. These locations have an increased potential for green-blue interventions such as hedgerows/shelterbelts and hedgerows to reduce overland flow and potentially flooding. Furthermore, these maps also show by default where the dense urban areas are located (all other layers are turned on but the urban layer), with the heavy rain hazard maps as background. This could also be used as an effective planning tool for the location of green-blue interventions on the agricultural slopes above urban areas, so in addition to reducing the runoff that flows to rivers and streams, it could reduce runoff flooding into urban areas. Similarly, if there is sensitive infrastructure downstream, green-blue interventions could also be implemented to reduce the runoff coming from highly impervious urban areas that can lead to damage downstream.

Table 2: Rankings for potential impact of landscape characteristics on hydrology

Landscape / feature type	Feature Characteristics	Potential for green-blue intervention in Wupper Basin	Justification
Proximity to river or stream	Riparian	High	High propensity for hydrological risk and also potential for reducing the risk (Englund et al. 2021). Slope greater than 30% makes a highly significant contribution to runoff (Marapara et al., 2021) and is only suitable for revegetation.
	Further out from the riparian zone	Low-Medium	Lower propensity to impact hydrology unless site is on a slope that will result in increased runoff such as a concave or divergent slopes (Aryal et al., 2005; Marapara et al. 2021; Zhu and Lin 2011).
Location along slope	Floodplains	Low	Reconnection of floodplains to the river body is considered highly successful in reducing flood peaks in rivers with previously wide floodplains (ICPR, 2020; Klijn et al., 2018). However, the Wupper Basin doesn’t contain extensive floodplains due to topography, where floodplains do exist they are often under highly urban land cover.
	Hilltop	High	Hilltops can provide pathways for preferential flow and vegetation cover may increase the ability for often thin soils to retain water (Bachmair and Weiler 2012; Graham and Lin 2011; Zhu et al. 2014). Highland forest rainfall interception is maximised at around 420 m.a.s.l (around peak hilltop height across the Wupper basin) which results in reduced rainfall runoff (Köhler et al., 2015).

	Upper slope - Mid slope	Low-Medium	Unless the mid slope position is located in a concave and divergent hillslope, the middle slope tends to exert less influence on runoff than the higher or lower slope positions (Ayral et al., 2005; Bachmair and Weiler 2012; Zhu et al., 2014). If high TWI is present then the landscape features create preferential pathways for water accumulation and flow (Sørensen et al., 2006) and green-blue interventions such as tree buffer strips can be implemented.
	Lower Slope - Toe slope	High	The water table is closer to the land surface across the lower slope areas, also these areas receive a higher proportion of subsurface flow and are important as buffers for soil erosion and nutrient losses (Zhu et al., 2014). Reforestation /afforestation or buffer strips, shelterbelts/hedgerows at this landscape level can be highly effective at reducing subsurface flow and runoff. High TWI is used to indicate where tree buffers can be located to intercept preferential pathways of water flow (Sørensen et al., 2006). Slope greater than 30% at these locations makes a highly significant contribution to runoff (Marapara et al., 2021) and is only suitable for revegetation to slow the flow.

5.2.3. Spatial analysis indicating potential green-blue intervention locations

The following maps display the spatial intersection of the landcover/land use categories that were identified as high priority and the landscape characteristics identified as having high potential for green-blue interventions. These maps show the sites that this study has found would provide the best location for green-blue interventions to address hydrometeorological hazards across the study area. The map legends display the suggested intervention, the landcover or land use and the landscape criteria for which the location has been chosen (riparian ≥30% slope, for example).

5.2.3.1. Limitations

There are several limitations with the maps, some of which originates from the datasets. As previously mentioned with the CORINE Landcover dataset (BKG, 2021a) there is no way to differentiate permanent grasslands from grazed pasture or to ascertain whether the permanent pasture is ‘permanent’ for the purposes of the CAP, so for the purposes of this study it is assumed (based on visual evidence in the basin see *Figure 15*) that there are no mandatory rules place on grassland renewal and tillage. The CORINE datasets are not perfect at the local level as the resolutions 5 ha and often the non-major roads and small urban areas are not recognised as such.

Furthermore, there are limitations with authors ability to carry out some spatial analyses. For this reason the upper limit of the lower slopes and the lower limit of the upper and middle slopes was not able to be semi-accurately calculated and isolated for further processing, so the suggested interventions for the lower slope locations do not feature in the spatial analysis presented although they are included in the final implementation guide (*Table 3*). Whilst the interventions for lower slope were not able to be mapped, the recommended interventions for the riparian, hilltop and toe slope locations are represented on the maps, along with the former coniferous plantation sites across all locations.

5.2.3.2. Mapping outcomes

The first set of maps (*Figure 18* and *Figure 19*) illustrate the layout of a number of suggested interventions together across the study area. These include flood retention/detention locations identified for green urban spaces and agricultural sites (at riparian zones with slope ≤15%), revegetation of cropland with slope ≥30% along riparian and toe slope locations, soil grazing and grassland management for agricultural lands located along the toe slope (slope≤30%) and along the hilltops. The potential interventions are displayed together to demonstrate that the interventions could work together. Implementation of any kind of measure across a broader landscape is known to have more impact (Ayalew et al., 2015; Bathurst et al., 2020). Each of the interventions can also work on different aspects of basin hydrology using different mechanisms. For example, the revegetation of the high slopes along the riparian zone provides greater surface roughness to slow the flow of water, reforestation of the former coniferous plantations with broadleaf trees acts to intercept rainfall in the leaves and bark, soil amendments, shelterbelts/hedgerows and buffer strips create better soils conditions for soil moisture storage and retention/detention of water reduces the flood peak height. Therefore, the different strategies working together as an interconnected system can have more impact than a single or isolated intervention.

The green-blue interventions for high TWI lines and the former coniferous plantations are illustrated separately in *Figures 20,21,22,23 and 24* as there is too much information to include on one map. Separating them allows the reader can better observe the intervention locations and understand the spatial analysis concept. *Figure 25* shows the location of options for retention/detention to take advantage of wider catchment coverage or the local impact.

The Nacker Bach and the Weinsbergerbach, Solingen

Figure 18 shows that there are some opportunities for retention or detention areas along the Nacker Bach in Solingen, although some of the areas are separated from the stream and some lie across roads so these need to be rejected. There is a section along the Weinsbergerbach that is protected even though there is agricultural grassland within the protected area. There are several toe slope locations along the Nacker Bach and the Weinsbergerbach for which buffer strips/coppice intercropping and shelterbelts would act to increase soil water storage capacity and bulk density and reduce rainfall runoff. To plan the layout of buffer strips and shelterbelts/hedgerows *Figure 20* and *Figure 21* show that for both streams there are some sections of high TWI lines down to the streams in the grasslands where there are also no riparian forests. Buffer strips and shelterbelts/hedgerows planted here to increase soil water storage capacity and bulk density and reduce rainfall runoff should be planted at right angles to the TWI lines for the best results.

The Wupper, Solingen

Figure 18 illustrates some locations that may be suitable for mixed-use retention or detention along the Wupper (for fluvial flooding) as the Wupper moves into Rheinisch-Bergischer Kreis. These sites are also selected for potential retention/detention for local impact on *Figure 25*. There are very few toe slope sites under agricultural land use along the study area section of the Wupper because here the floodplains widen as the relief levels out. *Figure 20* and *Figure 21* show multiple high TWI lines down to the Wupper, notably on the left bank under cropland as the river moves through Solingen. These areas are not recognised as toe slope as they lie across the floodplain (see *Figure 2*). However, they could also benefit from strategically placed buffer strips and hedgerows of shrub species, as inundation during heavy rainfall across these areas is confirmed by the heavy rainfall hazard map (*Figure 9*). Providing the mechanisms to increase soil water storage capacity and improve bulk density would reduce improve the runoff response and may also reduce the loss of key nutrients from the agricultural fields and pollution to the river. *Figure 19* also shows a section of green urban land with potential for retention/detention as the Wupper moves into Leverkusen, this would overflow naturally due to the low relief of this area (see *Figure 2*). The green space has an existing pond but backs onto dense urban areas, this section has potential for retention/detention, but would likely require significant excavation to hold more water and engineering to protect the local urban areas.

The Weltersbach and Murbach, Rheinisch-Bergischer Kreis

The Murbach already features a line of water basins (some of which are currently empty) so there is no need for additional retention/detention on this stream (see *Figure 18* and *Figure 25*). The downstream sections of the Weltersbach have a high percentage of riparian forest which means that there is reduced need for intervention (see *Figure 21*). However, the headwater sections of the Weltersbach tributary, closest to the Wupper, has a lot of agriculture distributed across the riparian zone and toe slopes, with no forest buffer (see *Figure 18* and *Figure 20*). However, the heavy rainfall hazard map (*Figure 9*) doesn’t show a lot of runoff arising or pooling in this section so there is little need for any intervention here. There are several sections of cropland distributed across the toe slopes around these two streams for which strip tillage and/ or conservation tillage would bring higher infiltration capacity and reduced soil erosion during rainfall.

The Ölbach and Weimbach, Leverkusen

Figure 18 (wider view) and *Figure 19* (close-up view) show that both the Ölbach and the Weimbach have significant potential for mixed purpose retention/detention basins on agricultural land (also illustrated in *Figure 25*). There are also a number of opportunities along the upper to mid Weimbach for buffer strips/coppice intercropping and shelterbelts on the toe slope locations to increase soil water storage capacity and bulk density and reduce rainfall runoff from the agricultural sites. *Figures 20 and 21* also show areas of high TWI in riparian locations for both streams without any riparian forest. These would be a priority for shelterbelt/hedgerows and buffer strips if the locations were not suitable for retention/detention as these streams receive significant runoff and produce localised flooding during convective storms, see the heavy rainfall hazard map (*Figure 9*).

The Eifgenbach, Rheinisch-Bergischer Kreis

The upper sections of the Eifgenbach are shown only once in the maps on *Figure 18*. The reason for this is that there is little room or need for intervention along this part. The majority of the riparian zone is protected in this area, and furthermore, there is no possibility of retention/detention as the relief is steeper and the stream valley is constrained with high coverage of forest across the riparian and slopes (see *Figure 5*). The grassland/pasture located across some of the toe slope sections may benefit from the intervention of reduced tillage so that runoff and erosion is reduced, as river is set in a steep valley making it susceptible to erosion. There are also a number of hilltop sites which may see increased soil water storage capacity with the application of biochar.

The Leimbach, Leverkusen

Figure 19 shows that there are sections of agricultural land in the riparian zone at the upper and mid-sections of the Leimbach that have a slope greater than 30%. These have the potential to produce high velocity runoff to the stream during storms and would benefit from revegetation both to slow the flow and improve the soil water infiltration capacity of the soil. To confirm the recommendation of revegetation *Figure 22* and *Figure 23* also show high TWI down to the river along these sections and only a thin strip of riparian forest. There are also parcels of farmed land spread across the hilltop in the upper sections which may also benefit from increased soil water storage capacity with the application of biochar. Prior to flowing into the Dhünn there are sections of agricultural riparian land along the Leimbach that have the potential for mixed use retention/detention and the heavy rainfall hazard map (*Figure 9*) shows that this would be a suitable location. While land pressure here is undoubtably high, there may be a way to make a sharing arrangement worthwhile for the landowner. This section is also illustrated in *Figure 25* as potential retention/detention with local impact.

There are three other un-named drainage lines shown in *Figure 19* within Leverkusen. The closest to the Leimbach already holds the Ophovener Weiher retention basin, which the Wupperverband are planning to expand (Wupperverband, 2022c). The next is protected and the last drainage line to the west shows several opportunities for retention/detention on agricultural land, and there is forest that would take-up the overflow as seen on the landcover and land use map (*Figure 4)*. These forests also feature sections of coniferous forest which could be reforested as occasionally flooded broadleaf forests as discussed in *Section 5.2.1.1*.

The Dhünn, Leverkusen and Rheinisch-Bergischer Kreis

Along the Dhünn in Leverkusen (see *Figure 19*) there are several agricultural locations that may have potential for mixed-use retention/detention. These areas potentially flood anyway during convective storms and during fluvial floods. However, the retention or detention of water at this location would take the pressure off the settlement of Schlebusch which is just downstream and suffered from inundation and damage during the July 2021 floods (Wupperverband, 2022a). As mentioned above this section is also illustrated in *Figure 25* as potential retention/detention with local impact. If not suitable for retention/detention these sites are quite extensive and would benefit from shelterbelts or buffer strips and coppice intercropping to improve the soil water holding capacity and reduce runoff. As shown in *Figures 22 and 23*, these are relatively extensive agricultural holdings which are affected by storm water ponding during large storms, (see the heavy rainfall hazard map *Figure 9*). These fields would also benefit from strip tillage and/or reduced tillage to reduce bare soils and improve the water holding capacity of the soil and increase plant available water during dry times, and especially seeing that these fields are all under Luvisol soils, that are highly vulnerable to structure loss and erosion when subjected to extensive tillage.

There is a small section of riparian land under agriculture just inside the Leverkusen border that has a slope higher than 30% (*Figure 19*). This has the potential to produce high velocity runoff during storms and would benefit from revegetation both to slow the flow and improve the soil water infiltration capacity of the soil.

Within the study section of Rheinisch-Bergischer Kreis, there is little opportunity for intervention along the Dhünn River (see *Figure 19*). The banks are lined with forest and protected along the riparian zone below the Groß Dhünn Dam and closer to Leverkusen’s borders small urban centres line the banks (see landcover and land use map *Figure 5*). *Figure 19* shows a small site for potential mixed-use retention/detention in the mid-section. This section also has high TWI lines and no riparian forest (*Figures 22 and 23*) so if not used as retention the runoff down to the river at this section could be improved from strategically placed hedgerows or crop buffer strips.

Figure 24 also shows sections of former coniferous plantations along the toe slope areas. These should be reforested to ensure that interception occurs during storms and to improve the soil water holding capacity.

The Scherfbach, Rheinisch-Bergischer Kreis

The Scherfbach has plentiful sections for retention or detention (see *Figure 19*). In the high headwaters there would be little need for flood or storm water retention, at the second and third order stream sections and lower, however, there is need for mixed-purpose retention or detention. While there are also protected sections along the stream, the protection only covers the river section itself in places and not the riparian zone. The heavy rainfall hazard map (*Figure 9*) shows that the Scherfbach system carries a lot of water during storms. *Figure 25* shows that there are several opportunities for retention/detention that might have an overall impact on basin flooding and also a local impact. *Figures 22 and 23* also show that these sections all have high TWI lines leading down to the waterways, and little forest riparian buffer except in the very top sections. The high TWI lines also present the opportunity for strategic planting of shrub hedgerows, reduced tillage, reduced mowing height and frequency, and the reduction of grazing pressure as these sites are relatively extensive pasture or grasslands. These interventions work to improve the soils water holding capacity, slow runoff and reduce preferential pathways for stormwater runoff.

Figure 19 also shows that there are opportunities for shelterbelts or buffer strips, reduced tillage and potentially reduced grazing pressure on the toe slope locations to increase soil water storage capacity. There are also some sections of the Scherfbach with agricultural lands in the riparian zone with a slope greater than 30%, some even in the protected zone. These have the potential to produce high velocity runoff to the stream during storms and would benefit from revegetation both to slow the flow and improve the soil water infiltration capacity of the soil.

Figure 24 shows the areas of former coniferous plantations. The majority of these in the study area are located in the Scherfbach and between the Scherfbach and the Dhünn, with only a minor number along the Wupper in Solingen. These provide a valuable opportunity for reforestation as discussed in Section 5.2.1.1. Furthermore, harvested sites can present low soil filtration and high runoff features, while reforestation with broadleaf species provides the best option for rainfall interception, maximising soil water infiltration and water holding capacity and runoff reduction. Species options for reforestation based on aspect and the location along the slope are discussed in the next section.

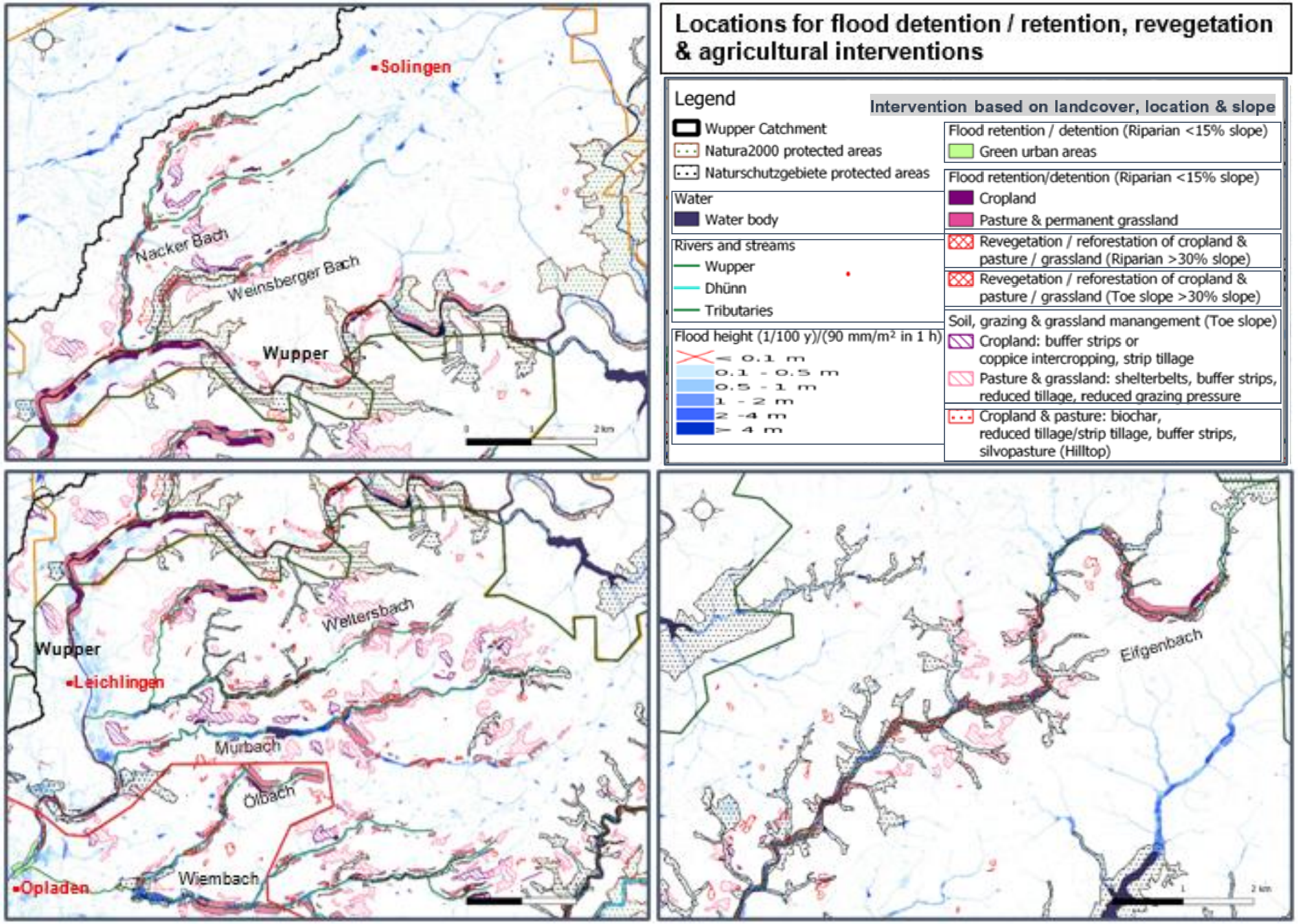


Figure 18: Locations for retention/detention, revegetation and agricultural green-blue interventions (Solingen and Rheinisch-Bergischer Kreis)
(Data source: BKG, 2021a&b; Diva-GIS n.d; IT.NRW, 2023; Prepared in QGIS)

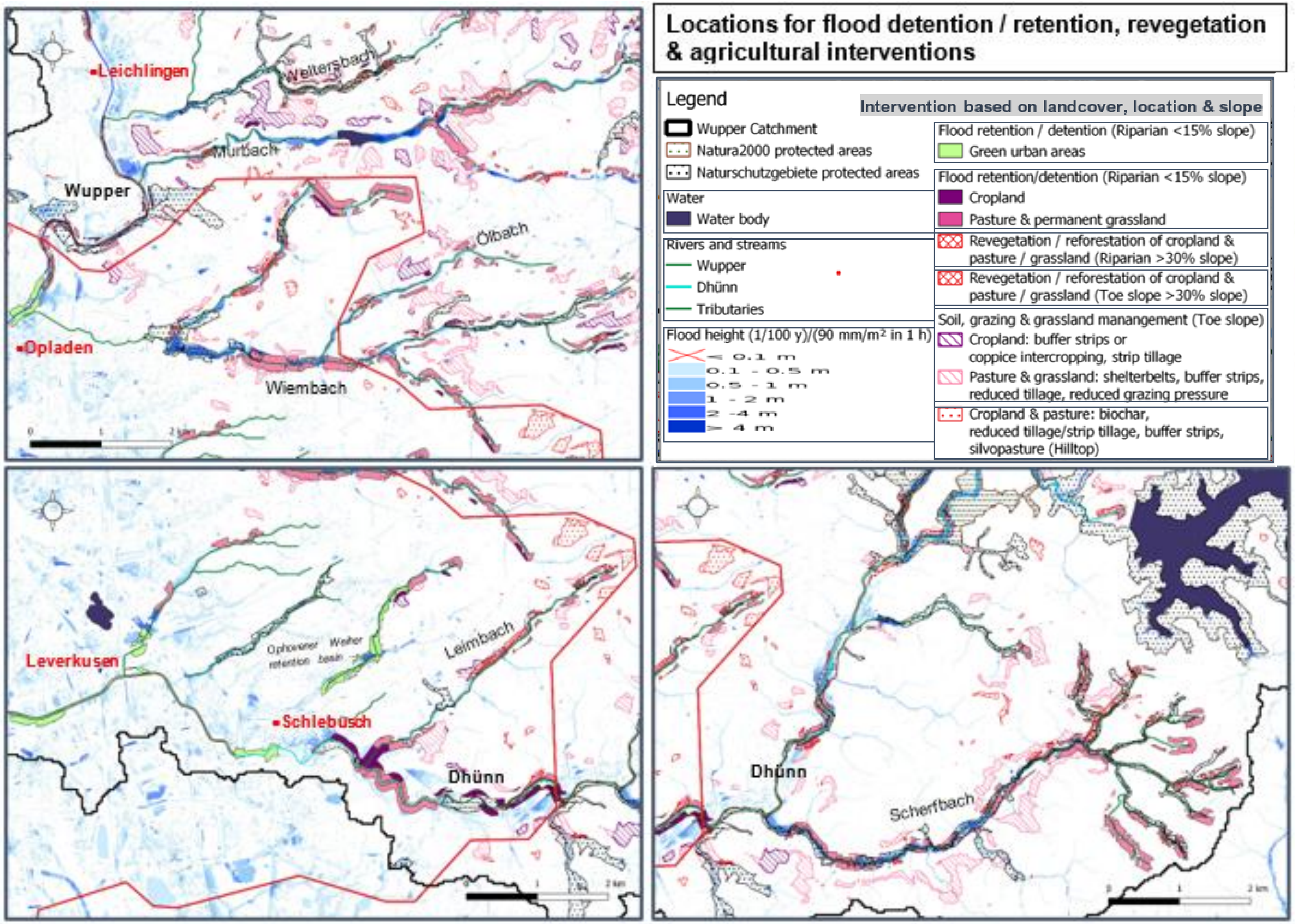


Figure 19: Locations for retention/detention, revegetation and agricultural green-blue interventions (Leverkusen and Rheinisch-Bergischer Kreis)
(Data source: BKG, 2021a&b; Diva-GIS n.d; IT.NRW, 2023; Prepared in QGIS)

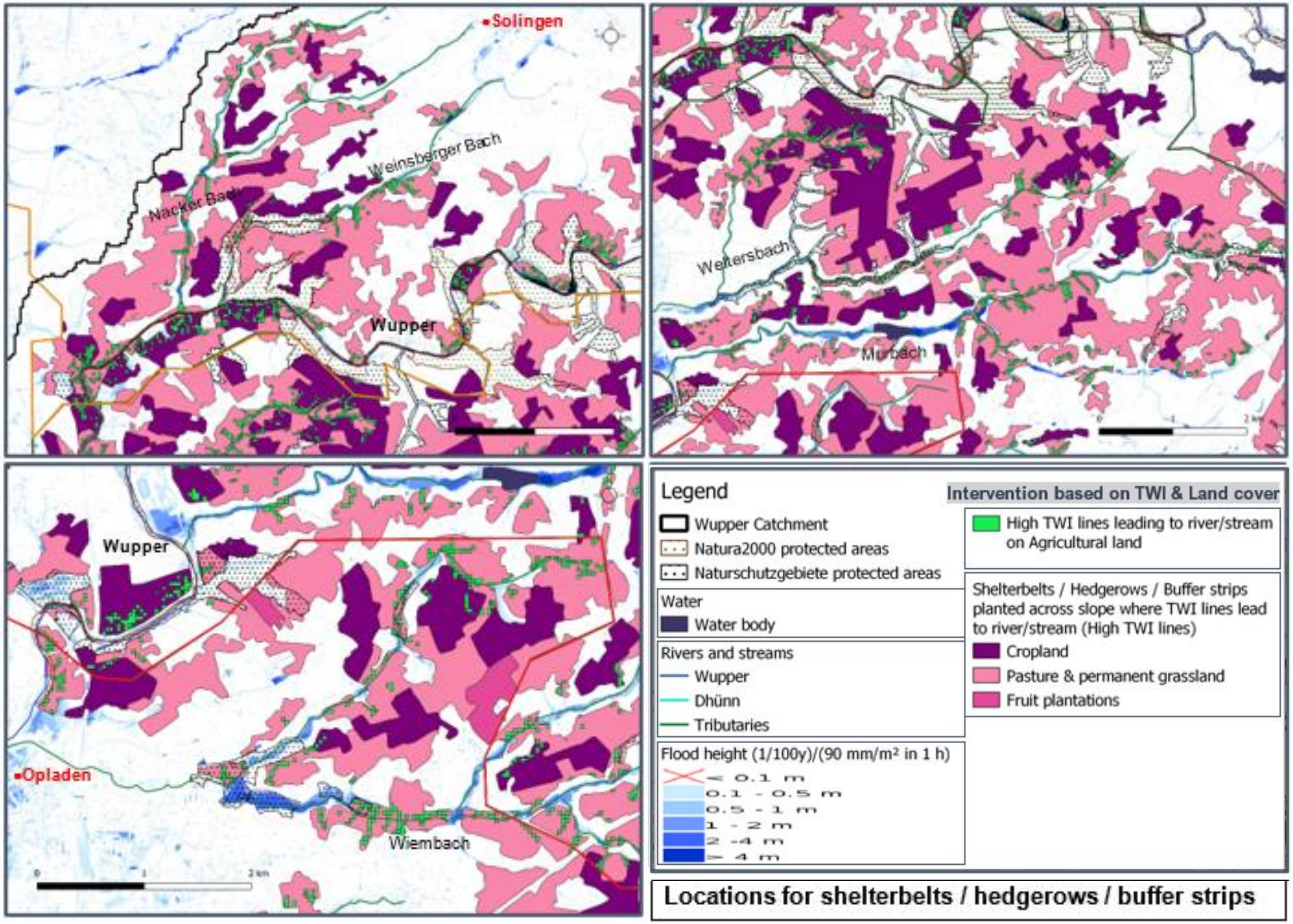


Figure 20: Locations for shelterbelts, hedgerows and tree buffer strips (Solingen and Rheinisch-Bergischer Kreis)
(Data source: BKG, 2021a&b; Diva-GIS n.d; IT.NRW, 2023; Prepared in QGIS)

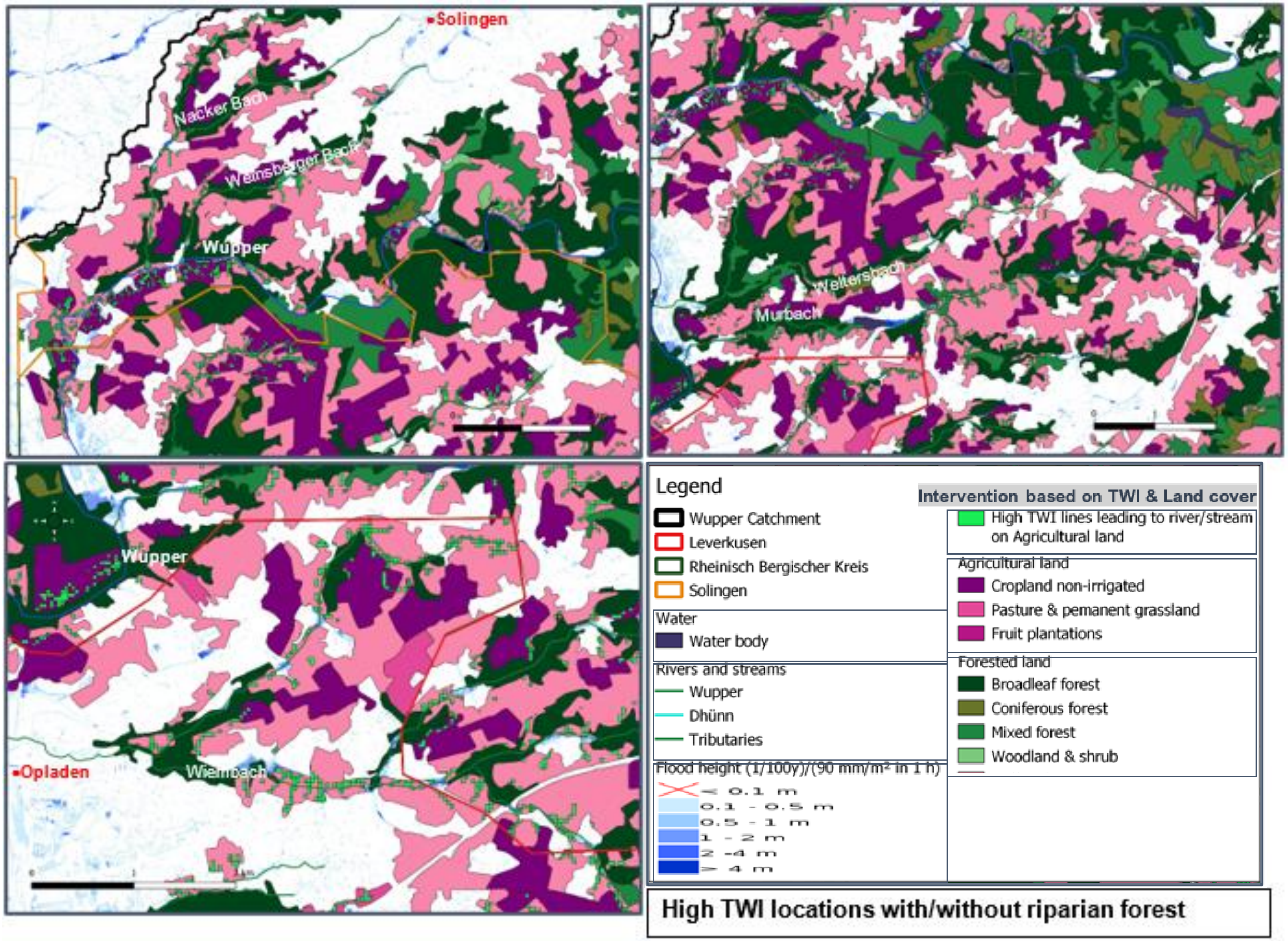


Figure 21: Locations for shelterbelts, hedgerows and tree buffer strips with additional guidance from riparian forest locations
(Data source: BKG, 2021a&b; Diva-GIS n.d; IT.NRW, 2023; Prepared in QGIS)

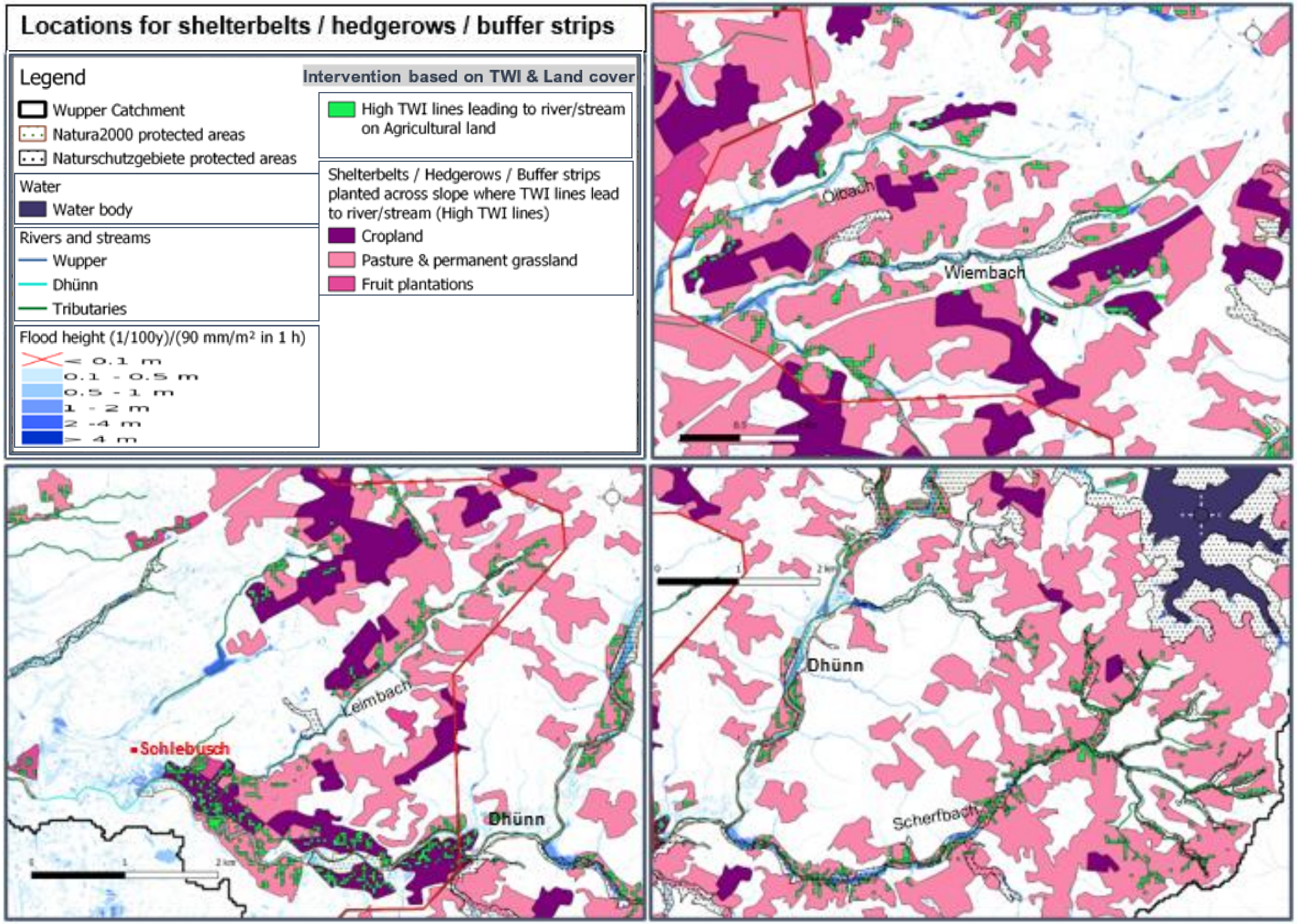


Figure 22: Locations for shelterbelts, hedgerows and tree buffer strips (Leverkusen and Rheinisch-Bergischer Kreis)

(Data source: BKG, 2021a&b; Diva-GIS n.d; IT.NRW, 2023; Prepared in QGIS)

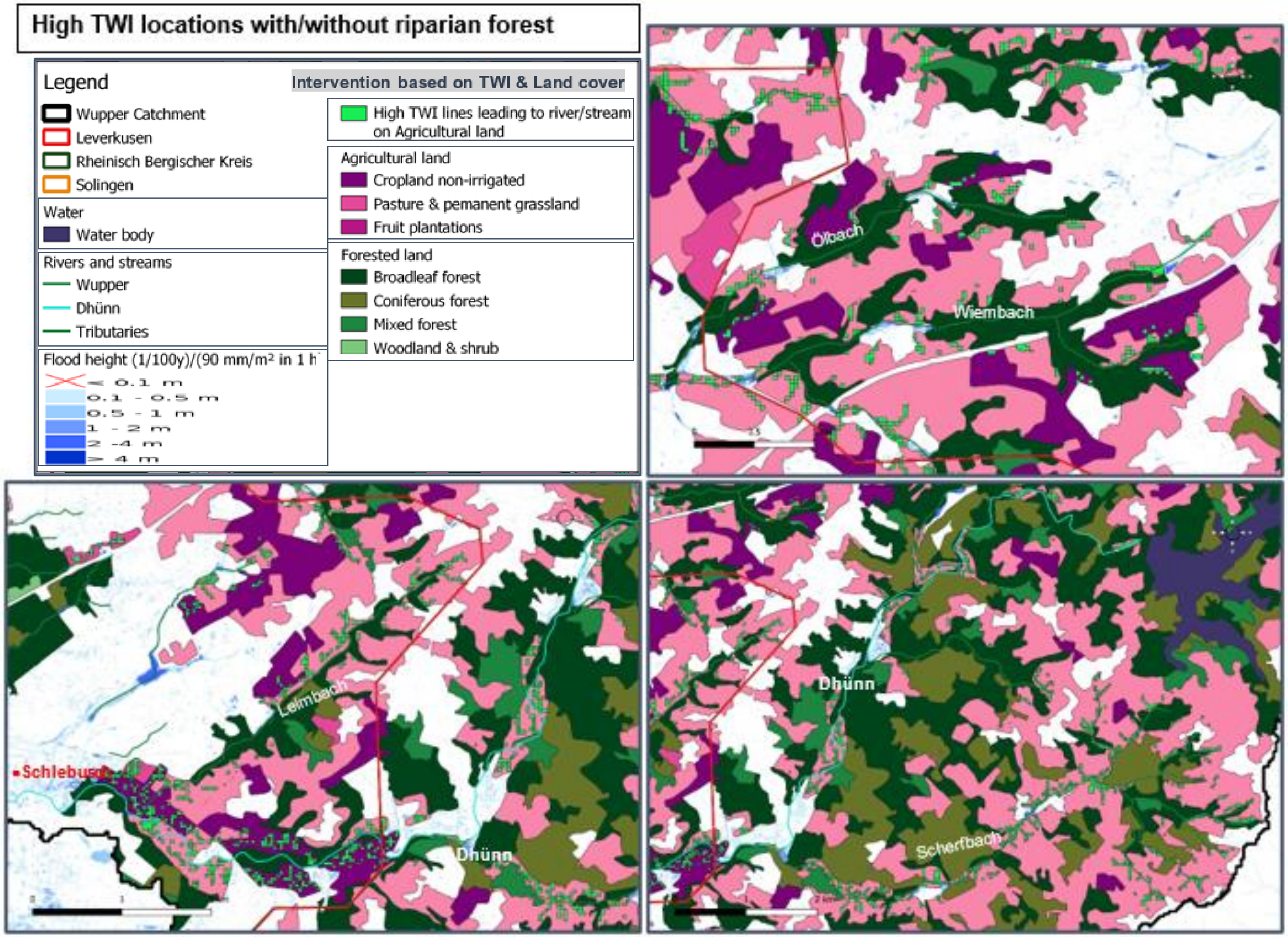


Figure 23: Locations for shelterbelts, hedgerows and tree buffer strips with additional guidance from riparian forest locations
(Data source: BKG, 2021a&b; Diva-GIS n.d; IT.NRW, 2023; Prepared in QGIS)

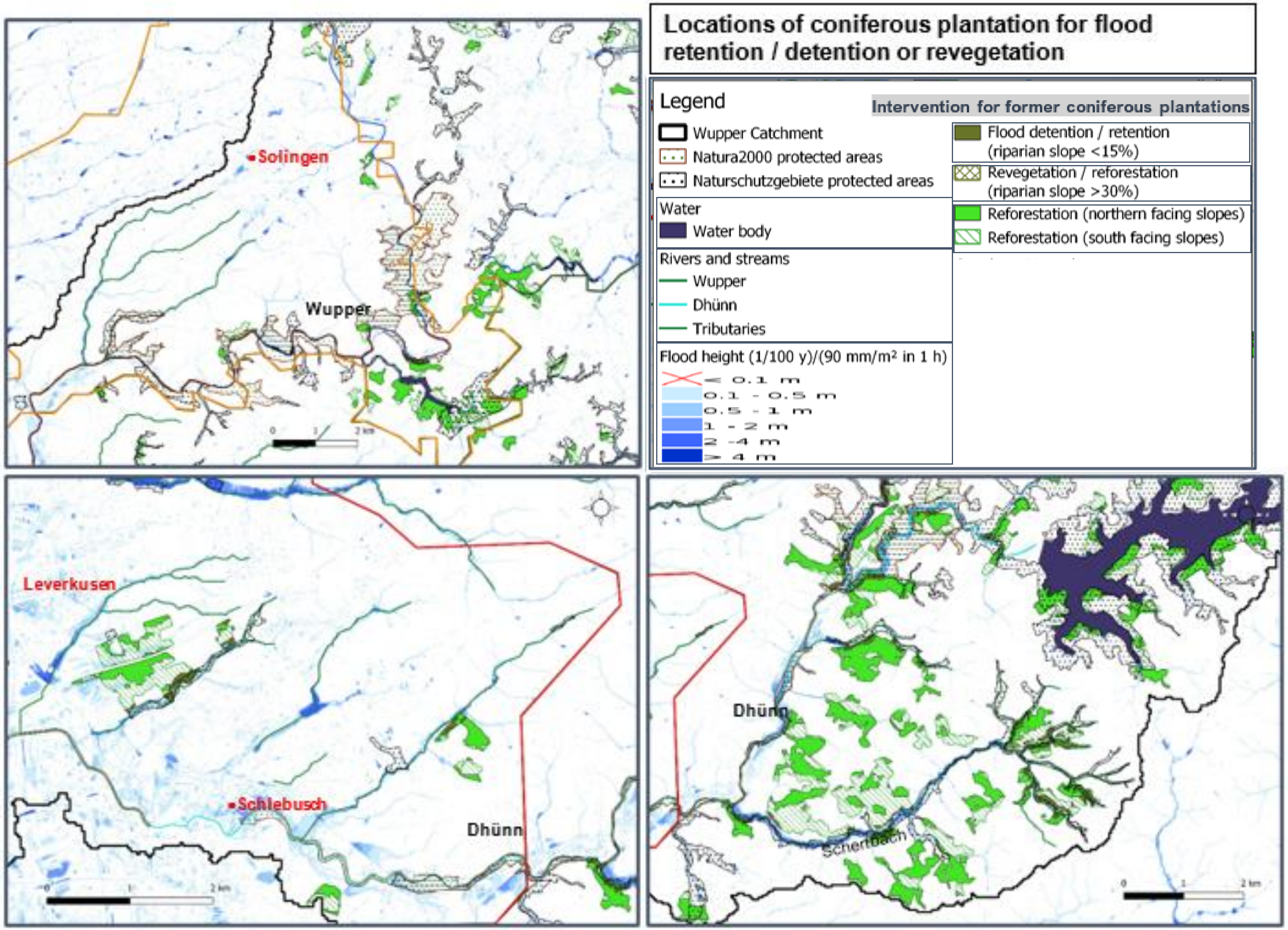


Figure 24: Locations of coniferous plantations for retention, revegetation and reforestation interventions (Leverkusen, Solingen and Rheinisch-Bergischer Kreis)
(Data source: BKG, 2021a&b; Diva-GIS n.d; IT.NRW, 2023; Prepared in QGIS)

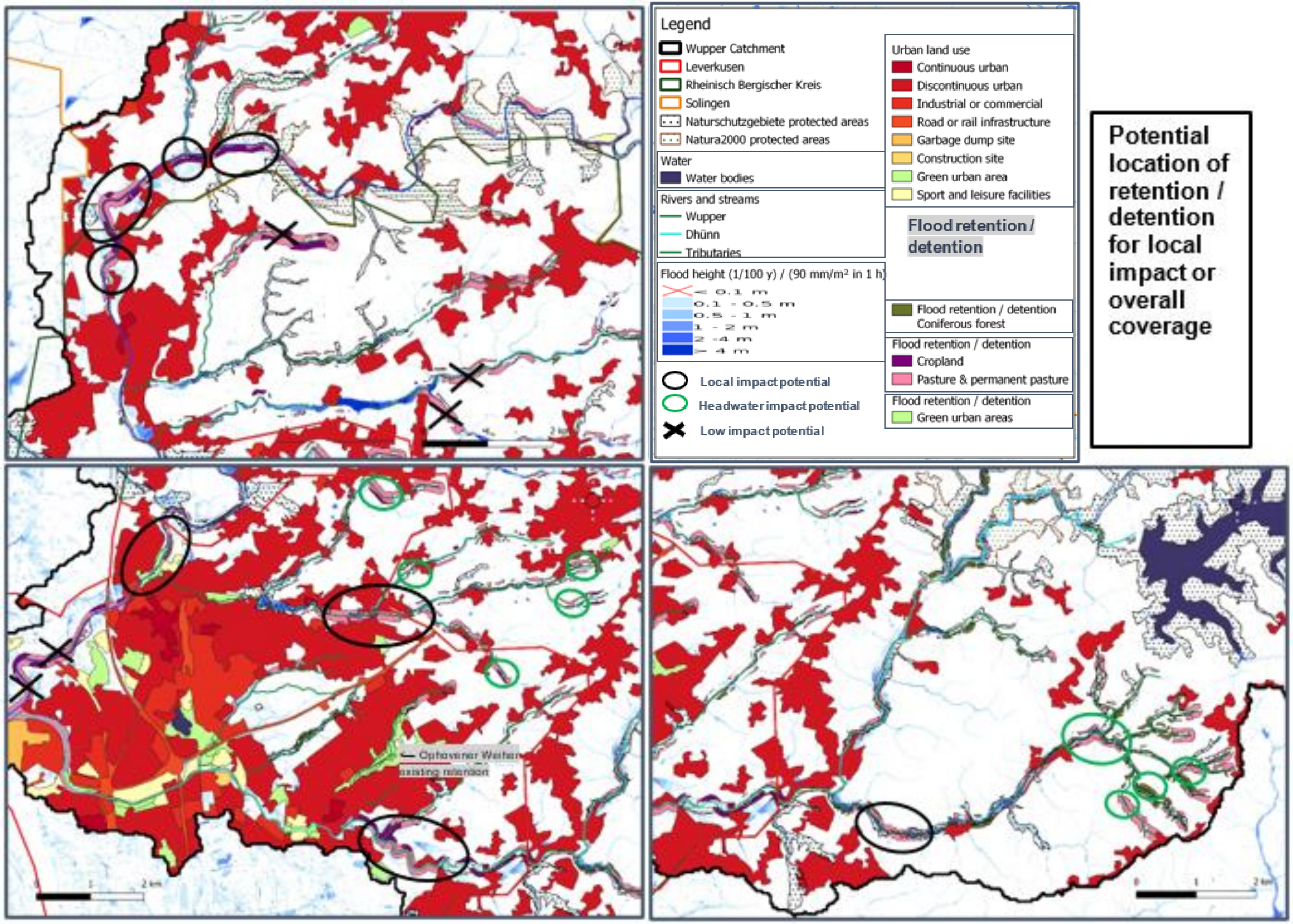


Figure 25: Locations of retention/detention basins/areas, preliminary site selection based on local impact or catchment impact

(Data source: BKG, 2021a&b; Diva-GIS n.d; IT.NRW, 2023; Prepared in QGIS)

5.3. Species options for green-blue interventions

There are many considerations in choosing species for the green aspect of green-blue interventions and the following section discusses some of those considerations.

5.3.1. Species options for agricultural land

In Section 4.2.4 some of the factors in relation to shelterbelts/hedgerows and tree buffer strips in agricultural fields are discussed. Species selection especially for growth within crop or pastural systems is especially intricate as there are so many factors to take into account beginning with slope, aspect and light requirements (of the crop), water requirements (of the trees or shrubs and the crops), growth cycles, tree pruning requirements and additional uses (animal husbandry or timber), soil-species suitability, avoiding allelopathy and pest suppression (Borin et al., 2010; DBU, 2010; Nerlich et al., 2013). Farmers and foresters know their local conditions best, and often know which species can be used successfully (or have been used successfully in the past) to achieve production aims. This report only suggests potential species that are used in the literature reviewed, from similar regions and climates. What is evident from the literature is that shelterbelts/hedgerows and buffer strips are useful in agricultural systems firstly for the purposes of this study, to reduce rainfall runoff and increase water infiltration, but also to reduce nutrient loss and erosion (Borin et al., 2010; DBU, 2010; Marshall et al., 2014; Nerlich et al., 2013; Xiong et al. 2018). Furthermore, in order to achieve maximum runoff attenuation on slopes, shelterbelts/hedgerows and buffer strips must be planted cross-slope (Carroll et al., 2004; Cooper et al. 2021; Marshall et al., 2009;2014).

In regards to species selection in agricultural systems, the literature offers a range of selections and also give an indication of which crop species perform the best with shelterbelts/hedgerows and buffer strips. In a cropping system Borin et al. (2010) combined the trees *Platanus hybrida* Brot. (Plane tree or London Sycamore) and the lower growing hedge bush *Viburnum opulus* L. (European Cranberry) to form buffer strips on low-sloping land within maize, soyabean and sugar beet crops in north-eastern Italy. The authors found that the crop yield was less than optimum within four metres of the hedgerow due to increased shade which affected sugar beet more so than the others. However, to make up for this loss, wood yield increased threefold from year six to year twenty and there were also considerable improvements in nitrogen and phosphorous losses. Nerlich et al. (2013) found similar outcomes with runoff and nutrient retention using buffer strips of *Acer pseudoplatanus* (Sycamore Maple), *Prunus avium* (Wild Cherry), *Juglans* spp. (Walnut) and short rotation poplar (*Populus deltoides*) trees and crops of barley and oats in central west Germany. Although the authors did not report on yield outcomes, they recommend a north south orientation for tree strips to minimise shading on crops. This is important because of the greater shadow cast by trees or hedges on crops either side when rows are aligned east-west compared to north-south. When rows are at 7m in height it is possible that crops with north-south aligned rows receive 12% more sunlight (SAFE, 2004).

In their work on agroforestry systems in Germany, DBU (2010) suggest a range of tree types specifically for use in German agriculture, including the species *Quercus* (oak varieties), *Acer campestre* (Field Maple) and *Carpinus betulus* (European Hornbeam) as they provide only light to partial shade when planted in buffer strips and the timber can also be an alternative source of income. They also recommend varying the species of both buffer strips and hedgerows to maximise income possibilities, biodiversity co-benefits and to reduce the likelihood of disease or pest infection. For the hedgerow species DBU (2010) recommend a variety of fruit tree species (*Prunus*), *Sambucus (Elderberry), Euonymus (Strawberry bush), Lonicera (*Honeysuckle)*, Rosa* (Roseaceae), *Berberis* (Barbery shrub), *Viburnum* (European Cranberry*)*, *Crataegus (Thornapple), Ligustrum* (privits) *and Cornus* (dogwoods). There would be other suitable species such as the shrubs *Calluna vulgaris* (heather), *Erica tetralix and Sarothamnus Scoparius* which Laussmann et al. (2021) describe as growing naturally in the Wuppertal region in the 1800s.

DBU (2010) also conducted shade trials with crops of maize, barley, potatoes and grassland. They found that maize, barley and grass yields were impact only slightly by light to medium shading, with yield loss of around 6%, 5-8% and 7% (respectively) compared to the control, whereas grassland yields increased under light to medium shade compared to the control after the first mowing, and potato crops increased by 10% under light to medium shade compared to the control. Maize and barley yields fell by around 26-28% under heavy shading, but potato and grass yields under heavy shade (after the first mowing) showed no difference to the control. Therefore, shelterbelts/hedgerows and tree buffer strips can work to reduce runoff and maintain agricultural yield in the Wupper basin by pairing the lighter shading tree species or the lower growing shrub species in hedgerows with grassland, maize or barley. Pruning tree rows up to the height of 10m also allows greater light through and allows the same amount of light through nomatter whether the row orientation is north-south or east-west (SAFE, 2004). Also, by combining buffer strips more densely planted or with reduced pruning, with potato crops, may even increase the yield.

5.3.2. Species options based on aspect for former coniferous plantations

Aspect must also be considered, especially with regard to reforestation of the former coniferous plantations in the study area. The extensive die-off of the coniferous trees in the Wupper Basin was introduced in Section 5.2.1.1. The majority of coniferous trees plantations in Wupperverband managed forests are located within the protected areas around the Groß Dhünn Dam in the study area and are predominantly spruce (Wupperverband, 2002). These plantations will not be reforested with coniferous species, instead the Wupperverband have been focussing on reforesting with Beech, and also with Oak on the slopes that receive more hours of sunlight and are therefore dryer (Wupperverband, 2002). In the northern hemisphere the south facing slopes generally receive more sunlight. This can mean higher temperatures and higher evaporation rates and reduced soil moisture, whereas on the more shaded north facing slopes soil often has higher moisture levels (Marapara et al. 2021).

In terms of potential species for the reforestation of former coniferous plantations in the Wupper, the Wupperverband foresters have possibly selected these species based on both aspect and projected climate change outcomes which include higher temperatures and warmer, dryer summers (BINGO, 2019). *Fagus sylvatica* L. (the European Beech tree) is one of the most widespread trees in central Europe but also potentially more susceptible to drought than other species (Bolte et al., 2007; Dulamsuren et al., 2017; Walentowski et al., 2017). The European Beech is already experienced a growth decline at elevations lower than 300 m.a.s.l in central Europe so it is better suited to the northern slopes, whereas the oaks species such as *Quercus petraea* (Sessile Oak) are better able to survive dry conditions and drought, so more suited to the southern slopes (Dulamsuren et al., 2017; Walentowski et al., 2017). Species such as *Carpinus betulus L.* (European Hornbeam), *Acer campestre*, *Tilia* spp*.* (Linden species), *Prunus avium* L. (Wild Cherry) which already grow well along with *Quercus petraea* in the warm southern Germany rain shadow mountains are also options for the southern facing slopes (Walentowski et al., 2017). While *Quercus robur* (Common Oak) *and Fraxinus excelsior* (Ash) whose survival depends more on soil moisture supply are more suited to the north facing slopes. Walentowski et al. (2017) also suggests *Acer campestre* or the Field Maple, *Ulmus minor* (Field Elm), *Tilia platyphyllos* (Linden tree), *Sorbus torminalis (Wild Servis tree)* and *S. aria (Whitebeam)* for broadleaf reforestation in the warm southern ranges of Germany, these drought tolerant and more rare species could also be planted on the dryer southern slopes in the Wupper Basin.

5.3.3. Species options based on location along slope

This study suggests that parcels of agricultural land located along the riparian zone and toe slopes with gradient 30% and more are revegetated due to their likely contribution to overland flow and soil erosion (see Section 5.2.2.4). Species selected for the riparian zone revegetation include the attributes discussed previously including shrub species as opposed to trees and they should be tolerant of periodic inundation. Shrub species such as *Cornus sanguinea* (Common Dogwood) and *Prunus padus* (Bird Cherry) are suitable as they are found along the Rhine and tolerant of periodic inundation (Deiller et al., 2003). For the highly sloping toe slope zone *Fagus sylvatica* L. is an option for reforestation (Bolte et al., 2007) along with other native shrubs discussed in Section 5.2.3.

For revegetation of the former coniferous plantation sites selected for natural retention/detention areas the Rhine floodplain species may be suitable. Species including

Quercus robur, *Fraxinus excelsior* (Ash), *Ulmus spp*. (Elm species) and *Populus alba* (White Elm) together formed the upper stories of the natural Rhine floodplain forests that withstood periodic flooding along with the fast growing pioneer species including *Salix alba* (Willow) and *Populus spp.* or Poplar and sometimes the *Betula pendula (Birch) and Alnus incana (Grey Alder)*, although the latter cannot survive successive flooding events long term (Schnitzler, A., 1994). Away from the riparian zone other native European species such as *Acer pseudoplatanus* (sycamore), *Prunus avium* (sweet cherry), *Acer campestre* and *Carpinus betulus L* are suitable for non-flooded areas.

Issues with pests and disease are not unique to the coniferous species. Invasive fungus has impacted native populations of both *Ulmus minor and Fraxinus excelsior* in recent decades (Schnitzler, A., 1994; Stocks, et al, 2019). Weakened trees that have been planted within an unsuitable climatic niche, subject to severe climatic disturbances or simply planted in monocultures or at the edge of clearings, are potentially at most at risk from invasive pest and disease (Berthelot et al., 2021). Ensuring that forests are replanted with consideration for potential climate changes, especially given the growth during and life expectancy of hardwood tree species, and also with sufficient diversity of species and genetics are the most common strategies employed in efforts to minimise pest or disease infestations (Berthelot et al., 2021; DBU, 2010). Therefore, every effort should be made to ensure that reforested sites are suitably restocked, having considered all of these factors. In fact, a high level of tree species diversity is also highly influential in promoting the co-benefits to reforestation, such as a biodiverse bird, insect and small mammal population.

5.4. Implementation guide

The following table is an implementation guide for green-blue interventions in the Wupper Basin. The guide is an easy-to-follow summary of the analysis carried out in this report to find the highest potential landcover and land use sites and the priority locations for green-blue interventions. The guide puts together the analysis carried out to combine landcover and land use categories and landscape characteristics which together have the best chance of increasing interception and infiltration and reducing runoff and flooding, all to minimise the impacts of hydrometeorological hazards. The guide provides a description of the mechanisms working to address the issues of interception, infiltration, runoff and flooding at the sites where case studies and modelling outcomes indicate that the intervention will be most effective. The guide also contains lists of suggested species for agricultural, revegetation and reforestation interventions according to the literature, along with a summary of the co-benefits that make outcomes of NbS or green-blue interventions more durable and more sustainable in the long term. The guide could be used by land use planners, land care practitioners and by students, each adding to it to make it a better document or using it as a template for to be applied to other regions or river basins.

Table 3: Implementation guide for green-blue interventions in the Wupper Basin

Landcover / land use	**Location to river**	**Location in basin**	**Slope location**	**% Slope**	**Aspect**	**Mechanism addressing hydrometeorological hazards**	**Green-Blue Intervention Options**	**Species Options / layout**	**Co-benefits**
Urban	**Riparian**	-	-	≤15%	-	Capture of excess runoff to reduce flood peak affecting nearby urban areas	• Retention/detention ponds	Due to space limitations strategic placement to have dual purpose and have local impact	Blue and green parks for human recreation, aesthetics, wildlife refuge in the city, additional income for landholders, reduced flood risk for city
	Floodplain & slopes	-	-	-	-	• Keeping the rain where it falls • Reducing runoff	Urban green-blue measures such as micro detention/retention ponds, permeable pavements, infiltration trenches, filter strip/drain, bio-retention, rain gardens and tree box filters drains		
Arable land / Cropland & Pasture / Permanent grassland	**Riparian**	**Midstream in the basin (all sections of tributaries)**	-	≤15%	-	Capture of excess runoff to reduce flood peak or delay flood peak downstream	Retention/detention ponds & areas	Multiple detention ponds or areas set in parallel configuration along overflow /runoff zones in the upstream regions of waterways	Additional income for landholders, reduced flood risk for urban areas
				≥30%	-	Increasing surface roughness to slow the flow of flood waves and permanent land cover to stabilise banks	Revegetated of riparian zone	Revegetation with native shrub species (due to the slope) such as dogwood, bird cherry, or beech trees and reeds & grasses at high velocity flood zones	Carbon sequestration, reduced soil erosion, consolidation of riparian banks

Landcover / land use	Location to river	Location in basin	Slope location	% Slope	Aspect	Mechanism addressing hydrometeorological hazards	Green-Blue Intervention Options	Species Options / layout	Co-benefits
Arable land / Cropland & Pasture / Permanent grassland	**Slopes**		**Hilltop**	-	-	• Keeping the rain where it falls • Reducing runoff response time and runoff volume through enhancing soil water infiltration and storage capacity • Increasing rainfall interception	Arable land/cropland: 1. Biochar soil amendments 2. Strip tillage / reduced tillage 3. Buffer strips/coppice intercropping	Buffer strip/coppice: Plane tree, European cranberry, walnut, wild cherry, sycamore maple, oak species, field maple, European hornbeam, poplar Crops: potato, maize, barley, grass varieties	Carbon sequestration, soil carbon retention, carbon sequestration, increased earthworm numbers
							Pasture: 1. Grazed woodlands or silvopasture (without loss of groundcover) 2. Reduced grazing pressure Grasslands: 1. Biochar soil amendments 2. Reduced tillage		Shade for stock, aesthetics, habitats for birds, small mammals & insects, better aesthetics, reduction in fossil fuel use
			Upper and Middle	>30%	-	• Reducing runoff response time and runoff volume through enhancing the soil water infiltration and storage capacity • Increasing surface	Arable land/cropland: 1. Revegetation 2. Buffer strips/coppice intercropping 3. No tillage	Revegetation: Native shrub species (due to the slope) such as heather, glocken-heide, scotch broom, beech trees Buffer strip/coppice: Plane tree, European cranberry, walnut, wild cherry, sycamore maple,	Habitat for small mammals, birds, insects, reduced nutrients in runoff (reduced water pollution), soil carbon retention, increased earthworm numbers, reduction in fossil fuel use

Landcover / land use	Location to river	Location in basin	Slope location	% Slope	Aspect	Mechanism addressing hydrometeorological hazards	Green-Blue Intervention Options	Species Options / layout	Co-benefits
Arable land / Cropland & Pasture / Permanent grassland						roughness to delay runoff times	Pasture: 1. Revegetation 2. Hedgerows 3. Reduced grazing pressure Grasslands: 1. Revegetation 2. Buffer strips/coppice intercropping 3. Reduced mowing height and/or frequency 4. No tillage	oak species, field maple, European hornbeam, poplar Hedgerows: Fruit trees, elderberry, honeysuckle, barberry shrub, European, thornapple, privets, dogwoods	Habitat for small mammals, birds, insects, reduced methane emissions, soil carbon retention, increased insect habitat, increased earthworm numbers, reduction in fossil fuel use
			Lower Slope	-	-	- Reducing runoff response time and runoff volume through enhancing soil water infiltration and storage capacity - Increasing rainfall interception - Moderating soil water content at high TWI lines through uptake via tree roots - Increasing surface roughness to	Arable land/cropland: 1. Reforestation 2. Agroforestry (multiple tree strips) 3. Buffer strips/ coppice intercropping 4. Strip tillage / reduced tillage	Reforestation: (moist soil tolerant species) Beech, common oak, ash, willow, poplars, alder, birch, elm Agroforestry / woodlands / coppice intercropping: Plane tree, European cranberry, walnut, wild cherry, sycamore maple, oak species, field maple, European hornbeam, poplar, beech, oak, alder	Habitat for small mammals, birds, insects, reduced nutrient losses, soil carbon retention, increased insect habitat, increased earthworm numbers, reduction in fossil fuel use
							Pasture: 1. Reforestation 2. Grazed Woodlands or silvopasture (without loss of groundcover) 3. Reduced grazing pressure Grasslands: 1. Reforestation 2. Buffer strips/ coppice intercropping		Habitat for small mammals, birds, insects, reduced methane emissions, soil carbon retention, diversification of income, increased earthworm

Landcover / land use	Location to river	Location in basin	Slope location	% Slope	Aspect	Mechanism addressing hydrometeorological hazards	Green-Blue Intervention Options	Species Options / layout	Co-benefits
						delay runoff times. Moderating soil water content through uptake via tree roots	3. Reduced mowing height and/or frequency 4. Reduced tillage		numbers, reduction in fossil fuel use, reduced nutrient loss
Arable land / Cropland & Pasture / Permanent grassland			**Toe Slope**	**0-30%**	-	• Moderating soil water content at high TWI lines through uptake via tree roots • Enhancing soil water infiltration and storage capacity • At times of high temperatures and drought, minimising soil water loss	<u>Arable land/cropland:</u> 1. Buffer strips/ coppice intercropping 2. Strip tillage / reduced tillage <u>Pasture</u> 1. Shelterbelts/ hedgerows 2. Reduced grazing pressure <u>Grassland:</u> 1. Buffer strips 2. Reduced tillage	<u>Buffer strip/coppice intercropping:</u> Plane tree, European cranberry, walnut, wild cherry, sycamore maple, oak species, field maple, European hornbeam, poplar <u>Crops:</u> potato, maize, barley, grass <u>Hedgerows:</u> Fruit trees, elderberry, honeysuckle, barberry shrub, European, thornapple, privets, dogwoods	Habitat for small mammals, birds, insects, reduced methane emissions, soil carbon retention, diversification of income, increased earthworm numbers, reduction in fossil fuel use, reduced nutrient loss
				>30%	-	• Moderating soil water content at high TWI lines	<u>Arable land/cropland:</u> 1. Revegetation 2. Buffer strips/coppice intercropping 3. No tillage	<u>Revegetation:</u> (moist tolerant shrubs) Common dogwood, bird cherry (heathers)	Habitat for small mammals, birds, insects, reduced nutrients in runoff (reduced water

Landcover / land use	Location to river	Location in basin	Slope location	% Slope	Aspect	Mechanism addressing hydrometeorological hazards	Green-Blue Intervention Options	Species Options / layout	Co-benefits
Arable land / Cropland & Pasture / Permanent grassland						- Reducing runoff response time and runoff volume through enhancing soil water infiltration and storage capacity	Pasture: 1. Revegetation 2. Hedgerows 3. Reduced grazing pressure Grasslands: 1. Revegetation 2. Buffer strips/coppice intercropping 3. No tillage	heather, glocken-heide, scotch broom (moist soil tolerant tree species) Beech, common oak, ash, willow, poplars, alder, birch, elm Buffer strips/ coppice intercropping: Plane tree, European cranberry, walnut, wild cherry, sycamore maple, oak species, field maple, European hornbeam, poplar Hedgerows: Fruit trees, elderberry, honeysuckle, barberry shrub, European, thornapple, privets, dogwoods	pollution), soil carbon retention, increased earthworm numbers, reduction in fossil fuel use
Coniferous Forest	**Riparian**	**Upstream/ midstream**	**-**	**<15%**	**-**	Capture of excess runoff to reduce flood peak or delaying flood peak downstream	Natural detention areas revegetated with species that prefer wet soils and are tolerant of periodic inundation without long-term die-back	Common oak, ash and elm species including white elm	Reinstatement of once widespread floodplain forests of the Rhine valley

Landcover / land use	Location to river	Location in basin	Slope location	% Slope	Aspect	Mechanism addressing hydrometeorological hazards	Green-Blue Intervention Options	Species Options / layout	Co-benefits
Coniferous Forest				**≥15%**	**-**	• Reducing runoff response time and runoff volume through enhancing soil water infiltration and storage capacity • Increasing rainfall interception • Moderating soil water content through uptake via tree roots	Revegetation with broadleaf species tolerant of wet soils and periodic inundation	Beech, common oak, ash, willow, poplars, alder, birch, elm, grey alder and shrubs common dogwood, bird cherry and grasses and reeds in areas of high velocity	Habitat for small mammals, birds, insects, increased biodiversity of forest species, increased roughness to slow floodwaters
Coniferous Forest	**Lower slopes**		Toe Slope and Lower	-	**-**	• Enhancing soil water infiltration and storage capacity • Increasing rainfall interception • Moderating soil water content through uptake via tree roots	Revegetation with species with tolerance for moist to wet soils	Ash, beech, elm, sweet cherry, maple, hornbeam	Habitat for small mammals, birds, insects, increased biodiversity of forest species

Landcover / land use	**Location to river**	**Location in basin**	**Slope location**	**% Slope**	**Aspect**	**Mechanism addressing hydrometeorological hazards**	**Green-Blue Intervention Options**	**Species Options / layout**	**Co-benefits**
Coniferous Forest	**Slopes / floodplain**		Upper, Middle & Hilltop	-	South facing	• Reducing runoff response time and runoff volume through enhancing soil water infiltration and storage capacity • Increasing rainfall interception • Moderating soil water content through uptake via tree roots	Revegetation with mixed and broadleaf species tolerant of dry periods and drought	Sessile oak, European hornbeam, linden tree, field maple, field elm, wild cherry, white servis tree, whitebeam	Habitat for small mammals, birds, insects, increased biodiversity of forest species
					North facing		Revegetation with mixed and broadleaf species tolerant of higher rainfall and shade	Forests consisting of predominately common oak, ash, beech, sycamore,	Habitat for small mammals, birds, insects, increased biodiversity of forest species
Broadleaf and Mixed Forests	**Riparian**		-	≤15%	-	Capture of excess runoff to reduce flood peak or delaying flood peak downstream	Natural overflow areas – no intervention	-	Retaining all of the current benefits to society and biodiversity
	Slopes and Floodplain		Lower and Toe Slope, Upper, Middle & Hilltop	**>15%**	-	Ongoing services	No intervention	-	

6. Conclusion

CO_2 concentrations are now at levels higher than they have been for the last two million years because of anthropogenic actions. Along with the turbulence that we are creating in the earth’s climate system, we are also leading the sixth major extinction across the planet with biodiversity and habitat loss at an all-time high. As a result, many countries around the world, including Germany, are experiencing more intense natural hazards and finding that degraded natural environments are also less resilient to such disturbances.

Because of the many issues that we face, solutions to natural hazards are now being sought from natural processes that can offer multiple benefits at the same time as increasing the resilience of the environment to absorb climatic perturbations. While this concept and the subsequent practices pertaining to it are described by a wide range of terms the most all-encompassing is nature based solutions or NbS. NbS includes a subcategory of green-blue infrastructure that describes the functions that occur at the intersection of the terrestrial and aquatic environment such as the part of the water cycle that occurs on land. The hydrology of any particular part of the landscape is affected by the meteorological cycle. Green-blue infrastructure refers to the hardware and green-blue interventions refers to the actions taken to modify the green-blue infrastructure.

This report sought to identify the most critical hydrometeorological hazards affecting the study area in the Wupper Basin, to identify the most effective interventions that could be undertaken within the green-blue infrastructure in the basin, with a minimum level of land use change, and to determine which landscape features were most likely to afford the best results from the interventions.

The study area was selected in the Wupper Basin because of the experiences in the basin during an unprecedented hydrometeorological event that occurred in July 2021. During this event more rainfall fell on the basin in a 24-hour period than in recorded history and flash floods occurred followed by fluvial flooding that inundated numerous parts of the landscape and cities. Green-blue interventions are more often centred in urban locations in efforts to make the highly modified landscape more natural to absorb excess rainfall, however because of the pattern of land-use in the Wupper Basin this study focussed on urban, agricultural and forested landscapes. The study area was chosen as a sub-set of the wider basin, excluding a number of large dams in the headwaters of the Wupper and Dhünn Rivers which act as a man-made regulation and obscure the potential for more natural solutions.

Current trends and forecast for the Wupper basin were for increased winter rainfall and dryer warmer spring/summer periods. Data from the study area was analysed with SPI-3 to show seasonal trends and found that trends in the study area were similar only with slightly increasing rainfall in the spring season, but increasing from a historic deficit. Researchers also forecast an increase in summer convective rainfall due to increasing temperatures.

A state of the art review involved searching for field studies and modelling outcomes that were undertaken in similar climates (temperate), landscapes (slopes) and land uses (predominantly agricultural and forest plantations). The information found indicates that the baseline status of the peri-urban and rural areas in the study area under agriculture is potentially low in hydraulic conductivity, soil water storage capacity and producing high runoff during rainfall events. The coniferous forests that have recently cleared due to the infestation of the bark beetle are likely to be in a similar state, along with of course the highly impervious urban and industrial areas. The remnant forests and woodlands were likely to be absorbing the excess but at a decreasing capacity as floods occur even in fully forested catchments. However, forests and also natural grasslands, have the ability to reduce at least some of the flood peak and duration due to interception of rainfall on leaves, branches and stems, and soil conditioning by roots, organic matter and biota which improves hydraulic conductivity and soil water retention, which in turn reduces the amount of rainfall runoff, which in turn minimises the flood peak and duration, and enables better storage of water in the soils that can be accessed by vegetation during dryer times.

With the baseline established, research turned to finding practices that could be undertaken with minimum disruption to current land use practices that would enable greater interception, increased soil water infiltration and reduced runoff and flooding. A series of practices were found, including the following: Revegetation, while reforestation of the catchment would provide the best results, it is completely impractical and impossible. Reforestation or revegetation was suggested for locations where the slope of the land was greater than 30% and in the case of the former coniferous plantations. Crop and pasture management, whereby tree buffer strips and/or coppice intercropping acts to reduce runoff and nutrient loss from the field, and shelterbelt and hedgerows for the pastoral sites which also acts to reduce runoff especially if planted cross slope. Grazing management includes reduced stocking intensity and grazed forests (without resulting in loss of groundcover) which act to reduce compaction and reduce rainfall runoff. Grassland management in the form of reduced mowing height or intensity for sown/permanent grasslands which can slow the flow of runoff. Soil tillage management, including strip tillage, no tillage and reduced tillage on cropland and sown grasslands acts to reduce runoff, soil erosion and nutrient losses, by increasing soil water storage capacity. Soil management with biochar, whereby the application of biochar can increase the soil water storage capacity of soils. Retention/detention basins or areas, which can be incorporated with urban, agricultural or forestry, act to take water out of the system during flooding, thereby reducing the flood peak.

According to the objectives literature was also sought on the effect of landscape locations on basin hydrology. Certain landscape features have a greater potential to influence basin hydrology and this impact that different landscape features have on hydrology was assessed according to the following themes: Proximity to river or stream, this matters most for retention/detention as it is necessary for a connection with the riparian zone. Location in the basin, several studies found that several smaller scale retention/ detention located in the upstream/second order streams were optimal. Location in catchment, across the entirety of the basin the majority of the study focuses on the midstream section. However, for the tributary sub-basins the study area covers the entirety of the sub-basin. This is important for retention/detention location as rainfall doesn't always fall evenly across the basin, and large retention/detention basins are most effective when located (where safe) close to the urban areas or sensitive infrastructure to take advantage of the local effect, but smaller retention in the headwaters is often more effective to reduce the flood peak across the whole basin. The location along the slope is also very important, because of slope hydrology the hilltops are often sources of runoff and subsurface flow while the lower and toe slopes are most often the sites that receive the majority of the subsurface flow. Slope percentage also has a major impact on runoff and a simple explanation is that the greater the slope the higher velocity the runoff. The topographic wetness index is calculated based on slope characteristics to illustrate preferential sites for water accumulation and flow, this tool can be used as a guide for strategic placement of green-blue interventions.

A spatial analysis was undertaken to identify the best placement of green-blue interventions. Interventions were shown on the same maps where possible to demonstrate that the interventions could work together and in this way have greater impact by operating through a variety of mechanisms such as creating greater surface roughness to slow the flow of water, creating a higher canopy mass to intercept rainfall in the leaves and bark, creating better soil conditions for soil moisture storage and by taking water out of the system to reduce the flood peak. Tentative recommendations were given on each of the river and tributary sub-catchments. For the Wupper in the study area there are some locations that appear to be suitable, based on the analysis criteria, for mixed-use retention or detention for fluvial flooding purposes. This is also the case along the Ölbach and the Weimbach however retention / detention in this case would be more likely for flash flood events. Along the Leimbach there are areas with slope greater than 30%, that would benefit from revegetation to slow the flow and improve the soil water infiltration capacity of the soil. Along the Dhünn River in Leverkusen there appear to be locations that may have potential for mixed-use retention/detention that would reduce the flood impact to Schlebusch. There are also extensive agricultural fields along the Dhünn that are affected by storm water ponding during convective storms which could benefit from strip tillage and/or reduced tillage to minimise the occurrence of bare soils and improve soil bulk density. The heavy rainfall hazard map shows that the Scherfbach system carries a lot of water during storms and there are potential locations that would be suitable for mixed-use retention/detention at the level of second and third order stream sections. Multiple small retention/detention at these locations could provide basin wide flood coverage if paired with similar sites within the basin. There are also agricultural sites along the riparian zone in the Scherfbach with a slope greater than 30%, and revegetation of these areas would be highly effective at reducing runoff. The majority of the former coniferous sites are located along the Scherfbach and between the Scherfbach and the Dhünn that provide a valuable opportunity for reforestation with a variety of native broad leaf species. Broadleaf forests have a higher capacity to intercept rainfall during storms than the former coniferous plantations and offer many more opportunities for biodiversity enhancement in the catchment.

In addition to the spatial analysis maps, an implementation guide for green-blue interventions in the Wupper Basin was developed. The guide is an easy-to-follow summary of the high potential landcover and land use sites and priority locations for green-blue interventions which together have the best chance of increasing interception and infiltration and reducing runoff and flooding. The guide also provides a description of the mechanisms at work, species options and potential co-benefits.

6.1. Outlook and recommendations

As already mentioned, this work can be considered a preliminary assessment of the potential for a number of green-blue interventions to reduce meteorological hazards in the study area. This work sets a baseline and provides a guide for more in-depth investigation. The importance of landscape hydrology along with landcover and land use must be considered when green-blue infrastructure is designed, or green-blue interventions planned and hopefully this report has demonstrated the importance of this combination.

There are many aspects of the spatial analysis in this study that need to be refined and ground-truthed. If more accurate data is available than the same spatial analysis techniques could be used, with a more refined outcome. Data such as aquifer and groundwater details, underlying geology, more specific soil characteristics and sensitive infrastructure details would be highly valuable in planning floodwater retention or detention locations. Further work could also be done to estimate the economic cost of mixed-use retention in the Wupper Basin as this may result in a win-win outcome for the municipalities and the farmers. The potential impact of pollution from flood water would also need to be investigated, including the potential for micro-plastic pollution. There is also a lot more work that could be done on species selection for shelterbelt/hedgerows, buffer strips/coppice intercropping and reforestation of the former coniferous plantations. This work could be carried out in consultation with foresters, farmers, botanists and ecologists. The literature suggests that there has been a lot of forest degradation over the past few hundred years in the Wupper

Basin, and the implementation of green-blue infrastructure could also improve forest species diversity along with that of birds, insects and small mammals.

Modelling studies also need to be carried out to further this work. The Wupperverband would have already carried out many hydrology studies, it would be interesting now to combine those with soil function models and vegetation models, to get an understanding of how the hydrology of the basin is impacted by soil, livestock and vegetation management. Modelling could also be used to evaluate the most successful and cost-effective combinations of urban and rural/agricultural green-blue infrastructure interventions.

Lastly this study did not include any legal or land administration investigations, this would also be a necessary step for any further planning for green-blue interventions, along with a cost benefit analysis.

Bibliography:

All papers listed in German were translated to English by Google translate (https://translate.google.com/?hl=en&tab=TT)

Ahmadisharaf, E., Tajrishy, M. and Alamdari, N., 2016. Integrating flood hazard into site selection of detention basins using spatial multi-criteria decision-making. *Journal of environmental planning and management*, *59*(8), pp.1397-1417.

Albert, C., Brillinger, M., Guerrero, P., Gottwald, S., Henze, J., Schmidt, S., Ott, E. and Schröter, B., 2021. Planning nature-based solutions: Principles, steps, and insights. *Ambio*, *50*(8), pp.1446-1461.

Alves, A., Gersonius, B., Sanchez, A., Vojinovic, Z. and Kapelan, Z., 2018. Multi-criteria approach for selection of green and grey infrastructure to reduce flood risk and increase CO-benefits. *Water* Resources Management, 32(7), pp.2505-2522.

Anderson, S.H., Udawatta, R.P., Seobi, T. and Garrett, H.E., 2009. Soil water content and infiltration in agroforestry buffer strips. *Agroforestry systems*, *75*(1), pp.5-16.

Archer, N.A.L., Bonell, M., Coles, N., MacDonald, A.M., Auton, C.A. and Stevenson, R., 2013. Soil characteristics and landcover relationships on soil hydraulic conductivity at a hillslope scale: A view towards local flood management. *Journal of hydrology*, *497*, pp.208-222.

Aryal, S.K., O'Loughlin, E.M. and Mein, R.G., 2005. A similarity approach to determine response times to steady-state saturation in landscapes. *Advances in Water Resources*, *28*(2), pp.99-115.

Ayalew, T.B., Krajewski, W.F. and Mantilla, R., 2015. Insights into expected changes in regulated flood frequencies due to the spatial configuration of flood retention ponds. *Journal of Hydrologic Engineering*, *20*(10), p.04015010.

Bachmair, S. and Weiler, M., 2012. Hillslope characteristics as controls of subsurface flow variability. *Hydrology and Earth System Sciences*, *16*(10), pp.3699-3715.

Badischer Landwirtschaftlicher Hauptverband e.v. (BLHV), 2022. GAP: Pflugeinsatz erhält Ackerstatus Available at: https://www-blhv-de.translate.goog/gap-pflugeinsatz-erhaelt-ackerstatus/?_x_tr_sl=de&_x_tr_tl=en&_x_tr_hl=en&_x_tr_pto=sc. Accessed, 01.04.2023.

Barbier, S., Balandier, P. and Gosselin, F., 2009. Influence of several tree traits on rainfall partitioning in temperate and boreal forests: a review. *Annals of Forest Science*, *66*(6), pp.1-11.

Bathurst, J.C., Fahey, B., Iroumé, A. and Jones, J., 2020. Forests and floods: using field evidence to reconcile analysis methods. Hydrological Processes, 34(15), pp.3295-3310.

Bayala, J. and Prieto, I., 2020. Water acquisition, sharing and redistribution by roots: applications to agroforestry systems. *Plant and Soil*, *453*, pp.17-28.

Bell, C.D., Wolfand, J.M., Panos, C.L., Bhaskar, A.S., Gilliom, R.L., Hogue, T.S., Hopkins, K.G. and Jefferson, A.J., 2020. Stormwater control impacts on runoff volume and peak flow: A meta-analysis of watershed modelling studies. *Hydrological Processes*, *34*(14), pp.3134-3152.

Bellu, A., Fernandes, L.F.S., Cortes, R.M. and Pacheco, F.A., 2016. A framework model for the dimensioning and allocation of a detention basin system: The case of a flood-prone mountainous watershed. *Journal of Hydrology*, *533*, pp.567-580.

Berthelot, S., Frühbrodt, T., Hajek, P., Nock, C.A., Dormann, C.F., Bauhus, J. and Fründ, J., 2021. Tree diversity reduces the risk of bark beetle infestation for preferred conifer species, but increases the risk for less preferred hosts. *Journal of Ecology*, *109*(7), pp.2649-2661.

Birkinshaw, S.J. and Krivtsov, V., 2022. Evaluating the Effect of the Location and Design of Retention Ponds on Flooding in a Peri-Urban River Catchment. *Land*, *11*(8), p.1368.

Birkinshaw, S.J., Bathurst, J.C. and Robinson, M., 2014. 45 years of non-stationary hydrology over a forest plantation growth cycle, Coalburn catchment, Northern England. *Journal of Hydrology*, *519*, pp.559-573.

Blöschl, G., Gaál, L., Hall, J., Kiss, A., Komma, J., Nester, T., Parajka, J., Perdigão, R.A., Plavcová, L., Rogger, M. and Salinas, J.L., 2015. Increasing river floods: fiction or reality?. *Wiley Interdisciplinary Reviews: Water*, *2*(4), pp.329-344.

Bolte, A., Czajkowski, T. and Kompa, T., 2007. The north-eastern distribution range of European beech—a review. *Forestry*, *80*(4), pp.413-429.

Borin, M., Passoni, M., Thiene, M. and Tempesta, T., 2010. Multiple functions of buffer strips in farming areas. *European journal of agronomy*, *32*(1), pp.103-111.

Bringing INnovation to onGOing water management (BINGO), 2016. D3.1 Characterization of the catchments and water systems. European Union Horizon 2020 Research and Innovation Program. Available at: http://www.projectbingo.eu/downloads/BINGO_Deliverable3.1_EC.pdf. Accessed 06.04.2023.

Bringing INnovation to onGOing water management (BINGO), 2019. Special Report: Impacts of long-term climate change effects on typical water problems in Europe. European Union Horizon 2020 Research and Innovation Program. Available at: http://www.projectbingo.eu/downloads/BINGO_Deliverable3.pdf. Accessed 06.04.2023.

Bundesamt für Kartographie and Geodäsie (BKG), 2021a. CORINE Land Cover 5 ha, as of 2018 (CLC5-2018). Available at: https://gdz.bkg.bund.de/index.php/default/corine-land-cover-5-ha-stand-2018-clc5-2018.html. Accessed 28.01.2023.

Bundesamt für Kartographie and Geodäsie (BKG), 2021b. WMS Starkregengefahrenhinweise Nordrhein-Westfalen (wms_starkregen). Available at: https://gdz.bkg.bund.de/index.php/default/open-data/wms-starkregengefahrenhinweiskarten-nrw-wms-starkregen.html. Accessed 01.09.2022.

Bundesamt für Naturschutz (BfN), 2014. Grünland-Report: Alles im Grünen Bereich? Available at: https://www.bfn.de/sites/default/files/2021-04/PK_Gruenlandpapier_30.06.2014_final_layout_barrierefrei_0.pdf. Accessed 01.04.2023.

Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), 2020. Soil Map of Germany at scale 1:200,000 (BÜK200). Available at: https://www.bgr.bund.de/EN/Themen/Boden/Projekte/Informationsgrundlagen_laufend/BUEK200/BUEK200_en.html. Accessed 24.02.2023.

Caretta, M.A., A. Mukherji, M. Arfanuzzaman, R.A. Betts, A. Gelfan, Y. Hirabayashi, T.K. Lissner, J. Liu, E. Lopez Gunn, R. Morgan, S. Mwanga, and S. Supratid, 2022: Water. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 551–712, doi:10.1017/9781009325844.006.

Carroll, Z.L., Bird, S.B., Emmett, B.A., Reynolds, B. and Sinclair, F.L., 2004. Can tree shelterbelts on agricultural land reduce flood risk?. *Soil use and Management*, *20*(3), pp.357-359.

Chambers, M, 2021. Fire, drought, beetles ravage German forests, study finds. *Reuters, Environment*. Available at: https://www.reuters.com/article/us-germany-politics-forests-idUSKBN2AO1IA. Accessed 09.08.2022.

Chandler, K.R., Stevens, C.J., Binley, A. and Keith, A.M., 2018. Influence of tree species and forest land use on soil hydraulic conductivity and implications for surface runoff generation. *Geoderma*, *310*, pp.120-127.

Collentine, D. and Futter, M.N., 2018. Realising the potential of natural water retention measures in catchment flood management: Trade-offs and matching interests. *Journal of Flood Risk Management*, *11*(1), pp.76-84.

Cooper, M.M., Patil, S.D., Nisbet, T.R., Thomas, H., Smith, A.R. and McDonald, M.A., 2021. Role of forested land for natural flood management in the UK: A review. *Wiley interdisciplinary reviews: Water*, *8*(5), p.e1541.

Debele, S.E., Kumar, P., Sahani, J., Marti-Cardona, B., Mickovski, S.B., Leo, L.S., Porcù, F., Bertini, F., Montesi, D., Vojinovic, Z. and Di Sabatino, S., 2019. Nature-based solutions for hydro-meteorological hazards: Revised concepts, classification schemes and databases. *Environmental Research*, *179*, p.108799.

Deiller, A.F., Walter, J.M.N. and Trémolières, M., 2003. Regeneration strategies in a temperate hardwood floodplain forest of the Upper Rhine: sexual versus vegetative reproduction of woody species. *Forest ecology and management*, *180*(1-3), pp.215-225.

Deutscher Bundesstiftung Umwelt (DBU), 2010. *Multifunktionale Bewertung von Agroforstsystemen*. Schlussbericht. Available at: https://www.dbu.de/OPAC/ab/DBU-Abschlussbericht-AZ-25786.pdf. Accessed 17.12.2022.

Deutscher Wetterdeinst (DWD), 2022, Observations Germany Available at: https://opendata.dwd.de/climate_environment/CDC/observations_germany/climate/. Accessed 24.06.2022.

Diva-GIS, n.d. Downland data by country. Available at: https://www.diva-gis.org/gdata. Accessed 01.09.2022.

Dulamsuren, C., Hauck, M., Kopp, G., Ruff, M. and Leuschner, C., 2017. European beech responds to climate change with growth decline at lower, and growth increase at higher elevations in the center of its distribution range (SW Germany). *Trees*, *31*(2), pp.673-686.

Englund, O., Börjesson, P., Mola-Yudego, B., Berndes, G., Dimitriou, I., Cederberg, C. and Scarlat, N., 2021. Strategic deployment of riparian buffers and windbreaks in Europe can co-deliver biomass and environmental benefits. *Communications Earth & Environment*, *2*(1), pp.1-18.

European Commission (EC), 2012. *A Blueprint to Safeguard Europe's Water Resources, COM(2012)673 final, Brussels.* Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52012DC0673. Accessed 27.01.2022.

European Commission (EC), 2015. Guidance document on the implementation by member states of permanent grassland provisions in the context of the payment for agricultural practices beneficial for the climate and the environment (greening). Available at: https://marswiki.jrc.ec.europa.eu/wikicap/images/0/05/DS-EGDP-2015-02_rev4_clean.pdf. Accessed 11.04.2023.

European Commission (EC), 2015. Towards an EU Research and Innovation Policy Agenda for Nature-Based Solutions & Re-Naturing Cities: Final Report of the Horizon 2020 Expert Group on 'Nature-Based Solutions and Re-Naturing Cities'; *Publications Office of the European Union*: Luxembourg, 2015; pp. 3–70, ISBN 9789279460517. Available at: https://data.europa.eu/doi/10.2777/479582. Accessed 19.11.2022.

European Commission (EC), 2019. Commission Staff Working Document; Guidance on a strategic framework for further supporting the deployment of EU-level green and blue infrastructure. Available at: https://ec.europa.eu/environment/nature/ecosystems/index_en.htm#:~:text=This%20network%20of%20green%20(land,of%20the%20EU%20green%20infrastructure. Accessed 22.11.2022.

European Commission (EC), n.d. Areas of EU Action. Available at: https://commission.europa.eu/about-european-commission/what-european-commission-does/law/areas-eu-action_en. Accessed 22.02.2023.

European Drought Observatory (EDO), 2020. Product Fact Sheet: SPI Europe. In: Technical Report. European Commission, Joint Research Centre, LMNH Unit. Available on http://edo.jrc.ec.europa.eu/documents/factsheets/factsheet_spi.pdf. Accessed 7-02-22

European Environment Agency (EEA), 2022. *Economic losses from weather and climate-related extremes in Europe reached around half a trillion euros over past 40 years*. Available at: https://www.eea.europa.eu/highlights/economic-losses-from-weather-and#:~:text=Extreme%20weather%20events%20like%20storms,000%20human%20fatalities%20across%20Europe. Accessed 20.02.2023.

Falkenmark, M. and Rockström, J., 2006. The new blue and green water paradigm: Breaking new ground for water resources planning and management. *Journal of water resources planning and management*, *132*(3), pp.129-132.

Falkenmark, M. and Rockström, J., 2010. Building water resilience in the face of global change: From a blue-only to a green-blue water approach to land-water management. *Journal of Water Resources Planning and Management*, *136*(6), pp.606-610.

Fekete, A. and Sandholz, S., 2021. Here comes the flood, but not failure? Lessons to learn after the heavy rain and pluvial floods in Germany 2021. *Water*, *13*(21), p.3016.

Ferguson, C. and Fenner, R., 2020. Evaluating the effectiveness of catchment-scale approaches in mitigating urban surface water flooding. *Philosophical Transactions of the Royal Society A*, *378*(2168), p.20190203.

Ferreira, C.S., Mourato, S., Kasanin-Grubin, M., Ferreira, A.J., Destouni, G. and Kalantari, Z., 2020. Effectiveness of Nature-Based Solutions in Mitigating Flood Hazard in a Mediterranean Peri-Urban Catchment. *Water*, *12*(10), p.2893.

Food and Agriculture Organisation of the United Nations (FAO) IUSS Working Group WRB, 2015. World Reference Base for Soil Resources 2014, update 2015 International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No. 106. FAO, Rome. Available at: https://www.fao.org/3/i3794en/I3794en.pdf. Accessed 17.04.2023.

Food and Agriculture Organisation of the United Nations (FAO), 2006. Guidelines for Soil Description, Fourth Description. Available at: https://www.fao.org/3/a0541e/a0541e.pdf. Accessed 26.03.2023.

Förster, S., Kuhlmann, B., Lindenschmidt, K.E. and Bronstert, A., 2008. Assessing flood risk for a rural detention area. *Natural Hazards and Earth System Sciences*, *8*(2), pp.311-322.

Giacomoni, M.H., Gomez, R. and Berglund, E.Z., 2014. Hydrologic impact assessment of land cover change and stormwater management using the hydrologic footprint residence. *JAWRA Journal of the American Water Resources Association*, *50*(5), pp.1242-1256.

Gonzalez-Sosa, E., Braud, I., Dehotin, J., Lassabatère, L., Angulo-Jaramillo, R., Lagouy, M., Branger, F., Jacqueminet, C., Kermadi, S. and Michel, K., 2010. Impact of land use on the hydraulic properties of the topsoil in a small French catchment. *Hydrological processes*, *24*(17), pp.2382-2399.

Graham, C.B. and Lin, H.S., 2011. Controls and frequency of preferential flow occurrence: A 175-event analysis. *Vadose Zone Journal*, *10*(3), pp.816-831.

Guillemette, F., Plamondon, A.P., Prévost, M. and Lévesque, D., 2005. Rainfall generated stormflow response to clearcutting a boreal forest: peak flow comparison with 50 world-wide basin studies. *Journal of hydrology*, *302*(1-4), pp.137-153.

Haag, I., Luce, A., and Gerlinger, K., 2006. Effects of conservation tillage on storm flow: a model-based assessment for a mesoscale watershed in Germany. *IAHS PUBLICATION*, *303*, p.342.

Horák, J., Šimanský, V. and Igaz, D., 2019. Biochar and biochar with N fertilizer impact on soil physical properties in a silty loam Haplic Luvisol. *Journal of Ecological Engineering*, *20*(7), pp.31-38.

Hrnčíř, M., Šanda, M., Kulasová, A. and Císlerová, M., 2010. Runoff formation in a small catchment at hillslope and catchment scales. *Hydrological processes*, *24*(16), pp.2248-2256.

Hümann, M., Schüler, G., Müller, C., Schneider, R., Johst, M. and Caspari, T., 2011. Identification of runoff processes–The impact of different forest types and soil properties on runoff formation and floods. *Journal of Hydrology*, *409*(3-4), pp.637-649.

Iacob, O., Brown, I. and Rowan, J., 2017. Natural flood management, land use and climate change trade-offs: the case of Tarland catchment, Scotland. *Hydrological Sciences Journal*, *62*(12), pp.1931-1948.

Information und Technik, Nordrhein-Westfalen (IT.NRW), 2021. Statistische Berichte Bodenflächen in Nordrhein-Westfalen nach Art der tatsächlichen Nutzung, Ausgabe 2021. Available at: https://webshop.it.nrw.de/gratis/C179%20202100.pdf. Accessed 31.03.2023.

Information und Technik, Nordrhein-Westfalen (IT.NRW), 2022. Bevölkerung nach Gemeinden. Available at: https://www.it.nrw/statistik/eckdaten/bevoelkerung-nach-gemeinden-315. Accessed 31.03.2023.

Information und Technik, Nordrhein-Westfalen (IT.NRW), 2023. Landschaftsinformationssammlung (LINFOS) NRW. Available at: https://www.opengeodata.nrw.de/produkte/umwelt_klima/naturschutz/linfos/. Accessed 14.09.2022.

International Commission for the Protection of the Rhine (ICPR), 2020. Assessment Rhine 2020. Available at: https://www.iksr.org/fileadmin/user_upload/DKDM/Dokumente/Broschueren/EN/bro_En_Assessment_%E2%80%9CRhine_2020%E2%80%9D.pdf. Accessed 04-09-2022.

IPCC, 2021. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V. P., Zhai, A., Pirani, S.L., Connors, C., Péan, S., Berger, N., Caud, Y., Chen, L., Goldfarb, M.I., Gomis, M., Huang, K., Leitzell, E., Lonnoy, J.B.R., Matthews, T.K., Maycock, T., Waterfield, O., Yelekçi, R., Yu, and Zhou, B. (Eds). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2391 pp. doi:10.1017/9781009157896.

IPCC, 2022: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Pörtner, H.-O., Roberts, D.C., Tignor, M., Poloczanska, E.S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., Okem, A., Rama, B. (eds.). Cambridge University Press. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp., doi:10.1017/9781009325844.

Jackson, B.M., Wheater, H.S., McIntyre, N.R., Chell, J., Francis, O.J., Frogbrook, Z., Marshall, M., Reynolds, B. and Solloway, I., 2008. The impact of upland land management on flooding: insights from a multiscale experimental and modelling programme. *Journal of Flood Risk Management*, *1*(2), pp.71-80.

Jose, S., Gillespie, A.R. and Pallardy, S.G., 2004. Interspecific interactions in temperate agroforestry. *Agroforestry Systems*, *61*, pp.237-255.

Keim, R.F., Skaugset, A.E. and Weiler, M., 2006. Storage of water on vegetation under simulated rainfall of varying intensity. *Advances in Water Resources*, *29*(7), pp.974-986.

Klijn, F., Asselman, N. and Wagenaar, D., 2018. Room for rivers: Risk reduction by enhancing the flood conveyance capacity of the Netherlands' Large Rivers. *Geosciences*, *8*(6), p.224.

Klik, A. and Rosner, J., 2020. Long-term data from field erosion plot studies in eastern Austria. *Data in brief*, *31*, p.105810.

Köhler, L., Leuschner, C., Hauck, M. and Hertel, D., 2015. Cloud water interception and element deposition differ largely between Norway spruce stands along an elevation transect in Harz Mountains, Germany. *Ecohydrology*, *8*(6), pp.1048-1064.

Köln Assekurance Risiko Lösungen (KARL), 2021. *The July Flood 2021 in the West of Germany*. Available at: https://www.koeln-assekuranz.com/documents/20147/76732/2021-09+K.A.R.L.+Insights+-+The+July+Flood+2021+in+the+West+of+Germany.pdf/125660f8-6349-045a-fa16-276f477c23c5. Accessed 29.06.2022.

Kottek, M., Grieser, J., Beck, C., Rudolf, B. and Rubel, F., 2006. World map of the Köppen-Geiger climate classification updated.

Krämer, I. and Hölscher, D., 2009. Rainfall partitioning along a tree diversity gradient in a deciduous old-growth forest in Central Germany. *Ecohydrology: Ecosystems, Land and Water Process Interactions, Ecohydrogeomorphology*, *2*(1), pp.102-114.

Krampl, M., Sohm, S., Suntiger, N., 2016. Retentionsbereiche und Rückhalteräume im Hochwasserschutz – eine Herausforderung für die Raumplanung. Available at: https://publik.tuwien.ac.at/files/PubDat_250083.pdf. Accessed 14.08.2022.

Kreienkamp, F., Philip, S.Y., Tradowsky, J.S., Kew, S.F., Lorenz, P., Arrighi, J., Belleflamme, A., Bettmann, T., Caluwaerts, S., Chan, S.C. and Ciavarella, A., 2021. *Rapid attribution of heavy rainfall events leading to the severe flooding in Western Europe during July 2021*.

Küstermann, B., Munch, J.C. and Hülsbergen, K.J., 2013. Effects of soil tillage and fertilization on resource efficiency and greenhouse gas emissions in a long-term field experiment in Southern Germany. *European Journal of Agronomy*, *49*, pp.61-73.

Landberatung, 2023. Pflugeinsatz auf dem Grünland. Available at: https://www-landberatung-de.translate.goog/pflugeinsatz-gruenland/?_x_tr_sl=de&_x_tr_tl=en&_x_tr_hl=en&_x_tr_pto=sc. Accessed, 1.04.2023.

Landesamt für Natur Umwelt und Verbraucherschutz, Nordrhein-Westfalen (LANUV), 2021. Hydrologischer Monatsbericht Juli 2021, Available at: https://www.lanuv.nrw.de/umwelt/wasser/hydrologische-berichte/juli-2021. Accessed 24.06.2022.

Landesamt für Natur Umwelt und Verbraucherschutz, Nordrhein-Westfalen (LANUV), 2022a, Hydrologische Rohdaten Online. Available at: https://luadb.it.nrw.de/LUA/hygon/pegel.php?karte=nrw_n. Accessed 24.06.2022.

Landesamt für Natur Umwelt und Verbraucherschutz, Nordrhein-Westfalen (LANUV), 2022b, Hydrologische Rohdaten Online. Available at: https://luadb.it.nrw.de/LUA/hygon/pegel.php?art=pegel&einzugsgebiet=Wupper. Accessed 24.06.2022.

Landesamt für Natur Umwelt und Verbraucherschutz, Nordrhein-Westfalen (LANUV), 2023. ELWAS WEB. Available at: https://luadb.it.nrw.de/LUA/hygon/pegel.php?stationsname=Manfort&ersterAufruf=aktuelle%2BWerte. Accessed 24.06.2022.

Laufer, D., Loibl, B., Märländer, B. and Koch, H.J., 2016. Soil erosion and surface runoff under strip tillage for sugar beet (Beta vulgaris L.) in Central Europe. *Soil and Tillage Research*, *162*, pp.1-7.

Laussmann, T., Dahl, A. and Radtke, A., 2021. Lost and found: 160 years of Lepidoptera observations in Wuppertal (Germany). *Journal of Insect Conservation*, *25*, pp.273-285.

Li, Y., Feng, G., Tewolde, H., Yang, M. and Zhang, F., 2020. Soil, biochar, and nitrogen loss to runoff from loess soil amended with biochar under simulated rainfall. *Journal of Hydrology*, *591*, p.125318.

Liu, J., Schulz, H., Brandl, S., Miehtke, H., Huwe, B. and Glaser, B., 2012. Short-term effect of biochar and compost on soil fertility and water status of a Dystric Cambisol in NE Germany under field conditions. *Journal of Plant Nutrition and Soil Science*, *175*(5), pp.698-707.

Llorens, P. and Domingo, F., 2007. Rainfall partitioning by vegetation under Mediterranean conditions. A review of studies in Europe. *Journal of hydrology*, *335*(1-2), pp.37-54.

López-moreno, J.I., Beguería, S. and García-Ruiz, J.M., 2006. Trends in high flows in the central Spanish Pyrenees: response to climatic factors or to land-use change?. *Hydrological Sciences Journal*, *51*(6), pp.1039-1050.

Lorza-Villegas, M.P., Becker, R., Scheibel, M. and Roehrig, J., 2021. Assessing short-term climate change impacts on water supply at the Wupper catchment area, Germany. *Natural Hazards and Earth System Sciences Discussions*, pp.1-27.

Madarász, B., Jakab, G., Szalai, Z., Juhos, K., Kotroczó, Z., Tóth, A. and Ladányi, M., 2021. Long-term effects of conservation tillage on soil erosion in Central Europe: A random forest-based approach. *Soil and Tillage Research*, *209*, p.104959.

Maetens, W., Vanmaercke, M., Poesen, J., Jankauskas, B., Jankauskiene, G. and Ionita, I., 2012. Effects of land use on annual runoff and soil loss in Europe and the Mediterranean: A meta-analysis of plot data. *Progress in Physical Geography*, *36*(5), pp.599-653.

Makaske, B., Maas, G.J., Van den Brink, C. and Wolfert, H.P., 2011. The influence of floodplain vegetation succession on hydraulic roughness: is ecosystem rehabilitation in Dutch embanked floodplains compatible with flood safety standards?. *Ambio*, *40*, pp.370-376.

Marapara, T.R., Jackson, B.M., Hartley, S. and Maxwell, D., 2021. Disentangling the factors that vary the impact of trees on flooding (a review). *Water and Environment Journal*, *35*(2), pp.514-529.

Marshall, M.R., Ballard, C.E., Frogbrook, Z.L., Solloway, I., McIntyre, N., Reynolds, B. and Wheater, H.S., 2014. The impact of rural land management changes on soil hydraulic properties and runoff processes: results from experimental plots in upland UK. *Hydrological Processes*, *28*(4), pp.2617-2629.

Marshall, M.R., Francis, O.J., Frogbrook, Z.L., Jackson, B.M., McIntyre, N., Reynolds, B., Solloway, I., Wheater, H.S. and Chell, J., 2009. The impact of upland land management on flooding: results from an improved pasture hillslope. *Hydrological Processes: An International Journal*, *23*(3), pp.464-475.

Martín, E.G., Costa, M.M. and Máñez, K.S., 2020. An operationalized classification of Nature Based Solutions for water-related hazards: From theory to practice. *Ecological Economics*, *167*, p.106460.

McKee, T.B., Doesken, N.J. and Kleist, J., 1993, January. The relationship of drought frequency and duration to time scales. In Proceedings of the 8th Conference on Applied Climatology. Vol. 17, No. 22, pp. 179-183.

Meijles, E.W., Dowd, J.F., Williams, A.G. and Heppell, C.M., 2015. Generation of storm runoff and the role of animals in a small upland headwater stream. *Ecohydrology*, *8*(7), pp.1312-1325.

Meredith, E.P., Rust, H.W. and Ulbrich, U., 2018. A classification algorithm for selective dynamical downscaling of precipitation extremes. *Hydrology and Earth System Sciences*, *22*(8), pp.4183-4200.

Meyles, E.W., Williams, A.G., Ternan, J.L., Anderson, J.M. and Dowd, J.F., 2006. The influence of grazing on vegetation, soil properties and stream discharge in a small Dartmoor catchment, southwest England, UK. *Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group*, *31*(5), pp.622-631.

Minea, G., Mititelu‐Ionuș, O., Gyasi‐Agyei, Y., Ciobotaru, N. and Rodrigo‐Comino, J., 2022. Impacts of grazing by small ruminants on hillslope hydrological processes: A review of European current understanding. *Water Resources Research*, *58*(3), p.e2021WR030716.

Ministerium für Umwelt, Landwirtschaft, Natur- und Verbraucherschutz des Landes Nordrhein-Westfalen (Umwelt.nrw), 2022a. HocHwasser – risiken – Vorsorgema naHmen im Teileinzugsgebiet Wupper. Available at: https://www.flussgebiete.nrw.de/hochwasser-im-einzugsgebiet-der-wupper-wie-gehen-wir-mit-dem-risiko-um-727. Accessed 28.03.2023.

Ministerium für Umwelt, Landwirtschaft, Natur- und Verbraucherschutz des Landes Nordrhein-Westfalen (Umwelt.nrw), 2022b. Lernen aus dem Hochwasser: 10 Punkte Arbeitsplan Hochwasserschutz in Zeiten des Klimawandels. Available at: https://www.land.nrw/media/25821. Accessed 29.03.2023.

Monger, F., Bond, S., Spracklen, D.V. and Kirkby, M.J., 2022a. Overland flow velocity and soil properties in established semi‐natural woodland and wood pasture in an upland catchment. *Hydrological Processes*, *36*(4), p.e14567.

Monger, F., V Spracklen, D., J Kirkby, M. and Schofield, L., 2022b. The impact of semi‐natural broadleaf woodland and pasture on soil properties and flood discharge. *Hydrological Processes*, *36*(1), p.e14453

Murphy, T.R., Hanley, M.E., Ellis, J.S. and Lunt, P.H., 2021. Native woodland establishment improves soil hydrological functioning in UK upland pastoral catchments. *Land Degradation & Development*, *32*(2), pp.1034-1045.

Nehren, U., Arce-Mojica, T., Barrett, A.C., Cueto, J., Doswald, N., Janzen, S., Lange, W., Vargas, A.O., Pirazan-Palomar, L., Renaud, F. and Sandholz, S., 2023. Towards a typology of nature-based solutions for disaster risk reduction. *Nature-Based Solutions*, p.100057.

Nerlich, K., Graeff-Hönninger, S. and Claupein, W., 2013. Agroforestry in Europe: a review of the disappearance of traditional systems and development of modern agroforestry practices, with emphasis on experiences in Germany.

Nicholson, A.R., O'Donnell, G.M., Wilkinson, M.E. and Quinn, P.F., 2020. The potential of runoff attenuation features as a Natural Flood Management approach. *Journal of Flood Risk Management*, *13*, p.e12565

Niehoff, D., Fritsch, U. and Bronstert, A., 2002. Land-use impacts on storm-runoff generation: scenarios of land-use change and simulation of hydrological response in a meso-scale catchment in SW-Germany. *Journal of hydrology*, *267*(1-2), pp.80-93.

Nordmann, B., Göttlein, A. and Binder, F., 2009. Einfluss unterschiedlicher Waldbestockung auf die Abflussbildung–ein Beispiel aus einem Wassereinzugsgebiet im Frankenwald. *Hydrologie und Wasserbewirtschaftung*, *53*(2), pp.80-95.

OECD, 1997. Managing across levels of government, Germany. Available at: https://www.oecd.org/governance/budgeting/1902398.pdf. Accessed 20.03.2023.

Öllerer, K., Varga, A., Kirby, K., Demeter, L., Biró, M., Bölöni, J. and Molnár, Z., 2019. Beyond the obvious impact of domestic livestock grazing on temperate forest vegetation–A global review. *Biological Conservation*, *237*, pp.209-219.

Olson, D.M., E. Dinerstein, E.D. Wikramanayake, N.D. Burgess, G.V.N. Powell, E.C. Underwood, J.A. D'Amico, I. Itoua, H.E. Strand, J.C. Morrison, C.J. Loucks, T.F. Allnutt, T.H. Ricketts, Y. Kura, J.F. Lamoreux, W.W. Wettengel, P. Hedao, and K.R. Kassem., 2001. Terrestrial Ecoregions of the World: A New Map of Life on Earth. *BioScience* 51:933-938.

Pacetti, T., Cioli, S., Castelli, G., Bresci, E., Pampaloni, M., Pileggi, T. and Caporali, E., 2022. Planning Nature Based Solutions against urban pluvial flooding in heritage cities: A spatial multi criteria approach for the city of Florence (Italy). *Journal of Hydrology: Regional Studies*, *41*, p.101081.

Page, T., Chappell, N.A., Beven, K.J., Hankin, B. and Kretzschmar, A., 2020. Assessing the significance of wet-canopy evaporation from forests during extreme rainfall events for flood mitigation in mountainous regions of the United Kingdom. *Hydrological Processes*, *34*(24), pp.4740-4754.

Pan, C., Ma, L., Wainwright, J. and Shangguan, Z., 2016. Overland flow resistances on varying slope gradients and partitioning on grassed slopes under simulated rainfall. *Water Resources Research*, *52*(4), pp.2490-2512.

Pawattana, C. and Tripathi, N.K., 2008. Analytical hierarchical process (AHP)-based flood water retention planning in Thailand. *GIScience & Remote Sensing*, *45*(3), pp.343-355.

Petrow, T. and Merz, B., 2009. Trends in flood magnitude, frequency and seasonality in Germany in the period 1951–2002. *Journal of Hydrology*, *371*(1-4), pp.129-141.

Pfeifer, S., Bülow, K., Gobiet, A., Hänsler, A., Mudelsee, M., Otto, J., Rechid, D., Teichmann, C. and Jacob, D., 2015. Robustness of ensemble climate projections analyzed with climate signal maps: seasonal and extreme precipitation for Germany. *Atmosphere*, *6*(5), pp.677-698.

Purr, C., Brisson, E. and Ahrens, B., 2021. Convective rain cell characteristics and scaling in climate projections for Germany. *International Journal of Climatology*, *41*(5), pp.3174-3185.

Pypker, T.G., Bond, B.J., Link, T.E., Marks, D. and Unsworth, M.H., 2005. The importance of canopy structure in controlling the interception loss of rainfall: Examples from a young and an old-growth Douglas-fir forest. *Agricultural and forest Meteorology*, *130*(1-2), pp.113-129.

QGIS Development Team, 2021. QGIS Geographic Information System. Open Source Geospatial Foundation. Available at: http://qgis.org

Razzaghi, F., Obour, P.B. and Arthur, E., 2020. Does biochar improve soil water retention? A systematic review and meta-analysis. *Geoderma*, *361*, p.114055.

Redeker, C., 2018. Rhine cities-Urban Flood Integration (UFI): German and Dutch adaptation and mitigation strategies. *A+ BE Architecture and the Built Environment*, (4), pp.1-394.

Rheinisch-Bergischer Kreis (RBK), 2021. *Geoportal*. Available at: https://rbk3.rbkdv.de/MapSolution/apps/app/client/appkatasteropen. Accessed 25.08.2022.

Salazar, S., Francés, F., Komma, J., Blume, T., Francke, T., Bronstert, A. and Blöschl, G., 2012. A comparative analysis of the effectiveness of flood management measures based on the concept of" retaining water in the landscape" in different European hydro-climatic regions. *Natural Hazards and Earth System Sciences*, *12*(11), pp.3287-3306.

Schnitzler, A., 1994. Conservation of biodiversity in alluvial hardwood forests of the temperate zone. The example of the Rhine valley. *Forest ecology and management*, *68*(2-3), pp.385-398.

Shamshirband, S., Hashemi, S., Salimi, H., Samadianfard, S., Asadi, E., Shadkani, S., Kargar, K., Mosavi, A., Nabipour, N. and Chau, K.W., 2020. Predicting standardized streamflow index for hydrological drought using machine learning models. Engineering Applications of Computational Fluid Mechanics, 14(1), pp.339-350.

Silverable Agroforestry for Europe (SAFE)., 2004. *Third SAFE report*, contractor report, vol 3. Available at: http://www1.montpellier.inra.fr/safe/english/results/annual_report_3/SAFE%20third%20Year%20Annual%20Report %20Volume%203.pdf. Accessed 26.01.2023.

Smith, B.K., Smith, J.A., Baeck, M.L. and Miller, A.J., 2015. Exploring storage and runoff generation processes for urban flooding through a physically based watershed model. *Water Resources Research*, *51*(3), pp.1552-1569.

Soane, B.D., Ball, B.C., Arvidsson, J., Basch, G., Moreno, F. and Roger-Estrade, J., 2012. No-till in northern, western and south-western Europe: A review of problems and opportunities for crop production and the environment. *Soil and Tillage Research*, *118*, pp.66-87.

Socher, S.A., Prati, D., Boch, S., Müller, J., Baumbach, H., Gockel, S., Hemp, A., Schöning, I., Wells, K., Buscot, F. and Kalko, E.K., 2013. Interacting effects of fertilization, mowing and grazing on plant species diversity of 1500 grasslands in Germany differ between regions. *Basic and Applied Ecology*, *14*(2), pp.126-136.

Sørensen, R., Zinko, U. and Seibert, J., 2006. On the calculation of the topographic wetness index: evaluation of different methods based on field observations. *Hydrology and Earth System Sciences*, *10*(1), pp.101-112.

Stadt Leverkusen, 2013. Geoportal Leverkusen, Hochwasser. Available at: https://www.leverkusen.de/rathaus-service/geoportal/index.php. Accessed 5.07.2022.

Stadt Leverkusen, 2022. Hochwasser-Katastrophe: Stadt und Wupperverband informierten Bürgerinnen und Bürger. Available at: http://www.presse-service.de/data.aspx/static/1095020.html#:~:text=Entsprechend%20wurde%20der%20h%C3%B6chste%20Pegelstand,der%20Dh%C3%BCnn%20von%20319%20Zentimetern. Accessed 13.08.2022.

Stadt Leverkusen, 2023a. City portrait. Available at: https://www.leverkusen.de/leben-in-lev/stadtportraet/index.php. Accessed 30.03.2023.

Stadt Leverkusen, 2023b. Hochwasser. Available at: https://www.leverkusen.de/vv/produkte/FB32/Hochwasser.php. Accessed 28.03.2023.

Statistiches Bundesamt, 2023. The plough dominates the tillage. Available at: https://www.destatis.de/EN/Themes/Economic-Sectors-Enterprises/Agriculture-Forestry-Fisheries/Production-Methods/production-methode-nd.html. Accessed 31.03.2023.

Stocks, J.J., Metheringham, C.L., Plumb, W.J., Lee, S.J., Kelly, L.J., Nichols, R.A. and Buggs, R.J., 2019. Genomic basis of European ash tree resistance to ash dieback fungus. *Nature ecology & evolution*, *3*(12), pp.1686-1696.

Tembata, K., Yamamoto, Y., Yamamoto, M. and Matsumoto, K.I., 2020. Don't rely too much on trees: Evidence from flood mitigation in China. *Science of The Total Environment*, *732*, p.138410.

Trémolières, M., Schmitt, L., Defraeye, S., Coli, C., Denny, E., Dillinger, M., Dor, J.C., Gombert, P., Gueidan, A., Lebeau, M. and Manné, S., 2008. Does restoration of flooding and reconnection of anastomosing channels in the upper Rhine floodplain improve alluvial ecosystem functions and biodiversity?. *4th ECRR, Conference on river restoration*. Italy, Venice S. Servolo Island, pp.16-21.

Troch, P.A., Paniconi, C. and Emiel van Loon, A.E., 2003. Hillslope-storage Boussinesq model for subsurface flow and variable source areas along complex hillslopes: 1. Formulation and characteristic response. *Water Resources Research*, *39*(11).

Umwelt Bundesamt (UBA), 2021. 2019 Monitoring Report on the German Strategy for Adaptation to Climate Change: BO-R-2: Permanent grassland. Available at: https://www.umweltbundesamt.de/en/topics/climate-energy/climate-impacts-adaptation/impacts-of-climate-change/monitoring-report-2019/indicators-of-climate-change-impacts-adaptation/cluster-soil/bo-r-2-permanent-grassland#bo-r-2-permanent-grassland. Accessed 31.03.2023.

UNEP, 2022. Resolution adopted by the United Nations Environment Assembly on 2 March 2022: Resolution adopted by the United Nations Environment Assembly on 2 March 2022. Available at: https://wedocs.unep.org/bitstream/handle/20.500.11822/39864/NATURE-BASED%20SOLUTIONS%20FOR%20SUPPORTING%20SUSTAINABLE%20DEVELOPMENT.%20English.pdf?sequence=1&isAllowed=y. Accessed 30.03.2023.

United Kingdom (UK) Environment Agency, (UKEA), n.d. Nisbet, T, Case study 24. Investigating the impact of upland conifer afforestation on catchment hydrology at Coalburn, northern England. Available at: http://www.gov.uk/government/publications. Accessed 02.08.2022.

US Geological Survey (USGS), 2014. Earth Explorer Digital Elevation Model, Shuttle Radar Topography Mission 1 Arc-Second Global: SRTM1N51E006V3. Available at: https://earthexplorer.usgs.gov/. Accessed 16.06.2022.

US global change research program (USGCRP), 2022, Heavy Precipitation. Available at: https://www.globalchange.gov/browse/indicators/heavy-precipitation. Accessed 19.09.2022.

Vieira, I., Barreto, V., Figueira, C., Lousada, S. and Prada, S., 2018. The use of detention basins to reduce flash flood hazard in small and steep volcanic watersheds–a simulation from Madeira Island. *Journal of Flood Risk Management*, *11*, pp.S930-S942.

Vogt, J., Klaus, V., Both, S., Fürstenau, C., Gockel, S., Gossner, M., Heinze, J., Hemp, A., Hölzel, N., Jung, K. and Kleinebecker, T., 2019. Eleven years' data of grassland management in Germany. *Biodiversity Data Journal*, *7*, p.e36387.

Voormansik, K., Zalite, K., Sünter, I., Tamm, T., Koppel, K., Verro, T., Brauns, A., Jakovels, D. and Praks, J., 2020. Separability of mowing and ploughing events on short temporal baseline Sentinel-1 coherence time series. *Remote Sensing*, *12*(22), p.3784.

Wahren, A., Schwärzel, K. and Feger, K.H., 2012. Potentials and limitations of natural flood retention by forested land in headwater catchments: evidence from experimental and model studies. *Journal of Flood Risk Management*, *5*(4), pp.321-335.

Wald und Holz NRW, 2020, Regionalforstamt Rhein-Seig-Erft, Borkenkäferkatastrophe in den Waldern – Fichtenbestände flächenhasft betroffen, Forest sign.

Walentowski, H., Falk, W., Mette, T., Kunz, J., Bräuning, A., Meinardus, C., Zang, C., Sutcliffe, L.M. and Leuschner, C., 2017. Assessing future suitability of tree species under climate change by multiple methods: a case study in southern Germany. *Annals of Forest Research*, *60*(1), pp.101-126.

Wilkinson, M.E., Quinn, P.F. and Welton, P., 2010. Runoff management during the September 2008 floods in the Belford catchment, Northumberland. *Journal of Flood Risk Management*, *3*(4), pp.285-295.

Wittman, O., Blume, H., P., Filipinski, M., Witt, S., 1997. Soil Classification of the Federal Republik of Germany. Available at: https://www.dbges.de/de/system/files/AG_Bodensystematik/Klassifikation-engl.pdf. Accessed 21.03.2023.

Wupperverband, 2002. Die Wupper. Available at: https://web.archive.org/web/20120313031159/http://www.wupperverband.de/aufgaben/gewaesser/die.wupper.html. Accessed 22.07.2023.

Wupperverband, 2012. WRRL-Umsetzungsfahrplan Hydromorphologie für die Fließgewässer der Planungseinheiten: PE_WUP_1000 Untere Wupper, PE_WUP_1100 Obere Wupper, PE_WUP_1200 Dhünn.

Wupperverband, 2022a. Präsentation zur Informationsveranstaltung am 22.02.2022 in Leverkusen Hochwasser vom 14.07.2021. Available at: https://www.leverkusen.de/leben-in-lev/downloads/klimaschutz/2022_02_22_Buergerinfo_Leverkusen_Hochwasser_20210714.pdf. Accessed 27.06.2022. Translated by Google Translate.

Wupperverband, 2022b. Talsperren, Available at: https://www.wupperverband.de/unsere-anlagen/talsperren. Accessed 15.10.2022.

Wupperverband, 2022c. Wupperverband stellt Zukunftsprogramm Hochwasserschutz vor. Available at: https://www.wupperverband.de/meldung/pressemitteilungen/2022/02/wupperverband-stellt-zukunftsprogramm-hochwasserschutz-vor. Accessed 14.11.2022.

Wupperverband, n.d. Über uns. Available at: https://www.wupperverband.de/ueber-uns . Accessed 29.03.2023.

Xia, J., Zhang, Y., Xiong, L., He, S., Wang, L. and Yu, Z., 2017. Opportunities and challenges of the Sponge City construction related to urban water issues in China. *Science China Earth Sciences*, *60*(4).

Xiao, L., Robinson, M. and O'Connor, M., 2022. Woodland's role in natural flood management: Evidence from catchment studies in Britain and Ireland. *Science of The Total Environment*, *813*, p.151877.

Xiao, Q., Zhu, L.X., Shen, Y.F. and Li, S.Q., 2016. Sensitivity of soil water retention and availability to biochar addition in rainfed semi-arid farmland during a three-year field experiment. *Field Crops Research*, *196*, pp.284-293.

Xing, W., Li, P., Cao, S.B., Gan, L.L., Liu, F.L. and Zuo, J.E., 2016. Layout effects and optimization of runoff storage and filtration facilities based on SWMM simulation in a demonstration area. *Water Science and Engineering*, *9*(2), pp.115-124.

Xiong, M., Sun, R. and Chen, L., 2018. Effects of soil conservation techniques on water erosion control: A global analysis. *Science of the Total Environment*, *645*, pp.753-760.

Zhang, F., Huang, C., Yang, M., Zhang, J. and Shi, W., 2019. Rainfall simulation experiments indicate that biochar addition enhances erosion of loess-derived soils. *Land Degradation & Development*, *30*(18), pp.2272-2286.

Zhu, Q. and Lin, H., 2011. Influences of soil, terrain, and crop growth on soil moisture variation from transect to farm scales. *Geoderma*, *163*(1-2), pp.45-54.

Zhu, Q., Nie, X., Zhou, X., Liao, K. and Li, H., 2014. Soil moisture response to rainfall at different topographic positions along a mixed land-use hillslope. *Catena*, *119*, pp.61-70.

Zikeli, S. and Gruber, S., 2017. Reduced tillage and no-till in organic farming systems, Germany—Status quo, potentials and challenges. *Agriculture*, *7*(4), p.35.

Appendix 1: Green-Blue Intervention Toolbox

Green-Blue Intervention Toolbox									
Green-Blue infrastructure or intervention	Author Location of study	Landcover & land use	Soil	Slope / aspect	M.A.S.L; Precipitation (mm/y); Flow velocity	Catchment area size	Impact on flood/drought investigated	Hydrology / Flood type investigated	Method detail
Landcover impact on infiltration, runoff & flooding									
Old growth broadleaf mixed and Pine Forests aged 45 years paired with grazing land along various hillslope positions and floodplain to assess soil permeability	Archer et al. 2013 Scottish Borders UK	1&2. 500/180-year-old Mixed forests (Beech, Blackthorne, Oak, Birch & conifer), 3. Pine plantation, 4. Willow forest all paired with grassland pasture	Cambisols on the slopes Fluvisols on the floodplain	1. 0-0.5% 2. 0-10% 3. 5-22% 4. 0-2%	1. 250m OD 2. 240m OD 3. 230-210m OD 4. 197m OD Rainfall: No Info	0.5km^2	Soil infiltration / permeability for rainfall storage under different land uses and slope to reduce flooding	Field saturated hydraulic conductivity and runoff that contributes to flooding	Saturated hydraulic conductivity measured to 0.15cm and 0.25cm with constant head well permeameter and statistical analysis
Result	Hydraulic conductivity under 180- & 500-year-old broadleaf forest is 6 and 5 times higher than neighbouring 250-year-old pasture areas on the same soils Median hydraulic conductivity (174mm/h & 119mm/h) of 500- & 180-year-old broadleaf forests exceed infiltration rate of 1 in 100-year storm event (68mm/h) due to thick organic layer and coarse roots (>20mm) providing flow conduits Below 0.15cm soil depth median hydraulic conductivity in the Broadleaf forest decreased by 6 times which could mean that there is subsurface storm flow 45-year-old Pine forest median recorded hydraulic conductivity of 42mm/h which is less than the 1 in 50 year storm infiltration (56.4mm/h) and just over 1 in 10 year (36.3mm/h) perhaps due to illuviation of organic colloids causing soil repellence from pine residue Willow forest on the floodplain shows extremely poor hydraulic conductivity (8mm/h)								
Hydraulic properties of topsoil under broadleaf and conifer forests and different forest land uses investigated	Chandler et al. 2018 Glensaugh Scotland	Sycamore forest (grazed and ungrazed), Scots pine forest (grazed and ungrazed), and grazed pasture	Leptic podzols or cambisols	No info	140-205 m.a.s.l Rainfall: 1168 mm/y	Experimental field site	Factors inhibiting surface runoff in soils under different forest types and land use	Field saturated hydraulic conductivity	Hydraulic conductivity taken from small single ring infiltrometers and the pressure infiltrometer and results statistically analysed
Res	Field saturated hydraulic conductivity (mm/s) Scots pine ungrazed forest 20.65 Scots pine grazed forest 0.32 Sycamore ungrazed forest 6.32 Sycamore grazed forest 0.40 Grazed pasture 0.53								

Green-Blue Intervention Toolbox									
Green-Blue infrastructure or intervention	Author Location of study	Landcover & land use	Soil	Slope / aspect	M.A.S.L; Precipitation (mm/y); Flow velocity	Catchment area size	Impact on flood/drought investigated	Hydrology / Flood type investigated	Method detail
ult	Undisturbed forest has the capacity to not only reduce surface runoff but also to 'soak up' runoff generated further up the hillslope. Although different tree species can create large differences in soil hydraulic properties, the influence of land use can mask the influence of trees given the similarity of the grazed forest under Scots pine and Sycamore trees. The choice of tree species may therefore be less important than forest land use for mitigating the effects of surface runoff.								
Hydraulic properties of topsoil under broadleaf forest, conifer forest, pasture and various crops were investigated	Gonzalez-Sosa et al. 2010 Yzeron catchment France	Broadleaf forest Conifer forest Small woods Permanent pasture Improved pasture Orchards Cropland	Sandy loam, silty clay loam	Slope mostly >10%	162-917 m.a.s.l Rainfall: 800 mm/y	150km^2	Factors inhibiting surface runoff in soils under different land use	Hydraulic properties of topsoil and impact on runoff	Samples from 20 locations, were tested for soil texture, dry bulk density and infiltration using single ring and mini-disk infiltrometers and results statistically analysed
Result	Saturated hydraulic conductivity (mm/s); Organic matter (g/kg); Sorptivity (mm/s); Dry bulk density (kg/m): Small woods: 1.50; 65.0; 5.77; 1058 Broadleaf forest 1.32; 88.8; 4.86; 676 Permanent pasture 0.51; 61.3; 3.15; 969 Orchard 0.40; 28.3; 3.62; 1472 Conifer forest 0.23; 84.5; 1.50; 84.5 Cropland 0.13-0.28; 18.2-19.5; 0.84-2.80; 1411-1549 Cultivated pasture 0.11; 35.6; 1.64; 1269 Forest clearing 0.05; 51.00; 1.16; 1180 Factors inhibiting surface runoff are highest in small and broadleaf forest and lowest in forest clearing and croplands								
Impact of different forests and soils on runoff and flooding	Hümann et al. 2011 2 low mountain catchments in Rhineland-Palatinate, Germany	• Frankelbach - 30% forest (Alder, Beech, Oak, Douglas Fir stands) & 70% pasture / cropping • Holzbach – 100% forest (Beech and Spruce stands)	• Haplic /Stagnic Cambisols • Haplic /Stagnic Cambisols and Podzoles	Upper & Upper -Mid (9-12◦) Mid (10-15◦) Lower-mid (9◦)	210-430 m.a.s.l 400-650 m.a.s.l Rainfall: 700-800 mm/y 950-1200 mm/y	• Frankelbach (5km^2) • Holzbach (4.2km^2)	Rainfall runoff from the surface and subsurface	Runoff coefficient and runoff type	Rainfall simulation at field sites, deflector plates fitted at different depths and collected for measuring and statistical analysis of the results to produce runoff coefficient
Resu	Frankelbach: Runoff coefficient; Flow overland/subsurface/deep subsurface: 1 year old afforestation with Adler (RC) 20% (OF) 0% (SSF) 93.2% (dSSF) 6.8% 30 y afforestation, Beech/Oak/Hornbeam (RC) 11.6% (OF) 21.1% (SSF) 70.9% (dSSF) 8.8% Mature deciduous forest, Oak/Hornbeam (RC) 17.3% (OF) 1.4% (SSF) 73.3% (dSSF) 25.3% 40 y old Douglas Fir Forest (RC) 5.6% (OF) 47.5% (SSF) 48.% (dSSF) 3.8% Holzbach: Runoff coefficient; Flow subsurface/deep subsurface: Mature Beech forest (upper slope) (RC) 1.9% (SSF) 22% (dSSF) 78% Mature Spruce forest (upper slope) (RC) 0.6% (SSF) 100% Mature Mature Spruce forest (upper mid-slope (RC) 0.0% Beech forest (upper mid-slope) (RC) 3.7% (SSF) 59% (dSSF) 40.6%								

Green-Blue Intervention Toolbox

Green-Blue infrastructure or intervention	Author Location of study	Landcover & land use	Soil	Slope / aspect	M.A.S.L; Precipitation (mm/y); Flow velocity	Catchment area size	Impact on flood/drought investigated	Hydrology / Flood type investigated	Method detail
lt	Mature Douglas Fir Forest (RC) 5.5% (OF) 0% (SSF) 100% Mature Beech forest (lower mid-slope) (RC) 0.2% (SSF) 100% Cropland after seed sowing (RC) 16.0% (OF) 75% (SSF) 25% Higher runoff coefficients in Beech forest compared to Spruce could be explained by more extensive root development and higher biological activity Soils under afforested stands can retain soil compaction issues from previous agricultural land use for many years as evidenced with the 30 year old afforested site								
Different land use types in Temperate, Mediterranean, cold climates	Maetens et al. 2012 Temperate, Mediterranean and cold climate areas	Forest (natural or plantation), cropland, rangeland, grassland, vineyards, orchards, shrubland etc.	Various	Various	No Info.	Various	Runoff, runoff coefficient and soil loss for each landuse type	Rainfall runoff	Comparison of 213 publications on Runoff, runoff coefficient and soil loss
Result	The length of the experimental plot had increasingly negative correlation to runoff for forest landuse On average across all climates forests have the lowest annual runoff (13.9mm/y) and runoff coefficient (2.9%) compared to other land uses Forests in temperate climates have higher mean runoff (28.7mm/y) and runoff coefficient (3.3%) than forests in Mediterranean climates (9.6mm/y; 2.8%), Authors suggest possible reasons including soil characteristics and positive correlation of rainfall to vegetation. The high values may also be a larger range and outliers, as the median runoff and runoff coefficient is lower (2.0mm/y & 0.9%) in temperate forests compared to Mediterranean (4.6mm/y & 1.6%) All other land use types (cropland, rangeland, tree crops, shrubland, vineyards, grassland etc) had lower runoff and runoff coefficient in temperate climate compared to Mediterranean Significant differences occur in frequency distribution of runoff between precipitation when annual rainfall is 250-500mm compared to 500-750mm								
Impact of mature broadleaf forests and pasture in small catchments on flooding	Monger et al. 2022b Lake District National Park, UK	Semi natural mixed broadleaf woodland (Oak, Ash, Alder, Birch, Hazel) & unimproved pastures	Umbrisol and Histosol	Pasture 4.6-20.2° S-SE-SW Forest 17.7-24° N-NW	Pasture 260-390 m.a.s.l Forest 270-310 m.a.s.l Rainfall: 1779mm/y	Pasture 0.08-0.14km^2 Forest 0.03-0.06 km^2	Broadleaf forests interception, soil infiltration and storage of water to reduce flood peaks	Specific peak discharge, peak runoff (coefficient), volume runoff (coefficient), time to flow response	9 similar sized catchments with different landcovers monitored for soil properties, rainfall, storm events and stream discharge. Data statistically analysed and compared across forest and pasture land uses
Resu	Hydraulic conductivity of topsoil is 11-20% higher in Woodland catchments Peak discharge response to storms (>20mm/day) 23-60% lower in Woodland catchments compared to grazing catchments Peak runoff response to storms 30-60% lower in woodland catchments compared to grazing catchments								

Green-Blue Intervention Toolbox

Green-Blue infrastructure or intervention	Author Location of study	Landcover & land use	Soil	Slope / aspect	M.A.S.L; Precipitation (mm/y); Flow velocity	Catchment area size	Impact on flood/drought investigated	Hydrology / Flood type investigated	Method detail
lt	Runoff volume response to storms 21-35% lower in woodland catchments compared to grazing catchments Average response time from storm to flow 14-50% slower in woodland catchments compared to grazing catchments For larger storms (>1.5 year return period) peak runoff was 48-58% lower in woodland catchments compared to grazing catchments, and volume 26-41% lower in woodland catchments								
Reestablishment of woodland along slopes and valley bottom of flash-flood prone catchment	Murphy et al. 2021 Dartmoor National Park, Southwest UK	Reforested woodlands (Sessile & European Oak/ Ash dominated) aged 7-15 years paired with grazed pastures	Podzolic and gley	2x Valley bottom sites (0◦), 1 site slope of 7◦ and 1 site slope 9.1◦	250-319m Rainfall: No Info	Entire catchment $900km^2$	Reforested catchments ability to improve soil hydrological functioning	Flash floods	Samples and cores taken at each of the sites. Saturated soil conductivity measured with single ring infiltrometer. Samples analysed for soil water infiltration, soil compaction and soil organic matter content
Result	In ¾ catchment pairings the mean soil infiltration rate was 1-3 times higher in forest soils (all forest soils on average 1.8 higher) compared to pasture soils The sites recording 3 times higher infiltration after 10 years of reforestation were from both a bottom (gley soil) under European and Sessile Oak plantings and sloping catchment (podzol soil) under Oak and Ash plantings, indicating that reforestation can improve runoff/flood response in both situations Largest physical difference between forest and pasture soils was soil compaction (4/4 pairings) and best reflects best the soil water infiltration results indicating a large influence on infiltration Lowest infiltration rate of the 4 forest sites was also the site with highest previous grazing intensity and demonstrates the impact of prior land use even after 15 years of reforestation								
Comparison of runoff generation in Beech-Spruce, Beech-Sycamore and Spruce dominated forests	Nordmann et al. 2009 Nordhalben Bavaria, Germany	1.Spruce-Beech 2.Beech-Spruce 3.Spruce only 4.Beech-Sycamore 5. Beech-Sycamore (already damp) 6.Spruce only (ground fresh)	Brown Earths (from hard clay and silt slates)	1. 21◦ NW 2. 21◦ NW 3. 21◦ NW 4. 31◦ NE 5. 28◦ SE 6. 24◦ SE	1. 565 m.a.s.l 2. 565 m.a.s.l 3. 570 m.a.s.l 4. 565 m.a.s.l All upper mid 5. 555 m.a.s.l 6. 550 m.a.s.l Both mid slope Rainfall: 1025mm/y	$13.4 km^2$	Soil water storage capacity and subsurface runoff in forested catchments	Heavy rainfall events	Large scale irrigation rain system to mimic heavy rainfall and collection and measurement of runoff.

	Irrigation 1	Irrigation 2	Irrigation 3		Irrigation 1	Irrigation 2	Irrigation 3
1. (Runoff Coefficient)	0	1.5	12	4. (Runoff Coefficient)	0	3.5	16.5
2. (Runoff Coefficient)	0	3.5	13	5. (Runoff Coefficient)	37.5	84	83
3. (Runoff Coefficient)	0.2	9.5	17.5	6. (Runoff Coefficient)	0	24.5	30

Green-Blue Intervention Toolbox									
Green-Blue infrastructure or intervention	Author Location of study	Landcover & land use	Soil	Slope / aspect	M.A.S.L; Precipitation (mm/y); Flow velocity	Catchment area size	Impact on flood/drought investigated	Hydrology / Flood type investigated	Method detail
Result	Spruce stand (3) 70 years old is the only dry site to produce runoff in the first irrigation after 2hours 24minutes, possibly due to high rock content in soil, however Spruce stand (6) 93 years old also produced very high runoff following the second and third irrigations Spruce-Beech & Beech-Spruce stands (1&2) 103 years old were overall best in terms of total volume of runoff/water retained Beech-Sycamore stand (4) 70 years old showed best water retention even though soil had high rock content, taking 7 hours to react to the third irrigation, however runoff volume at that stage exceeds that of the mixed Beech and Spruce stands possibly due to a higher propensity of macro-pores that store water, but once full-up lead to runoff Runoff from the pre-wet stand (5) 88 years old exceeded all others at each irrigation stage, potentially also because of the deep rooting Sycamore providing pathways for preferential flow to occur All subsurface water flows were observed between 0.6 m to 1.5 m below the ground surface								
Broadleaf, mixed and coniferous tree forests impact on flooding	Tembata et al. 2020 China	Broadleaf, mixed and coniferous tree forests	Various	No Info.	No Info. Rainfall:	Various	Different types of forest impact on flood frequency	Flood frequency	Satellite data observation, observed flood and gridded rainfall data added to Cox proportional distribution and Weibull models to estimate forest/flood relationship
Result	Model outcomes indicate that an increase in the area of broadleaf and mixed forests can reduce flood frequency (-0.01 to -0.74 & -0.008 to -0.064), but results for coniferous forests were both positive (increased flooding) and negative (reduced flooding) were very small (+0.011 to -0.003) and were not statistically significant Model coefficient outcomes for broadleaf forests were larger (negative) than that of mixed forests, indicating that broadleaf forests had greater impact In temperate regions mixed forests the coefficient remained negative and statistically significant but the coefficient for broadleaf forests is no long statistically significant								
Deforestation, reforestation and afforestation impact on basin infiltration, runoff & flooding									
Combines 4 long-term (3 paired) studies to evaluate flood mitigation and return period impacts of forests	Bathurst et al. 2020 Temperate UK, NZ, US & Chile	Forested vs grassland or cleared	No Info	No Info	275-330 m.a.s.l 460-680 m.a.s.l 439-1080 m.a.s.l 35-225 m.a.s.l Rainfall: 1672mm/y 1330mm/y 2300mm/y 2576mm/y	150ha 310ha 101ha 34ha	Forest vs no grassland or cleared landcover impact on flood peak and return periods	Small, medium and very large flooding events	Data series: UK 1967-present NZ 1980-2013 US 1955-1988 Chile 1997-2018 Observed data from each study used to chronologically pair peak discharges and create flood frequency curves

Green-Blue Intervention Toolbox

Green-Blue infrastructure or intervention	Author Location of study	Landcover & land use	Soil	Slope / aspect	M.A.S.L; Precipitation (mm/y); Flow velocity	Catchment area size	Impact on flood/drought investigated	Hydrology / Flood type investigated	Method detail
Result	In paired studies the catchment where forest is removed shows significant increase (>50%) in peak discharge during low to moderate flooding events – although vegetation cover has no impact if soil moisture conditions (soil depth a factor in this) are high prior to the event Forest/lack of forest does not impact peak flows during very large events Frequency of return periods for small to medium floods is reduced in forested catchments compared to cleared catchments Forest/lack of forest does not impact return periods of very large events								
Upland afforestation – impact on catchment hydrology	Birkinshaw et al. 2014 & UKEA, n.d. Coalburn, northern England	Afforestation of moorland with conifer (Sitka spruce)	Peat & peaty gley over clay	No info.	Uplands - Headwaters of River Irthing Rainfall: 1400 mm/y	1.5km^2	Forest growth stages impact peak flows differently	Fluvial	Study years: 1966 to 1996 Weir & gauge discharge measurements Shetran model used for comparison of tree height and discharge changes
Result	Deep ploughing in advance of tree planting increased annual flow by 50-100mm in annual streamflow Afforestation with trees at maturity reduces annual streamflow by 250-300mm compared to original grassland and by 350mm compared to ploughing at tree planting Modelling suggests that the impact on discharge is due to rainfall interception by tree canopy (growing from 22% in 93-96 to 32% in 2006-11 as the forest matured)								
Result	Modelling to remove climate variability (increasing annual average rainfall) suggests a 10-15% reduction of peak flows due to forest growth. Overall impact was reduced with increased event size ie. at 1/100 year event all impact was lost. Deep ploughing in advance of tree planting increased peak flows (15-20%) and increased velocity by 1/3.								
Afforestation/reforestation of grassland slopes and placement of in-channel woody debris (50m from infrastructure)	Ferguson and Fenner 2020 Dorset, UK	Currently 62% grassland, 24% cropland/pasture and 8% forest	No info (Forests modelled on free draining/ slowly permeable soils)	Forests modelled on areas of 10-30° slopes	254 m.a.s.l Rainfall: No annual information	48 km^2	Afforestation/reforestation and wood debris placement impact flooding in downstream urban centre	Storms and flash flooding from runoff	dynamic TOPMODEL and HEC-RAS models run to test rural catchment response and Infoworks ICM model run for urban response to flood intervention

<table>
<tr><th colspan="11">Green-Blue Intervention Toolbox</th></tr>
<tr><th colspan="2">Green-Blue infrastructure or intervention</th><th>Author
Location of study</th><th>Landcover & land use</th><th>Soil</th><th>Slope / aspect</th><th>M.A.S.L;
Precipitation (mm/y);
Flow velocity</th><th>Catchment area size</th><th>Impact on flood/drought investigated</th><th>Hydrology / Flood type investigated</th><th>Method detail</th></tr>
<tr><td>Result</td><td colspan="10">Forest and woody debris reduced peak of 1/10 year storm by 57% and reduce the period of downstream inundation of urban area by 3.75 hours. Forest and woody debris reduced peak of 1/33 year storm by 49% but may increase the period of downstream inundation of urban area by 0.5 hours. Forest and woody debris reduced peak of 1/100 year storm by 35% but may increase the period of downstream inundation of urban area by 1 hour.
Afforestation/reforestation alone reduces peak flooding of 1/10 year storm by 42.5%, 1/20 year storm by 30%, 1/33 year storm by 25%, 1/50 year storm by 20% and 1/100 year storm by 15%</td></tr>
<tr><td colspan="2">Fir/Spruce forest harvest impact on discharge
Full basin</td><td>Guillemette et al. 2005
Canada 80km north of Quebec City</td><td>Basalm Fir,
White Spruce
Black Spruce
White Birch</td><td>Basal til</td><td>14-19%
Southeast</td><td>Rainfall: 1416 mm/y
Snowfall: 465 mm/y</td><td>122ha & 394ha</td><td>Plantation harvest has small impact on flooding</td><td>Peak Flow</td><td>Observed data (hourly discharge from v-notch weirs) and multivariate linear model evaluation</td></tr>
<tr><td>Result</td><td colspan="10">Maximum impact was measured as 63% increase on peak flow - at the stage when 61% of the forest catchment had been harvested
After five years and 85% of the total basin area was harvested the maximum increase on peak flow remained at 57%
Harvesting from 61 to 85% of basin 7A, in the upper areas of the southern part of the watershed, did not cause a higher increase in bank-full peak flows</td></tr>
<tr><td colspan="2">Modelled afforestation of catchment to investigate impact on peak flows</td><td>Iacob et al. 2017
Northeast Scotland</td><td>Cropland, improved and unimproved pasture, conifer forest and heathlands</td><td>Cambisol & Podsols</td><td>No Info.</td><td>100-617 m.a.s.l</td><td>72km^2</td><td>Modelling higher forest cover impact on flood peaks</td><td>Fluvial</td><td>Distributed hydrological model (WaSiMETH) calibrated with observed data
4 scenarios (2x47% forest, 2x30% forest) & baseline (26% forest) modelled</td></tr>
<tr><td>Result</td><td colspan="10">Sensitivity testing shows that coniferous forests have superior ability to reduce peak flows during the winter season compared to broadleaf forests
Peak flow reduction was greater when forests replaced farmland in the lowlands (10% increase of forest resulted in 8% peak reduction by conifer forest and 1% by broadleaf forest) compared to highlands (10% increase of forest resulted in 5% peak reduction by conifer forest and 0.5% by broadleaf forest)
Full catchment afforestation impact on extreme high flows was 30% reduction and impact on high flows was 60% reduction
75% (&50%) afforestation by coniferous forest impacts (decreases) low flows in summer by 50% (25%) in comparison broadleaf afforestation reduces flows by 40% (4%)</td></tr>
<tr><td colspan="2">Reforestation of farmland impact on flood frequency and magnitude</td><td>López-Moreno et al. 2006</td><td>Recolonisation of former farmland with evergreen broadleaf</td><td>No info.</td><td>South facing (north facing</td><td>Below 1600 m.a.s.l
Rainfall:</td><td>No info.</td><td>Impact of reforrestationof former farmland</td><td>Fluvial</td><td>Study years: 1955 to 1995
Observed data from rainfall and gauging stations</td></tr>
</table>

Green-Blue Intervention Toolbox

Green-Blue infrastructure or intervention	Author Location of study	Landcover & land use	Soil	Slope / aspect	M.A.S.L; Precipitation (mm/y); Flow velocity	Catchment area size	Impact on flood/drought investigated	Hydrology / Flood type investigated	Method detail
	Central Pyrenees, Spain	trees/shrubs and/or pine plantations		retains native forests)	600-2000 mm/y		on south facing slopes		
Result	Average number of annual events that are greater than 10 x mean discharge decreased by 0.03 events per year from 1959-1995 despite precipitation averages not decreasing 1/5-year floods were reduced by 8-40% 1/25-year floods reduced by 9-46%								
Varying forest cover (35-99%) and forest composition to investigate impact on catchment flooding	Wahren et al. 2012 Saxony, Germany	Varying forest cover from 35% spruce forest (actual) to 99% forest cover Coniferous in higher altitudes & Deciduous in lower altitudes (natural)	Haplic/stagnic cambisols	All	600-800 m.a.s.l Rainfall: 900 mm/y	6.8km^2	Modelling higher forest cover (99%) and natural forest composition results in greater peak flood reduction	Fluvial	Observed data model upscaled to generate catchment outcome 3 scenarios modelled - • 35% forest (Spruce, some Beech) • 64% forest (no details) • 99% forest (Coniferous (Silver Fir & Spruce) and Deciduous (Beech and Oak))
Result	99% forest cover results in flood peak reduction of between 7-70% 64% forest cover results in flood peak reduction of between 3-46% Positive results are due to interception and transpiration of trees (also evergreen of conifers), but when soil is already saturated pre- rain event (due to rainfall intensity or duration) there can be little impact The reforested/afforested area must be sufficiently in proportion with catchment size to make a reasonable difference in flood peak reduction Reforestation/afforestation of headwater area has most impact on small-medium floods								
Spruce/pine forest harvest impact on discharge	Xiao et al. 2022 Wales, Ireland, England	3 sites • Wales - Norway and Sitka Spruce • Ireland - Lodgepole Pine	3 sites • Clay/peat/ mudstone • Blanket bog • Peat & peaty gley	No info	No info Rainfall: 2500mm/y Wales 2000 mm/y Ireland 1400 mm/y Uk	No info	Plantation harvest impact on flooding	Low flow and high flow	20% (Wales), 60% (Ireland) and 90% (Uk) of the forests were harvested Results were compared to adjacent control sites

Green-Blue Intervention Toolbox

Green-Blue infrastructure or intervention	Author Location of study	Landcover & land use	Soil	Slope / aspect	M.A.S.L; Precipitation (mm/y); Flow velocity	Catchment area size	Impact on flood/drought investigated	Hydrology / Flood type investigated	Method detail
		- Uk - Sitka Spruce							Runoff/streamflow data collected via flumes every 5-15 minutes
Result	Baseflows in the basins increased at all sites after forest harvest; 8% increase at site with 20% forest removed and 41% increase at site with 90% tree removal Impact of forest harvest on high flows not statistically different to control sites; conclusion that if deforestation has little impact on increasing peak flows that afforestation will have little impact on reducing peak flows, likely due to the reduced effectiveness of interception during heavy rainfall								
Rainfall interception - effectiveness of different forest types									
Comparison of temperate forests species impact on interception, throughflow and stemflow during rainfall	Barbier et al. 2009 Temperate regions in Europe and Northern America	- Beech (deciduous), - Douglas Fir (evergreen), - Spruce (evergreen), - Larch (deciduous and evergreen) and - Pine (evergreen)	N/A	N/A	Data assembled from range of studies based in temperate region catchments Rainfall: 600mm/y Europe to 2500mm/y N America	Various	Rainfall interception, throughflow and stemflow	Rainfall to potential runoff in forested regions	Observed data from 28 studies on interception, throughflow and stemflow reviewed. Data from 50+ year old forests used to model estimates for each category
Result	Growing period Broadleaves: throughfall 70.6%; stemflow 6.3%; interception 23.1% Conifers: throughfall 63.8%; stemflow 2.2%; interception 31.4% Deciduous: throughfall 70.6%; stemflow 5.4%; interception 23.6% Evergreens: throughfall 62.3%; stemflow 2.5%; interception 33.1% Annual Broadleaves: throughfall 76.3%; stemflow 6.9%; interception 17.7% Conifers: throughfall 64.5%; stemflow 4.1%; interception 28.7% Deciduous: throughfall 76.6%; stemflow 5.7%; interception 17.8% Evergreens: throughfall 62.6%; stemflow 4.5%; interception 30.7% Throughfall and stemflow is lower for the evergreen species both during the deciduous growing season and on an annual basis, and interception higher. Leaf area index and/or fascicled leaf structure of conifers may explain this Throughfall decreased by 8.8% with each successional group from pioneer to late-successional species								
Storage of rainwater on leaf and branch	Keim et al. 2006 N/A	Broadleaved and needleaved forest/ shrub species from	N/A	N/A	N/A	N/A	Rainfall storage on leaf biomass allows for	Rainfall of different intensities	Rainfall simulation within laboratory, sample analysis and modelled extension of rainfall intensity

Green-Blue Intervention Toolbox

Green-Blue infrastructure or intervention	Author Location of study	Landcover & land use	Soil	Slope / aspect	M.A.S.L; Precipitation (mm/y); Flow velocity	Catchment area size	Impact on flood/drought investigated	Hydrology / Flood type investigated	Method detail
		Northern America					interception via evaporation		
Result	Needle leaf species store more rainfall per leaf area than broadleaf species, up to 0.775 mm at 400mm/h rainfall intensity (Hemlock) compared to 0.35mm (Bramble) Broadleaf species store more rainfall per leaf biomass than needleaf species, up to 11.5 g/g at 400mm/h rainfall intensity (Maple) compared to 3.5 g/g (Hemlock) Broadleaf species store more rainfall per total biomass than needleaf species, up to 4.5 g/g at 400mm/h rainfall intensity (Bramble) compared to 2.25 g/g (Hemlock) Although all storage decreased as rainfall intensity increased, models indicate that broadleaf species demonstrate higher linearity as rainfall intensity increases, storing less than needle leaf species under low rainfall but more than needle leaf species under higher rainfall intensities								
Interception, throughfall and stemflow in forests of different diversity levels	Krämer & Hölscher 2009 Thuringia Central Germany	• Beech dominated forests, • Beech mixed with Lime, Ash, Birch & Sycamore	Luvisols	Northeast facing	290-370 m.a.s.l Rainfall: 544-662 mm/y	N/A	Ability of forests of different diversities to intercept rainfall in summer storms	Summer storms and year round rainfall	Observed data with rainfall and stemflow captured in and compared to gross rainfall captured in nearby grass meadow and statistically assessed. Leaf area index calculated from samples.
Result	Throughfall increased with increasing forest diversity Beech dominated forests recorded similar throughfall across different intensities of summer rainfall Stemflow decreased with increasing forest diversity Beech dominated forests recorded highest stemflow percentages Interception was lower in winter than summer despite higher intensity rainfall occurring in summer Interception differences between forests of differing species diversity was low, where Beech may intercept more rainfall on leaves due to heterogenous crown coverage, more diverse forests may intercept more on the range of different woody branches and trunks								
Interception loss and throughfall in Norway Spruce plantations at different elevations	Köhler et al. 2015 Harz mountains Germany	4 Norway Spruce forests (to 260 years old) at higher elevations and 1 Spruce plantation (100 year old) at	Nutrient poor cambisols	North facing	420-1060 m.a.s.l Rainfall: 582-1814mm/y	N/A	Spruce forest/plantation contribution to Interception loss during rainfall	Summer /Autumn rainfall	Observed data, precipitation funnels collected gross precipitation and throughfall under forest story. Cloud water deposition as calculated by the

Green-Blue Intervention Toolbox

Green-Blue infrastructure or intervention	Author Location of study	Landcover & land use	Soil	Slope / aspect	M.A.S.L; Precipitation (mm/y); Flow velocity	Catchment area size	Impact on flood/drought investigated	Hydrology / Flood type investigated	Method detail
		lowest m.a.s.l. All single species with no shrub understory.							canopy water balance model. Results statistically analysed.
Result	Interception losses to gross precipitation increases with decreasing elevation: 44% intercepted at 420 m.a.s.l; 39% at 590 m.a.s.l; 29% at 790 m.a.s.l; 24% at 1020 m.a.s.l; 9% at 1060 m.a.s.l Higher forest stands gain water additional to gross precipitation through cloud water deposition, increasing with elevation with 2mm added at 420 m.a.s.l; 10mm at 590 m.a.s.l; 65mm at 790 m.a.s.l; 195mm at 1020 m.a.s.l & 162mm at 1060 m.a.s.l As a result throughfall accounts for 56% of gross rainfall at 420 m.a.s.l and 113% at 1020 m.a.s.l								
Rainfall interception and throughfall properties of Mediterranean forest species	Llorens & Domingo 2007 European Mediterranean	Mediterranean forests of trees and shrubland	N/A	N/A	Various Rainfall: 228 mm/y to 2027 mm/y	N/A	Rainfall interception and throughfall in Mediterranean climate		Review of 90 studies on rainfall partitioning carried out in the European Mediterranean on 29 different tree and shrub species
Result	Sessile Oak, Turkey Oak, Maritime Pine and Pyrenean Oak have highest throughfall (85%-88% of rainfall) Lowest throughfall recorded for Stone Pine, Aleppo Pine, Silver Fir, Evergreen Oak and European Beech at 69.9%-72.8% of rainfall Mean throughfall for shrubs was lower but with a higher variation and increased with increasing rainfall intensity Highest stemflow was for Austrian Pine (12%) and Turkey Oak (6.8%) and lowest for Norway Spruce, Pyrenean Oak and Scotts Pine Interception highest for Austrian Pine (52.5%) and Turkey Oak (67.5%)								
Analysing conditions that enhance wet canopy evaporation during large rainfall events	Page et al. 2020 various	Forests (data from evergreen and deciduous forests combined – majority evergreen)	N/A	N/A	Data assembled from range of studies based in temperate region catchments	Various	Rainfall interception during large rainfall events	Large rainfall events >50mm per day	Data from 18 studies on wet canopy evaporation studies from temperate regions collated and analysed using the Penman–Monteith equation.
Resu	Interception losses up to 40mm per day are observed from temperate forests during high rainfall events (>50mm) Interception loss from temperate forests range between 2-38% of gross rainfall during high rainfall events								

<table>
<tr><th colspan="10">Green-Blue Intervention Toolbox</th></tr>
<tr><th>Green-Blue infrastructure or intervention</th><th>Author
Location of study</th><th>Landcover & land use</th><th>Soil</th><th>Slope / aspect</th><th>M.A.S.L;
Precipitation (mm/y);
Flow velocity</th><th>Catchment area size</th><th>Impact on flood/drought investigated</th><th>Hydrology / Flood type investigated</th><th>Method detail</th></tr>
<tr><td>lt</td><td colspan="9">To enable the highest interception loss during high rainfall, atmospheric conditions of relative humidity must be <97.5% and aerodynamic resistance needs to be <2sm to enhance vapour transport</td></tr>
<tr><td>Canopy water storage, interception and throughfall of young (25 year old) Douglas Fir and old growth (>450 year old) forests compared</td><td>Pypker et al. 2005
Washington USA</td><td>• Young Douglas Fir forest (25 year old)
• Old growth Douglas Fir and Hemlock forest (>450 year old)</td><td>No Info.</td><td>No Info.</td><td>368 m.a.s.l
Rainfall: 2500 mm/y</td><td>N/A</td><td>Comparison of canopy water storage, interception and throughfall of 25 year old and >450 year old forests</td><td>Storm througfall</td><td>Observed rainfall/storm data captured in tipping buckets for Spring, Summer & Autumn for intensities of 10mm to 198mm. Stemflow not measured and assumed low because of high bark roughness. Data fitted to Gash model to test variables and predict outcomes</td></tr>
<tr><td>Result</td><td colspan="9">Throughfall during June-November was least in the young forest and 3.5 times larger in the old growth forest due to canopy gaps due to forest age and mixed species composition
Measured interception loss was similar in both young and old growth forests, modelled storms (10-100mm) predict a slightly higher interception loss in old growth forests
Canopy water storage capacity is almost double for the old growth forest compared to the young forest even though leaf area index are similar because of a higher species composition and storey mix in the old growth forest
Loss of older needles during the Autumn period impacts Spruce forest throughfall – this occurred for both young and old growth forests but impact is more pronounced for old growth forest in terms of canopy water storage capacity
Modelling suggests that the young forest has higher interception (due to lower throughfall) during lower intensity storms, and old growth forests have higher interception loss during higher intensity storms due to their higher canopy water storage capacity and throughfall onto a variety of species with varying canopy heights</td></tr>
<tr><td colspan="10">**Shelterbelt/hedgerows and buffer strips in agriculture - impact on infiltration & runoff**</td></tr>
<tr><td>Buffer strips around cropland impact on runoff and impact on crop yield and quality</td><td>Borin et al. 2010
Veneto, North Eastern Italy</td><td>6m wide buffer strip of 2x rows London Sycamore and European cranberry bush and crops of maize, soyabean and sugar beet</td><td>No Info.</td><td>1.8%
No Info.</td><td>6 m.a.s.l</td><td>No Info.</td><td>Impact of buffer strips around cropland on surface and sub-surface runoff</td><td>Rainfall and runoff reduction</td><td></td></tr>
<tr><td>Resu</td><td colspan="9">A young (planted 1998 measured 2002) hedgerow/buffer strip of sycamore and cranberry bush reduced total runoff by 78% compared to cropland with no buffer strip
A twenty year old hedgerow/buffer strip (single tree strip and grass 4m wide) on cropland reduced runoff by 37% compared to cropland with no buffer strip</td></tr>
</table>

Green-Blue Intervention Toolbox

Green-Blue infrastructure or intervention	Author Location of study	Landcover & land use	Soil	Slope / aspect	M.A.S.L; Precipitation (mm/y); Flow velocity	Catchment area size	Impact on flood/drought investigated	Hydrology / Flood type investigated	Method detail
It	Additional benefits include reduced Nitrogen and Phosphorous losses by 12.8kg/ha and 80% respectively Yield losses occurred for soyabean and maize to within 2m of the hedgerow after which yield increase normalised rapidly, however, in sugar beet crops losses were 20% more and continued to 7m out from the hedgerow								
Tree shelterbelt placement in grazing pasture impact on soil infiltration capacity	Carroll et al. 2004 Nant Pontbren, Wales, UK	Birch, Alder, Blackthorne, Oak, Ash plantings of 2, 6 and 7 years old, compared to grassland pastures	Cambic stagnogleys & stagnogleyic brown earths	No info.	150-400 m.a.s.l Rainfall: 800mm/y	No Info.	Water infiltration and storage capacity of soils	Rainfall and runoff reduction	Observed data collected from single ring infiltrometer to 10cm depth
Result	Highest infiltration rate 62cm/h measured within the shelterbelt and lowest under grazed pasture 1cm/h 1m out from the shelterbelt boundary fence, infiltration under grazed pasture increases to around 12cm/h Difference between shelterbelt tree age increase with age of tree plantings, mean of around 17cm/h at 2 years of age, 67cm/h at 6 years of age and around 82cm/h at 7 years of age								
Tree shelterbelt placement and location relative to slope in pastureland impact on overland flow runoff and drainage	Jackson et al. 2008 Nant Pontbren, Wales, UK	12% of landcover modelled as shelterbelt and 88% as grazed pasture	N/A	1:20	170-425 m.a.s.l Rainfall: 1200 mm/y	12.5 km^2	Drainflow and overland flow response to shelterbelt placement within pasture land	Drainflow and overland flow in response to rainfall	Three dimensional hydrological model calibrated with observed data
Result	Little change to drainflow (presumed subsurface flow) is found under grazed or tree shelterbelt simulations Planted shelterbelt strips that are diagonal to downslope produce best reduction in overland flow, highest intensity flood peak flows reduced by 40% (highest intensity rainfall) and 60% of mean overland flow Shelterbelts planted in strips parallel to downslope are less effective in reducing flood peaks with a 10% reduction simulated								
Tree shelterbelt placement in grazing pasture impact on soil infiltration capacity and overland flow	Marshall et al. 2009 Nant Pontbren, Wales, UK	Field with grazed pasture and shelterbelt of Birch, Oak, Hazel, Ash and Scotts Pine	Cambic stagnogleys and stagnogleyic brown earths	Average 12.5% slope East facing	279-317 m.a.s.l Rainfall: 1501 mm/y	Whole catchment 18 km^2 Sub-catchment 4 km^2	Soil infiltration capacity and overland flow contribution to flooding	Surface and subsurface flow due to landcover role in flooding	Observed data, overland flow and drain (? Subsurface flow) collected via inserted gutter and v-notch weirs and tipping buckets

Green-Blue Intervention Toolbox									
Green-Blue infrastructure or intervention	Author Location of study	Landcover & land use	Soil	Slope / aspect	M.A.S.L; Precipitation (mm/y); Flow velocity	Catchment area size	Impact on flood/drought investigated	Hydrology / Flood type investigated	Method detail
Result	Soil under cross-slope shelterbelt has median saturated hydraulic conductivity of 8.34m/d and under grazed pasture 3.43 m/d Soil water storage capacity in the A horizon under shelterbelt vegetation is 0.17cm3 per cm3 of soil compared to 0.09 cm3 per cm3 of soil under grazed pasture Subsurface drainage is the major contributor to hillslope drainage (compared to overland flow) and overland flow occurs predominately when the soil surface is already saturated								
Exclusion of grazing and broadleaf tree planting in former pasture impact on soil infiltration capacity and overland flow	Marshall et al. 2014	4 sites of pasture grassland; shelterbelt of Alder, Ash, Birch, Blackthorne, Hazal, Cherry, Plumb & Rowan and control	Cambic stagnogleys and stagnogleyic brown earths	3.7-4.9° Aspect - no Info.	220-312 m.a.s.l Rainfall: 1309-1338 mm/y	Whole catchment 18 km^2	Soil infiltration capacity and overland flow contribution to flooding	Surface and subsurface flow due to landcover role in flooding	Observed data collected via surface runoff traps, v-notch weirs, tipping bucket rain gauges, neutron probes for soil moisture, soil infiltration via double ring infiltrometer, soil bulk density analysed and vegetation assessed.
Result	Two years after grazing exclusion, peak runoff on grazing excluded pasture site (compared to control) was reduced by 1.5 mm/h and runoff duration by around 1 hour Two years after tree planting, peak runoff on shelterbelt site (compared to control) was reduced by 2 mm/h and runoff duration by around 45 minutes Six years after tree planting, infiltration rates were more than doubled in each of the 4 shelterbelt sites compared to the 4 control sites with the maximum difference 8:1000 mm/h Six years after tree planting infiltration rates were at least doubled in each of the 4 shelterbelt sites compared to the 4 grazing excluded sites, with a maximum difference 10:1000 mm/h								
Agroforestry, orchard, silvopasture intercropping, buffer strips, wind breaks, impact on soil organic matter, erosion and runoff	Nerlich et al. 2013 Karlsruhe-Stupferich, Germany	Four rows of Sycamore, Wild Cherry, Hybrid Walnut & short rotation poplar interplanted with winter barley and oats compared with mono-cropped barley and oats	Clayey-loam	Low slope Trees planted in north-south orientation	250 m.a.s.l Rainfall: 750 mm/y	No Info.	Runoff and nutrient Leaching generated from agroforestry and mono-cropping	Torrential rain (up to 25 L/m^{-2}), long rainfall periods (up to 3.5 L/h) and snowmelt	Erosion pans embedded into the soil connected to pipes and accumulation barrels measured from November 2009 to April 2010
Result	Runoff from mono-cropped winter Barley and oats sewn land totalled 759L and runoff from agroforestry system totalled 79L, a difference of nearly 90% Soil organic matter in 0-30cm horizon was higher in agroforestry system by 0.7% Nitrogen and Phosphorus losses from runoff were lower in the agroforestry system (compared to mono-cropped site) by 25% and 70% respectively								

<table>
<tr><th colspan="10">Green-Blue Intervention Toolbox</th></tr>
<tr><th>Green-Blue infrastructure or intervention</th><th>Author
Location of study</th><th>Landcover & land use</th><th>Soil</th><th>Slope / aspect</th><th>M.A.S.L; Precipitation (mm/y);
Flow velocity</th><th>Catchment area size</th><th>Impact on flood/drought investigated</th><th>Hydrology / Flood type investigated</th><th>Method detail</th></tr>
<tr><td colspan="10">Grazing and grassland management impact on infiltration & runoff</td></tr>
<tr><td>Relationship between grazing animals, stocking rates and runoff</td><td>Meijles et al. 2015
Dartmoor, UK</td><td>Grazed grass and heath</td><td>Podzolic and ironpan stagnopodzol soils</td><td>No Info.</td><td>340-480m
Rainfall: 2022 to 2052mm/y</td><td>No Info.</td><td>Runoff pathways caused by higher stocking rates</td><td>Rainfall runoff and flash flooding</td><td>Runoff from animal paths measured by thin-plate weir, overland flow captured by thin-plate weir fitted with a gutter. Stocking rates mapped. Rainfall totals recorded via tipping bucket and stream discharge monitored from October 2006 to April 2007</td></tr>
<tr><td>Result</td><td colspan="9">Areas with higher stocking intensity respond to rainfall by producing runoff that flows to streams
First, water was observed flowing down animal tracks during rainfall and contributing to runoff that feeds to the streams
Second grasslands had higher stocking density and therefore higher bulk density and lower soil porosity, and were quicker than lower stocked areas to reach soil saturation and produced runoff</td></tr>
<tr><td>Impact of grazing animals on rainfall runoff from slopes</td><td>Meyles et al. 2006
Dartmoor, UK</td><td>Grazing grassland consisting of:
• Bracken & grass
• Short grass
• Heather & grass
• Gorse and grass</td><td>Peat, peaty gley and podzols</td><td>North facing</td><td>290m – 450m
2100mm/y</td><td>61 ha</td><td>Grazing animal impact on rainfall runoff on slopes</td><td>Rainfall runoff from slopes contributing to flood peak</td><td>Rainfall (tipping bucket), soil moisture (domain reflectometer and in soil), runoff and discharge measured (fibreglass trapezoidal Lothian flume), soil samples analysed in laboratory. Runoff plotted against soil moisture</td></tr>
<tr><td>Result</td><td colspan="9">Bulk density and total soil porosity was higher under short grasses (more heavily grazed areas)
Soil water holding potential from 0-19cm was reduced under heavily grazed short grasses indicating that the time to saturation of the more heavily grazed sites is reached more quickly
Runoff occurs preferentially on areas where grasses are shorter and more heavily grazed compared to less heavily grazed areas</td></tr>
<tr><td>Overland flow velocities in semi</td><td>Monger et al. 2022a</td><td>Grazed grass & wood pasture, grazed bracken</td><td>Chromic Endoleptic Umbrisol</td><td>0.22 to 0.24 radians</td><td>Rainfall: 88-231mm per month</td><td>N/A</td><td>Rainfall runoff and runoff velocity</td><td>Flood peak due to</td><td>Overland flow at each site collected via flume and funnel, tracer dye injected to</td></tr>
</table>

Green-Blue Intervention Toolbox

Green-Blue infrastructure or intervention	Author Location of study	Landcover & land use	Soil	Slope / aspect	M.A.S.L; Precipitation (mm/y); Flow velocity	Catchment area size	Impact on flood/drought investigated	Hydrology / Flood type investigated	Method detail
natural woodland and woodland pasture	Cumbria, UK	& wood pasture and un-grazed seminatural broadleaf woodland						overland flow velocity	measure velocity, shipiro wilk statistical analysis and Tukey's test
Result	Mean bulk density: grass & wood pasture 0.63 g/cm^3; bracken & wood pasture 0.65 g/cm^3; un-grazed woodland 0.51 g/cm^3 Mean permeability: grass & wood pasture 3x 10^{-5} m/s; bracken & wood pasture 2.9x10^{-4} m/s; un-grazed woodland 2.28x10^{-3} m/s Overland flow velocity: 3 L/m grass & wood pasture 0.011 m/s; bracken & wood pasture 0.008 m/s; un-grazed woodland 0.010 m/s Overland flow velocity: 30 L/m grass & wood pasture 0.047 m/s; bracken & wood pasture 0.038 m/s; un-grazed woodland 0.043 m/s Woodlands with closed canopy cover will have sparse understorey vegetation and lower surface roughness and higher overland flow velocity Woodlands with open canopy combine the higher soil permeability typical of woodland soils in combination with the higher surface roughness associated with a denser understorey provided grazing intensity is not too high								
Contribution of grain, leaf, stem and litter of grass vegetation on slopes to overland flow resistance	Pan et al. 2016 Laboratory simulation	Grassland (ryegrass) plots and bare soil plots for control	Loessal loam	2.5-50%	Rainfall intensity: 30-90mm/h	N/A	Flow resistance in grassed slopes	Overland flow	Laboratory simulation with simulated rainfall and dye tracer, using runoff plots with grass configuration grassed, grassed with litter, grassed with stems only etc.
Result	For grassed plots the friction provided by grass decreases with increasing slope Grass leaves provide the highest friction (52%), stems (32%), litter (16%) and grains (1%) 80% of resistance comes from stems and leaves therefore grass cutting prior to a significant rainfall event or high frequency of cutting could significantly reduce the overland flow resistance								
Soil management (conservation tillage / reduced tillage / strip tillage) impact on infiltration and runoff									
Impact of mulch tillage (crop residue remaining) and no tillage agricultural crops on rainfall runoff and erosion over 22 years	Klik and Rosner 2020 Vienna, Austria	Agricultural crops of grain and root crops	Silt loam and silty clay loam	No Info.	Rainfall: range from 629 to 916 mm/y	N/A	Runoff induced from rainfall on agricultural fields	Rainfall runoff across 22 years duration	Runoff collected in channels and collecting tanks. Samples all taken from summer cops. Data collected from 1994 to 2018 and analysed in laboratory
Res	On silt and loam soils mulch tillage reduced runoff by 25-55% and no till led to reduction of runoff by 49-60% compared to conventional tillage On silty clay loam soils with high bulk density runoff increased by 12-21% under reduced tillage								

<table>
<tr><th colspan="10">Green-Blue Intervention Toolbox</th></tr>
<tr><th>Green-Blue infrastructure or intervention</th><th>Author
Location of study</th><th>Landcover & land use</th><th>Soil</th><th>Slope / aspect</th><th>M.A.S.L; Precipitation (mm/y); Flow velocity</th><th>Catchment area size</th><th>Impact on flood/drought investigated</th><th>Hydrology / Flood type investigated</th><th>Method detail</th></tr>
<tr><td>ult</td><td colspan="9">Soil loss on silty clay loam reduced by 38% under mulch tillage and by 65% by no tillage compared to conventional tillage
Soil loss on silt loam reduced by 74-88% under mulch tillage and by 84-93% by no tillage compared to conventional tillage
Nitrogen and phosphorus losses under conventional tillage 13.3–48.1 kg/h; mulch tillage 4.5–18.7 kg ha and under no tillage 1.6–9.4
SOC losses reduced under mulch tillage by 34–86 %; and by 58–89 % under no tillage compared to conventional tillage</td></tr>
<tr><td>Strip tillage impact on runoff and soil loss on agricultural slopes compared to reduced tillage and intensive tillage</td><td>Laufer et al. 2016
Bockshaft, Gieshügel, Sailtheim Southern Germany</td><td>Agricultural fields growing sugar beet</td><td>Haplic Luvisol from loess at all four trial sites</td><td>8.4% to 13.8%</td><td>No Info.</td><td>No Info.</td><td>Impact of runoff under heavy rainfall for three different tillage operations</td><td>Heavy rainfall of 24mm over 20 minutes simulated</td><td>Rainfall simulated over 2 crop cycles via VeeJet 80/100) and runoff collected at the end of each trial plot. Soil loss and runoff calculated and statistically analysed</td></tr>
<tr><td>Result</td><td colspan="9">Cumulative surface runoff from 100% of rainfall applied under: intensive tillage 32%; under reduced tillage 15%; under strip tillage 3%
Rainfall runoff under reduced tillage was 55% lower than intensive tillage and 92% under strip tillage than in intensive tillage
Soil loss in reduced tillage was 85% lower than intensive tillage and in strip tillage soil loss was 98% lower than in intensive tillage
Strip tillage also has the benefit of increasing plant available water due to the reduction in rainfall runoff</td></tr>
<tr><td>Impact of conservation tillage to rainfall runoff and catchment flooding</td><td>Haag et al. 2006
Glems River Catchment, Stuttgart Germany</td><td>37% of landuse is tilled agricultural land</td><td>Silty luvisols above Loess</td><td>No Info.</td><td>Rainfall: 750mm/y</td><td>195 km^2</td><td>10, 20 and 50% conversion of agriculture to conservation tillage compared to conventional tillage</td><td>Flooding and flash floods</td><td>LARSIM hydrological model with additional infiltration module</td></tr>
<tr><td>Results</td><td colspan="9">Floods generated by moderate long-lasting rainfall (<25mm/h) the effect of changing tillage practices is not noticeable, for short duration high precipitation events (flash floods) the reduced runoff from conservation tillage is noticeable even if the change is over 10-50% of 37% landuse
Conservation tillage (50% scenario) produces 1.4% reduction in peak discharge for 1 in 2 year return period storm, compared to conventional tillage
Conservation tillage (50% scenario) produces 1.6% reduction in peak discharge for 1 in 10 year return period storm, compared to conventional tillage
Conservation tillage (50% scenario) produces 1.7% reduction in peak discharge for 1 in 20 year return period storm, compared to conventional tillage
Conservation tillage (50% scenario) produces 1.8% reduction in peak discharge for 1 in 50 and 1 in 100 year return period storm, compared to conventional tillage</td></tr>
</table>

Green-Blue Intervention Toolbox

Green-Blue infrastructure or intervention	Author Location of study	Landcover & land use	Soil	Slope / aspect	M.A.S.L; Precipitation (mm/y); Flow velocity	Catchment area size	Impact on flood/drought investigated	Hydrology / Flood type investigated	Method detail
Impacts of conservation tillage (non inversion disc leaving 30% of soil surface with crop residue) on runoff and soil loss in cropland over 16 years	Madara´sz et al. 2021 Southwest Hungary	Cropland under maize, rape, winter wheat and sunflower	Luvisol (silty loam from loess)	10% South west	150 m Rainfall: 700mm/y	N/A	Reduction in rainfall runoff and soil loss	Rainfall runoff, low and high intensity	Four plots, two of each under conservation tillage and ploughing. Runoff collected in channels and collecting tanks. Rainfall data collected via automated meteorological station. Random forest modelling.
Result	Mean annual runoff from ploughed plots was 18 mm and conservation tillage plots 4mm Mean soil loss from ploughed plots was 2.8 t/ha and conservation tillage plots 0.2 t/ha Earthworm activity in last two years of the experiment in ploughed plots was 55 worms/m and ploughed plots was 168 worms/m Runoff reduced by 75% across the years of the experiment and soil loss reduced by 95% compared to the ploughed plots, however weeds in the conservation tillage plots were a problem								
Soil management - biochar additions									
Impact of biochar and N fertilizer additions on soil moisture, soil bulk density and water filled pore space	Horak et al. 2019 Slovakia	Barley, maize and wheat crop rotations	Haplic Luvisol	No Info.	No Info. Rainfall: 540mm/y	N/A	Improvement of soil moisture retention		Biochar of paper fibre sludge and grain husks (10 & 20 t/ha) and N fertiliser added at varying volumes to 9 different trial plots. Soil samples taken, water content and bulk density calculated.
Result	All plots that received biochar (with and without N fertilizer) resulted in increased soil moisture and lower bulk density across three years of the experiment A higher rate of water retention and bulk density was found when biochar was applied at a higher rate, regardless of N fertiliser rate Soil temperature was not influenced by biochar application								
Addition of biochar and compost to dystric cambisol soils under maize crop	Liu et al. 2012 Brandenburg Germany	Maize crop	Dystric Cambisol	No Info.	No Info. Rainfall: March – Oct average 320mm	N/A	Improvement of soil water retention to reduce runoff	Rainfall runoff	Biochar (charcoal 5, 10 and 20 Mg/ha) compost (greenwaste & chopped wood) and compost (greenwaste & chopped wood) added to agricultural fields prior to maize crop.

<table>
<tr><th colspan="10">Green-Blue Intervention Toolbox</th></tr>
<tr><th>Green-Blue infrastructure or intervention</th><th>Author

Location of study</th><th>Landcover & land use</th><th>Soil</th><th>Slope / aspect</th><th>M.A.S.L; Precipitation (mm/y); Flow velocity</th><th>Catchment area size</th><th>Impact on flood/drought investigated</th><th>Hydrology / Flood type investigated</th><th>Method detail</th></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>Samples analysed in lab and with statistical analysis</td></tr>
<tr><td>Result</td><td colspan="9">Compost with the highest biochar addition (20 Mg/ha) recorded 12% plant available water holding capacity and control (no addition) recorded 6%

Total organic carbon (TOC) recorded in highest biochar-compost as 20 g/kg and in control 8 g

Nutrients N and K also highest in highest biochar-compost compared to control, N: 1.0 g kg compared to 0.5 g kg; K: 282 mg kg compared to 114 mg kg</td></tr>
<tr><td>Soil water retention properties of biochar enriched soil</td><td>Xiao et al. 2016

Changwu, Northern China</td><td>Maize crops</td><td>Cumuli-Ustic Isohumosols based on loess</td><td>No Info.</td><td>1200m

Rainfall: 555mm/y</td><td>N/A</td><td>Soil water holding properties</td><td>Rainfall runoff</td><td>0, 10,20 & 30 t/ha of maize straw biochar applied to four plots 40% prior to crop 30% after sowing over years years. Soil sampling, lab analysis and statistical analysis of results</td></tr>
<tr><td>Result</td><td colspan="9">Soil water content of soils treated with biochar were consistently higher than the control during the five days monitoring period after each rainfall event across the three years trial, maximum was generally found in the 30 t/ha addition to a depth of 40 cm

Soil permeability was also enhanced to 60 cm with the addition of biochar

Crop yield and water use efficiency were also enhanced by biochar 20 & 30 t/ha addition resulted in 10.2% and 14.2% higher crop yield and 9.4% and 12.3% water use efficiency respectively compared to the control plot</td></tr>
<tr><td colspan="10">**Storm and flood water retention / detention areas & basins**</td></tr>
<tr><td>Integrating flood hazard scale into site selection for flood detention basin</td><td>Ahmadisharaf et al. 2016

Tehran, Iran</td><td>N/A</td><td>N/A</td><td>Highly mountainous</td><td>N/A</td><td>43.7 km^2 made of 17 km^2 urban 26.7 km^2 rural</td><td>Tool to determine best placement of flood detention basins</td><td>1 in 100 year flood</td><td>Hydrologic-hydraulic modelling, flood hazard calculation, multi-criteria site selection</td></tr>
<tr><td>Result</td><td colspan="9">The flood hazard is scaled based on model outcome, start time, duration, height and discharge (highest hazards at midstream and most downstream site)

Site selection criteria – slope 0-5 (highest score),5-10,10-15 to >15; distance to channels 0-100 (highest score), 100-250m, 250-500m, 500-1000m; distance to social hotspots and highways >5000m (highest score), 2000-5000m, 1000-2500m, <1000m; soil permeability (CN) 65-70 (some but not high permeability highest score), 70-75, 75-80, 80-90 (very low permeability); land acquisition open land/parks (highest score), urban areas, mountainous, residential/services</td></tr>
<tr><td>Comparison of small retention pond placement in the catchment and</td><td>Ayalew et al. 2015

Iowa, USA</td><td>Agricultural</td><td>N/A</td><td>Low slope</td><td>N/A
N/A</td><td>30 km^2</td><td>Impact of configuration and size of retention ponds</td><td>Flood peak with probability of exceedance 1 to 0.001 and</td><td>Mandelbrot-Viseck tree generic river network. Stochastic rainfall model is used to generate 1,000 year</td></tr>
</table>

<table>
<tr><th colspan="11">Green-Blue Intervention Toolbox</th></tr>
<tr><th colspan="2">Green-Blue infrastructure or intervention</th><th>Author

Location of study</th><th>Landcover & land use</th><th>Soil</th><th>Slope / aspect</th><th>M.A.S.L; Precipitation (mm/y); Flow velocity</th><th>Catchment area size</th><th>Impact on flood/drought investigated</th><th>Hydrology / Flood type investigated</th><th>Method detail</th></tr>
<tr><td colspan="2">which is more effective at reducing flood peak and return</td><td></td><td></td><td></td><td></td><td>Runoff coefficient:0.5m/s
Channel flow velocity:0.5m/s
Hillslope overland flow:0.02m/s
Subsurface flow velocity:0.005m/s</td><td></td><td>(2 x small =300,000 m^3; 1 x large =600,000 m^3) on flood peak reduction</td><td>peak discharge to 50m^3/s</td><td>rainfall series. Rainfall data is used in rainfall-runoff model to generate regulated and unregulated streamflow series.</td></tr>
<tr><td>Result</td><td colspan="10">Retention ponds set parallel in catchment can better reduce flood peaks with low-medium probability of exceedance (0.5 to 0.001 & max 4 m^3/s at 0.1) than sequential ponds because they regulate a wider area of rainfall and runoff

Ponds with higher storage capacity (or larger number) located upstream achieve higher reduction of low-medium exceedance floods (0.8 to 0.04 & max 15 m^3/s) and same reduction of high exceedance floods than retention built at deltaic or downstream locations (although this does not moderate against high rain in delta region)

Flood control benefits of retention ponds are mainly local and the impact reduces correspondingly further from the retention pond and as catchment size increases

Retention ponds also offer greater multi-event impact if upstream ponds have greater drainage capacity and are drained before downstream ponds following a flood</td></tr>
<tr><td colspan="2">Retention ponds situated from upper to lower within the catchment</td><td>Birkinshaw & Krivtsov 2022

Edinburgh, Scotland</td><td>Mix of forest, rural and urban</td><td>Mixed thin soils and brown soils</td><td>No Info.</td><td>150-486 m
Rainfall: N/A

Saturated hydraulic conductivity Soils: 50 & 150m/d
Aquifer:1m/d
Overland Flow
Forest:1$m^{1/3}$/s
Grassland:4$m^{1/3}$/s
Urban:10 $m^{1/3}$/s
Water:30$m^{1/3}$/s</td><td>22.8 km2</td><td>Rainfall induced</td><td>Peak river discharge</td><td>Modelled retention ponds through Shetran a physically based distributed model. Storages modelled as 1 x 12,500m^2 % 3 x 2500 m^2 x 0.25, 1 and 4 Strickler coefficient (large, medium and small retention)</td></tr>
<tr><td>Res</td><td colspan="10">Outcome of modelling retention areas in the upper, mid and lower basin is that the upper pond generally reduces peak flow, the mid pond has no effect, and the lower pond increases peak flow as the shorter time delay in outflow once the pond is full can coincide with the flood peaking in the lower catchment</td></tr>
</table>

Green-Blue Intervention Toolbox

Green-Blue infrastructure or intervention	Author Location of study	Landcover & land use	Soil	Slope / aspect	M.A.S.L; Precipitation (mm/y); Flow velocity	Catchment area size	Impact on flood/drought investigated	Hydrology / Flood type investigated	Method detail
ult	When modelled for 10 rainfall events the 12,500m^2 pond on headwaters in a larger non-urban catchment reduces the peak in 10/10 cases by average 0.67%; the upper 2500 m^2 pond reduces the peak 7/10 times at 0.34% and the lower 2500 m^2 pond produces an increase 10/10 times at 0.16%; all ponds working together reduce peak flow 10/10 times by 0.82%								
Review and comparison of effectiveness of stormwater collection measures (SCM) and impervious surface cover (ISC)	Bell et al. 2020 Various	Various	Various	No Info.	Various	Various	Illuvial (rainfall runoff) and Fluvial (peak flow) reduction	Stormwater runoff and	Comparison of modelling studies by analysing area mitigated, reductions in runoff and peak flow and testing of environmental factors that may influence the outcome, regression analysis in R.
Result	At equal implementation volumes SCMs reduce peak flows by a greater percentage than runoff reduction through increased infiltration because infiltration is limited by the percolation rate which is influenced by soil properties and the footprint area The performance of SCMs in reducing runoff volume and peak flows is limited during larger rainfall events and even if 100% of ISC is treated by SCMs the peak discharge will still be higher than a fully impervious catchment due to storage limitations With ISC mitigation, higher reductions in runoff and peak flow result from catchments with higher ISC before mitigation occurs								
Planning site selection for detention basin using hydrology and geomorpholoy	Bellu et al. 2016 Lima River Catchment Portugal	2.5% urban 23% cropland 34.5% forest	No information	Mean slope: 28%	30-1400 m.a.s.l Rainfall: 1780 mm Discharge: 3298 h m3/yr	1140 km^2	Attenuation of peak discharge	Runoff and river flooding	Hydrological modelling, GIS mapping, multi-criteria analysis
Result	Sub basins with highest contribution to flood discharge identified through hydrological modelling Values: Slope: 0-5% (highest score), landuse: semi natural (highest score), minimised point source pollution (population density 1.7-3.3) used to map potential sites for detention basins Because of the very high slope in this catchment, no easy solutions are found, authors suggest a centralised basin with very high dam wall, or multiple decentralised basin also with high dam walls or extensive reforestation of catchment headwater area								
Retention ponds and urban permeability improvements (low impact) such as permeable pavements, green	Giacomoni et al. 2014 Village Creek Watershed, Arlington USA	Changing Urban (28 to 56%), Industrial (stable 3%), forest/wetland (15 to 10%) & rural/ agricultural	No Info.	No Info.	No Info. Rainfall: No Info.	Catchment 370 km^2 wider area	Comparison of retention ponds (14 x 194,000 m^3) and (low impact) permeable pavements etc.	Runoff capture and peak flow attenuation for 1 in 2-y (107mm), 1 in 10-Y (173mm) and 1 in 100-	Simulations using a CA land cover change model, a rainfall hydrologic model (SWAT), a streamflow hydraulic model (HEC-RAS) to calculate Hydraulic Footprint Residence (HFR)

Green-Blue Intervention Toolbox

Green-Blue infrastructure or intervention	Author Location of study	Landcover & land use	Soil	Slope / aspect	M.A.S.L; Precipitation (mm/y); Flow velocity	Catchment area size	Impact on flood/drought investigated	Hydrology / Flood type investigated	Method detail
roofs, rainwater harvesting etc.		(52 to 28%). 14 ponds located along tributaries to the main stream					in relation to current scenario and increased development	year (257mm) storms	to assess the area and duration of inundation of a streamflow segment during a rainfall event.
Result	For 1 in 2-year storm, retention ponds perform better to reduce peak flow (19.8% reduction compared to 2.6% increase) but low impact solutions produce better HFR results as the retention ponds act to extend the falling limb of the hydrograph as retained waters are released For 1 in 10-year storm, retention ponds reduce peak flow by 8.5% (-7.3 m^3/s) compared to 1.6% (+1.4 m^3/s) increase of runoff by low impact solutions. HFR is better balanced by retention pond scenario as the rising limb is lowered and the falling limb higher compared to the before change scenario, but the differences balance out For 1 in 100-year storm, retention ponds reduce peak flow by 16.8% (-31.9 m^3/s) compared to 2.5% (+4.8 m^3/s) increase of runoff by low impact solutions. HFR result is similar to 1 in 10-year storm hydrograph, however, the HFR is not suitable for comparisons at this scale because the reduction of the peak is most important								
Small scale runoff attenuation via temporary storage ponds across hillslope pastureland	Nicholson et al. 2019 Belford, Northumberland UK	Construction of downstream earth bund along flow lines to hold 300-1000m^3 in pastureland	No Info.	No Info.	55-185 m.a.s.l Rainfall: 738 mm/y Flood flow velocity >5.5m^3/s or 3.5mm/h	5.7 km^2	Ability of temporary storage ponds to moderate flash floods as a result of heavy rainfall	Flash floods	Pond created with excavated material. Gauge measurement of rainfall, river height and pond storage. Pressure transducers to measure stream stage. Pond Network Model to model impact of multiple ponds
Result	The constructed pond (400m^3) reduced peak flow of a November storm where around 26mm rainfall over 5 days, by 12% During larger July (120 mm 3 day) and March (65 mm over 2 day) events the constructed pond fills prior to the peak streamflow Modelling shows that the small scale ponds are better at attenuating flash floods as greater volume of storage is required to reduce peaks of slower and higher peaked floods Modelling shows that a network of ponds (combined total 20,000 m^3 storage) could reduce peak flows (>3.5 mm/h) that impact downstream urban area by up to 30%								
Retaining water in the landscape with micro-pond and small reservoirs, and the impact on flooding	Salazar et al. 2012 • Poyo, Spain • Upper Iller, Germany • Kamp River, Austria	• Mediterranean • Alpine & • Continental catchments	Cambisols - Poyo Catchment Fluvisol/Histosol & Cambisol/Leptosol – Upper Iller Catchment	12.3% 17.9% 6%	111-1030 m.a.s.l 658-2638 m.a.s.l 500-996 m.a.s.l Rainfall: 450 mm/y 2000 mm/y 900 mm/y	184 km^2 954 km^2 621 km^2	Water retention during flash flooding	Flash flooding	Process-oriented distributed rainfall-runoff models

<table>
<tr><th colspan="10">Green-Blue Intervention Toolbox</th></tr>
<tr><th>Green-Blue infrastructure or intervention</th><th>Author
Location of study</th><th>Landcover & land use</th><th>Soil</th><th>Slope / aspect</th><th>M.A.S.L;
Precipitation (mm/y);
Flow velocity</th><th>Catchment area size</th><th>Impact on flood/drought investigated</th><th>Hydrology / Flood type investigated</th><th>Method detail</th></tr>
<tr><td></td><td></td><td></td><td>Podzol – Kamp River Catchment</td><td></td><td>Discharge: 0-300m^3/s</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Result</td><td colspan="9">Small reservoirs were most effective at reducing flooding in the Poyo catchment, reducing peak discharge during small events by up to 12.8%
Micro-ponds (100m^3 x7,500 or 12 per km^2) modelled to retain hillslope runoff were most effective at reducing flooding in the Kamp catchment, reducing peak discharge of small events by up to 14%
This was the case for Kamp even with wet antecedent conditions, because the fraction of surface runoff is greater in the case of high soil moisture and more water drains into the micro-ponds
In the Upper Iller micro-ponds modelled to retain hillslope runoff were more effective than small reservoirs, but the maximum impact on a small event is only 3.4%</td></tr>
<tr><td>Retention basins to capture storm runoff</td><td>Smith et al. 2015
Baltimore County, USA</td><td>Urban, forest (deciduous, evergreen, mixed), grassland & wetlands. Pervious land area totals 48%</td><td>Silt loam</td><td>No Info.</td><td>No Info.</td><td>14.3km^2</td><td>Impact of varying the location of retention ponds throughout the basin</td><td>Storm rainfall runoff, the highest 21 peak discharges from 2008 to 2012</td><td>Gridded Surface Subsurface Hydrologic Analysis (GSSHA) model, a gridded, distributed, and physically based hydrologic model validated with observed rainfall and streamflow data</td></tr>
<tr><td>Result</td><td colspan="9">Modelling retention basins on second order streams resulted in the most efficient reduction of storm runoff (1.03%) as opposed to placing basins on first (0.45%), or third (0.775%) order streams. The reduced efficiency of the third order is due to the reduction in coverage of spatially diverse rainfall by concentrating retention in the smaller number of third order streams
The difference between retention basins and no retention basins had no measurable difference on peak discharge timing but reduced the flood peak magnitude by median 0.03 to 27.5% across sub-basins</td></tr>
<tr><td>Small scale runoff attenuation via temporary storage ponds across hillslope pastureland</td><td>Wilkinson et al. 2010
Belford, UK</td><td>Timber and earth ponds along pasture hillslopes</td><td>Shallow soils</td><td>No Info.</td><td>185 m.O.A.D
Rainfall: No Info
Peak discharge: 2.1m^3/s</td><td>6 km^2</td><td>Runoff attenuation by micro-ponds along hillslope</td><td>Rainfall leading to overland flow</td><td>Pond created with green oak (800-1000 m^3), 3 further ponds created from scraped soil created a storage of approximately 2800 m^3. Rainfall, stream levels and pond levels monitored and analysed</td></tr>
<tr><td>Resu</td><td colspan="9">By comparison of events before and after the pond creation, on average the 800-1000 m^3 capacity retention pond slowed peak flow travel time from 20 to 35 minutes
On average the 800-1000 m^3 capacity retention pond slowed pre-peak flow travel time from 19 to 22 minutes
The 4 ponds in total are estimated to be able to create a reduction in flood flow of 0.4m3/s or 8% of a 1 in 5-year event</td></tr>
</table>

Green-Blue Intervention Toolbox									
Green-Blue infrastructure or intervention	Author Location of study	Landcover & land use	Soil	Slope / aspect	M.A.S.L; Precipitation (mm/y); Flow velocity	Catchment area size	Impact on flood/drought investigated	Hydrology / Flood type investigated	Method detail
I t									
Effectiveness of runoff storage and filtration pond layout	Xing et al. 2016 Northern China	New development with urban and green areas	No Info.	No Info.	Rainfall: 539 mm/y	2km^2	Optimum location of runoff storage and filtration landcover/ structures	Rainfall events of 30mm, 50mm & 80mm	Runoff simulation model with SWMM based on a new development. Multiple scenarios run for different rainfall events and for different layouts with the same runoff storage and filtration features
Result	In 30mm rainfall events the amount of runoff generated was attributed to the area of impervious vs runoff storage ponds and rainfall absorbing landcover In 80mm rainfall events the area of impervious landcover is not a factor as the amount of runoff generated is as if all runoff storages and porous rural/urban features are full The most effective placement of water retention ponds (to achieve 90% reduction of peak outflow) were, in a comparison of 16 sub-catchment areas (numbered from the top of the watershed downstream), within two head sub-catchments; 1 (10% reduction), 2 (17% reduction) and mid-catchment 7 (11% reduction) a factor was also the greater length of the drainage conduits from these retention ponds to the drainage network. Least effective was to place the retention ponds in the lower sub-catchments 16 (1% reduction), 15 (2% reduction) and 14 (2% reduction) Waterlogging must also be considered when choosing the areas to implement runoff storages and porous rural/urban features								
Location of intervention in catchment, along slope and impact on infiltration, runoff & flooding									
Response time from hillslope saturation to subsurface flow	Aryal et al. 2005	N/A	Assumed	Convergent, divergent, concave, convex, planar	N/A	Variable	Subsurface flow drainage time	Rainfall to discharge	Numerical analysis of hillslope response time for divergent and convergent, and concave, convex and planar hillslopes
Result	Simple equation to explain hillslope Travel time = f(L/KS,B,CR,Δq/smd); where L= hillslope length, K = hydraulic conductivity, S = slope, B = degree of concavity or convexity, CR = degree of convergence, divergence or parallel, Δq = change in precipitation, smd = soil moisture deficit. Subsurface flow travel times for divergent hillslopes can be double (quicker) that of convergent slopes, but does not always occur in real world due to simplicity of the equation Concave slopes often have faster travel times than that of convex or planar hillslopes, but does not always occur real world due to simplicity of the equation								
Influence of slope soil and vegetation characteristics on subsurface flow	Bachmair and Weiler 2012 Black Forest, Germany	• Grassland • Coniferous forest • Mixed forest (Beech, Fir,	Cambisol	Northwest facing	340-585 m.a.s.l Rainfall: 970 mm/y	0.21 km^2	Subsurface flow and how water moves through the soil	Rainfall runoff	Observed data collected via wells with water level recorders, weather stations and soil testing. Hillslope characteristics analysed via GIS. Statistical analysis and

Green-Blue Intervention Toolbox

Green-Blue infrastructure or intervention	Author Location of study	Landcover & land use	Soil	Slope / aspect	M.A.S.L; Precipitation (mm/y); Flow velocity	Catchment area size	Impact on flood/drought investigated	Hydrology / Flood type investigated	Method detail
		Sycamore, Ash, Spruce)							modelling to determine the significance of variables.
Result	Characteristics determined as highly influential controls of subsurface flow at all sites and events: soil hydraulic conductivity, profile curvature (convex/concave/linear parallel to slope), slope degree and plan curvature (convex/concave/linear perpendicular to slope), in that order Landcover characteristics that are determined as most influential: Percentage canopy cover and maximum throughfall percentage. Seasonally, these were found to be more important in the summer period Stemflow and the number of trees (in vicinity of measurement) were low indicators of subsurface flow								
Review of natural flood management research by classifying forested areas into catchment coverage, cross slope, floodplain and riparian areas	Cooper et al. 2021 Europe mainly the UK	• Catchment forest • Cross-slope forest • Floodplain forest • Riparian forest	Various	Various	Various	Various	Rainfall and runoff reduction by forested landscapes	Rainfall and runoff	Literature review
Result	On a catchment basis the removal of forest increases water yield, and the increase of forest reduces water yield, with the highest impact coming from conifer forests, however depending on catchment specifics the results can vary depending on how much and the location of the forest cover or removal in the catchment Multiple studies on cross-slope woodland in the form of shelterbelts used in combination with agricultural land (even with some coppice harvested) report reduction in runoff through improved infiltration and soil drainage Only around 10% of Europe's natural floodplain forests remain making it difficult to conclusively measure their impact. Modelling studies show that restoration of floodplain forests would decrease the flow rate and delay the flood peak, however, the magnitude of predicted impact varies Riparian forests are thought to have most impact on flood peaks through increasing woody debris slowing the flow of water, although this can cause problems to downstream infrastructure so is considered controversial. Riparian forests may work best in combination with river renaturing to restore meanders and further slow flows.								
Characteristics that influence preferential flow	Graham and Lin 2011 Pennsylvania USA	Oak, Hickory, Hemlock and Pine	Dystrudepts & Aquic Hapludults	Asymetrical with swales average slope 23◦ (4-42◦) South facing	No Info Rainfall: 823 mm/y	7.9 ha	Preferential flow can increase peak subsurface stormflow generation	Storm induced drainage	Observed data collected via soil moisture probes, rain gauges and statistical analysis to determine influences on out of sequence response to precipitation (deeper layer response to rainfall prior to shallow layers)

Green-Blue Intervention Toolbox

Green-Blue infrastructure or intervention	Author Location of study	Landcover & land use	Soil	Slope / aspect	M.A.S.L; Precipitation (mm/y); Flow velocity	Catchment area size	Impact on flood/drought investigated	Hydrology / Flood type investigated	Method detail
Result	Preferential flows occurred at hilltop and planar hillslope sites most frequently when soils were dry before rainfall events, higher air temperatures and season. This is likely due to soil cracks and hydrophobicity leading to preferential flow along lower soil horizons Leading controls on mid-slope preferential flow found to be high initial soil moisture and long duration of rainfall events For preferential flows to be detected at the valley and lower swales sites, soils were initially wet and rainfall tended to be of greater intensity, this likely means soils were sufficiently wet so that flows were continuing down from the hillslopes above								
Rainfall volume and other environmental conditions that lead to subsurface runoff	Hrnčíř et al. 2010 Uhl´ırsk´a Czech Repulic	Currently deforested & used as laboratory, previously mixed forest of Spruce, Ash, Beech & Reed grass	Dystric Cambisol on slopes (0.6-0.9m) & Histosol along valley bottom	No Info	822 m Rainfall: 1400 mm/y	1.78 km^2	Subsurface runoff after rainfall along deforested slope	Runoff produced by storm rainfall	Observed rainfall collected by tipping bucker rain gauge, subsurface flow trenches and tipping bucket flowmeters, tensionmeters for soil moisture. Data statistically analysed and fitted to models.
Result	The statistically significant parameter defining subsurface flow and subsequently peak discharge is the initial saturation of the soil When rainfall is up to 60-70 mm subsurface runoff and discharge occurs no matter the initial soil moisture content observed When the rising and falling limbs of streamflow and subsurface flow are compared it demonstrates that soil has to reach threshold % saturation prior to streamflow and subsurface flow recedes more quickly than streamflow								
Hillslope profiles uniform, convergent and divergent influence on subsurface flow	Troch 2003 N/A	N/A	N/A	Convergent, divergent & uniform	N/A	N/A	Convergent, divergent, uniform plan form influence on subsurface flow	Rainfall runoff	Boussinesq equation is reformulated in terms of soil water storage rather than water table height
	Convergent hillslopes drain more slowly than divergent hillslopes Drainage from convergent slopes graphs as a bell-shaped curve Drainage from divergent slopes displays higher early peak which flattens more quickly with shorter drainage time								
Soil moisture response to rainfall along different hillslope elevations	Zhu et al. 2014 Liyang County, China	• Masson Pine (hilltop) • Tea plantation (middle & upper slope)	Dystric Cambisol <0.2m and >1.5m at base	30° down to <15°	No Info. Rainfall: 1100 mm/y	No Info.	Rainfall impact on soil moisture	Rainfall small (<10mm) medium (10-50mm) & large (>50mm)	Observed data collected through automatic soil moisture monitors installed under each different landuse type and rain gauges

Green-Blue Intervention Toolbox									
Green-Blue infrastructure or intervention	Author Location of study	Landcover & land use	Soil	Slope / aspect	M.A.S.L; Precipitation (mm/y); Flow velocity	Catchment area size	Impact on flood/drought investigated	Hydrology / Flood type investigated	Method detail
under varying land use		• Meadow clover (lower slope) • Masson Pine and Magnolia forest (toe slope)		West facing				mostly during summer	installed to collect rainfall data.
Result	Soil moisture at the middle, upper and hilltop responded to different rainfall intensities in the same way, reflecting precipitation volume and intensity regardless of the vegetation landcover Soil moisture at the lower slope under meadow clover also reflected the rainfall intensity but received greater moisture than cumulative precipitation, this was repeated for medium and large rainfall events, indicating that the slope site received flow from other sites. During medium & high rainfall events soil moisture at 0.65m depths held more water than 0.6m depth indicating the presence of subsurface flow Soil moisture at the toe slope position with forest landcover recorded no response to the small rainfall events, at the medium event additional soil moisture was recorded at the 0.1-0.2m depths but less than cumulative rainfall. During large rainfall events soil moisture at the toe slope position with forest landcover responded differently depending on antecedent soil moisture. When initially dry, soil moisture at 0.1-0.2m depths increased strongly but less than cumulative rainfall. When initially wet, soil moisture at lower depths 0.4m recorded higher soil moisture and sometimes greater than cumulative rainfall indicating the presence of subsurface flow Lower and toe slope positions receive both sub and surface flows so maintenance of perennial vegetation at these areas can reduce runoff and nutrient loss								

Declaration in lieu of oath

By

Ali Cara Barrett

This is to confirm my master thesis was independently composed/authored by myself, using solely the referred sources and support.

I additionally assert that this thesis has not been part of another examination process.

Leverkusen 05/05/2023

Place and Date *Signature*