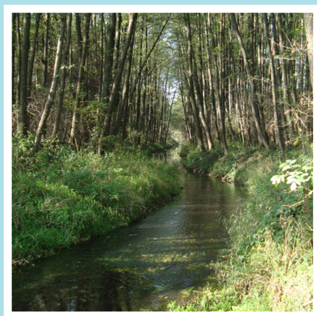
Green Infrastructure and Flood Management

Promoting cost-efficient flood risk reduction via green infrastructure solutions

ISSN 1977-8449



European Environment Agency

Green Infrastructure and Flood Management

Promoting cost-efficient flood risk reduction via green infrastructure solutions

European Environment Agency

Cover design: EEA
Cover photo: © Giulia Soriente/EEA
Left photo: © Andrei Marin/EEA
Right photo: © Polona Köveš/EEA
Layout: EEA/Alejandra Bize

More information on the European Union is available on the Internet (http://europa.eu).

Luxembourg: Publications Office of the European Union, 2017

ISBN 978-92-9213-894-3
ISSN 1977-8449
doi:10.2800/324289

European Environment Agency
Kongens Nytorv 6
1050 Copenhagen K
Denmark

Tel.: +45 33 36 71 00
Web: eea.europa.eu
Enquiries: eea.europa.eu/enquiries

Contents

Acknowledgements

Authors

This report has been managed and prepared by Gorm Dige (EEA), Lisa Eichler (Trinomics), Jurgen Vermeulen (Trinomics), Alipio Ferreira (Trinomics), Koen Rademaekers (Trinomics), Veronique Adriaenssens (Arcadis) and Dagna Kolaszewska (Arcadis).

Contributors

The EEA would like to thank the following experts for their support, comments and data throughout the development of this report: Wouter Vanneuville (EEA), Nihat Zal (EEA), Beate Werner (EEA), Stephane Isoard (EEA), Andre Jol (EEA), Birgit Georgi (EEA), Blaz Kurnik (EEA), Trine Christiansen (EEA), Sergio Castellari (EEA), Aleksandra Kazmierczak (EEA), Andrus Meiner (EEA), Ronan Uhel (EEA), Marco Fritz (Directorate-General for Research and Innovation), Julie Raynal (Directorate-General for Environment (DG Environment)), Lucia Bernal Saukkonen (DG Environment), Patrick Murphy (DG Environment), Jaroslav Mysiak (Euro-Mediterranean Center on Climate Change-Fondazione Eni Enrico Mattei), European Topic Centre on Climate Change Impacts, Vulnerability and Adaptation), Katharine Cross (International Water Association), Sander Happaerts (Directorate-General for Regional Policy), Stefan Kleeschulte (European Topic Centre on Urban, Land and Soil Ecosystems), Barbara Anton (International Council for Local Environmental Initiatives), Alberto Pistocchi (Joint Research Centre), Jelena Milos (Directorate-General for Climate Action), Guillaume Poquette (Arcadis), Dominique Van Erdeghem (Arcadis) and Werner Verheyen (Arcadis).

Abbreviations

7th EAP	Seventh Environment Action Programme
CFA	Controlled flood area
Climate-ADAPT	European Climate Adaptation Platform
DG CLIMA	Directorate-General for Climate Action
DG Environment	Directorate-General for Environment
DG Regional Policy	Directorate-General for Regional Policy
EEA	European Environment Agency
EIB	European Investment Bank
EMFF	European Maritime and Fisheries Fund
ERDF	European Rural Development Fund
ETC/CCA	European Topic Centre on Climate Change Impacts, Vulnerability and Adaptation
EU	European Union
FHM	Flood hazard map
FHRM	Flood hazard and risk map
FRMP	Flood risk management plan
GI	Green infrastructure
GIS	Geographic information system
IKSE	International Commission for the Protection of the Elbe
IPCC	Intergovernmental Panel on Climate Change
JRC	Joint Research Centre
NCFF	Natural Capital Financing Facility
NGO	Non-governmental organisation
NWRM	Natural water retention measures
PFRA	Preliminary flood risk assessment

PoM	Programme of Measures
RBD	River basin district
RBMP	River basin management plan
TEEB	The Economics of Ecosystems and Biodiversity
WFD	Water Framework Directive

Terminology

Terminology	Definition
Cost-efficiency versus cost-effectiveness	Cost-efficiency in this study refers to the maximisation of effects per unit cost of investment. In other words, we would like to know what level of protection has been achieved and possibly what other types of services the measure provides for the amount of money invested in the measure. Although the word cost-effectiveness is also often used in this context, we prefer to use cost-efficiency, as effectiveness often focuses on the extent to which a measure serves its direct purpose for the money that has been invested, while efficiency is a more suitable measure to gauge overall 'value for money', i.e. also taking into account ancillary effects per unit of investment. As green infrastructure solutions have the potential to provide multiple benefits at once, measuring cost-efficiency is more appropriate.
Flood protection measure	The report uses this broad term to refer to any measures implemented for flood prevention/protection. Measures could include a mixture of green and grey infrastructure.
Green infrastructure (GI)	In this report we will use the definition of green infrastructure of the European Commission (EC, 2013a): Green Infrastructure is a strategically planned network of high quality natural and semi-natural areas with other environmental features, which is designed and managed to deliver a wide range of ecosystem services and protect biodiversity in both rural and urban settings.
Grey infrastructure	Grey infrastructure refers to man-made infrastructure. In the context of floods, it refers to dams, dikes, channels, storm surge defences and barriers in general. It is called 'grey' because it is usually made of concrete.
Hazard	'Hazard' is defined as the 'potential occurrence of a natural or human-induced physical event that may cause loss of life, injury or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, and environmental resources' (IPCC, 2012).
Hydromorphological measure	In this report, we use the term 'hydromorphological measures' for measures that change the riverbed, the riverbanks, and the shape of the river or its sedimentary composition. All the green infrastructure measures considered in this report fall under this category. For example: re-meandering, wetland restoration, riverbed re-naturalisation.
Indirect benefits, co-benefits, ancillary benefits	In this report, the terms 'indirect benefits', 'co-benefits' and 'ancillary benefits' are used interchangeably. They refer to all benefits that can be achieved from flood protection measures, in addition to the initial flood protection objective itself. For example: biodiversity improvements, water quality improvements, opportunities for recreation.
Natural water retention measure (NWRM)	The Natural Water Retention Measures website defines these measures as: Multi-functional measures that aim to protect and manage water resources and address water-related challenges by restoring or maintaining ecosystems as well as natural features and characteristics of water bodies using natural means and processes. Their main focus is to enhance, as well as preserve, the water retention capacity of aquifers, soil, and ecosystems with a view to improving their status.
Nature-based solution	Nature-based solutions are measures designed to face a particular problem by bringing 'more nature and natural features and processes to cities, landscapes and seascapes' (EC, 2016a).
Risk	'Risk' is defined as the presence of a specific natural hazard, exacerbated by a lack of ecosystem services to mitigate the hazard, and the demand for such a service caused by the presence of exposed elements (e.g. population and infrastructure).
Sunk cost	A sunk cost is a cost that has already been incurred and thus cannot be recovered. A sunk cost differs from future costs that a business may face, such as decisions about inventory purchase costs or product pricing. Sunk costs (past costs) are excluded from future business decisions, because the cost will be the same regardless of the outcome of a decision.
Vulnerability	'Vulnerability' refers to the 'characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard' (UNISDR, 2009), or 'the propensity or predisposition to be adversely affected' (IPCC, 2012).

Executive summary

Europe's floodplains once covered wide stretches along European rivers and were valued for their high ecological importance. Over a number of years they have been cleared for agricultural purposes and changed through urban expansion and artificial flood control structures. Existing natural waterways do not always have the capacity to bear any excess water which can lead to the flooding of downstream areas. As a rough estimate, around 20 % of European cities are classified as being vulnerable to river floods. Therefore, increasing urbanisation and soil sealing, along with wetland conversion or degradation, have contributed to increased run-off and flood risk.

Green infrastructure (GI) can provide essential benefits to flood management and co-benefits to society and the economy. Evidence shows that investment in green solutions, such as landscape conservation and restoring for upstream floodplains or wetlands, is more cost-efficient and provides improved infrastructure solutions. This comes at an opportune moment as decision-makers and investors from both the public and private sectors are seeking out new, innovative and more sustainable infrastructure-based solutions to mitigate flood management. Green solutions can also provide additional benefits such as increased biodiversity, recreational opportunities, and carbon sequestration, which makes for a compelling investment case. This European Environment Agency (EEA) report looks at a number of case studies that demonstrate the effectiveness of so-called 'GI solutions'.

Limited budgets and emerging drivers, such as climate change, resource limitations, regulatory requirements, and stakeholder expectations, are pushing for low cost solutions that provide additional benefits to communities. The social, human and economic costs of flood risks and flood damage continue to be documented and debated. Making the financial case for GI, although currently less high profile, is essential.

It can be difficult to make a valid comparison between GI and grey (manufactured) infrastructure for the following reasons:

i. a focus on incurred expenses and benefits is challenging since GI often provides multiple benefits (e.g. clean water, carbon sequestration, etc.) which can be difficult to account for. Meanwhile grey infrastructure solutions typically only fulfil single functions that often reach their desired benefit levels straight after construction (but with increasing maintenance costs over time);

ii. cost-efficiency assessments of specific measures should be done on a case-by-case basis taking into account site-specific characteristics and analyses, which determine the precise cost figures and feasible combinations of green and grey infrastructure measures;

iii. comparing the benefits of green versus grey infrastructure solutions needs a comparable time horizon, which often is difficult to establish as the benefits of GI measures tend to increase over time as ecosystems adjust;

iv. the methodology of how to account for the capability of GI (ecosystems) to deliver services and other co-benefits over the lifetime of GI measures should be consistent across Europe in order to ensure comparability of valuation methods and, where relevant, monetary figures for investment decisions.

These factors show that generating an accurate and reliable comparison at EU level is challenging. This EEA report presents various options for reducing the risks of flooding with GI solutions in European floodplains and presents improved evidence for the financial justification of green investments. The findings are based on a number of case studies, whose evidence shows the benefits of GI and its potential for mitigating river floods in a cost-efficient way. The case studies indicate that the cost-efficiency ratio ([1]) of GI solutions for flood management is generally higher than for grey alternatives, and provide further economic incentives with regards to the multiple co-benefits of GI solutions. 'Wetland restoration' and 'floodplain restoration' infrastructure measures seem particularly attractive due to the high degree of flood risk protection they offer and the provision of many additional ecosystem services.

There are significant differences in scale, in possibilities to actually carry out the work, and the potential results. For instance, although projects on re-meandering and floodplain restoration necessitate a significant amount of work, their benefits in terms of flood protection and additional ecosystem services are high. A smaller-scale measure, such as streambed re-naturalisation, offers fewer options to reduce floods and fewer ecosystem services. However, the costs involved are typically lower and the feasibility of carrying out these projects is higher as they do not require land acquisitions. Streambed re-naturalisation works particularly well in combination with other GI measures. The report looks at three cases studies on the Elbe, Rhône and Vistula river basins, and points to a large potential, in terms of suitable space, for restoring floodplains alongside them. However, various technical and legislative barriers may make the implementation of such measures difficult such as conflicting land use, previous hydromorphological changes, and an unfavourable regulatory environment. This may hinder the efforts of authorities to restore floodplains in these areas.

When taking into account climate change projections the report illustrates that the economic benefits, both direct and indirect, from the implementation of floodplain restoration are potentially large. Besides being cost-efficient, such measures meet the regulatory requirements of flood protection, biodiversity conservation, water quality improvement as stipulated in the EU's Water Framework and Floods Directives. It further documents that GI can serve as an effective climate change adaptation measure such as through floodplain restoration. However, there is still a gap in translating evidence into action. For example, 23 out of 28 EU Member States have adopted national adaptation strategies or plans which include measures such as adapting building regulations and building flood defences. However, in many of these Member States, there is insufficient knowledge, experience and capacity to put adaptation into practice in various sectors. The majority of reported GI initiatives for tackling climate change adaptation and disaster risk challenges are currently focused on local level initiatives (Belgium, Bulgaria, Germany, Ireland, Poland, Portugal, Spain and the United Kingdom). Regional GI measures addressing these challenges are being implemented in Germany, Portugal, Spain and the Netherlands. On a national level, Austria, Denmark, France, Spain and the Netherlands have indicated existing GI initiatives relevant for tackling both climate change adaptation as well as disaster risk reduction.

The report also looks at GI measures in the Flood Risk Management Plans (FRMPs) under the EU Flood Directive. From screening 32 draft FRMPs covering 15 Member States, it appears that 25 of the plans differentiate the measures by type but there is no specific distinction made concerning GI measures. The reported information in the draft FRMPs for the selected four river basins (Elbe, Rhône, Scheldt and Vistula) indicate that objectives are established for flood risk management. The review also indicates that there is an increase in Natural Water Retention Measures (NWRMs) except for the Scheldt. Creating space for water through land use change and spatial planning is clearly visible for the Elbe and Rhône whereas this is not the case for Scheldt and unclear for Vistula.

The analysis further illustrates that one of the key challenges and barriers to making progress with the implementation of GI has been identified as the level of coordination between upstream and downstream areas of river basins. The current status of the harmonisation and coordination of planning instruments between FRMPs and River Basin Management Plans (RBMPs) per selected river basin, demonstrate that there is a clear need for improved coordination (in particular between upstream and downstream areas) to enhance the decision-making process, as well as the implementation of GI for flood risk management.

It is clear from the report that the implementation of the EU policy framework is strongly dependent on the organisation or governance arrangements in and between the Member States including the river basin and climate change authorities in particular.

([1]) The cost efficiency ratio in this assessment is defined as the total one-off (e.g. construction) and structural (e.g. maintenance) costs versus direct and indirect co-benefits for grey and GI solutions.

The responsible actors and financial organisation need to be well organised. Public and private actors at national, regional and local levels need to strengthen coordination and collaboration between policy domains of water management, natural capital, climate change adaptation, spatial planning and disaster management to leverage bridging mechanisms that better connect strategies, actors, etc. towards more cost-efficient and sustainable flood protection solutions. This requires a shift in thinking at national and regional levels in and between Member States as GI solutions and its co-benefits, including an analysis of cost-efficiency, should be an integrated part of flood protection planning as backed up by current EU legislation.

A potential opportunity to encourage this process is to incorporate GI assessment requirements in Environmental Impact Assessments (EIAs) and Strategic Impact Assessments (SIAs) guidance documents. This would further contribute to synergetic implementation of the Floods Directive and the Water Framework Directive (WFD), by presenting GI measures that can protect and reduce the likelihood of floods and/or impact of floods on water quality in both the FRMPs and the RBMPs. To approach the cost and benefit calculations at basin/catchment level and not just locally would be more efficient to obtain a reliable assessment of the benefits of green versus grey infrastructure to communities.

1 Introduction

In general the European Commission and the national authorities across Europe are increasingly trying to plan across sectors, realising the important cross-sectoral linkages and benefits they can gain from considering and implementing green infrastructure ([2]) (GI) solutions. It is being recognised among policy-makers in Europe that conventional technical regulation measures and interventions related to extraction, infrastructure development and intensive land use cause a decrease in multi-functionality and negative effects for the supply of the services nature provides.

Even so, infrastructure development is fundamental to economic growth, and public and private investors are continually looking for more cost-efficient and better performing infrastructure solutions. New and emerging drivers, such as resource limitations, regulatory requirements, climate change, severe weather events and stakeholder expectations, are pushing public and private investors to seek out new, innovative and more sustainable infrastructure solutions to address these challenges.

GI represents an attractive option, as it can offer cost-efficient ways of tackling these questions. Improved evidence also demonstrates that GI solutions often provide multiple co-benefits to society, such as noise reduction, carbon sequestration, recreation opportunities, flood prevention and clean water. Often these ancillary benefits are considered passive-use values and have previously not been factored in when making the financial case for GI. But it is now becoming more evident that these co-benefits make the case for investment even more compelling, as GI solutions demonstrate solid financial performance, not to mention being more sustainable, both economically and socially.

Hence, governments and investors are beginning to realise that the traditional so-called grey infrastructure solutions ([3]) (e.g. sea walls, levees, dikes, sewerage systems) are not necessarily the most cost-efficient investments to solve some of the challenges facing the European Union (EU). In many cases, GI provides more benefits than grey infrastructure, while fulfilling the same function, being equally efficient, and providing the same level of performance.

The transition towards more sustainable infrastructure solutions is also pertinent because of continued economic and financial pressures, including natural and human resource limitations, which are critical for securing continued growth in the EU. There is a need to move towards a resource-efficient, low-carbon, inclusive green economy. This concept is consistently integrated in new European strategies and directives across various sectors, for example the Europe 2020 Strategy (EC, 2010) and related flagship initiatives including the EU Resource Efficiency Flagship Initiative (EC, 2011a) and 2050 Roadmap (EC, 2011b), as well as the European Commission's Circular Economy Package (EC, 2014a) and the EU Resource Efficiency Strategy. A sound appreciation of the value and role of nature can provide a core foundation for a transition towards these sustainability objectives.

The importance of GI is also recognised in other policy domains. The Seventh Environment Action Programme (7th EAP) measures to enhance ecological and climate resilience, such as ecosystem restoration and GI, can have important socio-economic benefits, including for public health. As such, they cover the entire cross-section of all key environmental themes from natural capital-related issues to clean air and environmental health, climate adaptation, sustainable cities, and challenges surrounding efforts to move towards a green and circular economy.

To improve practical implementation of the Biodiversity Strategy (which calls for a restoration of at least 15 % of degraded ecosystems in the EU and aims to expand the use of GI) and the Nature Directives, and to accelerate progress towards the EU 2020 goal of halting the loss of biodiversity and ecosystem services, including in relation to climate resilience and mitigation, a comprehensive Action Plan for Nature, People and the

([2]) For a definition of 'green infrastructure', see terminology table on page 8.
([3]) For a definition of 'grey infrastructure', see terminology table on page 8.

Economy (EC, 2017) has been launched. This includes the deployment of EU-level GI with specific focus on projects of European interest that contribute to the goals of the Nature Directives and enhance the delivery of ecosystem services throughout the EU territory.

The European Commission has further initiated a fitness check of the Nature Directives in particular. The fitness check reveals that the Natura 2000 network alone cannot deliver the Directives' objectives. Habitat and landscape management and restoration measures through GI are needed, both within and outside Natura 2000 sites, with a view to achieving favourable conservation status of protected habitats and species. This is to ensure the coherence of the Natura 2000 network, while delivering multiple environmental, economic and social benefits through enhanced ecosystems services, such as climate change mitigation and adaptation. According to the European Commission such EU-level strategic investments in GI would have the potential to provide even greater benefits per euro invested than the current GI policy implementation and funding allocation (EC, 2017).

In addition, the 2013 European Commission Strategy on GI (EC, 2013a) underlines that GI can make a significant contribution to the effective implementation of all policies, where some or all of the desired objectives can be achieved in whole or in part through nature-based solutions. By integrating natural processes in relevant EU policy areas the aim of the strategy is to develop synergies within these areas and opportunities for cost-efficient alternatives to grey infrastructure.

The Water Framework Directive (WFD) (2000/60/EC), Nitrates Directive (91/676/EEC) and the Floods Directive (2007/60/EC) offer GI-related opportunities, for instance, by supporting actions to put in place GI to improve soil retention, provide buffer strips between agricultural production and water sources, and provide water storage during flood events. The common agricultural policy (CAP) promotes ecological focus areas to guarantee added value for the environment and contribution to the enhancement of GI. The Regional Policy 2014–2020 continues to support nature and GI through financial instruments such as the European Regional Development Fund (ERDF) and the Cohesion Fund, which contribute to several policy objectives and deliver multiple benefits, in particular socio-economic development. The EU Strategy on Adaptation to Climate Change aims to make Europe more climate resilient by ensuring the full mobilisation of GI- or ecosystem-based approaches to adaptation.

GI is thus promoted in many policy domains and makes significant contributions to the implementation of several of the EU's main policy objectives, especially as regards regional and rural development, climate change, disaster risk management, biodiversity conservation, etc. However, the above-mentioned policies and their accompanying financial instruments are vital for mobilising the potential of EU regions and cities to invest in GI.

Basically, decision-makers have to think outside the local, regional or even national box, and across different policy areas and sectors, to find the optimal path for the future.

At large, the EU has made significant progress in terms of creating a healthier and more sustainable environment thanks to the various advances in environmental legislation across most thematic areas over the past decades. Nevertheless, many environment-related challenges remain and new ones have arisen. These need to be tackled in an integrated manner (as most environmental issues are cross-cutting, affecting water, air, soil, etc.). This is urgent in particular because vulnerability to climate change and related natural hazards ([4]) has been increasing over recent decades. This is due to increasing natural hazard frequency and intensity, combined with socio-economic trends such as continued environmental degradation and urbanisation, which render our societies and nature at higher risk of exposure to the effects of climate change.

Two of the most frequently occurring and most damaging types of natural hazard in Europe are river and flash floods (fluvial and pluvial). Increased occurrence and magnitude of flooding is likely to be one of the most serious effects experienced as a result of climate change in certain regions in Europe over the coming decades. Flooding is a natural and not unusual process, with positive and negative environmental effects generating river dynamics across Europe. Floodplains, for instance, are important ecosystems and fulfil key functions for biodiversity and the hydrological cycle, but floods also have serious direct and indirect impacts and cause damage to economic activities, human health and cultural heritage.

Due to these socio-economic impacts, efforts have been made in Europe to control flooding: for example, rivers have been dammed and constrained by levees. These traditional flood defence measures have transformed the natural landscape: wetlands have been converted to

([4]) For a definition of 'vulnerability' and 'hazard', see terminology table on page 8.

agricultural and urban land use, and rivers disconnected from their natural floodplains. Grey infrastructure solutions, while tackling local flood risk, therefore often come at a sizeable, permanent cost to water absorption capacity, wildlife, fish and riverine ecosystems. Often these solutions also result in aggravated consequences of floods further downstream, due to higher or cumulating water peaks and higher water speed.

European floodplains, as a GI solution, are therefore of particular interest, as they provide a high variety of ecosystem services, which not only contribute to reducing flood risks but also provide multiple benefits to society as a whole.

1.1 Objective and overall approach

To address the challenges mentioned above and to demonstrate the benefits of GI application, this assessment **focuses on the potential for implementation of GI in European floodplains**. It addresses the vulnerability of cities to river floods, the implementation of the river basin management plans (RBMPs) and flood risk management plans (FRMPs), and the integration of GI measures. Case studies have been selected (the river Elbe in Germany, the Rhône in France, the Scheldt in Belgium and the Vistula in Poland) to analyse the available 'potential' for GI implementation.

The assessment further analyses various options for reducing risks of flooding with GI solutions (i.e. natural water retention measures (NWRMs)) ([5]), and presents evidence (although limited to four case studies) of whether or not natural solutions provide cost-efficient flood protection when compared with traditional grey infrastructure solutions (e.g. dams or dikes).

Several studies have addressed the value of nature-based solutions ([6]) for flood risk reduction, with a great focus on the restoration of floodplains. This study elaborates more on practical implementation and opportunities that Member States have to include GI measures in their RBMPs and FRMPs.

The assessment has been organised around six chapters. Chapter 2 reviews the broader challenges related to flood risk and climate adaptation, requiring improved responses, as well as questions pertaining to GI as one of the possible response tools for flood protection and climate change adaptation. Chapter 3 looks into GI and flood protection, and provides some background to the concept of GI as an environmental tool and the link to flood management. Chapter 4 provides an introduction to the cost-efficiency of green versus grey infrastructure, which is followed with case studies on advancing the understanding of cost-efficiency considerations ([7]) of green versus grey solutions for flood management. Chapter 5 reviews the potential for further GI implementation in the case study areas and identifies future opportunities for GI in European floodplains through a modelling and mapping exercise. The results and findings are brought together in the concluding Chapter 6, drawing lessons learned and recommendations for advancing the implementation of GI solutions for flood risk management.

Given the focus on large-scale solutions, the analysis concentrates on **GI measures** related to fluvial floods, floodplains, and rivers and their surrounding areas. Measures that combat pluvial flooding in urban areas (e.g. green roofs, drainage measures and sewer adaptation) are not considered, as they are typically implemented on a smaller scale ([8]).

A detailed introduction to the cost-efficiency of green versus grey infrastructure is provided in Annex 1. An overview of the methodologies used for each research question is provided in Annex 2. Annex 3 provides a matrix of the selected river basins. Annex 4 describes the detailed methodology of mapping the additional floodplain potential. Detailed case study reports are located in Annex 5, and the modelled approach for determining flood potential is provided in Annex 6.

The report complements information provided in the published European Environmental Agency (EEA) Report No 1/2016 *Flood risks and environmental vulnerability: Exploring the synergies between floodplain restoration, water policies and thematic policies* (EEA, 2016a). Box 1.1 summarises the key findings of the report that are most relevant to this assessment.

([5]) For a definition of 'natural water retention measures', see terminology table on page 8
([6]) For a definition of 'nature-based solutions', see terminology table on page 8.
([7]) For a definition of 'cost-efficiency', see terminology table on page 8.
([8]) For more information on fluvial flooding in urban areas please refer to EEA, 2016d.

Box 1.1 Purpose and main conclusions of EEA Report 1/2016 relevant to this study

Purpose

The 'Flood risks and environmental vulnerability' report provides an overview of floods since 1980 and the related social, economic and environmental impacts. The report improves the knowledge base on the subject, as a European flood impact database had not existed prior to the publication of this report. The report combines the information from the Floods Directive, mainly from the preliminary flood risk assessments (PFRAs), with information from global databases, as well as an analysis of a questionnaire completed by national authorities. The result is an overview of significant floods events and their impacts given environmental vulnerability.

Main conclusions

- What remains of floodplains can be viewed as important for nature conservation and will play a part in the aim to restore at least 15 % of degraded ecosystems and their services by 2020 under the targets of the EU Biodiversity Strategy.
- There are many examples where 'hard' infrastructure can be adapted to make better use of the natural habitat and of the landscape ecology. Even when human developments that need to be protected against flooding make it (almost) impossible to go back to a completely natural state, NWRMs can contribute to reduced flood risk and soil erosion, or improve water purification and nutrient recycling. To manage floodplains and to assist in the restoration of wetlands and alluvial areas by promoting NWRMs, synergies between different policy fields have to be explored.
- The better the coordination across the various levels of planning and management, the more attention can go to reducing vulnerability and developing integrated measures that will be sustainable over the long term. Combining efforts on the Water Framework Directive and the Floods Directive may prove to be beneficial. However, these processes can only be driven at the European level and yet need to be implemented at the river basin level. Successes in nature, water and marine policies invariably depend on progress across various sectors.
- A coordinated implementation of the Water Framework Directive (2000/60/EC), the Marine Strategy Framework Directive (2008/56/EC), the Birds ((2009/147/EC (amended)) and Habitats (92/43/EEC) Directives, the Biodiversity 2020 strategy and the Floods Directive (2007/60/EC) would help achieve a higher quality environment by using integrated solutions and, through coherent measures and actions, enhance the effectiveness of the policies. As the objectives of water and nature legislation do not contradict themselves, no obvious obstacles should exist for efficient collaboration, as shown by many examples across Europe.

In addition, this report complements information provided in the EEA Report No 15/2017 *Climate change adaptation and disaster risk reduction in Europe: Enhancing coherence of the knowledge base and policies*. The key findings relevant to this study are summarised in Box 1.2. This report also adds to the EEA Report *Urban adaptation to climate change in Europe 2016 — Transforming cities in a changing climate* (EEA, 2016d).

Box 1.2 Purpose and main conclusions of EEA Report No 15/2017 *Climate change adaptation and disaster risk reduction in Europe: Enhancing coherence of the knowledge base and policies* relevant for this study

Purpose

The EEA report 'Climate change adaptation and disaster risk reduction in Europe' explores how public policies and risk management practices can foster coherence between climate change adaptation and disaster risk reduction, and to what extent transfer of knowledge and experience from using domain-specific methods and tools can drive mutually beneficial learning and capacity building. It builds upon review, knowledge elicitation and interaction with a large number of experts and countries' representatives from both policy domains, e.g. a survey sent to the EEA member countries in early 2016 and an expert workshop in April 2016. The report also includes an updated review of past trends and future projections of selected weather- and climate-related hazards, including their economic, social (health) and environmental impacts.

Main conclusions

The overarching goal of climate change adaptation and disaster risk reduction is to build risk resilient societies. Climate change adaptation and disaster risk reduction policies and actions make use of complementary and cross-cutting methods for assessing and managing climate risks. They face similar challenges such as incomplete and uncertain knowledge base, interplay of multiple actors and limited resources.

Climate change adaptation and disaster risk reduction are among the main goals of the UN 2030 Agenda for Sustainable Development. The Sendai Framework for Disaster Risk Reduction (SFDRR) of the United Nations Office for Disaster Risk Reduction (UNISDR) and the Paris Agreement on Climate Change of the United Nations Framework Convention on Climate Change (UNFCCC) are of great relevance for European countries, as parties to these conventions.

Impacts caused by heavy precipitation events, leading to floods and landslides, have increased in Europe and are projected to increase further in the future, dependent on land use changes. The number of flood events causing large economic losses in Europe has increased since 1980, but with large inter-annual variability.

The total reported economic losses caused by weather and climate-related extremes in the EEA member countries over the period 1980–2015 was around EUR 433 billion. Weather- and climate-related, hydrological and geophysical natural hazards cause sizeable and growing financial and economic losses. The largest share of the economic impacts are caused by floods (38 %) followed by storms (25 %), droughts (9 %) and heat waves (6 %).

Insurers can contribute to enhancing societal resilience and coherence between climate change adaptation and disaster risk reduction through incentivising risk prevention, helping to improve risk understanding and knowledge, and stimulating active engagement and investment.

Both climate change adaptation and disaster risk reduction are currently mainstreamed into key EU policies and strategies, including those for critical infrastructure protection, environmental protection, financial instruments of Cohesion Policy and the EU Structural and Investment Funds (ESIF), agriculture, food and nutrition security, and integrated coastal management.

A review of the current practices suggests that, although innovative examples exist, the full potential of a better integration of disaster risk reduction and climate change adaptation has yet to be exploited. On the other hand, in many countries, climate change adaptation and disaster risk reduction are well coordinated without making this coordination effort explicit. For example, flood risk prevention strategies often make use of assessments of long-term changes in flood intensity and frequency based on climate projections.

The impacts of extreme weather- and climate-related events on human society and the environment can often be reduced using GI solutions, which are often cheaper than 'grey' solutions.

Improved processes (e.g. risk assessments) and mutually beneficial approaches (e.g. nature-based solutions) present opportunities to enhance coherence between the two policy areas. Nature-based solutions are a prime example of means to mitigate natural hazard risks and boost societal resilience to address both climate change adaptation and disaster risk reduction.

Both climate change adaptation and disaster risk reduction communities use the concept of 'resilience', and this provides common ground upon which more coherent policies and actions might be built. At a strategic level, climate change adaptation and disaster risk reduction can be better integrated through the development of long-term national programmatic approaches and could be supported by more innovative risk financing instruments.

1.2 Purpose of the case studies

As examples for illustrating the applications of GI for flood protection and prevention, six selected case studies are presented, four on GI measures and two on grey measures, focusing on:

- floodplain restoration and management (green);
- wetland restoration and management (green);
- re-meandering (green);
- streambed re-naturalisation (green);
- riverbank protection (grey);
- longitudinal barriers (grey).

The cases represent selected stretches in four river basins in Europe: the Elbe (Germany), the Rhône (France), the Scheldt (Belgium) and the Vistula (Poland) ([9]). The RBMPs and the FRMPs of these four cases are studied in detail to map completed, ongoing and planned actions by the relevant authorities to reduce flood risks in their river basin districts.

The case studies perform several functions:

- They serve as concrete case study areas for carrying out the modelling and mapping exercise to determine the potential space for additional floodplains as cost-efficient solutions for reducing local flood risk levels.
- They highlight how various green (and grey) solutions are currently integrated into RBMPs and FRMPs.
- They serve as a selection tool for determining the focus on specific green and grey infrastructure measures to be assessed during the cost-efficiency analysis.
- Finally, the official cost-benefit analyses performed for these river basins (not available for the Rhône case study) allow a direct comparison of the costs and benefits of green vis-à-vis grey infrastructure measures, as they compare the alternative options for a specific local setting (including terrain, flood risk level, socio-economic context, etc.). Summaries of cost-benefit analyses (undertaken independently by researchers or requested by public authorities) are provided in boxes in Chapter 4. Such a direct comparison of costs and benefits between green and grey infrastructure is not possible at a more general analytical level, as the extent of costs and benefits is very site dependent.

([9]) For additional information on potential case studies, please refer to the European Climate Adaptation Platform (Climate-ADAPT) (http://climate-adapt.eea.europa.eu/), which is a partnership initiative between the European Commission (Directorate-General for Climate Action (DG CLIMA), the Joint Research Centre (JRC) and other Directorates-General (DGs)) and the EEA.

2 Challenges related to flood risk requiring improved responses

2.1 Increasing risk across Europe

The demand for natural resources has grown strongly due to increasing human population and exponential economic growth and consumption, resulting in an expansion of human settlements and infrastructure, fragmentation and degradation of natural landscapes, and an alarming loss of biodiversity and ecosystem services (Cardinale et al., 2012). Economic systems and societies as a whole tend to value the potential benefits of ecosystems and ecosystem services in a limited way, adjusting land management practices towards desired outputs by maximising the benefits gained from one or some of the services (often the provision of goods), leading to the loss of multi-functionality and the degradation of natural capital at the expense of human welfare (Schindler et al., 2014).

Europe's floodplains once covered wide stretches along European rivers, with high ecological importance. Floodplains are hydrologically important and ecologically productive areas that perform many natural functions. They contain both cultural and natural resources that are of great value to society. Floodplains are beneficial for wildlife and plants and important for the protection of water quality, recharge of groundwater, natural moderation of floods, etc. At the same time, floodplain landscapes are under increasing pressure from human land use, and it is becoming more evident that floodplains are particularly vulnerable to climate change impacts and that carefully planned floodplain management is more and more necessary, with growing demand for floodplain ecosystem services (Capon et al., 2013).

However, cleared for agriculture and changed through urban expansion and flood control structures, only fractions of floodplains remain. Although homogeneous spatial data are missing on the extension and quality of Europe's remaining floodplains, examples demonstrate that their ecological importance is dependent not only on land use in the floodplain area, including its water quality, but also on hydrological regime and connectivity between water bodies and floodplains (EEA, 2016a).

Flooding is a natural and not unusual process associated with river dynamics. Across Europe and throughout the ages floods have affected human health, the environment (both positive — e.g. recovery of natural fish stocks, return of nutrients to soil — and negative effects — e.g. riverbank erosion and sedimentation, local landscape and habitat destruction), cultural heritage and economic activities (e.g. damage to property) (EEA, 2016a). Increased occurrence and magnitude of flooding is likely to be one of the most serious effects of climate change in certain regions in Europe over coming decades, and has increased over time due to changes in land use.

Climate change will continue for many decades to come, having further impacts on ecosystems and society. Improved climate projections provide further evidence that future climate change will increase climate-related extremes (e.g. heat waves, heavy precipitation, floods, droughts, windstorms and storm surges) in many European regions (EEA, 2017).

Southern and eastern Europe more frequently experience heat waves, forest fires and droughts, while northern Europe is faced with heavier precipitation and flooding, with an increased risk of coastal flooding and erosion (IPCC, 2014; EEA, 2017a). The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (IPCC, 2014) concludes with high and medium confidence that heavy precipitation events, high-temperature extremes and droughts will markedly increase, with variations, across Europe. The densely populated floodplains and cities are particularly exposed to heat waves, flooding and rising sea levels, leading to economic losses, socio-economic impacts, public health problems and fatalities.

Studies to date are still inconclusive as to what extent the observed increase in overall losses incurred during recent decades is attributable to changing climatic conditions rather than other factors. The major cause of long-term increases in economic losses from weather- and climate-related disasters has been the increasing exposure of people and economic assets (IPCC, 2014). Long-term trends in economic disaster losses, adjusted for wealth and population increases, have not been attributed to climate change, but a role for climate change has also not been excluded.

Cities in particular are at risk. The most common source of flooding in cities is when water levels in rivers rise and overtop their banks ('fluvial' flooding). Another familiar source of flooding along coasts results from a combination of high tides and stormy conditions (coastal floods). Less well known and understood are 'pluvial' (rain-related) floods. These floods occur if water is unable to drain quickly into the ground and if sewerage systems cannot cope with the amount of water. Pluvial floods often occur with little warning in areas not prone to flooding — hence the 'invisible hazard' tag. The lack of natural water retention areas in built-up districts, together with the increased frequency and magnitude of rain events due to climate change, is one of the main causes of increased risk of surface water flooding. Furthermore, floodplain areas upstream of cities have been modified over time, allowing less natural flooding during the year. In times of peak flows, this causes serious problems, as the excess of water causes quickly rising water levels.

The vulnerability of a city to flooding depends on multiple factors, not only climatological, but also local geography and morphology, socio-environmental characteristics, etc. These factors determine the vulnerability of a city to flooding. To determine the vulnerability of a city to flooding, we need to understand its changed exposure and sensitivity to flooding over time, which depend on the characteristics of cities and their population (EEA, 2016d). Various responses (adaptation measures) are possible to reduce flood risk, including decreased soil sealing, technical and natural solutions, education and awareness raising (see Table 2.1 and EEA, 2016d).

Specifically in order to encourage stakeholders and authorities to take action — beyond the implementation of the European Floods Directive — towards reducing the risk of increased flooding and climate adaptation, the European Commission encourages city action via the Covenant of Mayors for Climate & Energy, through which cities can commit to adopt local adaptation strategies and awareness-raising activities (Mayors Adapt, 2016) ([10]).

It can be seen through various events that local city characteristics (city structure) is important, as socio-economic trends such as urbanisation can exacerbate the risk (EEA, 2012a). The highest numbers of people affected by severe floods will be in areas with large population densities in flood-prone areas. This urbanisation process and associated increases of impermeable land surface, coupled with housing and commercial development of river floodplains, exacerbate flood risk in urban areas (see Annex 5 for more concrete examples of cities' vulnerability to historic flood events).

Table 2.1 Indication of factors that can increase the vulnerability of cities to flooding by rivers, and possible responses

Factors that probably increase the vulnerability of cities to river flooding		
Exposure	**Sensitivity**	**Response capacity**
Geographical location (e.g. along major river) and topography (e.g. low-lying urban areas)	Socio-economic status (e.g. high share of low-income households)	Commitment to fight climate change — awareness of and trust in the city governance structure
Increase of frequency and levels of river floods	High share of assets (commercial, residential) in potentially flood-prone areas	Financial resources for prevention and adaptation measures
High and increasing degree of soil sealing	Critical infrastructure (e.g. transport and energy) in potentially flood-prone areas	Awareness raising and education
	High population living in potentially flood-prone areas	Decreasing soil sealing

Source: Own elaboration, based on EEA report *Urban adaptation to climate change in Europe 2016* (EEA, 2016d) and technical background document for the map book *Urban vulnerability to climate change in Europe* (http://climate-adapt.eea.europa.eu/tools/urban-adaptation/introduction), produced by the EEA, the European Topic Centre on Climate Change Impacts, Vulnerability and Adaptation (ETC/CCA) and the European Topic Centre on Spatial Information and Analysis (ETC SIA) (EEA, 2015c).

([10]) It should be noted that the Mayors Adapt and the Covenant of Mayors merged under a new integrated initiative, named Covenant of Mayors for Climate & Energy, in 2015.

2.2 European Floods Directive and other responses

The EU has a 40-year record of developing its water policy. The first 25 years resulted in a patchwork of legislation, covering different human uses and parts of the aquatic environment, and putting in place quality standards and emission controls as well as monitoring and management requirements. Over the past 14 years the policy has been fundamentally reorganised as a result of the Water Framework Directive (WFD, 2000/60/EC), which entered into force in 2000. It requires river basin planning and management, and sets a very broad and ambitious long-term target for water protection — achieving 'good status' in quality, quantity and space (morphology) ([11]). Fifteen years later, marking the deadline for achieving the general objective of the WFD, i.e. achieving 'good' status for all water bodies, the challenge faced by the EU remains immense.

In view of rising flood risks, in 2007 the EU adopted the Floods Directive (2007/60/EC). The Directive compels Member States to carry out a preliminary flood risk assessment (PFRA) and identify areas of potential significant flood risk (APSFR) by 2011. Most Member States have conducted detailed flood risk analysis and produced flood hazards maps and flood risk maps (FHRMs), and have adopted FRMPs, including programmes of measures to reduce the probability of flooding and its potential consequences. They address all phases of the flood risk management cycle but focus particularly on setting objectives and implementing the necessary measures on ([a]) prevention (i.e. preventing damage caused by floods by avoiding construction of houses and industries in present and future flood-prone areas, or by adapting future developments to the risk of flooding); ([b]) protection (by taking measures to reduce the likelihood of floods and/or the impact of floods in a specific location, such as restoring floodplains and wetlands); and ([c]) preparedness (e.g. providing instructions to the public on what to do in the event of flooding).

The FRMPs give information on the risks determined, the objectives set and the type of measures implemented. Table 2.2 offers an insight as regards the available information for the selected river basins.

The Floods Directive is to be implemented in coordination with the WFD. The implementation schedule of the Floods Directive in EU Member States is given below and is coordinated with the implementation schedule of the WFD. The Floods Directive sets out clear deadlines for each of the requirements. The key milestones are listed in Table 2.3.

Table 2.2 Selected information reported in flood risk management plans of the four river basins

MS	RBD/UoM	Objectives established for management of flood risk	Increase in NWRMs ([a])	Space for water through land use and spatial planning
DE	Elbe	Yes	Yes	Yes
FR	Rhône	Yes	Yes	Yes
BE	Scheldt	Yes/No	No	No
PL	Vistula	Yes	Yes	Not clear

Note: BE, Belgium; DE, Germany; FR, France; MS, Member State; NWRM, natural water retention measure; PL, Poland; RBD, river basin district; UoM, unit of management.

([a]) The EU Floods Directive also indicates measures to improve natural water retention and how these should be considered by Member States.

Source: Own analysis.

([11]) Status definitions can be simplified to the following three elements, which determine overall water status:
([a]) **quality (chemical and physico-chemical)**, determined by the level of anthropogenic emissions, including heat, nutrients, pesticides, industrial chemicals and micro pollutants, such as pharmaceuticals present;
([b]) **quantity (hydrology)**, the flow regime and quantity of water available, which is altered by water abstraction and consumption, water level regulation (dams, weirs) or changes to natural water retention capacities (land sealing and drainage); and
([c]) **space (morphology)**, the structure of the river, its bed and riparian zone (i.e. riverbanks), which is changed by reducing available space (using floodplains for settlement or agriculture), altering connectivity of ground and surface waters (canals, culverts), the connectivity between the river and adjacent land (dikes and levees) and the up- and downstream connectivity (dams).
These three elements are the main drivers for water status, determining whether or not the WFD's objective of good ecological, good chemical and good quantitative status for the different types of waters, rivers, lakes, coastal, transitional and groundwater can be achieved.

Table 2.3 Milestones for implementation of EU Floods Directive

Issue	Deadline	Reference
Entry into force	26.11.2007	OJ L 288, 6.11.2007 Art. 18
Transposition	26.11.2009	Art. 17
Reporting format preliminary flood risk assessment	22.12.2009	Art. 11
Administrative arrangements to be in place and to be notified to the European Commission	26.5.2010	Art. 3
Cut-off date transitional measure (availability of existing tools)	22.12.2010	Art. 13
Preliminary flood risk assessment	22.12.2011	Arts 4 and 5
Public participation process starts (publication of mechanism and timetable for consultation)	22.12.2012 ([a])	Arts 9.3 and 10
Flood hazard and risk maps	22.12.2013 ([b])	Art. 6
Flood risk management plans	22.12.2015 ([c])	Art. 7
Second preliminary flood risk assessment, specific requirement on climate change European Commission's first implementation report due	22.12.2018	Arts 14.1 and 4
Second flood hazard and risk maps	22.12.2019	Art. 14.2
End of first flood risk management cycle Second flood risk management plans, specific requirement on climate change Third Water Framework Directive river basin management plans	22.12.2021	Arts 14.3 and 4
Review/update every 6 years thereafter **Reporting to the European Commission: 3 months after**		

Note: ([a]) Coordination with Article 14 (WFD) requirements.

([b]) Date of first review of pressure and impact analysis under the WFD.

([c]) Date of first review of WFD river basin management plans

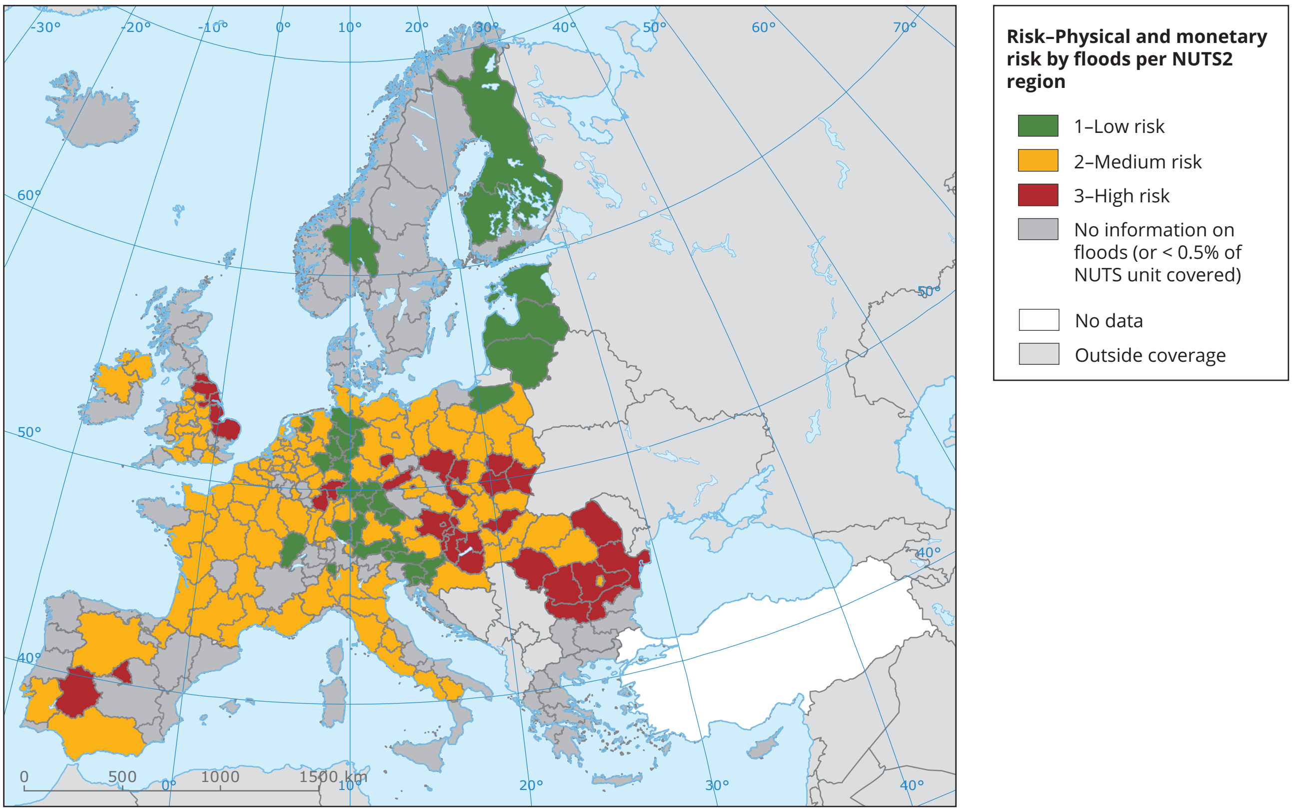
Source: Own elaboration, based on European Commission Directorate-General for Environment website (http://ec.europa.eu/environment/water/flood_risk/implem.htm).

Moreover, the EU Biodiversity Strategy to 2020 calls for further attention to natural systems to ensure that healthy ecosystems remain providers of services and benefits, such as clean water, protection from floods and soil erosion, and many more. Besides contributing to the achievement of the environmental and ecological quality objectives set by EU legislation, the 15 % restoration target and deployment of GI contribute to a range of social and economic benefits linked to flood control, water quality, health and recreation, etc. To improve practical implementation and accelerate progress towards the EU 2020 goal of halting and reversing the loss of biodiversity and ecosystem services, including in relation to climate resilience and mitigation, the European Commission has approved a comprehensive action plan (EC, 2017). Here guidance is provided for a strategic framework for further supporting the deployment of EU-level GI and its capacity to provide ecosystem services.

2.3 Flood risk management in Europe

Floods are natural phenomena but, because they affect human settlements and activity, the right measures have to be found and applied to limit their impacts on economy and society. Flood risk management aims to reduce the likelihood and/or the impact of floods. Bringing rivers back to their most natural state, by connection to the natural floodplains, would be most beneficial from an environmental point of view, but in the current socio-economic context this is not always feasible. The most effective approach is often referred to as ensuring risk management measures focus on prevention, protection and preparedness (PPP), also referred to in COM/2004/0472, the Communication on flood risk management (EC, 2004). Furthermore, the linkages/cooperation between upstream (rural) and downstream (urban) authorities is important (for example, ensuring that FRMPs take into consideration downstream flooding/impacts).

Map 2.1 Flood risk map aggregated to administrative regions (NUTS 2 level)



Source: EEA Report No 12/2015, Exploring nature-based solutions — The role of green infrastructure in mitigating the impacts of weather- and climate change-related natural hazards (EEA, 2015b).

In the recent report on nature-based solutions by the EEA (2015b), the risk of floods is looked at from a European scale per NUTS 2 region ([12]). Flood risk may change in a very short distance between locations, depending on capacity and hazard. One area showing such a complex combination of all three classes of risk is the upper section of the Rhine. More major regions at high risk of flood endangerment can be found at the Danube delta region, the central part of the Elbe in Germany, the central Rhine and the lower section of the Rhône. Map 2.1 provides an overview of flood risk at NUTS 2 scale.

The measures due to be implemented by the Member States and reported through the FRMPs should hold a variety of measures covering the PPP principles in various ways, and ensure prioritisation of measures building upon the most significant issues and using a cost-efficient approach.

Final reporting on the FRMPs is complete for 24 Member States ([13]). In most FRMPs, the plans differentiate the type of measures, but for GI this specific distinction does not seem to be made. Only a minority of the FRMPs make clear how the individual measures defined in the plans contribute to the achievement of overall objectives. These conclusions are based on observations from the draft FRMPs and the final versions submitted.

2.4 Climate change adaptation in Europe

Climate change adaptation is closely interconnected with both flood risk management and the wider topics covered by GI. GI can serve as an adaptation measure, e.g. floodplain restoration, urban green spaces to counteract the urban heat island effect, etc. The EU Strategy on Adaptation to Climate Change (EC, 2013d)

([12]) NUTS is the Nomenclature of Territorial Units for Statistics (NUTS). NUTS 2 is the category which refers to regions. NUTS is largely used by Eurostat and other European Union bodies.
([13]) The official reporting of the FRMPs can be located at: http://rod.eionet.europa.eu/obligations/603/deliveries

provides a framework including eight action points to encourage and facilitate the implementation of climate adaption measures across economic sectors and geographical areas and also to empower and complement those already taking place at national level (EC, 2016b). The EU's Adaptation Strategy aims to strengthen Europe's resilience to the impacts of climate change by:

- promoting action by Member States: the European Commission encourages all Member States to adopt comprehensive adaptation strategies and will provide guidance and funding to help them build up their adaptation capacities and take action (the Commission will also support adaptation in cities by launching a voluntary commitment based on the Covenant of Mayors initiative);
- promoting better informed decision-making by addressing gaps in knowledge about adaptation, and further developing the European Climate Adaptation Platform (Climate-ADAPT) as the 'one-stop shop' for adaptation information in Europe;
- promoting adaptation in key vulnerable sectors through agriculture, fisheries and Cohesion Policy, ensuring that Europe's infrastructure is made more resilient, and encouraging the use of insurance against natural and man-made disasters.

However, there is still a gap (and more so in some sectors than others) in translating high-level policy frameworks and evidence into action to integrate adaptation in sectoral policies and programmes at national levels. For example, as of May 2017, 23 out of 28 EU Member States had adopted national adaptation strategies or plans, which include measures such as using less water, adapting building regulations, building flood defences and developing crops that cope better in drought conditions. However, in many of these countries, there is insufficient knowledge, experience and capacity to put adaptation into practice in various sectors.

A continual cycle of awareness raising and knowledge transfer in sectors to build the capacity for adaptation is needed to equip Member States with the right tools and knowledge to mainstream adaptation (a core aim of the EU Adaptation Strategy) and take action to prepare for climate impacts. During evaluation of the EU Adaptation Strategy 2017–2018 ([14]), the European Commission will prepare an 'adaptation preparedness scoreboard' ([15]) for each Member State, including indicators for measuring Member States' levels of readiness ([16]). The scorecard will cover five steps with subsequent indicators related to the adaptation policy-making process, namely:

- preparing the ground for adaptation;
- assessing risks and vulnerabilities to climate change;
- identifying adaptation options;
- implementing adaptation action; and
- monitoring and evaluation.

A number of additional initiatives under way at EU level are concerned with various methods to increase our understanding of direct and indirect socio-economic impacts of climate change, such as ClimateCost (2016), the PESETA II project and the ESPON climate project, as well as other initiatives focused on assessing impacts on cities, development and implementation of adaptive actions, and exchange of knowledge and experiences (e.g. Covenant of Mayors for Climate and Energy). A lot of knowledge is therefore being developed to address specific aspects of the economics of adaptation.
A general problem, however, is associated with specificity of the spatial and geographical dimension of adaption, in terms of assessing vulnerability, costs and benefits of adaptation.

The urgency to properly translate high-level adaptation policy into action is clear: the costs of not adapting could be many times more expensive than the cost of taking early and well-planned action to adapt to climate change. The costs of not adapting to climate change, although associated with high uncertainties, has been estimated at an annual EUR 100 million in 2020 — a number likely to rise to EUR 250 million in 2050 in the EU (EEA, 2012a). 'Climate smart' decision-making faces many challenges and requires consideration of trade-offs, prioritisations and understanding the geographical and spatial differences in vulnerabilities and costs.

Nevertheless, climate change adaptation strategies, policies and actions, including their mainstreaming into other policies, are progressing at all governance levels

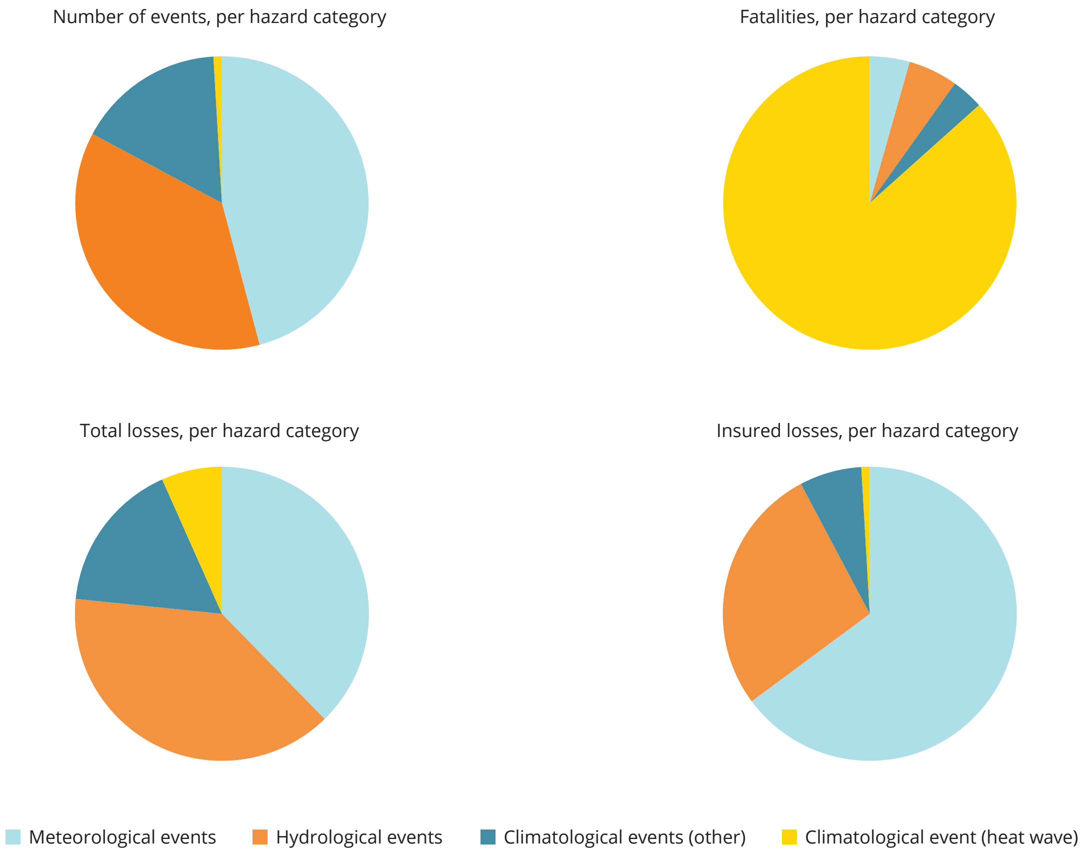
([14]) See http://ec.europa.eu/smart-regulation/roadmaps/docs/2016_clima_011_evaluation_adaptation_strategy_en.pdf for more information.
([15]) See http://climate-adapt.eea.europa.eu/eu-adaptation-policy/strategy/index_html/resolveuid/38ed3457cafb447596ddbeba2811465f for more information.
([16]) See page 3 in this document for more information: http://ec.europa.eu/smart-regulation/roadmaps/docs/2016_clima_011_evaluation_adaptation_strategy_en.pdf).

(EU, transnational, national and local levels). Further actions could include enhancing policy coherence across EU environmental and sectoral policies; effective and efficient action across all levels of governance, through multi-level governance and transnational cooperation platforms; enhancing flexible 'adaptive management' approaches; combining technological solutions, ecosystem-based approaches and 'soft' measures; involving the private sector; and placing more emphasis on 'transformational' adaptation actions as a complement to 'incremental' adaptation (EEA, 2017).

2.5 European vulnerability to climate change and related natural hazards

Vulnerability to climate change and related natural hazards has been increasing over the past decades. The IPCC's Fifth Assessment Report concludes that, globally and in Europe, climate change has led to detectable changes over the past decades in some extreme weather- and climate-related events, including extreme temperatures and, in many regions, intense rainfall. Growing exposure of people and assets to

Figure 2.1 Occurrence and damages from climate/weather-related natural disasters in Europe, 1980–2013



Note: **Geographic coverage:** Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Liechtenstein, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, United Kingdom

Definition of hazard types:
Meteorological events: storm
Hydrological events: flood, mass movement
Climatological events (other): cold wave, drought, forest fire
Climatological event: heat wave
Total values for losses and insured losses in millions of euros (2013 prices)

Source: Own elaboration based on Draft Indicator Assessment Report on Damages from weather and climate-related events (EEA, 2015a) and Munich Re (2016). See https://www.eea.europa.eu/data-and-maps/indicators/direct-losses-from-weather-disasters-3/assessment climate extremes can lead to climate-related disasters with substantial economic losses and health impacts (IPCC, 2012). Economic losses from natural hazards (climate and weather related) is high and is projected to increase further (EEA, 2016b; EEA 2017a). Growing population and economic wealth are driving the upward trend in disaster losses, which is indicative of unsound disaster prevention and protection.

Looking at natural disaster occurrence overall (including geophysical phenomena), climate- and weather-related hazard occurrence accounted for 90 % of total reported disasters (Munich Re, 2016) and around 82 % of the total incurred damages. Figure 2.1 illustrates the occurrence and resulting damages from climate- and weather-related natural disasters in Europe over the past three decades in further detail. As can be seen from Figure 2.1, Europe has been faced with a large number of storms and floods, and consequently high amounts of damages from these two types of natural disasters (EEA, 2017b).

As mentioned in Chapter 1, river (fluvial) ([17]) and flash floods (mainly pluvial) are one of the most damaging types of natural disaster in Europe. Whereas fluvial floods are triggered by heavy rainfall, melting snow in upstream areas or tidal-related influences, flash floods occur as a result of the rapid accumulation and release of run-off waters from upstream mountainous areas; they can be caused by extreme rainfall, cloud bursts, landslides, the sudden break-up of a dike or failure of flood control works (EEA, 2015b).

Growing population and land conversion/consumption also threaten to intensify flood risk, in addition to climate change. Many of Europe's large cities and conurbations are located close to major rivers in the middle or lower reaches of river basins (EEA, 2012c, 2016d). As a rough estimate, in the absence of accurate records of current flood protection measures, around 20 % of cities are classified as susceptible to fluvial floods. Progressive land use changes, such as urbanisation and soil sealing, along with floodplain development and wetland conversion or degradation, have contributed to increased run-off and flood risk (EEA, 2015b).

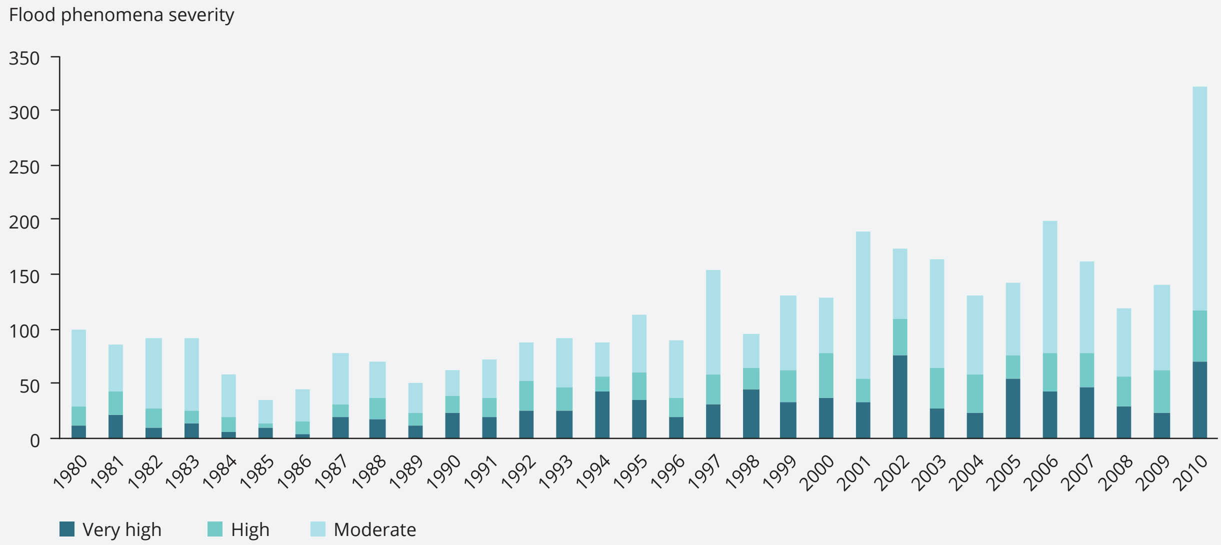
Heavy rainfall, expected to worsen as climate change progresses, swells rivers and leads to extreme flooding events, such as those experienced in 2009 and 2013 in central Europe. Extreme and catastrophic floods in Europe currently occur approximately once every 16 years, but this may increase to once every 10 years by 2050, according to new research (Jongman et al., 2014). Box 2.1 highlights hazard frequency and trends specifically for flood phenomena in Europe.

([17]) The EEA supports the distinction between sources, mechanisms and characteristics of flooding; see Guidance 29 (EC, 2013b).

Box 2.1 Increasing occurrence of floods in Europe

There is an increase in the number of reported floods, as can be seen from Figure 2.2, with a peak in 2010 (central European floods during May and June 2010).

Figure 2.2 Reported flood phenomena between 1980 and 2010



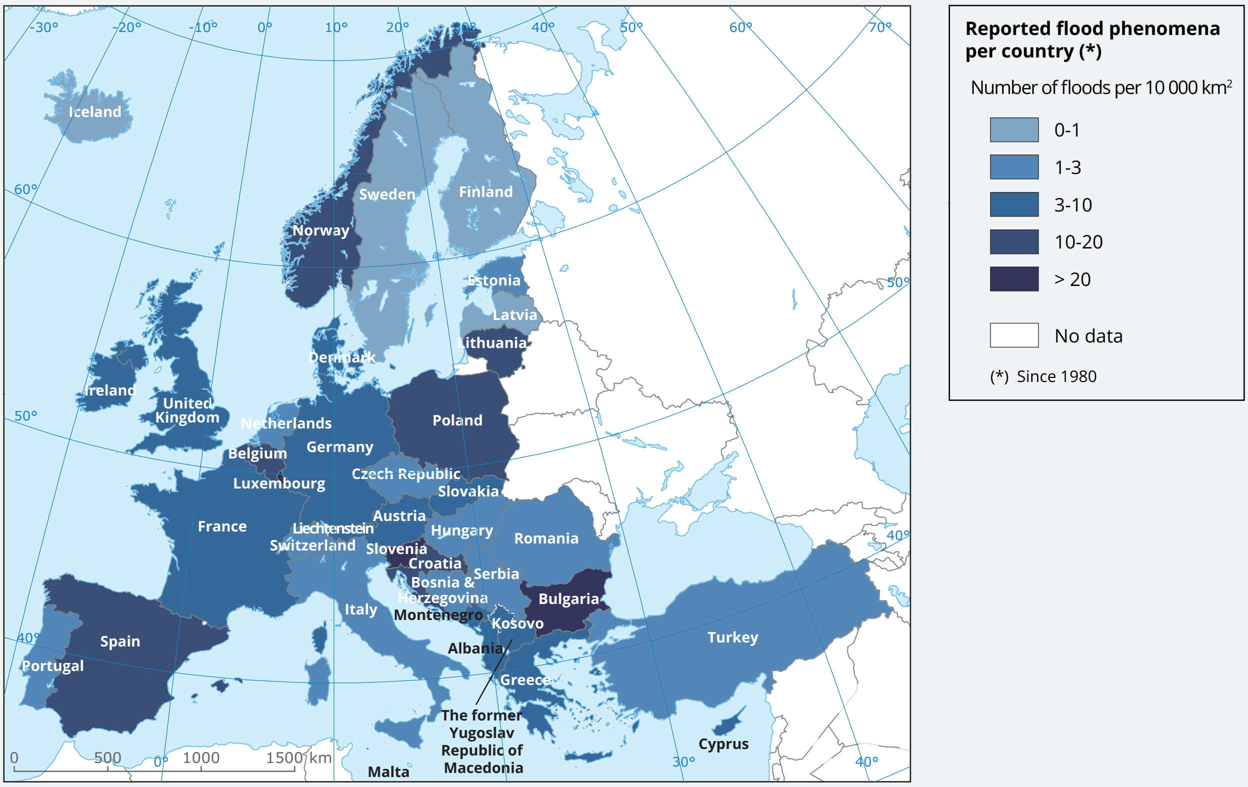
Note: Flood severity is an assessment of flood phenomena magnitude. It considers the reported values on frequency, reported total damage (in euros and descriptive classes), number of flood events within one flood phenomenon unit and severity classes as reported in the Dartmouth Flood Observatory database. E.g. all phenomena with fatalities are in the severity class 'very high'.

Source: EEA, 2016b; European past floods provided by the EEA. Dataset contains information on past floods in Europe since 1980, based on the reporting of EU Member States for the EU Floods Directive (2007/60/EC) and combined with information provided by relevant national authorities and global databases on natural hazards.

Box 2.1 Increasing occurrence of floods in Europe (cont.)

In terms of geographical spread, Map 2.2 shows the number of flood phenomena since 1980, weighted with respect to country areas.

Map 2.2 Reported flood phenomena (number of floods per 10 000 km²) per country (1980-2010)



Source: EEA, 2016c (data and maps).

2.6 Increasing costs of climate-induced natural disasters

The total reported economic losses caused by weather- and climate-related extremes in the 33 EEA member countries over the period 1980–2015 amount to around EUR 433 billion (in 2015 values). The average annual economic losses have varied between EUR 7.5 billion in the period 1980–1989, EUR 13.5 billion in the period 1990–1999, and EUR 14.3 billion in the period 2000–2009. In the period from 2010 to 2015 the average annual loss amounted to around EUR 13.3 billion ([18]). The observed variations in reported economic loss over time are difficult to interpret since a large share of the total deflated losses has been caused by a small number of events. Specifically, more than 70 % of the economic losses were caused by only 3 % of all registered events. Only around 33 % of the total losses were insured. The recent large-scale disasters, such as the 2003 heat wave that struck Paris and other European cities, the 2010 windstorm in northern Europe and the more recent 2013 flooding in Germany, show the urgency of better understanding and then adapting and preparing for such hazards,

([18]) See https://www.eea.europa.eu/data-and-maps/indicators/direct-losses-from-weather-disasters-3/assessment and Munich Re (2016) (www.munichre.com/natcatservice). The latter is one of the most comprehensive natural catastrophe loss databases, and is managed by Muniche Re, based in Munich, Germany. As a proprietary database, it is not publicly accessible. For the period 1980–2015, the entire Munich Re dataset has been made available to the EEA under institutional agreement (June 2014).

including understanding both their immediate and their long-term systemic impacts on the economy, society and the environment.

Economic losses from extreme climate- and weather-related natural disasters have increased, but with large spatial and inter-annual variability. Reported disaster losses often reflect only structural damages to tangible physical assets, neglecting damage to health, integrity of ecosystems and intangible cultural heritage. The reported losses should therefore be understood as lower-bound estimates. The changes in recorded damage are to a large extent influenced by increased economic wealth and, presumably, by improved reporting, particularly on the number of small loss events ([19]).

When considering economic losses of disaster events, flooding, along with windstorms, is the most important natural hazard facing Europe (ESPON, 2013). A recent study by Jongman et al. (2014) suggests that annual average economic losses caused by extreme floods could reach almost five times higher than 2013 values: the average annual economic losses due to flooding were expected to be in the region of EUR 23.5 billion by 2050, in comparison with the amount for the period 2000–2012 (EUR 4.6 billion annually). The study further indicates that around two thirds of increases in economic losses can be attributed to socio-economic growth, with the remaining one third due to climate change. The study also concludes that the most effective option for cost reduction would be investment in flood defences: 'An investment now of around EUR 1.75 billion could reduce estimated annual flood losses by around EUR 7 billion, an almost 30 % reduction, by 2050.'

Alfieri et al. (2016) suggest that further adaptation measures to reduce peak flow should make use of natural retention capacity upstream, while raising flood protection should be seen as a last resort, to compensate for the residual risk in areas where other options cannot be implemented.

Physical properties, such as magnitude and duration of climate- and weather-related natural events, have significant influence on the extent of damage inflicted on exposed individuals, households and economies (Chambers, 1989). The duration of recovery is also very important in estimating the economic costs of a climate change- and/or weather-related disaster (Smithers and Smit, 1997; Hallegatte et al., 2007). Studies have been published on post-disaster economic modelling aiming to better understand the consequences of natural disasters for a regional economy, and to develop prevention and recovery strategies (Bočkarjova et al., 2004; Steenge and Bočkarjova, 2007; Hallegatte, 2008).

Assessments of climate change extreme impacts have traditionally focused on the initial impact on people and assets. These initial estimates ('direct damage') are useful both in understanding the immediate implications of damage, and in marshalling the pools of capital and supplies required for rebuilding after an event. Since different economies as well as societies and ecosystems are linked, any small-scale damage may be multiplied and cascaded throughout wider economic systems and social networks, thus generating further economic, social and environmental impacts over the longer term (recovery period, etc.). This interaction of direct and indirect effects is illustrated for flood events in Figure 2.3.

([19]) Please refer to the upcoming EEA Report No 15/2017 *Climate change adaptation and disaster risk reduction in Europe: Enhancing coherence of the knowledge base and policies.*

Figure 2.3 Illustration of the total disaster footprint with direct and indirect damages

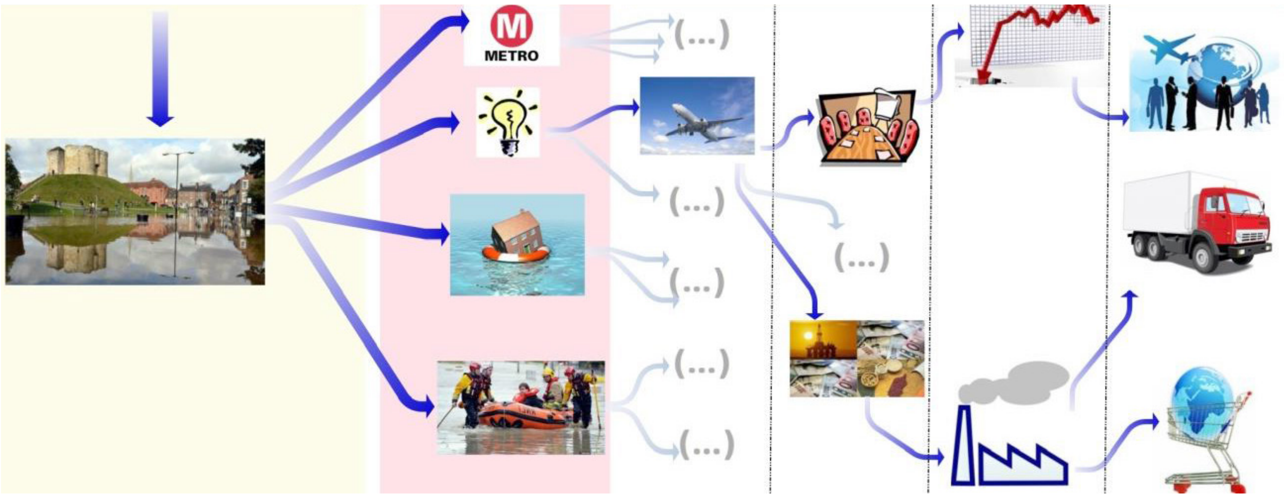
Flooding event

Direct damages

E.g. damage to houses; injuries/deaths; disruption of transport networks

Indirect damages throughout supply chain

E.g. lost working hours; wider impacts on industry and outputs regionally as well as across Europe



Source: Trinomics, 2015.

3 Green infrastructure for flood protection

3.1 An introduction to the green infrastructure concept

Healthy, resilient and productive ecosystems are a prerequisite for a smart, sustainable and inclusive economy. Ecosystem condition at a given location in Europe will determine the extent to which society can call upon nature-based solutions in full, or partial, response to the specific societal challenge(s) faced in that location, e.g. heat islands in urban areas. In the EU, as in other parts of the world, ecosystems continue to be degraded, compromising their capacity to deliver the optimum range of ecosystem services to human society (EC, 2015).

Landscapes across the EU typically comprise a mosaic of natural and man-made elements. The nature and dimensions of the various elements, or building blocks, are scale dependent. The spatial arrangement of green and grey elements has been shaped predominantly by geology, climate, nature and centuries of human intervention. However, opportunities for looking strategically at green elements in the landscape are usually greater than the use policymakers make of them.

GI can maximise the benefits from ecosystems services to society. In this assessment we will use the definition of GI employed by the European Commission:

> *Green Infrastructure is a strategically planned network of high quality natural and semi-natural areas with other environmental features, which is designed and managed to deliver a wide range of ecosystem services and protect biodiversity in both rural and urban settings. (EC, 2013a)*

A good example of GI is a healthy floodplain ecosystem which, unlike an artificial dike, not only provides flood prevention but also delivers water filtration and maintenance of the water table, as well as recreation opportunities, carbon storage, timber, areas of rich biodiversity and interconnected wildlife refuges.

The EU GI Strategy (EC, 2013c) recognises that GI can make a significant contribution to the effective implementation of a wide range of EU policies, where some or all of the desired objectives can be achieved through nature-based solutions. The strategy aims to create a robust enabling framework to promote and facilitate GI projects within existing legal, policy and financial instruments. The GI Strategy is made up of four main elements:

- promoting GI in the main EU policy areas;
- supporting EU-level GI projects;
- improving access to finance for GI projects;
- improving information and promoting innovation.

As expressed in the strategy, GI is an investment priority in the Commission's proposals for the Cohesion Fund and the ERDF. It is recognised as contributing to regional policy and sustainable growth in Europe, and facilitating smart and sustainable growth through smart specialisation.

The GI Strategy also encourages the full integration of GI into relevant EU policy objectives (regarding, for example, regional and rural development, climate change, disaster risk management, agriculture/forestry and the environment), arguing that where the desired objectives can be achieved through nature-based solutions, cost-effective GI should be prioritised over conventional grey infrastructure solutions. For instance, the 2013 CAP reform introduced a number of important greening elements that will facilitate a more coherent GI-across the rural landscape.

Furthermore, GI also offers cost-effective options for better implementing the Drinking Water Directive (EU, 1998) and the Groundwater Directive (EU, 2006). As mentioned earlier, GI is anchored in the EU's Biodiversity Strategy (EC, 2011c), which aims to ensure that 'by 2020, ecosystems and their services

Figure 3.1 Illustration of different types of green infrastructure measures applied in Europe

Source: Trinomics, 2016.

are maintained and enhanced by establishing GI and restoring at least 15 % of degraded ecosystems'. Beyond biodiversity, GI can make significant contributions to other EU policy objectives on, for example, CAP, health and climate change ([20]).

Given the wide definition of GI, measures can range from floodplains to green roofs, wildlife overpasses, urban farming and biodiversity-rich business parks. The large variety of cross-sectoral applications of GI on the one hand is an immense advantage to offer solutions to various societal and environmental challenges. On the other hand, the broad coverage also represents a certain weakness, as it is difficult for decision-makers to grasp the comprehensiveness and complexities of the topics and possible applications involved. Figure 3.1 provides a non-exhaustive visual illustration of types of GI measures that can be applied as solutions for various sectoral challenges.

GI is a spatial concept providing services at various scales. Application of GI measures can therefore range from local to regional, national and EU levels. Table 3.1 depicts the wide range of GI measures grouped by their different types of functions and their applicability on the different scales.

([20]) Please refer to the EEA Report No 15/2017 *Climate change adaptation and disaster risk reduction in Europe: Enhancing coherence of the knowledge base and policies*.

Table 3.1 Physical features of green infrastructure in relation to scale and function

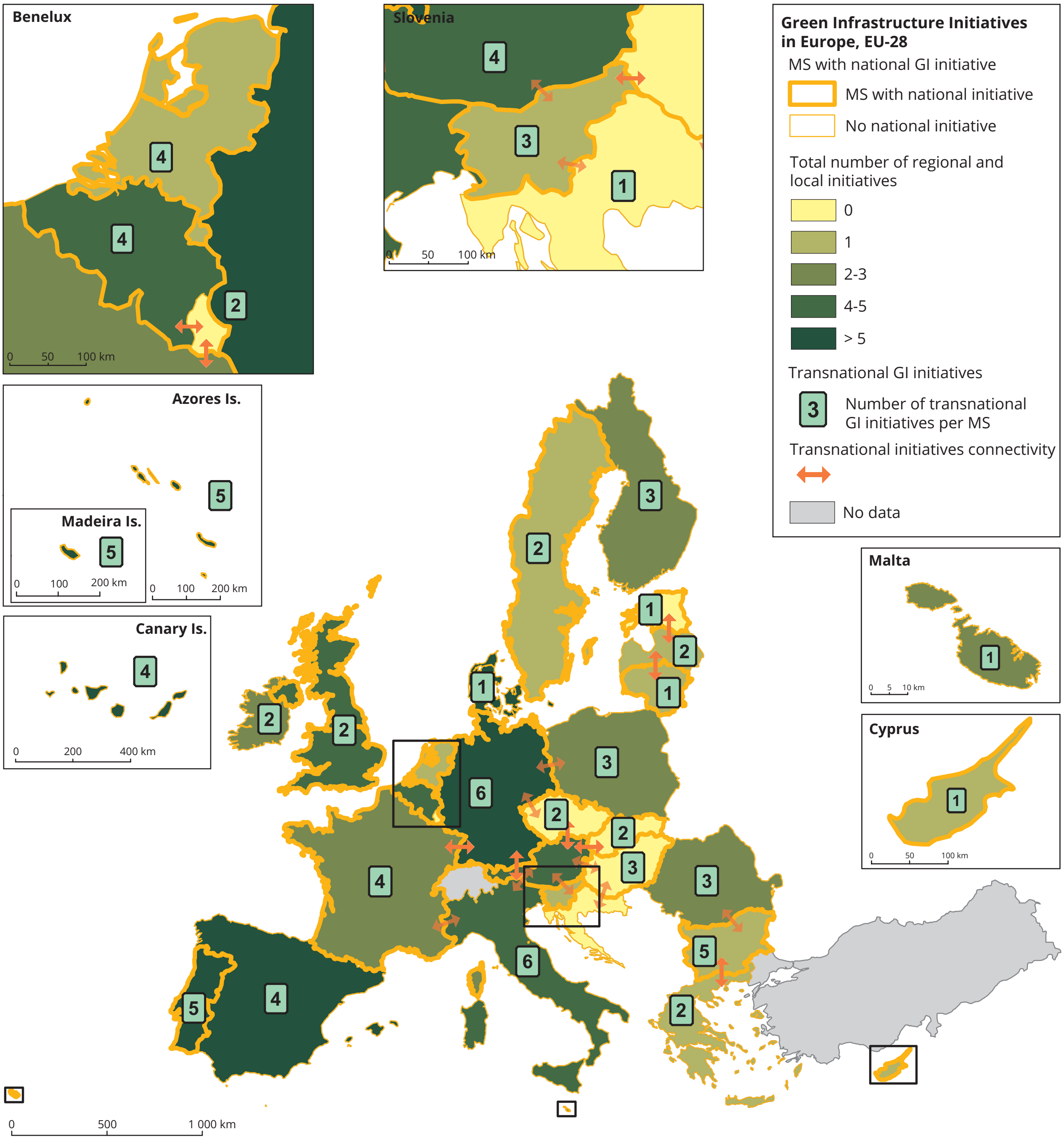
Descriptor	Local or town/city scale	Regional and national scale	EU level
Core areas — outside protected areas	Natural and semi-natural ecosystems, such as pastures, woodland, forest, ponds, bogs, rivers and floodplains, coastal wetlands, lagoons, beaches, marine habitats	Extensive agricultural and forest landscapes, large marsh and bog areas, rivers and floodplains, shorelines/coastal zones	Freshwater systems, major river basins, mountain ranges, regional sea basins
Core areas /protected areas	Local nature reserves, water protection areas, landscape protection areas, Natura 2000 sites	Regional and national parks, wilderness zones (including Natura 2000)	Ecological networks with cross-border areas, including Natura 2000 network
Restoration zones	Restored areas that were fragmented or degraded natural areas, brownfield land or disused quarries; transitional ecosystems undergoing land abandonment or regeneration processes	Restored ecosystem types	Restored landscape systems covering a substantial part of agricultural/forestry areas and industrialised sites, including cross-border areas
Sustainable use zones	High nature value farmland and multi-use forests (such as watershed forests); protection forests (against avalanches, mudslides, stonefall, forest fires); natural buffers such as protection shorelines with barrier beaches and salt marches	Extensive agricultural landscapes, sustainable forest management on national and regional levels, functional riparian systems	Transboundary landscape features on river basin or mountain range level, sustainable coastal and marine management zones related to the relevant sea basin
Green urban and peri-urban areas	Street trees and avenues, city forests/woodlands, high-quality green public spaces and business parks; green roofs and vertical gardens; allotments and orchards; storm ponds and sustainable urban drainage systems; city reserves including Natura 2000	Greenways; green belts; metropolitan park systems	Metropolitan areas with substantial share of high-quality green areas in Europe, including coherent approaches in cross-border urban zones
Natural connectivity features	Hedgerows, stone walls, small woodlands, ponds, wildlife strips, riparian river vegetation, transitional ecosystems between cropland, grassland and forests	Multi-functional, sustainably managed agricultural landscapes, riparian systems	Supra-national corridors, substantial share of structure-rich agricultural, forestry or natural landscapes
Artificial connectivity features	Eco-ducts, green bridges; animal tunnels (e.g. for amphibians), fish passes, road verges, ecological powerline corridor management	De-fragmented landscapes, improved areas along transport and energy networks, migration corridors, river continuum	European-wide or transnational defragmentation actions

Source: http://ec.europa.eu/environment/nature/ecosystems/docs/Table%203%20Gi.pdf

Map 3.1 provides an overview of reported GI initiatives across these different scale levels for the 28 EU Member States. The map depicts varying levels of GI initiatives per Member State. Orange country outlines represent the realisation of GI initiatives at national level. Projects limited to regional or local scale are visualised by shades of green for country territories, ranging from zero to six initiatives per Member State. At the highest spatial level, transboundary initiatives connecting multiple countries are described by arrow symbols at the common borders.

As can be seen from the map, cooperation and coordination not only across regional borders, but also on a national as well as cross-border level, is being initiated for various GI initiatives when such cooperation is seen as mutually beneficial. Furthermore, it should be noted that the total number of GI initiatives reported in this map is not exhaustive and the types of GI measures implemented also range across a wider spectrum.

Map 3.1 Reported green infrastructure (GI) initiatives across EU-28 by Member State (MS), 2015



Sources: EEA/ETC-ULS, 2015d, For the Green Infrastructure Implementation and Restoration Working Group, European Commission, 2015.

3.2 Knowledge and awareness of green infrastructure among decision-makers

An important barrier for furthering the implementation of GI across Europe is the lack of knowledge and awareness among decision-makers to take GI solutions into account when planning infrastructure solutions.

The EU's GI Strategy highlights the benefits that can accumulate to society from further investments in GI. Often, such investments are made only after a change in the perspective on the part of decision-makers, who appreciate that various options exist for delivering their objectives: decision-makers need to be able to appropriately consider alternatives to their 'traditional' ways of solving problems (i.e. grey infrastructure) by accounting for the multiple co-benefits of GI solutions beyond the defined immediate objective (when assessing the various costs and benefits of solution options prior to making an investment decision). Box 3.1 highlights the complexities of the GI concept that often render it difficult for decision-makers to fully understand its benefits, meaning that these stakeholders refrain from diverging from their 'conventional' infrastructure pathway. Practical demonstrations of alternative ways of delivering efficient results and appreciation of the wider benefits achieved can thus help to reduce perceived barriers to change.

Box 3.1 Highlighting the complexities of the green infrastructure concept that render it difficult to understand and act upon

Many definitions of GI have been developed (see EEA, 2011). In its 2013 EU GI Strategy, the European Commission defines GI as 'a strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services. It incorporates green spaces (or blue if aquatic ecosystems are concerned) and other physical features in terrestrial (including coastal) and marine areas. On land, GI is present in rural and urban settings' (EC, 2013c).

In addition, many countries may have had a form of GI in place for many years, but neither label it 'GI' nor see the need to evaluate it as such. For example, in their report on the design, implementation and cost elements of GI, Naumann et al. (2011) found that, of the 127 GI initiatives that they assessed, only 20 % explicitly identified themselves as GI. They concluded that, while many initiatives might cover specific purposes (e.g. re-connecting areas with high biodiversity values, restoring riparian forests to protect against floods, promoting green roofs in cities for water retention, planting hedgerows in agricultural areas for landscape enhancement/pollination/erosion control), they do not however fully consider GI's many co-benefits for other sectors, the environment and citizens, which the very same GI structure can offer if properly planned and managed. The multi-purpose character of GI, therefore, is in these instances not acknowledged or communicated, making it look less attractive as an alternative choice to conventional infrastructure.

Owing to its multi-functionality, there is no single science or discipline responsible for GI (Benedict and McMahon, 2002). The nearest integrative scientific discipline accountable for its evolution is 'landscape planning'. GI relies on the theories and practices of numerous scientific and land planning professions, such as conservation biology, landscape ecology, urban and regional planning, geographic analysis, information systems and economics.

GI has wide spread in spatial scales and its application can range from individual buildings to neighbourhoods and cities to entire regions, even across countries (see Natura 2000 network or European Green Belt). Furthermore, benefit groups are also different in scale: e.g. carbon storage by peatlands has beneficiaries worldwide, while the water retention function of the same peatland is felt locally.

The features or elements are not always simple to define and descriptions of GI can change depending on the stakeholder (Horwood, 2011). Different countries and sectors apply different standards for the same type of GI (e.g. different width or length requirements for a green bridge).

Related terminology includes landscape planning, natural infrastructure (US nomenclature), nature-based solutions, ecosystem services, natural capital, etc.

Through the adoption of the EU's GI Strategy in 2013, the common understanding of terminology and purpose of GI has made significant progress. However, the need for information sharing and communicating about GI will probably increase along with the increased deployment of GI in the EU.

The European Habitats Forum (EHF) Working Group on Green Infrastructure Implementation and Restoration has highlighted that the water sector is beginning to embrace changes and taking on a leadership role, which is reflected in the increasing use of nature-based solutions (EHF, 2015). However, even with these positive signs, GI solutions to deliver water-related objectives are still not fully mainstreamed across Europe. Stimulating such innovations across the water sector more fully would 'make a significant contribution to mitigating flood risks and conserving water resources, whilst providing support for species protection and sustainable fisheries and helping to restore biodiversity, landscape quality and ecological functionality'. The European Habitats Forum has also underlined the need to increase knowledge of nature-based solutions among decision-makers, in particular regarding the various co-benefits.

Existing tools on GI for guiding decision-makers, such as matrices or decision trees, exist on a very generic level. For example, the Joint-Industry White Paper (2013) created a table (Table 3.2) highlighting the key differences between green and grey infrastructure and illustrating the trade-offs involved when evaluating green versus grey solutions. These trade-offs help decision-makers identify the specific areas of opportunity for optimally resilient infrastructure, which can also often lead to new combinations of GI solutions integrated into existing facilities, creating so-called hybrid solutions.

Table 3.2 Evaluation of green versus grey infrastructure — decision support matrix

Evaluation criteria	Green infrastructure	Grey infrastructure
Stakeholder involvement	Extended stakeholders are often required to support the project and may have an active and ongoing role in the project's design and operation	Stakeholders are often engaged with the aim of creating local support but without actual involvement in design or operation
Engineering approach	GI solutions require a custom-made, location-specific design and do not always lend themselves to standardisation and exact replication	Traditional engineering solutions lend themselves to a certain level of standardisation, which facilitates replication and reduces project costs and delivery times
Physical footprint	A large physical footprint is often required	Typically, a small physical footprint is required
Environmental footprint	Often reduced environmental footprint due to GI solutions being nature based and self-generating	Often increased environmental footprint due to material- and energy-intensive processes
Speed of delivering the functionality	GI solutions may take time (years) to provide a certain service and capacity	Grey solutions provide the service and capacity from day 1 of operations
Operational and maintenance costs	Operating and maintenance costs are often significantly lower	Operating costs are often significantly higher due to power consumption, operational and maintenance requirements
Risk of price volatility	GI solutions are relatively insensitive to fluctuations in the cost of raw materials, oil, gas and power	Grey solutions are sensitive to fluctuations in the cost of raw materials, oil, gas and power
Approach to system monitoring and control	GI solutions are living and complex systems that can be monitored and effectively managed by a deep understanding of the key control variables	Grey solutions are man-made systems that are typically designed with established monitoring techniques
Need for recapitalisation	Recapitalisation during the life of the GI is usually not significant. The end of life replacement/decommissioning varies greatly depending on the type of GI technology but is usually not even necessary as GI solutions are self-sustaining and do not depreciate	Grey solutions are depreciating assets with a finite performance capacity and usually require significant replacement or decommissioning at the end of life

Source: Adapted from Joint-Industry White Paper, 2013.

Table 3.2 illustrates that both green and grey solutions have benefits and challenges. According to the Joint-Industry White Paper, areas of opportunity for green or hybrid infrastructure solutions often relate to:

- a means to strategically recapitalise ageing industrial infrastructure through the integration of GI solutions into existing facilities that need regular upgrading or replacement of existing equipment to provide functionality;
- an application in areas that are environmentally stressed and would benefit from improved land use, enhanced biodiversity, additional sources of water, and flood or erosion protection.

The White Paper furthermore provides decision-makers with key points to consider for a SWOT (strengths, weaknesses, opportunities, threats) analysis of GI measures, as well as an overview of the most commonly encountered perceived risk factors involved with GI solutions.

3.3 Green infrastructure implementation progress across Europe

Figure 3.2 depicts a cross-check of reported existing GI initiatives versus each Member State's primary GI objectives ([21]). As can be seen from the visualisation, no general trend patterns can be detected. While some Member States have worked solely on national-level implementation, others had only implemented local measures as of 2015. Similarly, there is a wide spread across the different types of GI measures that are being implemented, although it seems that, to date, GI measures implemented for the objectives of 'nature protection and ecological networks', 'defragmentation' and 'landscape feature function improvement' are prioritised in many Member States. However, this prioritisation also can be explained by the selection of GI measures that have been included here, which are probably those easily recognisable as 'GI', i.e. those that help defragment and build ecological networks.

The GI measures with a focus on 'climate change adaptation' and 'disaster prevention', depicted in Figure 3.2, illustrate that only a few Member States have reported ongoing progress (see summarised overview of relevant Figure 3.2 results presented in Table 3.3). Table 3.3 demonstrates that the majority of existing reported GI initiatives for tackling climate change adaptation and disaster risk challenges is currently focused on local-level initiatives (Belgium, Bulgaria, Germany, Ireland, Spain, Poland, Portugal and the United Kingdom). Regional GI measures addressing these challenges are being implemented in Germany, the Netherlands, Portugal and Spain. On a national level, Austria, Denmark, France, the Netherlands and Spain have indicated existing GI initiatives relevant to tackling both climate change adaptation and disaster risk ([22]).

Table 3.3 Member State reporting implementation of green infrastructure (GI) initiatives relevant to tackling ([a]) climate change adaptation and ([b]) disaster risk challenges

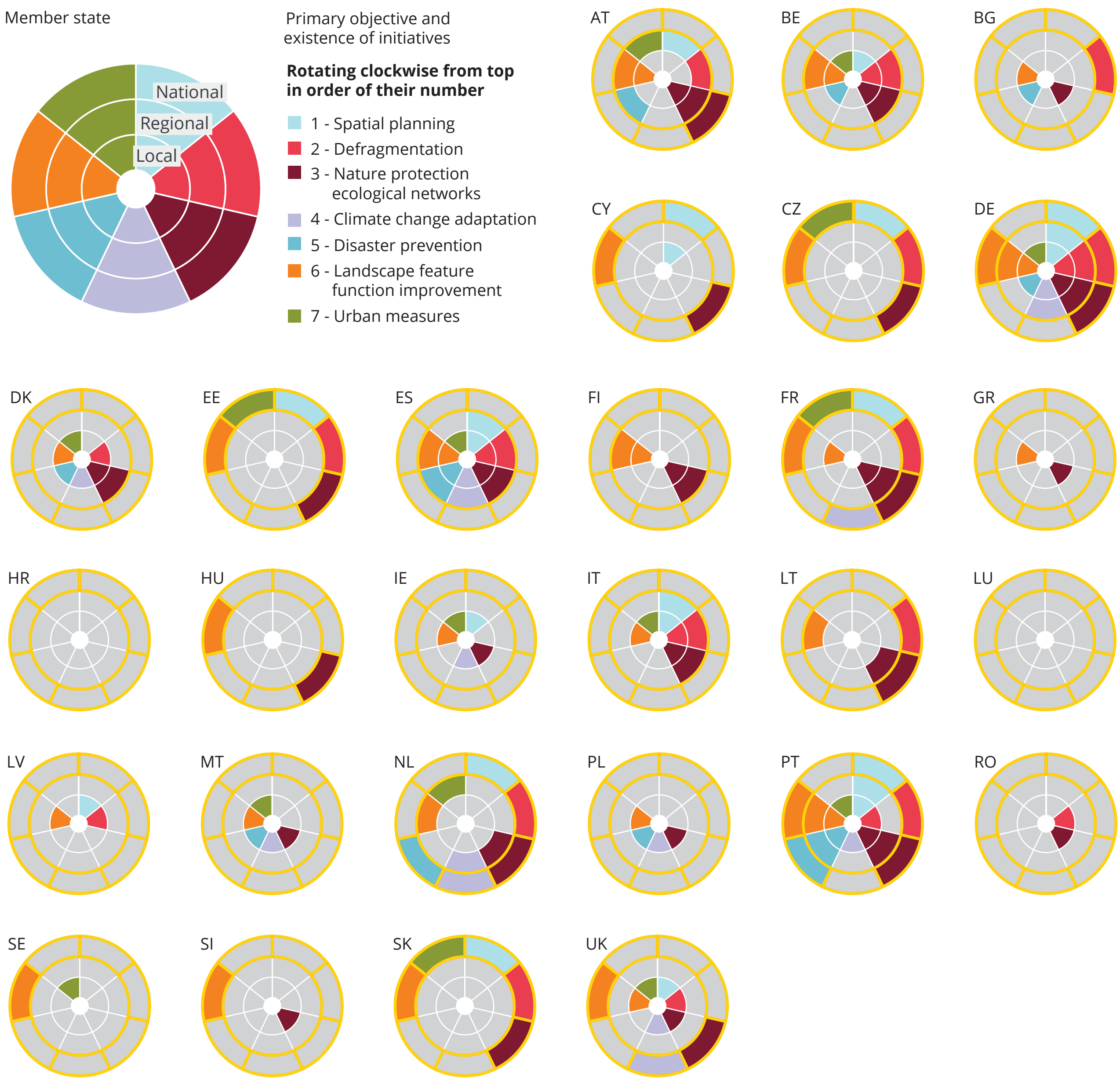
	Local level	Regional level	National level
'Disaster prevention'-focused GI initiatives	Belgium; Bulgaria; Poland; Portugal	Portugal; Spain	Austria; Netherlands; Spain
'Climate change adaptation'-focused GI initiatives	Germany; Spain; Ireland; Poland; Portugal; United Kingdom	Germany; Netherlands; Spain	Denmark; France; the Netherlands

Source: Own elaboration based on Figure 3.2.

([21]) It should be noted that in this figure does not provide a complete overview for every Member State. It represent the reported information from the national representatives to the EU Working Group on Green Infrastructure and Restoration. Projects, such as those funded under the European Cohesion Fund or the European Fisheries Fund, which may have a GI component as part of their overall project, are not captured here.

([22]) Please refer to the EEA Report No 15/2017 *Climate change adaptation and disaster risk reduction in Europe: Enhancing coherence of the knowledge base and policies.*

Figure 3.2 **Cross-check of reported existing green infrastructure initiatives versus primary green infrastructure objectives, EU-28**



Sources: EEA/ETC-ULS, 2015 (compiled for the Green Infrastructure Implementation and Restoration Working Group, European Commission, 2015).

3.4 Linking green infrastructure and flood management conceptually

Major flood events have provided renewed impetus to the development of improved policies and techniques for flood risk management across Europe. Sharing of knowledge and understanding of the practical problems, dilemmas and challenges will aid in the development and implementation of new technologies and strategies for the challenging issues of flood risk management in Europe. The importance of technical, socio-economic, environmental and policy aspects of flood risk management are of great relevance here.

Rebuilding dams and dikes after these have failed, including damaged buildings and infrastructure, is very costly. It is clear that flood protection measures such as dikes and dams are not the only solution: natural, ecosystem-based water retention measures can be very cost-effective. Not only can multiple benefits for nature and environment be generated, but investment and maintenance costs can also often be lower than those of 'hard' engineering solutions. In addition, ecosystem-based investments (such as floodplains) usually also make sense in direct socio-economic terms: they can provide new activities (tourism, eco-tourism, recreational and educational activities) and opportunities for local development and jobs. Therefore, to effectively reduce flood levels, it is important to explore nature-based options along catchments and coast lines to maximise the retention of water in soils and in wetlands, and to use temporary storage areas. This was first indicated in an EU context in the Floods Directives and then elaborated further in a note from the European Commission following major floods in 2010 (EC, 2011d).

When managing rivers, lakes and coastal areas, the best environmental options need to be identified, especially when new flood defence structures might lead to a degradation of water resources and thus hinder the achievement of the WFD objectives. An example of such an option is given by NWRMs which slow or reduce the flow of water downstream, leading to a more natural flow regime within a catchment, while allowing natural systems to store sufficient water, which makes them more resilient if periods of drought follow.

In 2012, the EU Water Blueprint Communication (EC, 2012) stressed that GI, and in particular NWRMs, should be included in the second RBMPs and first FRMPs for their potential to limit the negative effects of floods.

Following on from the Blueprint, the EU policy document on 'natural water retention measures' from 2014 — which aims to explain the policy relevance of NWRMs and to stimulate their uptake as effective tools for achieving water and related policy objectives — identifies a lack of knowledge and awareness on the potential costs and benefits of NWRMs, and the complexity of implementation, as the main hindrances to the wide implementation of such measures (EU, 2014).

In this respect, the European Commission's pilot project (www.nwrm.eu) is expected to be valuable in supporting the uptake of NWRMs in RBMPs and FRMPs, and in contributing to the achievement of a more widespread implementation by helping shed light on the contexts in which NWRMs may provide multiple and additional benefits — as compared to other measures — in a cost-efficient way. The JRC study 'Evaluation of the effectiveness of Natural Water Retention Measures' brings in more knowledge and supports implementation (EC, 2012). A typical hindrance for the implementation of NWRMs is limited financial resources. In this respect, measures such as integrating financial resources available from different sources, improving coordination between planning processes across different policy areas, or developing financial incentives and payment schemes facilitating NWRMs to deliver the multiple benefits it can provide, is lacking.

3.5 Overview of available green infrastructure measures for flood risk reduction

The pilot project on NWRMs provides a comprehensive mapping of available GI measures and was developed to provide a standardised classification of typical GI measures that can be applied as alternatives to traditional forms of infrastructure. This study uses the NWRM catalogue of GI measures as a starting point for the analysis of available solutions for flood protection management. NWRMs cover a wide range of actions and land use types.

Many different measures can act as NWRMs, by encouraging the retention of water within a catchment and, through that, enhancing the natural functioning of the catchment. NWRMs are measures that aim to safeguard and enhance the water storage potential of landscape, soil and aquifers, by restoring ecosystems, natural features and characteristics of water courses, and by using natural processes. They are adaptation measures that use nature to regulate the flow and transport of water so as to smooth peaks and moderate extreme events (floods, droughts, desertification, salination). They reduce vulnerability of water resources to climate change and other anthropogenic pressures and are relevant in both rural and urban areas.

In order to distinguish the many different actions that can function as NWRMs, this study has grouped the measures by sector (i.e. hydromorphological, agricultural, forestry and urban measures). For each of the four sectors a catalogue of measures have been identified as NWRMs, each provided with a number listed in Table 3.4. Under each measure a long list of benefits are mentioned, each of these also provided with a number that can be located in the NWRM catalogue ([23]). Only two that are related to flood management have been selected for this assessment, as mentioned in Table 3.4, i.e. ES7 (ecosystem service on 'flood risk reduction') and PO9 (policy objective on 'take adequate and coordinated measures to reduce flood risks'). The list of benefits is further divided into levels of 'high' or 'medium' impacts. Table 3.4 presents a selection of those NWRMs scoring either 'high' or 'medium' for ES7 and PO9.

([23]) For more information see: http://nwrm.eu/measures-catalogue

Table 3.4 Selected natural water retention measures (NWRMs) considered relevant for this study

Code	Name of sector/measure	Possible benefits with levels (high and medium)	
		ES7 — Flood risk reduction	PO9 — Take adequate and coordinated measures to reduce flood risks
Hydromorpholigical sector			
N01	Basins and ponds	High	High
N02	Wetland restoration and management	Medium	Medium
N03	Floodplain restoration and management	High	High
N04	Re-meandering	High	High
N05	Stream bed re-naturalisation	Medium	Medium
N06	Restoration and reconnection of seasonal streams	Medium	High
N07	Reconnection of oxbow lakes and similar features	Medium	High
N08	Riverbed material re-naturalisation	Medium	Medium
N10	Natural bank stabilisation	Medium	Medium
N11	Elimination of riverbank protection	High	Medium
N12	Lake restoration	Medium	Medium
N14	Re-naturalisation of polder areas	Medium	High
Agricultural sector			
A01	Meadows and pastures	High	High
A02	Buffer strips	High	High
A04	Strip cropping	Medium	High
A05	Intercropping	Medium	High
A08	Green cover	High	High
A09	Early sowing	High	High
A10	Traditional terracing	Medium	High
A11	Controlled traffic farming	Medium	High
A12	Reduced stocking density	Medium	Medium
A13	Mulching	Medium	Medium
Forest sector			
F02	Maintenance of forest cover in headwater areas	High	High
F03	Afforestation of reservoir catchments	Medium	High
F04	Targeted planting for 'catching' precipitation	Medium	Medium
F05	Land use conversion	High	High
F10	Coarse woody debris	Medium	Medium
F13	Overland flow areas in peatland forests	High	High
Urban sector			
U01	Green roofs	Medium	Medium
U03	Permeable surfaces	Medium	High
U04	Swales	Medium	High
U07	Soakaways	High	High
U08	Infiltration trenches	High	High
U09	Rain gardens	High	High
U10	Detention basins	High	High
U11	Retention ponds	High	High
U12	Infiltration basins	High	High

Note: The NWRMs have been selected from the overall NWRM catalogue based on the measures' scores towards contributing to either ES7 (ecosystem service function reducing flood risk) or PO9 (policy objective of coordinated measures towards reducing flood risk).

Source: NWRM benefit tables, available at: nwrm.eu/catalogue-nwrm/benefit-tables

Box 3.2 Examples of water-related functions of green infrastructure

Examples of water-related functions of GI include NWRMs, which are multi-functional measures that aim to safeguard water resources using natural means and processes, for instance by restoring ecosystems and changing land use to regulate flow and water quality. NWRMs provide multiple benefits, including reducing risks of flooding and water scarcity, and improving water quality, groundwater recharge and habitats. NWRMs can be applied in several types of area, such as water bodies and wetlands (floodplain reconnection, wetland restoration), urban areas (artificial infiltration of e.g. stormwater, green roofs), agricultural land (green cover, buffer zones), as well as forestry and semi-natural areas (meadows, riparian, woodland). Another example is integrated constructed wetlands (ICWs), artificial wetland systems that assist in wastewater treatment. Although artificial wetlands systems require more space than traditional wastewater management, they offer multiple benefits that go beyond water purification capacities (e.g. carbon sequestration and preserving biodiversity).

As illustrated by Box 3.2, GI can have many water-related functions, which is why not only hydromorphological ([24]) measures are relevant as potential infrastructure solutions for reducing flood risks. Other measures (e.g. forestry, agricultural and urban solutions) are also considered, although the primary focus will be on the hydromorphological solutions because they are highly related (and applied) to river basins. In addition, hydromorphological measures are often the most natural alternatives to typical (grey) flood protection infrastructure measures.

3.6 Contributions from EU funds for implementing green infrastructure for flood protection

GI projects can currently apply for (partial) funding from five European Structural and Investment Funds (the ERDF, the Cohesion Fund, European Social Fund, European Agricultural Fund for Rural Development and the European Maritime and Fisheries Fund (EMFF)). These funds operate under shared management, and it is largely up to the Member States to decide whether or not GI measures are used within the possibilities of the partnership agreements and operational programmes negotiated with the European Commission. For the 2014–2020 period, the European Commission has urged for openings for GI, but Member States are free to use these options. One issue with the currently available data and reporting format is that they do not allow for identifying what percentage was spent on GI-relevant measures. These factors represent a clear limitation as to how much impact the listed available EU funds may or may not have in contributing towards the implementation of GI across Europe.

In contrast, projects funded under other EU instruments, such as Horizon 2020 and LIFE, which are managed directly at EU level, can be influenced in terms of the percentage of GI funding. In addition, the European Investment Bank (EIB) has in 2014 launched the new Natural Capital Financing Facility (NCFF), which aims to 'demonstrate that natural capital projects can generate revenues or save costs, while delivering on biodiversity and climate adaptation objectives' (EC, 2016c). Under the NCFF, the EIB will provide loans and investments in funds to support projects (mainly a pipeline of replicable, bankable operations that will serve as a 'proof of concept' and demonstrate the attractiveness of such operations to investors) in Member States that promote the preservation of natural capital (including GI projects).

([24]) For a definition of 'hydromorphological', see terminology table on page 8.

Table 3.5 EU funds' contribution to relevant implementation-focused projects covering aspects of GI for flood protection, 2007–2013

	Total EU funded (EUR)	Average annual EU contribution (in nominal values) EUR	% Share
LIFE	142 380 810.00	20 340 115.71	99
ERDF	1 633 021.00	233 288.71	1
EMFF	43 842.00	6 263.14	0
Total	144 057 673.00	20 579 667.57	100

Note: Only those projects focused on GI implementation have been included in the calculations, and not those focused on research, innovation or communication.

Source: Own calculations based on data available for EU funds ([25]).

The figures in Table 3.5 provide a rough estimation of the amount of funds that have been spent on relevant GI projects contributing towards improved flood risk management in the programming period 2007–2013. As can be seen from Table 3.5, over the last programming period (2007–2013) EU funds supported flood-related GI implementation with more than EUR 20 million annually. The vast majority of the EU budget for flood protection-related GI implementation during the 2007–2013 funding period was spent via LIFE projects.

Figure 3.3 depicts this total amount split across the different types of GI measures for flood risk management. As can be seen from Figure 3.3, hydromorphological measures such as wetland restoration, floodplain restoration and re-meandering, have received most of the EU funding. Similarly, the restoration of meadows and pastures has received considerable funding. For some very specific measures, such as riverbed material restoration, there have been many fewer projects receiving EU support.

([25]) The following methodological consideration were taken into account when deriving estimations:

LIFE: To calculate the amount of funding allocated to GI projects within 2007 and 2013, the database of LIFE projects has been used. In the directory of projects, the search function allows filtering projects according to the date funding was awarded, and by themes and sub-themes. Projects financed in the period 2007–2013 (inclusive) for all themes (and sub-themes) that potentially encompass GI projects have been selected:

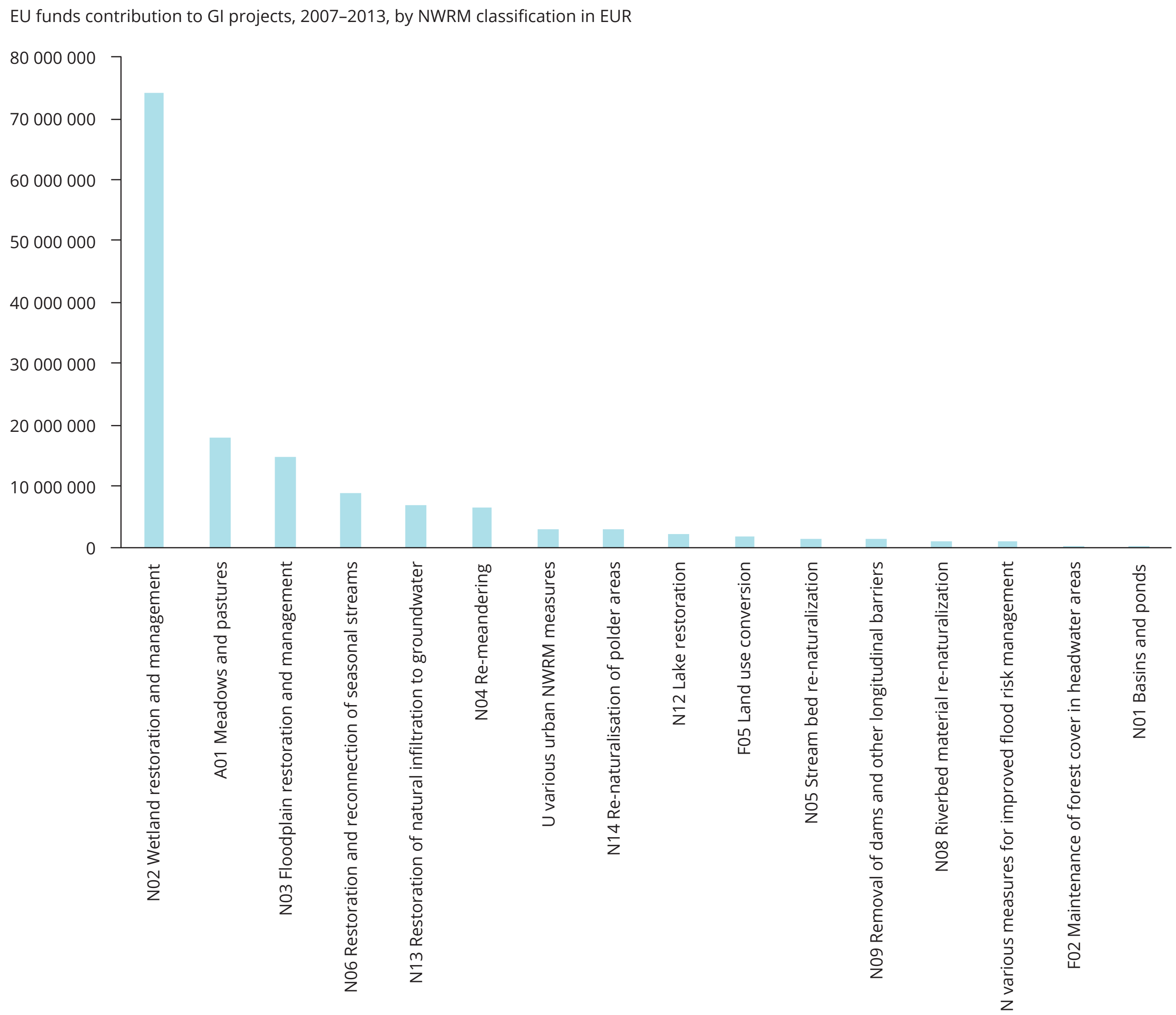
- biodiversity issues (with sub-themes: ecological coherence, high nature value farmland, invasive species, urban biodiversity);
- land use and planning (with sub-themes: soil and landscape protection, sensitive and protected areas management, spatial planning, urban-rural design, forestall management);
- water (with as sub-themes: river basin management, water quality improvement, water resources protection);
- climate change adaptation;
- habitats (with sub-themes bogs, coasts, forests, freshwater, grasslands, marine, heaths).

With the filtering option the website provides, Excel sheets for these topics were downloaded. Subsequently, Excel sheets covering 'what is GI (and what it is not)' were filtered. This obviously involved, to a certain extent, subjective judgement. The result is an Excel spreadsheet of over 700 projects (filtered from thousands of projects). In turn, only those relevant for water-related GI and climate adaptation have been considered for this estimation.

ERDF, Cohesion Fund and European Social Fund: the Directorate-General for Regional Policy (DG Regional Policy) website provides a database of hundreds of thousands of projects and the amounts awarded by these funds over the years (in combination, rather than individually for each fund) across Member States. The site allows filtering projects by period and theme, and for this estimation projects under the themes 'environment', 'rural development' and 'urban development' were selected. For the period 2007–2013, each of the themes highlights hundreds of projects supported by these funds. All were reviewed and the ones considered to involve GI were retrieved, along with the total EU contribution to each project. For other less obvious themes, a keyword search was performed for 'biodiversity', 'green infrastructure', 'green', 'infrastructure', 'ecological', 'conservation' and 'restoration'.

European Maritime and Fisheries Fund (EMFF): The European Commission provides an overview of the recipients of EU funding for activities involving fishing and fisheries. Yet this overview consists of links to sites on the topic managed by each of the Member States and authorities therein. There are significant differences in the degree of coverage and detail, and in the ways in which the information is presented. Moreover, each site is available only in the relevant national language. The approach followed has been to access each of those sites to obtain an overview of the projects funded between 2007 and 2013 in which the title of the project can provide hints of whether or not it can be considered a GI project.

Figure 3.3 Contribution of EU funds to relevant implementation-focused GI projects (2007–2013), by natural water retention measure (NWRM) classification



Source: Authors' own calculations based on data available for EU funds.

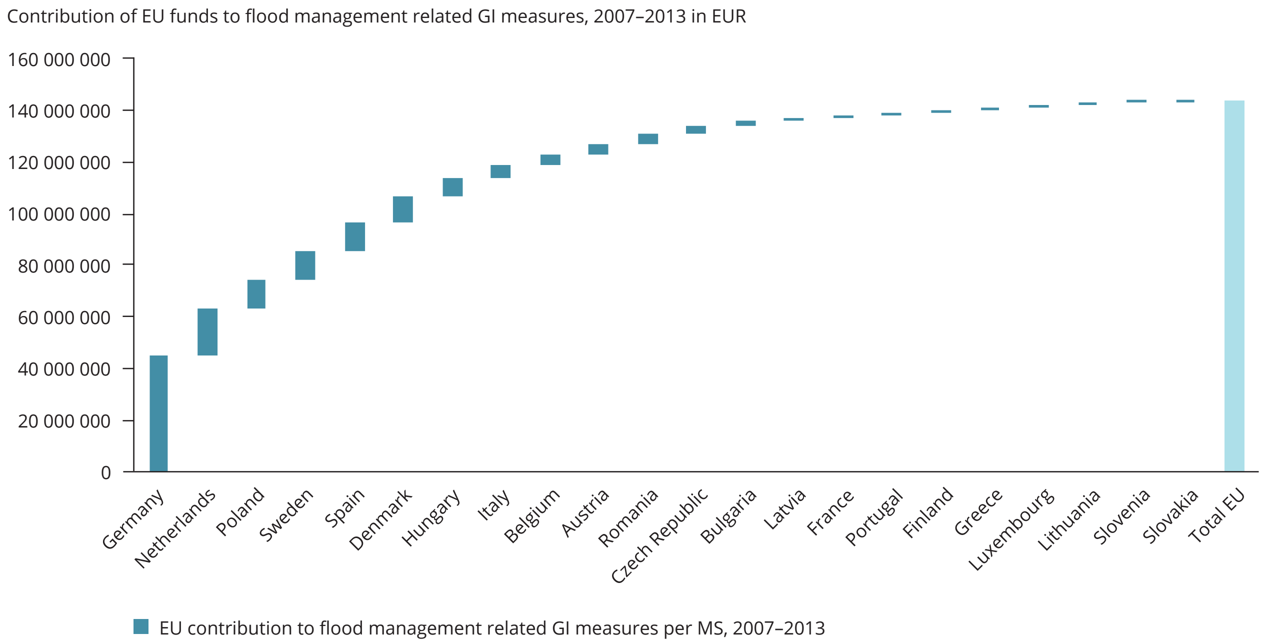
As regards the distribution of the implemented EU funding budget across Member States, Figure 3.4 indicates that Germany, the Netherlands, Poland, Sweden, Spain, Denmark and Hungary have been implementing the largest volume (in terms of EU budget) of GI projects relevant for flood risk management.

There is a wide variety of funds available, which mirrors the wide cross-sectoral applicability of GI solutions. The review indicates that there is a certain amount of EU-level funding available for GI that is being assessed. However, the available funds are spread across the various EU funds and they often provide only indirect indications as to whether or not a GI project is eligible.

This creates a rather large barrier between the available funds and the implementers on the ground, who do not necessarily know of their existence. The lack of (easy access to) finance has also been identified by experts ([26]) as a specific challenge for restoring

([26]) Interviews with Pieter Pollard (15 September 2014) and Pierre Strosser (25 September 2014).

Figure 3.4 **Contribution of EU funds to flood risk management-related GI measures (2007–2013), by Member State**



Note: GI, green infrastructure; MS, Member State.

Source: Authors' own calculations based on data available for EU funds.

floodplains and for improving hydromorphological conditions affected by existing grey infrastructure, such as dams and dikes.

This issue can be tackled in two ways:

- by reviewing the current funding approach and considering the possibility of either increasing the clarity of eligibility criteria or pooling all GI-related budgets under a dedicated fund; or
- by investing in awareness-raising and capacity-building efforts at Member State, regional and local level to better equip GI implementers with the know-how they need.

Interviews with implementers ([27]) have furthermore indicated that, even if EU funds can be accessed, one of the critical details posing a real barrier to effective GI implementation is the fact that the salary for a project manager is often not eligible as part of the project funding budget. This prevents many of the projects from being implemented, as local implementing agencies (e.g. non-governmental organisations (NGOs)) cannot afford to have a full-time manager focus on GI project implementation and fund him or her out of their own budgets.

In conclusion, it remains to be assessed whether or not the overall EU funding for GI is adequate. But what is clear already is that even the funding currently available is not optimised in terms of how (and whether or not) it is spent on GI projects, because the available funding is spread across various EU funds, without being clearly and specifically dedicated to GI.

([27]) Interviews/conversations with representatives of the EU Working Group on Green Infrastructure Implementation and Restoration, as well as during the workshop 'Development of a European defragmentation map for ecological and migration corridors due to the national and international transport network' on the island of Vilm (23–26 March 2015).

4 Cost-efficiency of green versus grey infrastructure solutions for flood management

4.1 Introduction

To provide a comparative review of the cost-efficiency of green versus grey infrastructure measures in the EU there is a need to collect evidence on the costs and effects of individual measures, and to provide insights into the relative advantages and disadvantages of green versus grey solutions.

A key determining factor for the magnitude and type of costs and benefits incurred for the realisation of green or grey infrastructure measures is the characteristics of the location and wider area in which the measures are planned, namely:

- the degree of urbanisation (which has a large effect on the cost of land);
- soil and hydromorphological characteristics (which have a direct effect on construction costs and the type of project needed);
- geographical location in the river-basin (more upstream or downstream); and
- local price levels, which are examples of factors that can differ strongly from region to region and have a large impact on the precise level of costs and benefits expected from infrastructure measures.

Flood prevention infrastructure measures (especially green measures) are hardly implemented in isolation, since their effectiveness increases when multiple measures are combined in a project. This makes their individual benefits (in isolation) difficult to judge when they are not modelled in the overall infrastructure project. Moreover, the marginal costs of a single GI measure can also decrease with the number of other GI measures implemented in the same project, as certain overall costs can be shared across a larger number of measures. An accurate ranking of green, grey and hybrid infrastructure solutions is therefore only possible at a site-specific level.

Comparing benefits of green versus grey infrastructure solutions is difficult without a fixed time horizon, as the benefits of GI measures tend to increase over time as ecosystems adjust. In contrast, grey solutions often reach their desired benefit level immediately after construction. These factors show that generating an accurate and reliable comparison at EU level is challenging.

As the availability of detailed and comparable cost and effect data is scarce, the analysis will focus only on a number of representative green and grey infrastructure measures (see Annex 1 for the description of types of costs and effects considered in the analysis). The relevant selection of GI measures is based on the NWRM catalogue (NWRM, 2016c) of GI measures, which classifies the measures into agricultural, urban, hydromorphological and forest categories. For this analysis the selection considers a list of hydromorphological infrastructure measures that are close to their grey alternatives in terms of application (situated near rivers). Four GI measures are selected for more detailed review, namely:

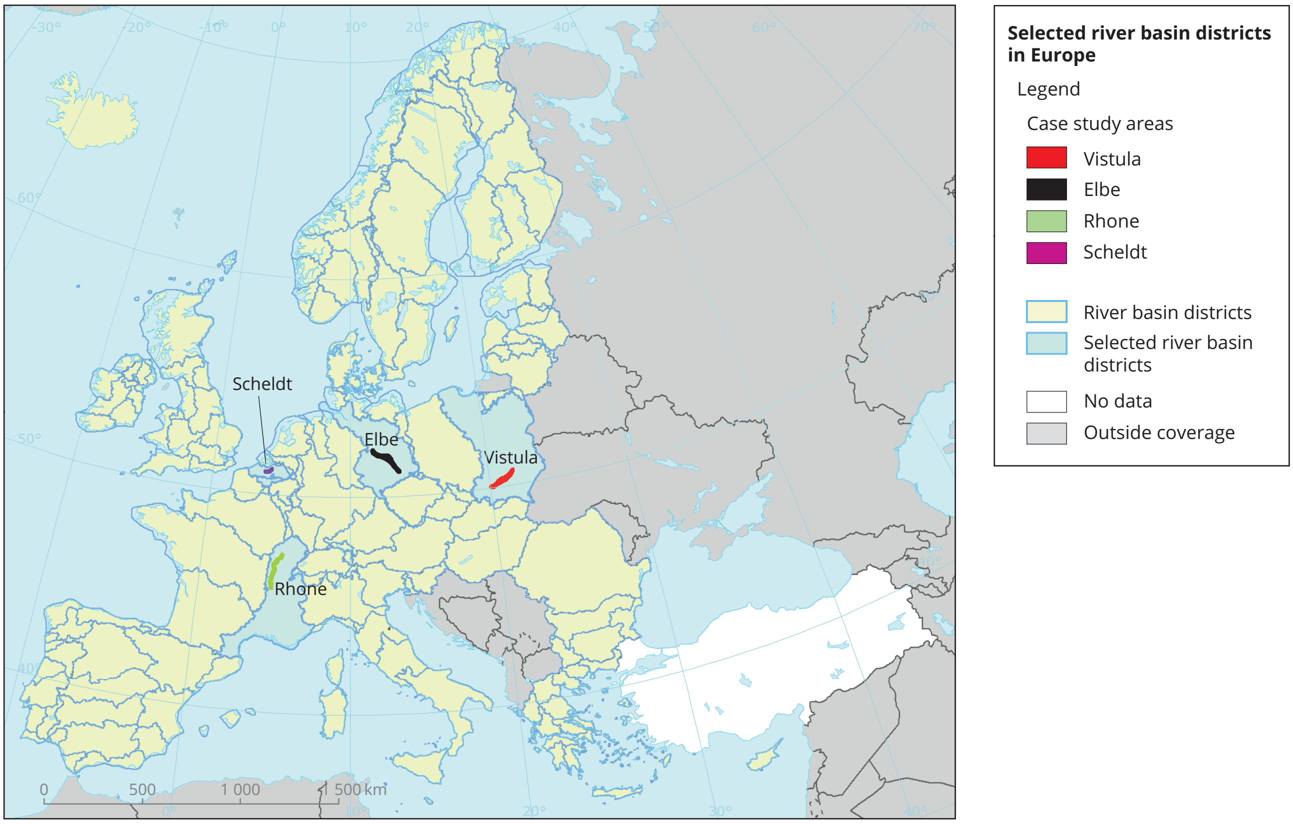
- wetland restoration and management;
- floodplain restoration and management;
- re-meandering;
- stream bed re-naturalisation.

For grey infrastructure, different types of measures can be envisaged, depending on the specificities of the location (see Annex 1). Two grey measures that are large scale and present in the case study areas have been selected for in-depth analysis (and will be compared with the GI measures outlined in Annex 1):

- riverbank protection (dikes, floodwalls);
- longitudinal barriers (dams, storm surge barriers, breakwaters).

These grey infrastructure measures are based on a list of representative grey flood protection infrastructure solutions (see Annex 1), acknowledged by the Working Group on Floods (WGF) under the Common Implementation Strategy of the Water Framework Directive and the Floods Directive. Here their scale and

Map 4.1 Selected river basin districts in Europe



Note: RBD, river basin district.

Source: Arcadis, based on EEA data, 2016.

presence were assessed in the selected case study areas (WGF, 2012).

In the following sections, the four selected GI measures and the two grey infrastructure measures mentioned above are reviewed in the case study areas: the Elbe in Germany, the Rhône in France, the Scheldt in Belgium and the Vistula in Poland (Map 4.1). The analysis provides insights into the cost-efficiency of the selected flood protection measures. Additional information on the cost-efficiency approach applied in the case studies is further elaborated in Annex 1 ([28]).

For more information on the case study areas in the selected river basins, Annex 5 provides a detailed description of each case study based on flood risk, the vulnerability of the main city of concern and the existence of FRMPs and their current status of implementation, as well as an overview of current coordination between upstream and downstream areas. Box 4.1 provides a synthesised example for the Elbe river in Germany.

([28]) Annex 1 provides information on the general categorisation of costs and effects, including a description of the types of direct and indirect effects considered. A more in-depth description of the selection of the relevant green and grey infrastructure measures, and how the cost-efficiency comparison is carried out, is also provided in Annex 1.

Box 4.1 Elbe river in Germany

1. Identification of flood risk

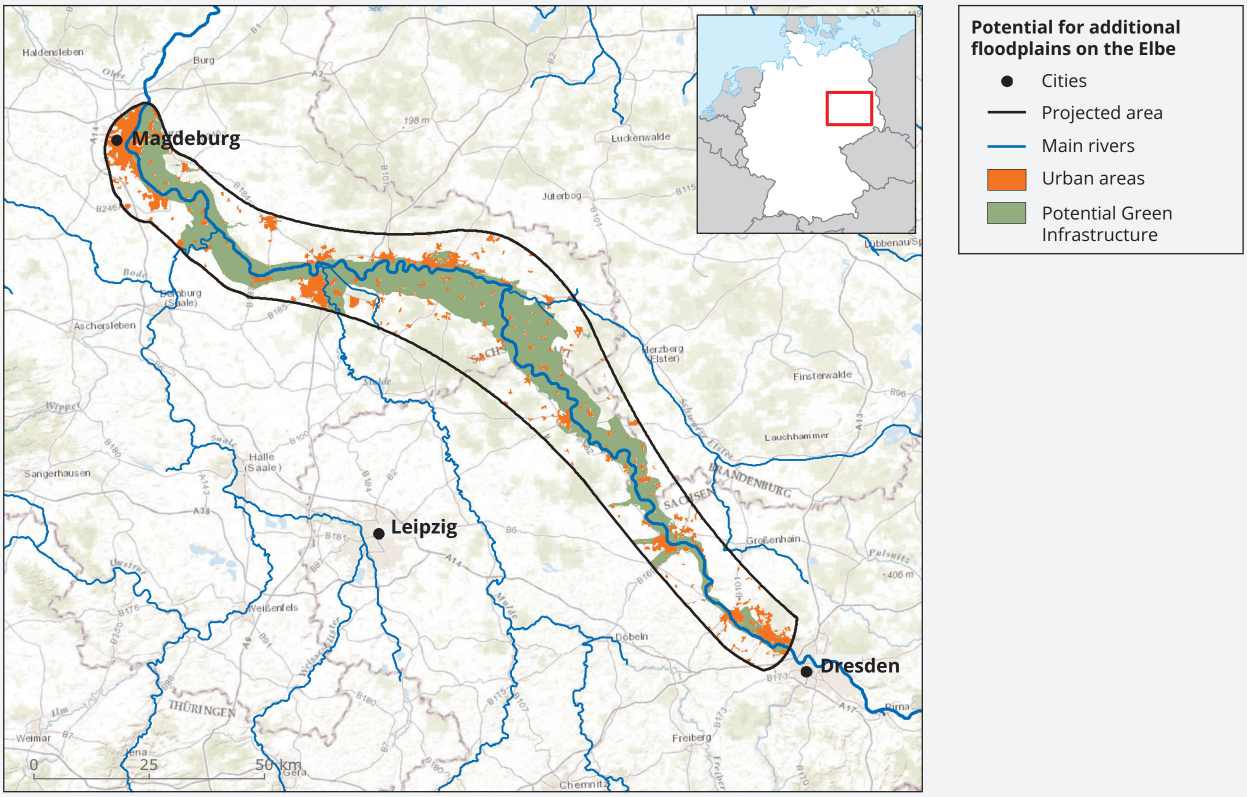
The Elbe starts in the Czech Republic and travels around 1 100 km before reaching the sea in Cuxhaven, northern Germany. More than two thirds of its length, as well as two thirds of the 150 000 km^2 of the basin's area and three quarters of its 24 million inhabitants, are in German territory. The Elbe crosses 10 German states and many important cities, such as Leipzig, Dresden, Hamburg and Magdeburg. Magdeburg, which will be addressed in more detail in this assessment, has 250 000 inhabitants and is the capital of the state of Sachsen-Anhalt. Magdeburg is located in Mittlere Elbe/Elde, one of the five regions into which the river basin is divided.

Photo 4.1 Mittlere Elbe/Elde

Source: RBMP 2009 (Bewirtschaftungsplan 2009).

The Mittlere Elbe/Elde region (see Photo 4.1), located in the middle of the Elbe river basin, is spread over 16 500 km^2 in central and northern Germany, and contains two important cities, Magdeburg and Schwerin, the former located on the river and the latter approximately 65 km away from it. Mittlere Elbe/Elde has 34 areas of potential significant flood risk, four of which are in the immediate vicinity of Magdeburg: Schrote, Polstrine, Elbumflut and Ehle/Ehleumflut (see Map 4.2.).

Map 4.2 Elbe river basin district — case study selection



Source: Arcadis, 2016.

Box 4.1 Elbe river in Germany (cont.)

Around 54 % of the land area of the Mittlere Elbe/Elde region is used for agriculture, with a further 15 % being pasture land. Approximately 24 % of the territory is occupied by forests and 3 % comprises water bodies, such as rivers and lakes. The remaining 4 % is used for human occupation (FGG Elbe, 2004). Many risk areas contain industrial facilities, agricultural crops and provide cultural services, all of which require measures for protection against eventual floods. In Mittlere Elbe/Elde, the draft FRMP estimates that up to 289 industrial facilities could be affected by an extreme flood (FGG Elbe, 2014). Such a catastrophic scenario would also affect 210 000 inhabitants of the Mittlere Elbe/Elde region. In a high-probability flood scenario, around 3 500 people and four industrial facilities would be hit by floods in this region. The Elbe region as a whole has a significant number of sites recognised by Unesco as Cultural World Heritage Sites. These include the palaces, churches, museums and gardens of Potsdam and Berlin, as well as the towns of Quedlinburg, Wittenberg, Eisleben, Weimar and Dessau.

2. Vulnerability of the main cities

The Magdeburg region is vulnerable to river floods, and it was strongly affected by major floods on the Elbe in 2002. Since then, some preventive measures have been taken to make the city better prepared for such events. The levee around Magdeburg has been rebuilt and strengthened, and a large number of sandbags (153 000 jute sacks, 200 000 plastic sacks and 80 000 large bags) are readily available to protect the levee (Ließmann, 2012). Other measures are improvements in the drainage system in Pechau/Zipkeleben (2007), the expansion of a trench system in Furtlake (2012), the construction of the Furtlake Canal and a pumping station at Steingrabensiel, and work on the Elbe's riverbed to increase flow rate (Landeshauptstadt Magdeburg, 2015). Floods hit the city in 2003, 2006 and 2013. Currently Magdeburg's authorities are willing to proceed with projects to reduce vegetation in the river and in the canal around Magdeburg *(Umflutkanal)*, increasing the space available for water, but this is currently impossible because vegetation in the area is protected under European legislation (MDR, 2015).

Photo 4.2 Flooding in Magdeburg in 2013

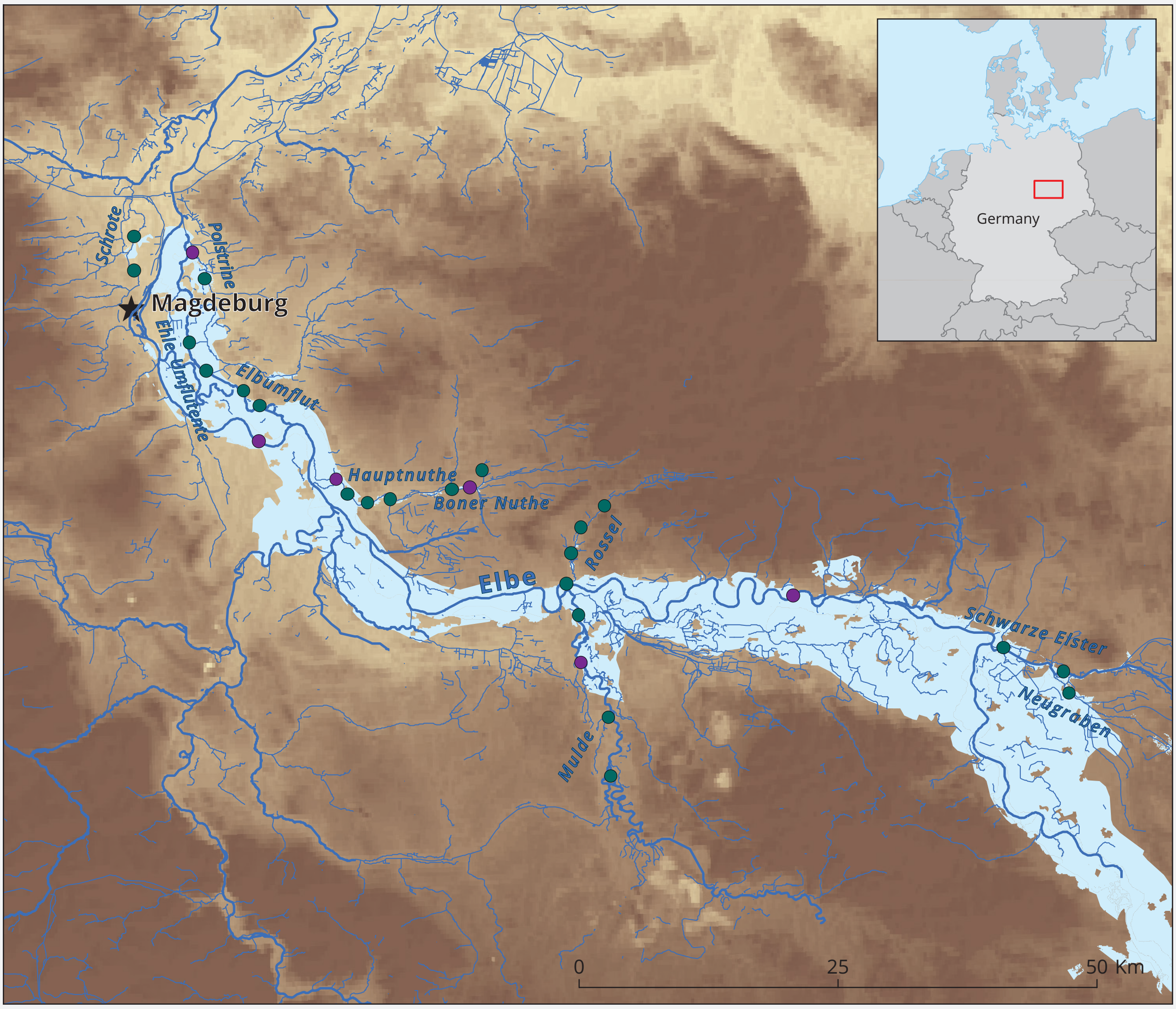
Source: FGG Elbe, 2014.available at: https://www.fgg-elbe.de/dokumente/oeffentlichkeitsmaterialien.html?file=tl_files/Download-Archive/Oeffentlichkeitsmaterialien/Flyer_broschueren/Broschuere_HWG_HWR_14-03-2014.pdf

Box 4.1 Elbe river in Germany (cont.)

3. Management plans and status of implementation

Map 4.3 depicts the GI measures already implemented and/or planned in the selected case study area of the Elbe river basin.

Map 4.3 Location of existing GI measures (planned and/or implemented) in the selected Elbe river basin district



Locations of Planned and Implemented Green Infrastructure Flood Management Measures near Magdeburg

★ Cities ● Implemented measures ● Planed measures — Waterways ▭ Floodplain

Note:
Locations of measures are estimates based on the number of measures per river segment according to the national draft RBMP.

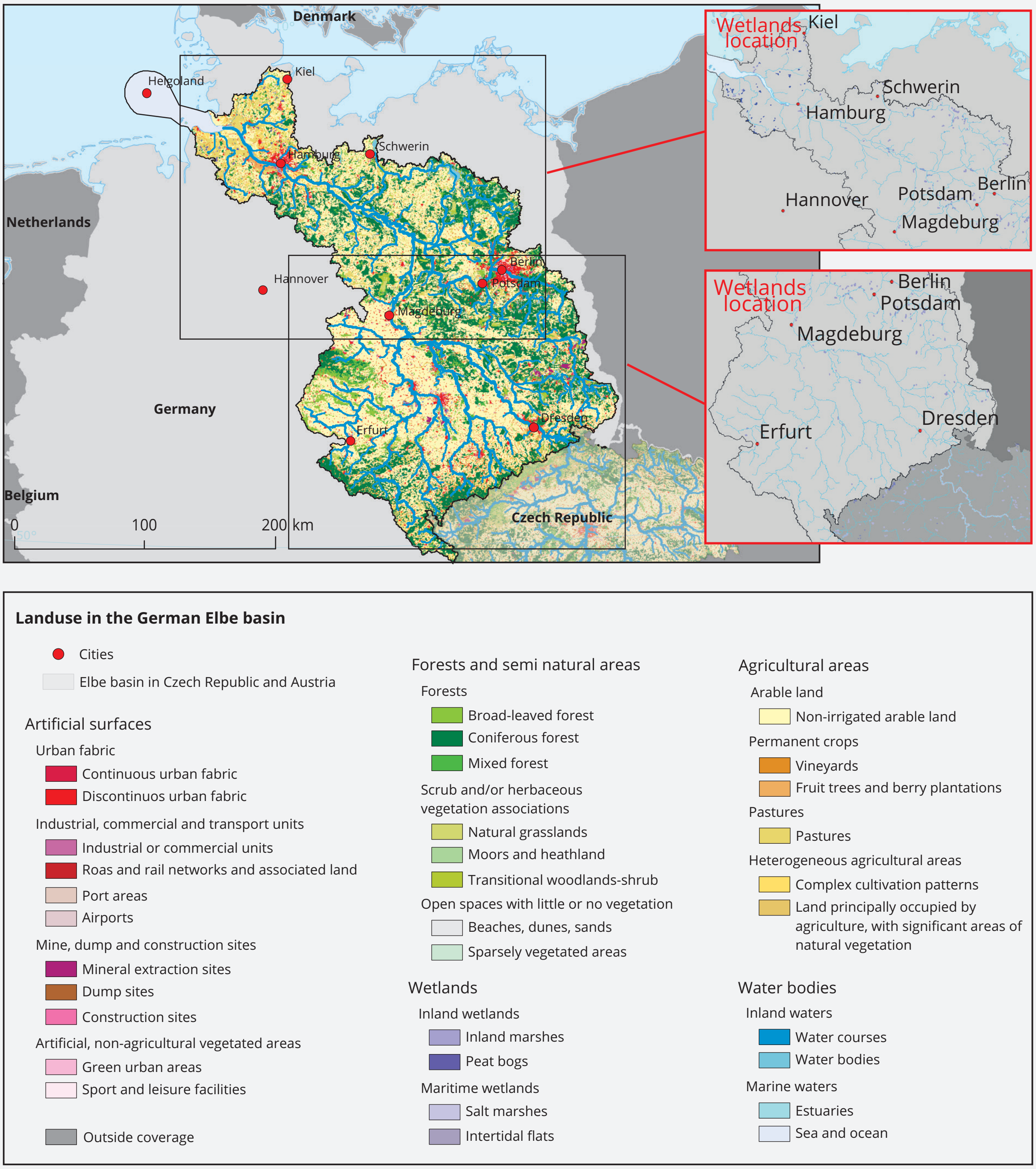
Source: Trinomics, based on location estimates of measures in national draft river basin management plan.

Box 4.1 Elbe river in Germany (cont.)

3.1 Summary of the consideration of land use, soil management and climate change in relation to flood risk management

In the general area of the Elbe basin (which extends beyond the Mittlere Elbe/Elde case study area), the distribution of the land use is as follows: 45 % agricultural farmland, 15 % pasture, 27 % forests, 8 % human occupation and the rest is basically occupied by water bodies (rivers and lakes). Map 4.4 is based on the PFRA (Vorläufige Bewertung des Hochwasserrisikos) and depicts the whole Elbe basin within Germany (FGG Elbe, 2011).

Map 4.4 Land use in the German Elbe Basin (2006)



Source: Trinomics, based on preliminary flood risk assessment and EEA Corine 2006 land use data.

Box 4.1 Elbe river in Germany (cont.)

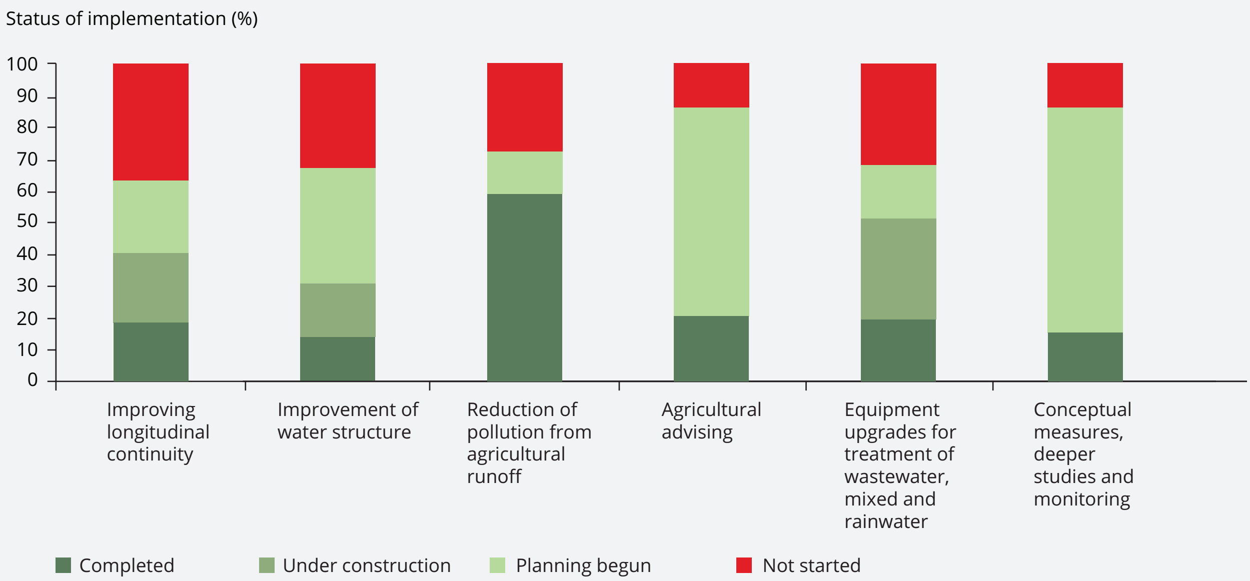
The PFRA for the Elbe identifies land use planning and construction planning measures as key aspects for the management of flood risk and prevention in the German section of the Elbe. For the German catchment areas of the Elbe, almost all flood risk areas have set measures to avoid flood risks via land use planning and the identification of floodplains. For the case study area of Mittlere Elbe/Elde, the identified land use planning measures include 18 measures involving regional land use regulation, 32 measures for the identification of floodplains, 32 measures to guide construction planning and zoning, and 3 measures involving change/adaptation of current land use. In addition to these regional or local measures, an example of a wider measure applicable for all areas (embedded in national legislation) is the establishment of floodplain locations and the embedding of these in land use planning regulations. This requires following the assigned land use restrictions for these floodplains and drainage areas. This may result in land use changes and/or restrictions in the zoning of new constructions, as identified floodplains have legal priority over new land use planning for the identified areas.

Regarding climate change, the Elbe river basin has been identified as one of the German areas under particular threat of future climate change, and in particular changes in rainfall and temperature (Hattermann et al., 2008). This in turn will trigger changes in the Elbe's water cycles. Flood risks may be affected because of changes in height, duration and frequency of flood run-off. The Elbe's 2015 draft RBMP and FRMP also identify that climate change will have indirect consequences on water management due to potential changes in land use. The climate change assessment carried out under the Elbe's 2015 draft RBMP concludes that all identified measures will still contribute to improved water management even under conditions of climate change. The 2015 draft RBMP highlights the important contribution of rivers with good ecological status towards climate change adaptation, given that they are more resilient to climate extreme events, e.g. floods or droughts. Building on this, the Elbe's FRMP incorporates the conclusion of the Sixth Elbe Ministerial Conference (5 December 2013) that additional floodplains and — if needed — infrastructure-based reservoirs for flood management installations should be prioritised, and extra financial resources provided.

3.2 Reality check

The mid-term review for the Elbe river basin (submitted in 2012) provides an overview of progress towards the implementation of the 2009 RBMP and other related EU water regulation. As can be seen in Figure 4.1, for the entire river basin, about 20 % of measures have been completed, 10 % have been started, 40 % are under implementation and the remaining 30 % have not yet been started. With respect to GI and flood management in particular, measures falling under the category of 'improvement of river flow' (*Längsdurchgängigkeit*) and the 'improvement of water circulation' (*Gewässerstruktur*) involve relevant aspects. For these two types of key measures, about 20 % of measures have been completed, about 35 % have not yet been started, and 45 % are currently being implemented. In the programme of measures (PoM) implementation report, published in 2015, it is stated that authorities in the Elbe river basin had not yet started 7 % of supplementary measures, indicating that further progress was made between the 2012 mid-term review and 2015.

Figure 4.1 Status of implementation of the listed key measures for FGG Elbe



Source: Mid-term assessment of river basin management plan implementation on the Elbe (2012).

Box 4.1 Elbe river in Germany (cont.)

Figure 4.1 depicts the level of implementation for measures on river flow in more detail. As can be seen from the figure, a few measures fall within the defined case study area. The mid-term review does not provide any conclusions on whether or not this is considered good progress. However, given that well over 50 % of the total measures have either been completed or are ongoing, progress is being made towards the implementation of measures. However, it is concluded for some river basin districts in Germany (including the Elbe) that ambitions were too high and that it was unrealistic to finalise planning and implementing measures by 2015.

Actions in the plans for the Elbe include:

- most actions are planned on the restoration and protection of flood areas, including morphological alterations to improve hydraulic conditions;
- restoration of wetlands; and
- removal or setback of levees.

4. Overview of current coordination between upstream and downstream areas

4.1 International coordination

The river basin of the Elbe extends over several EU Member States, namely Austria, the Czech Republic, Germany and Poland. These countries have agreed to coordinate all activities and responsibilities stemming from the EU's Floods Directive under one coordination group, the International Commission for the Protection of the Elbe (IKSE). IKSE is responsible for coordination on an international level, while each national authority (Austria, the Czech Republic, Germany and, Poland,) feeds into this international cooperation structure (IKSE, 2016)

4.2 Coordination between RBMP and FRMP

All measures are coordinated under the 'LAWA' catalogue of measures, which is jointly developed and managed by relevant national and regional authorities under a jointly established management umbrella organisation, 'FGG Elbe'. Urgency of measures, synergies and timing are cross-checked between the two plans.

FGG Elbe works closely together with IKSE. The content discussions and coordination of measures take place in the working group on flood protection.

Other relevant EU policies are also taken into account, e.g. all regulation falling under the WFD, such as the Drinking Water Directive. In addition, the EU Guidelines on Environmental Impact Assessment for public and private projects, plans and programmes (2011/92/EU and 2001/42/EG), as well as SEVESO-III (2012/18/EU), are taken into account in all measures carried out under FGG Elbe.

Several synergistic measures have been identified between the FRMP and RBMP, including the protection of natural floodplains from construction, as well as the improvement of natural water retention. Potentially conflicting results as regards goals within the RBMP and FRMP relate to technical infrastructure measures for flood protection preventing a more natural development of the river.

4.2 Green infrastructure — Floodplain restoration and management

When a river floods, the greater amount of water allocates itself to the surrounding areas. After millennia of water erosion, some areas around a river have turned into plains that are particularly prone to floods. These areas are named floodplains, and they are filled with water in periods of strong discharge. However, floods may take years or decades to occur again, and areas that are naturally risky may go unnoticed by humans and result in unsuitable development activities. Floodplains around the world have been occupied by humans, who in many cases develop and use the areas and hence transform the surface (as they are naturally soil-rich areas due to the sediments deposited by the river). Moreover, rivers provide good logistical solutions for economic activity to flourish.

However, this occupation becomes an acute problem when large water flows overcharge the river, which fills its surroundings with water, particularly those areas that are naturally prone to accommodating this extra discharge. When there is human occupation or construction in floodplains these floods often cause economic damage and loss of lives. Actions that may transform floodplains and increase the risk of flood damage, besides urbanisation, are land drainage and river channelisation (NWRM, 2013b).

Transforming floodplains with the aim of decreasing flood risk can be achieved in two ways: (1) by increasing water storage capacity; or (2) by improving water conveyance through the floodplain (Blackwell and Maltby, 2006). Apart from the benefits of reducing risk of flood damage, restoring floodplains may also fulfil other policy objectives, such as restoring biological and chemical balance. Photo 4.3 shows a floodplain in flooded and non-flooded contexts.

Different kinds of works can be performed in a floodplain to reduce flood risks, including the construction of dams or levees in strategic sites. Natural measures usually consist of enlarging the retention area, increasing the water storage capacity of floodplains and thus preventing water from occupying areas where human activities take place. The most typical examples of natural solutions for the creation or restoration of floodplains include:

- creation of green rives, or 'flood bypasses';
- removal or setting-back of embankments;
- connecting isolated water bodies;
- floodplain excavation (lowering/dredging of floodplain surface to provide flood capacity);
- restoration of vegetation;
- change in soil use, promoting retention of water.

A less natural way to implement this measure is to induce floods into areas where they would not naturally occur, or where they would not primarily take place. Human intervention can turn a 'passive' floodplain into an 'active' one by altering the morphological characteristics of the terrain. Floodplain restoration can be applied to a variety of land uses (agricultural and urban areas), topographic terrains (uplands or lowlands) and in different locations on the river (downstream and upstream) (Stella, 2012a). Floodplain restoration measures are not well suited for small infrastructure projects, as the catchment area for a floodplain restoration project must be at least 10 km^2 for it to provide sufficient water storage capacity (NWRM, 2013b). However, the reason for that is almost trivial, as small catchment areas generally do not have floodplains. Actions related to floodplain restoration and management are part of the management plans of the four river basins selected for our case studies (Elbe, Rhône, Scheldt and Vistula).

Table 4.1 summarises a selection of comparable and representative data on costs for recent (GI) floodplain restoration projects based on four cases where this measure has been realised in Europe (sources included in the table). An important cost element in a project of floodplain restoration refers to the acquisition of land. The area in which the project must be implemented may be occupied by human settlements or activities such as agriculture, all of which typically would have to be displaced. It is not always that farmers have to leave their land. An alternative is to reach agreements with the farmers allowing them to continue cultivating a crop that is resistant to floods, in which case the compensation costs could be lowered.

Still, depending on the market value of land in the area and the country's legislation, this cost item may amount to more than the actual construction costs (Blackwell and Maltby, 2006). Broekx et al. (2011) mention that

Photo 4.3 Floodplain restoration

Source: http://nwrm.eu/measure/floodplain-restoration-and-management adopted from Thomas Borchers' presentation in NWRM Workshop 1.

Table 4.1 Costs for floodplain restoration projects

			Costs		
			Land acquisition and compensation	Construction and rehabilitation	Operation and maintenance
	Floodplain restoration				
Case	**River**	**Source**	**EUR/ha**		**EUR/ha/y**
1	Rhine	ICPR, 2006		360 573	
2	Scheldt	Mazza et al, 2011	53 000	136 542	
3	Danube	Schwarz, 2010	5 000		
4	Scheldt	Broekx et al, 2011	(10 000–700 000)		1 226[a]

Note: ([a]) Based on NWRM (2014a), which reports maintenance costs of 0.5–1.5 % of investment costs (average = 0.8 %).

Source: Based on own interpretation of cases reported in NWRM (2014a) and Stella (2012a).

costs could range from EUR 10 000–700 000/ha, depending on whether the land serves an agricultural or residential purpose (respectively). Mazza et al. (2011) quote an average figure reported by the Flemish government of EUR 53 000/ha.

However, the restoration of a floodplain may involve building grey infrastructure, removing it or relocating it. The construction and rehabilitation costs for restoring a floodplain have been estimated at EUR 360 573/ha (in 2011 prices), for floodplain restoration along the Rhine, and EUR 136 542/ha for the Scheldt.

Another case for the lower Danube shows that costs can differ strongly across Europe. Based on Schwarz (2006), who studied the costs of floodplain restoration in the area after the 2006 floods, the costs for restoration including land compensation and technical structures is approximately EUR 500 000/km^2, i.e. EUR 5 000/ha.

Maintenance costs for floodplain projects are estimated at 0.5 % to 1.5 % of total investment costs (NWRM, 2013b). Based on the above average investment costs of EUR 153 279 ([29]) and assuming 0.8 % maintenance costs, the annualised estimate for average maintenance expenditure is EUR 1 226/ha.

The scores of the effects (benefits and co-benefits) of floodplain restoration projects for the standard effect categories (see also Annex 1) are illustrated in Table 4.2. The respective scores for the direct and indirect effects are sourced from the NWRM project (NWRM, 2013b). Like any flood protection infrastructure measure, the direct effects of carrying out a project of floodplain restoration depend on the extent to which human activities and population are exposed to floods and on the way the project is able to alter the morphological aspects of the terrain and the river to reduce flood damage risk.

For floodplain restoration, the effect of altering morphological aspects is especially difficult to assess because the relevant factors are intertwined and interact in a complex fashion: the composition of the soil, the velocity and temperature of the water, the meanders of the river and meteorological conditions all seem relevant to determining the extent to which a successful floodplain restoration can be undertaken. However, these factors are not fully understood (Stella, 2012c). In general, though, following the categorisation of effects, floodplain restoration is generally seen as a natural measure that is likely to reduce flood hazards in various ways.

([29]) (360 573 + 136 542) ÷ 2 + 53 000] + 5 000] ÷ 2 = EUR 153 279.

Table 4.2 Effects of floodplain restoration projects

	Storing and slowing run-off	Storing and slowing river water	Reducing run-off	Water storage	Fish stocks and recruiting	Natural biomass production	Biodiversity preservation	Climate change adaptation	Groundwater recharge	Erosion control	Filtration of pollutants	Recreational opportunities	Aesthetic/cultural value
Floodplain restoration	**Direct effects**			**Indirect effects (eco-system benefits)**									
0 = None, 1= Low, 2 = Medium, 3 = High	3,0	3,0	2,3	3	3	3	3	2	3	3	2	3	3

Source: NWRM (2013b); own illustration

Notably, flood mitigation occurs through the retention of excessive temporary water and run-off, which reduces peak flows. In addition, restoring and expanding floodplain areas in itself liberates space for water to flow, and the roughness of floodplain features reduces the speed of river surface water. Therefore, the NWRM project scored floodplain restoration projects with 'high' effects (score 3 out of 3 — see Table 4.2) for their potential to store and slow river water. In addition, the larger amount of vegetation increases water retention capacity. The joint score for reducing run-off (as a direct effect of reducing flood risk) in the NRWM project, however, was 2.3 ([30]) (see Table 4.2), as floodplains are unlikely to include the best type of vegetation for reducing run-off (NWRM, 2013b).

Beyond its features for direct flood protection, restoration of floodplains can bring a range of many significant additional ecosystem services, depending on the degree of restoration and the initial presence of ecosystem services. Restoration of floodplains can improve the functioning of the aquatic ecosystem through improved water quality, vegetation population and habitat conditions for a variety of species, which in turn can lead to an increase in fish populations, improved natural biomass production and greater biodiversity (all score 'high' (3/3) in the NWRM project on these ecosystem services) (NWRM, 2013b).

Box 4.2 provides additional detailed information on what the precise costs and effects of green, hybrid and grey infrastructure solutions, including floodplain restoration and management, are in an applied case for the Elbe in Germany.

([30]) Derived as an average from 'Medium' (BP5 — increase evapotranspiration), 'Medium' (BP6 — increase infiltration and/or groundwater recharge) and 'High' (increase soil water retention) impacts, for biophysical impacts related to reducing run-off (NWRM, 2013b) = (2 + 2 + 3) ÷ 3 = 2.3

Box 4.2 Elbe case study: Detailed cost-benefit assessment including floodplain restoration and management

The Elbe floodplains are almost entirely protected by dikes. In the area downstream of the city of Dresden, in which the city of Magdeburg is located, around 85 % of the floodplains are protected. These dikes were built in the 19th and 20th centuries, up to the 1970s. In past decades, infrastructure works intended to protect areas from flooding started focusing on measures that combined grey infrastructure (dikes) with green measures, especially recovering and re-naturalising floodplains. A cost-benefit assessment by Malte Grossman and Volkmar Hartje (2012) showed that measures that included floodplain restoration were greatly superior to purely grey measures.

Options considered

The study differentiates between two kinds of approaches. The grey approach (building or strengthening dikes) is called a 'hold-the-line strategy', whereas the green approach (restoring floodplains) is called 'give space to the river strategy'. The authors analysed the costs and benefits of seven flood management programmes, only one of which can strictly be considered a 'GI' measure. The other measures listed in Table 4.3a combine the construction of flooding areas (polders) with dikes and dams (grey measures), the relocation of dikes (hybrid measure) and the re-naturalisation of floodplains (green measure) to allow for 'ecological flooding'. Table 4.3a lists the seven programmes analysed in the study.

Table 4.3a Grey, green and hybrid measures

	Name of measure	Short description
Green	Controlled retention polders with ecological flooding	Restoring a wetland in a floodplain (3.2 K ha) and preserving it. This will increase the area for the river to flood.
Hybrid	Combination of polders with ecological flooding and dike relocation	Restoring a wetland in a floodplain (4.1 K ha), preserve it and relocate a dike (3.4 K ha).
Grey	Large scale dike relocation	Relocate a dike in large parts of the river (35 K ha)
	Small scale dike relocation	Relocate a dike in chosen parts of the river (9.4 K ha)
	Large scale controlled retention polder	Enclose areas (25.6 K ha) with a dike and a dam, flooding during overcharge.
	Small scale controlled retention polder	Enclose areas (3.2 K ha) with a dike and a dam, flooding during overcharge.
	Combination of polders and dike relocation	Enclose an area (4.1 K ha) and relocate a dike (3.4 K ha).

Source: Adapted from Grossmann and Hartje (2012).

Summary of scenarios considered

The authors calculated the net present value of the costs and benefits of each one of these measures over a period of 100 years (the assumed lifetime of a dike) and using a social discount rate of 3 %. The costs considered in the study refer to the construction and maintenance costs and the opportunity costs of the project (lost revenues from agricultural and forestry activities). Table 4.3b shows the type of (unit) costs that were incurred in the case of the Elbe for the floodplain restoration plans, which have been taken into account for the detailed net present value calculations shown in Table 4.4. Comparative costs for the grey measures were not presented at unit level (and therefore are not comparable).

Box 4.2 Elbe case study: Detailed cost-benefit assessment including floodplain restoration and management (cont.)

Table 4.3b Costs of floodplain measures in the Elbe

Costs of floodplain management measures in the Elbe			
Floodplain	**EUR/ha**	**EUR/ha**	**EUR/ha/y**
Opportunity costs of conversion of land use to flood plain			
Arable land	5 500		
Grassland	2 500		
Forestry land	2 000		
Opportunity costs of conversion from arable to grassland for flood polder operation (per annum)	250		
Flood damages of flood polder			25
Landscaping of restored floodplain		300	10
	10 250	300	35

Source: Adapted from Grossmann and Hartje (2012).

In terms of benefits, two scenarios were considered. The first was a scenario in which only flood risk reduction was counted as a benefit. This was calculated using probabilistic models of flood hazard in the areas around the Elbe, taking into account various frequencies of floods. Secondly, a broader assessment of benefits was considered, taking into account benefits from nutrient retention and biodiversity conservation. Under these indirect benefits, GI projects score much more highly than purely grey measures.

Table 4.4 show the results of the cost-benefit assessment for both scenarios. The authors found that the 'green' measure, which consisted of re-naturalising a polder area and allowing for 'ecological flooding', provided larger economic gains per hectare (net present value of almost EUR 430 000 per hectare), in both the 'flood risk management only' and the 'integrated floodplain management' scenarios. This shows — interestingly — that the green measure proves to be the most cost-efficient, even when the indirect benefits are not taken into account. However, accounting for the indirect effects increases the net present value of the GI measure by almost four times, highlighting the importance of these benefits.

Box 4.2 Elbe case study: Detailed cost-benefit assessment including floodplain restoration and management (cont.)

Table 4.4 Comparison of cost-efficiency results per option

Cost-effectiveness of infrastructure options for the Elbe Net Present Value of options		**Direct effects**	**Indirect effects**		**Net Present Value (in 2012 prices)**	
		Flood-risk reduction benefits in EUR/ha/y	**Nutrient retention**	**Biodiversity conservation**	**Only flood risk management — Scenario 1**	**Integrated floodplain management — Scenario 2**
Green	Controlled retention polders with ecological flooding (green)	4 120	+++	+++	108 261	429 746
Hybrid	Combination of polders with ecological flooding and dike relocation (hybrid)	1 825	++	++	43 227	196 337
Grey	Large scale dike relocation (grey)	165	+	+	– 3 706	72 707
	Small scale dike relocation (grey)	68	+	+	– 7 364	155 337
	Large scale controlled retention polder (grey)	1 015			13 836	13 836
	Small scale controlled retention polder (grey)	4 120			101 990	101 990
	Combination of polders and dike relocation (grey)	1 825	+	+	43 227	182 198

Source: Adapted from Grossmann and Hartje (2012).

4.3 Green infrastructure — Re-meandering

Rivers are very seldom straight. The course of a river may feature many U-turns or other large curves, which are named 'meanders'. For human usage these meanders may cause some inconvenience, as they increase the length of a river significantly, as well as the size of its surrounding area.

In most cases where rivers are surrounded by human agglomerations, they underwent straightening engineering works in the past. In relation to floods, removing a river's meanders may increase the risk of a natural disaster. The meanders in a river reduce the speed of water flow. Removing these meanders increases the water speed, in turn increasing the possibility of water overspilling and causing flood damage. The fact that islands and sand banks are often removed in the course of 'normalising' a river only adds to this effect (Blackwell and Maltby, 2006).

Re-meandering as a GI measure consists of re-establishing the original curves of a river, reducing water flow speed and thus increasing flood protection (see Photo 4.4). Re-meandering a river also increases its storage capacity, which potentially contributes to avoiding floods.

Since rivers of different lengths and widths have meanders, there is no minimum technical scale for a re-meandering project. There are no general technical restrictions in terms of soil type or terrain either (NWRM, 2013c). Re-meandering is often part of more general projects for environmental restoration, such as the floodplain restoration and management actions described earlier. Actions undertaken in a re-meandering project may include:

- recovering the meanders of a river, increasing its length; and
- widening and deepening a river.

Removing a river's meanders has been common practice for decades, and re-meandering is now becoming a more standard measure undertaken in flood prevention projects. One major project that included re-meandering the river was executed in Denmark in the River Skjern. The project extended the length of the Skjern from 19 km to 25.9 km. The River Brede, also in Denmark, was transformed from a 19 km straightened channel to a 25 km meandering river (Blackwell and Maltby, 2006). The same study also mentions re-meandering actions of the Tisza river (Hungary). Both re-meandering cases in Denmark have been used to assess the typical costs of this measure (included in Table 4.5). In the four case studies chosen for this study, re-meandering is listed as a planned measure to address flood risks in the Elbe and Rhône.

Like floodplain restoration, a significant cost for re-meandering projects is the requirement to utilise areas that may be owned, occupied or cultivated. In the past, rivers have sometimes been straightened with the sole purpose of providing land for cultivation and therefore reversing that decision by re-meandering would imply compensation costs, which, however, can vary strongly depending on the local usage

Photo 4.4 River re-meandering project

Source: http://nwrm.eu/measure/re-meandering, the Morava Anniversary Project (http://www.riverwatch.eu) http://riverwatch.eu/en/the-morava-anniversary-project-2014

Table 4.5 Costs of re-meandering

			Costs		
			Land acquisition and compensation	Construction and rehabilitation	Operation and maintenance
	Re-meandering				
Case	**River**	**Source**	**EUR/ha**	**EUR/km**	**EUR/ha/y**
1	Brede (DK)	Stella, 2012		277 012	
2	Skjern (DK)	Stella, 2012	610	535 689	2

Source: Based on Stella (2012d); NWRM (2014a); own interpretations.

characteristics of the land. In addition, compared with restoration of floodplains or wetlands, re-meandering often requires more engineering investment and can therefore be more intensive in construction costs.

Only two cases of re-meandering projects with detailed cost data have been identified, both of which were conducted in Denmark (Stella, 2012d). The River Brede in Denmark was re-meandered, increasing the length of the river from 19.3 km to 25.7 km for a total construction cost of EUR 2.12 million. No data on the costs of compensation are available for this project. Thus, the total unit cost per kilometre in average EU 2011 prices was calculated to be EUR 277 012/km.

For another LIFE+ project (River Skjern), the construction unit costs (per kilometre, average EU 2011 prices) were calculated to be EUR 535 689. In addition to this project, total unit costs for land acquisition and compensation of landowners of EUR 610/ha were incurred (in average EU 2011 prices). After implementation, the Skjern river project also reported monitoring costs of approximately EUR 400 000 per year (Stella, 2012d). For 2 200 ha of re-meandered area, the average monitoring costs equal EUR 2/ha.

To be able to compare the cost-efficiency of re-meandering projects, it is necessary to compare average unit costs with the same unit measurement across all measures, namely costs (in euros) per hectare. Since construction costs for re-meandering projects are incurred per kilometre, the average EU construction costs of EUR 406 351 (277 012 + 535 689/2) per kilometre of re-meandering were used. Land acquisition costs amounted to an EU average of EUR 610/ha and average maintenance costs of EUR 2/ha.

In combination with the estimated kilometres of re-meandering projects and associated land changes envisaged for these projects (in hectares) in each EU Member State (sourced from Stella, 2012d), the euros/km data were transformed in order to calculate average total costs for re-meandering projects in euros/ha. Figure 4.2 shows the average total costs per hectare per year (in euros adjusted for local price levels) for re-meandering projects planned in EU Member States between 2011 and 2030. The construction costs for re-meandering itself make up the largest share of costs (as shown in Table 4.5). The average total costs (euros per hectare per year) for EU re-meandering projects envisaged equals EUR 93 209, based on these calculations (individual Member State cost data weighted with area of re-meandering).

Re-establishing the meanders of a river offers two types of direct hydromorphological changes that can reduce risk of flooding (see Table 4.6). The impact scores for both the direct and the indirect effects are again taken from the NWRM (2013c) (as explained at the start of the section). First, re-meandering reduces the speed of water flow, forcing the river to run in curves instead of flowing straight (impact 'high' for slowing river water ( ) — score 3/3 — see Table 4.6). Second, it increases the length of the river and, consequently, the volume of water it is able to carry in any given area. These two changes are important to reduce the risk of run-off (NWRM score 'medium' for — 2/3). Evidence on the direct impacts of re-meandering on run-off control, erosion control and/or storage capacity is not available to date (Stella, 2012d), which softened the results attributed to storing and slowing run-off.

Figure 4.2 Average annual costs for re-meandering (euros per hectare per year)

Source: Stella (2012a); own calculations.

The impact on reducing flooding through evapotranspiration is low (a characteristic that leads to reduced run-off), as only small areas in the meanders can function like riparian wetlands. Soil water retention and groundwater recharge functions (also included as characteristics that contribute to reducing run-off as included in Table 4.6) are higher because of the creation of a wet environment and (if applicable) removing legacy sediment [2/3]. These three characteristics lead to a joint score of 1.7 ([31]) for re-meandering's impact on reducing run-off ().

Like other GI measures, re-meandering has other benefits unrelated to floods, notably increased biodiversity, natural biomass production, erosion control and groundwater recharge (3/3). Earlier normalisation of rivers, by increasing the river's speed, causes more erosion and reduces biodiversity. Restoring the river's meanders may also restore this biological balance. As regards biodiversity and fish stocks, evidence from reports covering the re-meandered Rivers Brede and Gels (Denmark) show that the number of trout doubled (Brede) and the number of spawning grounds in the Gels increased significantly (Stella, 2012d).

For all direct and indirect effects scored and listed by Stella (2012d) and the NWRM project, it was noted that evidence on the stated effects is in general scarce and sometimes questionable. The uncertainty associated with the direct flood risk reduction effects and indirect ecosystem services should duly be noted in the overall cost-efficiency assessment.

([31]) Increasing evapotranspiration (1/3); increasing groundwater recharge function (2/3) and increasing soil water retention (2/3) = 1 + 2 + 2 ÷ 3 = 1.7

Table 4.6 Effects of re-meandering

	Storing and slowing run-off	Storing and slowing river water	Reducing run-off	Water storage	Fish stocks and recruiting	Natural biomass production	Biodiversity preservation	Climate change adaptation	Groundwater recharge	Erosion control	Filtration of pollutants	Recreational opportunities	Aesthetic/cultural value
Re-meandering	**Direct effects**			**Indirect effects (eco-system benefits)**									
0 = None, 1= Low, 2 = Medium, 3 = High	2,0	2,5	1,7	2	2	3	3	2	3	3	2	3	3

Source: NWRM (2013c); own illustration.

4.4 Green infrastructure — Wetland restoration and management

Like floodplains, wetlands primarily provide water retention services and can therefore reduce the impacts of floods. Wetlands do not need to be directly connected to rivers, though, as they are usually in the case of floodplains (see Photo 4.5). The cost-efficiency of wetland restoration projects therefore critically hinges on land acquisition costs, in particular, and the additional benefits from ecosystem services.

Restoring a wetland entails partially flooding an area that is currently dry. Often it is the case that the restoration of wetland is associated with the removal of some water retention measures such as a dike or a dam. Once the dike is removed, water invades an area that was previously kept dry. However, a GI approach to this would leave the area not only flooded, but also re-naturalised with wetland vegetation and soil.

A re-naturalised wetland has better soil infiltration and higher capacity for absorbing water than a flooded plain that has not been re-naturalised. These properties are important for flood management, which may be one of the reasons why restoration of wetlands is listed in the FRMPs of the four case studies in this research (Elbe, Rhône, Scheldt and Vistula).

In some contexts, wetlands are explicitly separated from polder areas. However, this analysis will not pay attention to this difference, and will focus instead on the general functionalities of wetlands for flood protection.

The scale of wetland restoration projects is typically smaller than restoration of floodplains or re-meandering projects, and mostly applied for areas smaller than 100 km^2 (NWRM, 2014a). As a result of their average size and to increase the effectiveness of wetlands, they are often combined with other green or grey (hybrid) measures in one project. Consequently, separate cost data for the restoration of wetlands is scarce.

There have been relatively many projects in the EU in the past, including wetland restoration as part of the total set of infrastructure measures. Based on a number of these cases, construction cost data could

Photo 4.5 Wetland in a forest

Source: http://nwrm.eu/measure/wetland-restoration-and-management, based on Gebhard Schueler's presentation, NWRM Workshop 1.

Table 4.7 Costs of wetland restoration and management

			Costs		
			Land acquisition and compensation	Construction and rehabilitation	Operation and maintenance
	Wetland restoration & management				
Case	Area	Source	EUR/ha		EUR/ha/y
1	Alps (CH, AT, IT, FR, DE)	Kohler & Heinrichs, 2011	3 075		
2	Hautes-Fagnes Plateau (BE)	Naumann et al, 2011	2 244		
3	Scotland	Naumann et al, 2011	1 359		
4	Scheldt (BE)	Nocker and Mazza, 2011	53 949		
5	Denmark	Tucker and Mazza, 2011	5 885		
6	France	Stella (2012)			348

Note: AT, Austria; BE, Belgium; CH, Switzerland; DE, Germany; FR, France; IT, Italy.

Source: Based on Morris and Camino (2011); Stella (2012b); NWRM (2014a); own interpretations.

be gathered through the list of studies included in Stella (2012b) and Morris and Camino (2011). These have been included in Table 4.7. It was not possible to separate land acquisition costs from construction and rehabilitation costs, as they were not reported separately in the data available in these studies. As a consequence these costs are also presented jointly in Table 4.7. Indeed, land acquisition is expected to constitute a major cost item for wetland restoration projects. In the past wetlands have often been drained and used for agriculture. This kind of soil occupation is typically less expensive compared with land that has been occupied by urban buildings such as houses or industrial facilities. Therefore costs for wetland restoration projects are likely to vary significantly across Europe. Based on the representative construction costs from these cases, as reported in Table 4.7, the unit cost per hectare (at EU prices) can be calculated as EUR 13 302 ([32]).

Information on operation and maintenance of wetlands is perhaps even more difficult to obtain because the information is hardly ever gathered only for wetland management, but rather as part of overall nature reserve management costs in the area. Stella (2012b) estimates the costs to equal EUR 348/ha per year (see Table 4.7).

The benefits of wetland restoration in terms of flood protection are somewhat more moderate in individual terms compared with the previous two measures, as wetlands have a somewhat smaller effect on adjusting the morphological aspects of rivers. Table 4.8 shows that the impact scores for this particular measure are indeed somewhat lower for reducing run-off ( ) (NWRM, 2013d).

A recent study by Acreman and Holden (2013) concluded that the effect of wetlands on attenuating flood hazard depends on four characteristics:

i. landscape configuration (e.g. upland wetlands in rainy areas tend to be saturated and overflow easily);

ii. topography (e.g. a depression has more storage capacity than a plain area);

iii. soil characteristics (e.g. some kinds of soil are more porous than others); and

iv. management (e.g. preservation of vegetation contributes to reducing run-off speed).

([32]) Some evidence on costs data from Stella (2012) has been omitted in this analysis, as it was regarded as not representative. The average has been calculated as (3 075 + 2 244 + 1 359 + 53 949 + 5 885) ÷ 5 = 13 302.

Table 4.8 Effects of wetland restoration

	Storing and slowing run-off	Storing and slowing river water	Reducing run-off	Water storage	Fish Stocks and recruiting	Natural biomass production	Biodiversity preservation	Climate change adaptation	Groundwater recharge	Erosion control	Filtration of pollutants	Recreational opportunities	Aesthetic/cultural value
Wetland restoration and management	**Direct effects**			**Indirect effects (eco-system benefits)**									
0 = None, 1= Low, 2 = Medium, 3 = High	3,0	2,0	1,7	2	3	2	3	2	2	1	2	2	2

Source: NWRM (2013d) — N2 Wetland restoration and management; own illustration.

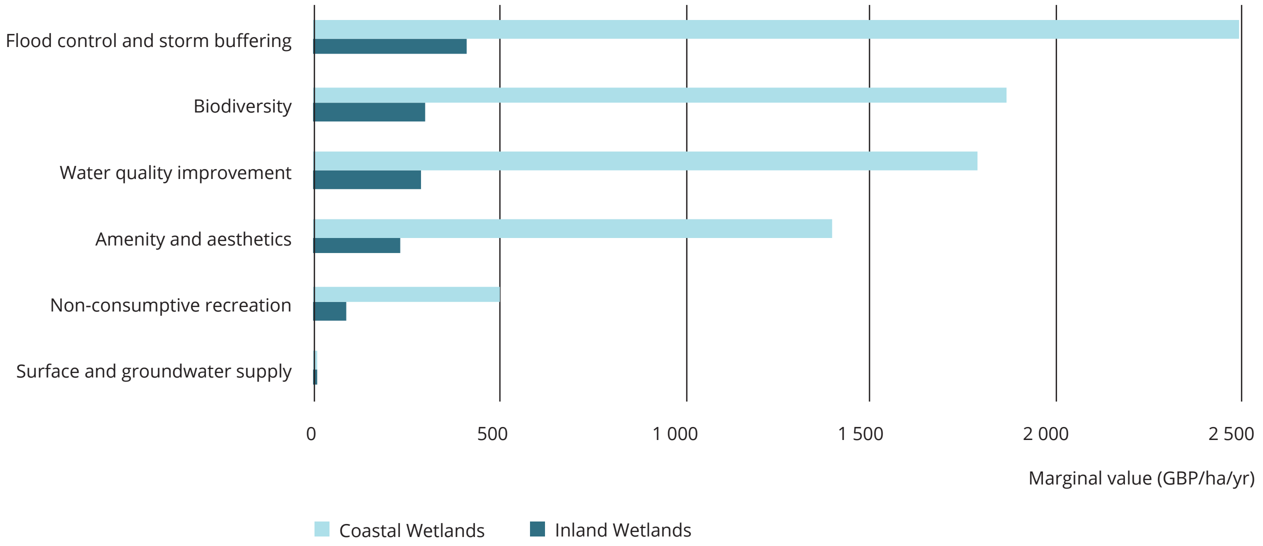
A typical wetland does not have a very large scale (although they also exist at large scale) and therefore the absorption and storage capacity of river water of the restored wetlands is more limited on average (impact score 'medium' 2/3). However, the existence and maintenance of wetlands is particularly effective for storing and slowing 'general' run-off and can play an essential role in flood mitigation due to wetlands' natural 'sponge' effect, improving hydraulic resistance through their water absorption capacity.

According to a study in Finnish wet forests, the restoration of wetlands reduced stream discharge by 47 % (Taylor, 2012). When located next to a river, wetlands can store, slow down and process floodwater and — further away from a river — they can regulate water flow (Stella, 2012b). The impact of their run-off storage function on reducing flood risks is therefore high (score 'high' 3/3). Without high ambitions as regards vegetation in wetlands, the impact on reducing run-off through evapotranspiration is limited (score 0/3 as the evapotranspiration potential is nil when there is no vegetation), and through groundwater recharge or soil water retention functions a medium effect can be expected (2/3).

Beyond the direct flood risk reduction characteristics, wetland restoration presents certain particular indirect benefits to the ecosystem, notably for fish stocks, birds and other species contributing to increased biodiversity (3/3 — 'high'). Wetlands are home to vegetation, fish and amphibians, besides being used for reproduction by insects and birds. More than two thirds of the fish consumed in the EU rely on coastal and inland wetland areas for their existence (Morris and Camino, 2011). For example in the six wetlands restored along the Danube, thirty additional species of fish were found (NWRM, 2013d). The existence of wetlands is also associated with moderate improvements in water quality (2/3); the presence of vegetation and riparian forests contributes to the reduction of nitrogen in water. Due to its water storage properties, a wetland protects an area from droughts, thus improving water availability.

A recent study on UK wetlands by Morris and Camino (2011) used economic valuation techniques to quantify the value of the flood protection and ecosystem services that wetlands provide. Their findings verify the above-mentioned conclusions that the highest value of wetland restoration is derived from their flood control function. Beyond the flood control characteristics,

Figure 4.3 Marginal value of provided ecosystem services by wetlands in the United Kingdom



Source: Morris and Camino, 2011.

the additional marginal value of wetlands beyond the 'default' services provided by the land is predominantly generated through increases in biodiversity and water quality improvements, such as water buffer function and filtration characteristics (see Figure 4.3). Predominantly because of their proximity to densely populated areas, the marginal value of coastal wetlands for these services is (even) higher than that of inland wetlands.

Box 4.3 provides additional information on the precise costs and effects of green (including wetland restoration and management), hybrid and grey infrastructure solutions, specifically for the case of the Scheldt in Belgium. It provides detail on the relative cost-efficiency advantage of wetland restoration projects in a specific region in the EU. Box 4.4 describes a hybrid solution of GI and grey infrastructure to reduce flood risk on the upper Vistula in Poland.

Box 4.3 Scheldt case study: Detailed cost-benefit assessment, including wetland restoration and management

Sigmaplan is a large-scale project aimed at protecting the areas around the Scheldt river against storm floods. It was set up in 1977, as a response to the extensive floods of 1976. Since then, approximately 500 km of dikes, a large protective barrier on the Scheldt and several flood areas have been created. Sigmaplan has not yet been completed, but in the course of its implementation new approaches to flood management have gained momentum, such as GI measures (Gauderis et al., 2005).

Options considered

A 2005 study compared 14 projects in the region against the baseline scenario, which was defined in line with the characteristics of the Sigmaplan as it stands now. This baseline scenario consisted of standardising dike heights around the Scheldt, maintaining existing flood areas and the realisation of a flood area in the Kruibeke-Bazel-Rupelmonde area.

In contrast, the several alternative plans consist of a combination of the following measures: heightening of dikes, building storm surge barriers, creating or restoring flood areas, and building a connection between the Western Scheldt and the Eastern Scheldt in the region Zuid-Beveland, in the Netherlands. The creation of flood areas is not necessarily a GI measure, but it sometimes can be, for example when this is done with re-naturalisation of polders or wetlands. Often, though, these flood areas are simply pieces of land to which overflow water is channelled by the use of dikes and weirs.

Based on the results of the cost-benefit assessment and technical considerations, the study also proposed an optimisation of the measures. The four optimised measures consist of changes in some features of the projects to increase benefits and reduce costs. These 'optimised' measures are included in the summary table of measures considered in the detailed cost-benefit assessment (see Table 4.9) (Gauderis et al., 2005). As shown in Table 4.9, there were no exclusively GI measures considered as part of the feasible set of flood control measures, only green measures in combination with grey infrastructure measures (hybrid measures, such as a combination of flood areas and dike heightening). Therefore, it is important to note that the optimised hybrid measure (measure 3 — see Table 4.9) represents a 'greener' version of the naturalisation of flood areas with dike heightening (measure 1 — see Table 4.9), with all flood areas being naturalised in order to maximise ecosystem benefits.

Table 4.9 Grey and hybrid measures

		Measures
Hybrid	1.	Flood areas and dike heightening
	2.	Flood areas, dike setback in the Durme Valley and dike heightening
	3.	Optimised: flood areas and large-scale dike heightening
Grey	4.	Closeable canal between Eastern and Western Scheldt
	5.	Large-scale storm flood barrier in Oosterweel
	6.	Small-scale storm flood barrier in Mechelen and Lier, with dike heightening
	7.	Small-scale storm flood barrier in Niel, with dike heightening
	8.	Medium-scale dike heightening
	9.	Large-scale dike heightening
	10.	Flood areas and large-scale dike heightening
	11.	Flood areas and medium-scale dike heightening
	12.	Flood areas and small-scale dike heightening
	13.	Optimised: large-scale storm flood barrier in Oosterweel with flood areas
	14.	Optimised: flood areas and large-scale dike heightening
	15.	Optimised: more flood areas and large-scale dike heightening

Summary of scenarios considered

The study estimated the costs and benefits of each project over a period of 97 years (from 2004 to 2100), using a discount rate for future values of 4 % per year in the baseline scenario. This scenario further assumes a sea level rise of 60 cm over the period and a moderate economic growth of 2.4 % until 2020 and 1.8 % after that. The outcome of the calculation is the net present value of each measure.

Box 4.3 Scheldt case study: Detailed cost-benefit assessment, including wetland restoration and management (cont.)

The study also performed a sensitivity analysis using a worst-case scenario in which the sea level rise is 30 cm and a 7 % discount rate is used. This reduces the size of benefits from flood protection dramatically and reduces the weight of future benefits in the calculation. By strongly reducing the size of benefits in the calculation, this exercise provides a picture of the vulnerability of the cost-efficiency of measures with respect to changing conditions.

Comparison of cost-efficiency results per option

The results (in Table 4.10) indicate that the measure with the highest net present value is the (optimised) hybrid measure (number 3) of re-naturalising flood areas (a GI measure) and heightening dikes (a grey infrastructure measure), followed by the optimised grey measures of constructing flood areas and dikes (measures 14 and 15).

Looking at the non-optimised measures, the hybrid measures also score highly. Among the non-optimised measures, naturalisation of flood areas with dike heightening (measure 1) presents the second highest net present value, behind the storm surge barrier in Niel with dike heightening (measure 7).

Table 4.10 Cost-effectiveness of infrastructure options for the Scheldt

Cost-effectiveness of infrastructure options for the Scheldt (Sigmaplan) — Net present value of options			Costs	Direct effects	Indirect effects						
			Investment costs (EUR)	Flood-risk reduction benefits	Shipping	Agriculture	Forestry	Aesthetical effects	Recreation	Other ecosystem services	Net present value (in 2004 prices)
Hybrid	1	Naturalization of flood areas and dike heightening	233	733	0	– 37	– 21	– 7	13	71	519
Hybrid	2	Naturalization of flood areas, dike setback in the Durme Valley and dike heightening	258	737	0	– 40	– 8	– 9	12	45	479
Hybrid	3	Optimized: naturalization of flood areas and large-scale dike heightening	139	730	0	– 14	– 10	– 5	9	53	624
Grey	4	Closeable cannal between Eastern and Western Scheldt	1 597	760	0	0	0	0	0	0	– 837
Grey	5	Large-scale storm flood barrier in Oosterweel	387	728	– 1	0	0	0	0	0	340
Grey	6	Small-scale storm flood barrier in Mechelen and Lier, with dike heightening	231	679	0	0	0	0	0	0	448
Grey	7	Small-scale storm flood barrier in Niel, with dike heightening	204	784	0	0	0	0	0	0	580
Grey	8	Medium-scale dike heightening	241	692	0	0	0	0	0	0	451
Grey	9	Large-scale dike heightening	255	711	0	0	0	0	0	0	456
Grey	10	Flood areas and large-scale dike heightening	217	731	0	– 30	0	– 7	13	0	490
Grey	11	Flood areas and medium-scale dike heightening	177	672	0	– 29	0	– 7	12	0	471
Grey	12	Flood areas and small-scale dike heightening	140	648	0	– 23	0	– 4	8	0	489
Grey	13	Optimized: Large-scale storm flood barrier in Oosterweel with flood areas	397	748	0	– 2	0	– 3	1	0	347
Grey	14	Optimized: flood areas and large-scale dike heightening	132	737	0	– 12	0	– 5	9	0	597
Grey	15	Optimized: more flood areas and large-scale dike heightening	149	752	0	– 13	0	– 8	10	0	592

Box 4.4 Vistula case study: Cost-benefit assessment including wetland restoration and management

The FRMP for the upper Vistula, in Poland, contained 'non-technical' measures, which consist of re-naturalising polder areas. A study of the economic benefits of these measures revealed large positive gains from implementing them (DHI Polska, 2013).

The plan envisages various hybrid measures, that is, actions that mix technical and green (non-technical) measures. These measures include building polders in the section from the Wisłoka outlet to the Sanna outlet, together with building and restoring dike functionalities. The aim of these hybrid measures is to increase retention capacity (via polder building) and reduce flood risk (via dike building).

The planned polders will significantly reduce the volume and height of cumulative waves, and restoration of dike functionality and development of new dikes on the Vistula will complete flood protection of urbanised areas. It is assumed that hybrid measures will eliminate the risk of dike overflow in the event of a '1 %' flood.

The total costs for the project (building the dikes and naturalising the polders, including land purchase) amounted to ~ EUR 217 million ([33]), whereas flood damage avoided (benefits) was projected to be worth ~ EUR 445 million ([34]) in constant values. Taking into account the costs of the whole project and only the benefits in terms of flood reduction, the study therefore concludes with a benefit-cost ratio of 2.05, which means that the benefits are approximately twice as large as the costs.

4.5 Green infrastructure — Stream bed re-naturalisation

The re-naturalisation of a river's streambed (also called riverbed) consists of removing concrete or inert constructions in the streambed, or on both riverbanks, and replacing these with natural structures such as vegetation. To neutralise floods or improve the use of the river, many transformations of riverbeds and riverbanks were made in the past in several important rivers. These changes consisted of setting up structures of concrete or stone that sped up the water flow (NWRM, 2013e). These grey infrastructure measures might help control the water flow and manage flood risk. However, the indirect effects of these undertakings could eventually backfire and increase flood risks. The installation of concrete structures on the riverbed and on the riverbanks removes natural vegetation and soil, replacing it with impermeable material. The effect of this artificial transformation on the river's surfaces increases erosion and changes the sedimentary balance of the stream. Though protecting a specific area of the river from floods, such structural transformation creates larger risks for other downstream areas, as well as damage to biodiversity.

On the other hand, re-naturalisation of the streambed restores the vegetation and soil of the riverbed. This reduces the river speed again, controlling erosion and re-establishing the previous sedimentary balance. This action also has potential to increase water infiltration and increase biodiversity in riparian habitats. Actions related to stream bed re-naturalisation are 'natural bank stabilisation', which consists of using high-absorption and natural material on riverbanks, and 'riverbed material re-naturalisation', which is the restoration of the composition of sediments on the river floor.

The types of costs incurred for the realisation of streambed re-naturalisation are different to those incurred for the previous three GI measures (see Table 4.11). Most importantly, land acquisition or compensation costs should constitute only a small fraction of the total costs for the project, as typically little land needs to be acquired for streambed or riverbank transformations.

([33]) Based on PLN 907 million in constant prices in 2013, according to the original source, and using an exchange rate of EUR 0.239/PLN.
([34]) Based on PLN 1 861 million in constant prices in 2013, according to the original source, using an exchange rate of EUR 0.239/PLN.

Table 4.11 Costs of streambed re-naturalisation

			Costs		
			Land acquisition and compensation	**Construction and rehabilitation**	**Operation and maintenance**
Streambed re-naturalisation					
Case	**Area**	**Source**	**EUR/ha**		**EUR/ha/y**
1	Seymaz River (CH)	NWRM, 2014a	548	12 671	
2	Cerný Potok (CZ)	Jongepierova et al, 2012	27 009		

Note: CH, Switzerland; CZ, Czech Republic.

Source: Jongepierová et al. (2012); NWRM (2014a); own interpretations.

It should be noted that there is little cost information available for the realisation of streambed re-naturalisation (Stella, 2012a; NWRM, 2014a). Nevertheless, on the basis of the two cases mentioned in Table 4.11 (in Switzerland and the Czech Republic), this analysis is able to derive some aggregate cost figures.

The first case involves a re-naturalisation project of the Seymaz river, located in the eastern part of the Geneva canton in Switzerland (NWRM, 2013a). The project involved softening riverbanks, widening the riverbed and eliminating concrete casts along the riverbed. The project therefore also applied a streambed re-naturalisation measure. In this case, land acquisition costs were incurred to widen the riverbed and to compensate farmers with EUR 1.6/m^2 for their future production losses or with EUR 819/ha to sign a 'nature' contract with the authorities. In total, the authorities provisioned as a minimum EUR 1.6 million for 2 920 ha of affected land (EUR 548/ha). Total investment costs therefore amounted to EUR 37 m for the 2 920 ha of affected land (EUR 12 671/ha), EUR 15 million construction costs and EUR 22 million capital investment costs. Operation and maintenance costs were also envisaged, but that approximate cost figure is not available.

Another case is a streambed re-naturalisation located in the Czech Republic, where the Cerný Potok stream was restored between 2001 and 2010 by re-establishing a natural gradient and a natural variety in calm and current riffles (Jongepierová et al., 2012). A second part of the project also realised new streambeds and reconnected the stream with alluvial meadows. In total, 7.4 ha with 4 km of restored stream sections was transformed to re-naturalise the streambed. In addition, 4.3 ha of marshes were restored. Regrettably, no separate cost data for land acquisition, construction or maintenance were available and hence only an aggregate cost figure for both the marsh restoration and streambed restoration was available. Taken together, the project cost amounted to EUR 316 000 for 7.4 + 4.3 ha of re-naturalisations (EUR 27 009/ha).

The effects of a more natural streambed and riverbanks in the context of flood control (direct effects) mainly stem from the slowing of river water, as streambed re-naturalisation increases streambed roughness and storage capacity due to vegetation on the riverbanks (especially in combination with riparian forests) (score 2/3 'medium' — for storing and slowing river water — see Table 4.12). In terms of storing or slowing more general run-off, streambed re-naturalisation does not have any effect, as the measure is fully targeted at the river stream (0/3). The effect on reducing run-off is moderate (1.7/3), as there could be some increase in evapotranspiration and soil water retention from more vegetation on the riverbanks (1/3), but particularly through the high average impact on groundwater recharge (3/3) as it increases stream-subsurface water exchange. The re-naturalisation of the Cerný Potok stream shows that effects on reduction of peak flow rates are limited (< 5 %), but a very significant effect on the delay of the flood wave was recorded, contributing to good run-off control.

In terms of the ancillary effects provided by streambed re-naturalisation, the most significant effects are expected for increased erosion control and improved biodiversity levels (3/3 — see Table 4.12). Better riparian vegetation in the riverbanks also decreases water temperature and as a result improves ecological status. Diversification of channel morphology, flows and water depth alleviates the diversity of habitats offered by a river. To illustrate the effect of the ancillary benefits of streambed re-naturalisation, a study in Flanders calculated public willingness to pay for more natural riverbanks (Liekens et al., 2009; De Nocker et al., 2011). The study found that improvement of the natural status of riverbanks from bad to moderate yields benefits of

Table 4.12 Effects of streambed re-naturalisation

Streambed re-naturalisation	Storing and slowing run-off	Storing and slowing river water	Reducing run-off	Water storage	Fish stocks and recruiting	Natural biomass production	Biodiversity preservation	Climate change adaptation	Groundwater recharge	Erosion control	Filtration of pollutants	Recreational opportunities	Aesthetic/cultural value
	Direct effects			Indirect effects (eco-system benefits)									
0 = None, 1= Low, 2 = Medium, 3 = High	0,0	2,5	1,7	1	1	2	3	0	1	3	2	2	2

Source: NWRM (2013e) — N05 Streambed re-naturalisation; own illustration.

EUR 23 000/km per river per year, and an additional EUR 28 000/km per river per year for improvement from moderate to good. To place these values in perspective, this corresponded with EUR 57 per household per year, which corresponded with approximately 30 % of the total (monetary) benefits for the achievement of 'good' surface waters in the same area.

4.6 Grey infrastructure — Dike building or reinforcement

Dikes (also called 'levees') are embankments on riverbanks that protect areas near a river from overflows. Dikes are the most common features in flood protection, often being combined with preventive measures to free an area from flood hazards (CIRIA, 2013). They can be artificial or natural, resulting from the accumulation of sediments deposited by numerous overflows. A similar protection against floods is provided by river walls. These are walls built on the sides of rivers with the purpose of blocking water from invading nearby areas. Extremely common in the Netherlands, dikes are used for protection against sea level rise and river overflows around the world.

The more resistant a dike and the larger the area a river is allowed to flood before reaching the dike, the more effective this infrastructure is expected to be in protecting areas against the risk of flooding. These two principles are to some degree substitutable: the less space a river has for overflow, the stronger the dike must be, and vice versa. Dikes are usually composed of a hard core of masonry, which is covered by other impermeable, cheaper, material such as rocks and gravel (CEREMA, 2014). Fluvial dikes are built parallel to rivers and channel overflow water further downstream, thus protecting the leveed area (CIRIA, 2013).

To enhance protection against floods, dikes may also be designed to canalise overflow water into a reservoir, which could be a lake or a dam. In this case the dike would help connect the river to the reservoir, increasing water storage and reducing the probability of overflow into the floodplain.

Dikes that are built closer to the river are more subject to erosion due to floods. There are 'greener' applications of this infrastructure, consisting of retreating the location of the dike and placing it behind floodplains or wetlands. This would increase absorption capacity in the case of an overflow, and at the same time it would relieve pressure on the dike. In addition, it provides for habitat restoration.

Many features unrelated to floods are also linked to building dikes. Dikes make access to rivers more difficult, bringing harm to the area in terms of aesthetic and recreational value. As a result, special access is normally built between the protected areas and the river itself, such as stairs or road embankments (CIRIA, 2013). Dikes also create opportunities for recreation, as sites for walking, fishing and cycling.

As dikes are essentially long protective structures that prevent water from reaching the dike's outer side, building a dike does not require acquisition of large swathes of land. A survey of eight French projects involving dike building found that land acquisition was only necessary for two of them, comprising 8 %

Table 4.13 Costs of dike building or reinforcement

			Costs		
			Land acquisition and compensation	**Construction and rehabilitation**	**Operation and maintenance**
Dike building or reinforcement					
Case	**River**	**Source**	**EUR/m**		**EUR/m/y**
1	Elbe (DE)	Grossmann et al (2010)		(1 500–2 800)	
2	Elbe (DE)	Tröltzsch et al (2011)		700	0.5 % of investment
3	Rhine (DE)	Dehnhardt et al (2008)		4 000	
4	Netherlands	CPB (2000)			1.5 % of investment

Note: DE, Germany.

and 11 % of total project costs. The costs are typically concentrated on the construction of the infrastructure, which can represent 75 % to 95 % of the total project (CEREMA, 2014).

Cost figures for building dikes are provided by cases in the Netherlands and Germany (see Table 4.13). Table 4.13 summarises the key findings from these cases with respect to the costs for realising dike building and reinforcement. Grossmann et al. (2010) estimated the costs of building new dikes in Germany within the range of EUR 1.5 million/km to EUR 2.8 million/km. However, individual projects vary dramatically in their costs. Costs for building 8 km of dikes in the city of Garbe-Niederung are estimated at EUR 0.7 million/km (Tröltzsch et al., 2012). In contrast, in the city of Mohnheim, on the Rhine, a project of retreating and rebuilding a dike estimates the construction costs at EUR 4 million/km for 3.5 km of dike (Dehnhardt et al., 2008). River walls are more expensive structures, but they are usually used for shorter distances in critical sites. In three German projects ([35]), the average cost of 1 km of river wall was between EUR 14 million and EUR 17 million.

Re-enforcement of dikes is estimated to be a much more expensive measure. A German study on the Elbe estimates costs of EUR 4 to 6 million/km (Grossmann et al., 2010). These figures are consistent with data from the Netherlands ([36]), which indicate that river dike re-enforcement costs are between EUR 3 and 5 million/km.

Maintenance costs of dikes vary from EUR 400/km to EUR 1 250/km according to Tröltzsch et al. (2012), which would represent less than 0.5 % of construction costs. However, an earlier Dutch study estimates maintenance costs at 1.5 % of construction costs (CPB, 2000).

The benefits of dikes for flood protection are intrinsic, as they constitute a barrier to the overflow water, and limit floods in an occupied area. The type of direct and indirect effects provided for by grey infrastructure measures are different in their nature from the effects provided by GI measures. Most importantly, they provide fewer ecosystem services and do not provide flood risk protection through biophysical characteristics. However, to keep the approach of comparing costs and benefits equal for green and grey infrastructure measures in this section, the effects of grey infrastructure measures (here, dike building) are still summarised based on the same characteristics as presented in Table 4.14. The direct effects of flood risk protection are scored only for preventing river water from overflowing (), whereas the other biophysical impacts are not scored, as they do not apply to grey measures. On the indirect benefit side, one could argue that some ecosystem services could even be scored negative, as grey infrastructure measures might reduce biodiversity or water quality, for example. However, in order to stick as closely as possible to the effect categorisation and its impact rankings as undertaken for the green NWRM measures (none-low-medium-high, and thus no negative scores), the same effect scores are used.

The efficacy of a levee in impeding floods depends crucially on three aspects:

([35]) Own calculations based on examples mentioned in Hamburg (2007).
([36]) EEA website: Information available at: http://climate-adapt.eea.europa.eu/metadata/adaptation-options/adaptation-or-improvement-of-dikes-and-dams/#costs_benefits

Table 4.14 Effects of dike building or reinforcement

Dike building or reinforcement	Storing and slowing run-off	Storing and slowing river water	Reducing run-off	Water storage	Fish stocks and recruiting	Natural biomass production	Biodiversity preservation	Climate change adaptation	Groundwater recharge	Erosion control	Filtration of pollutants	Recreational opportunities	Aesthetic/cultural value
	Direct effects			Indirect effects (eco-system benefits)									
0 = None, 1= Low, 2 = Medium, 3 = High	n.a.	3,0	n.a.	0	0	1	0	0	0	0	0	2	1

Note: N.a., not applicable.

Source: Author's expert judgement.

- its distance from the river itself, which determines the area the river is able to flood before reaching the dikes;
- the height of the dike determines the volume of water that can be kept from flooding the areas near the river;
- pressure from water overflows i.e. its ability to resist a flood.

Dikes are constantly being maintained and re-enforced to make them more resistant to floods. A breach of a dike during an overflow may cause severe damage, as a lot of water is released suddenly, and it can be compared with the speed of a flash flood, which can be very dangerous for the people living close to it.

Dikes are generally intended to protect an area from specific flood intensities, which are normally defined in terms of their frequency (e.g. 1 in 100 years). Since they are 'protective' measures rather than preventive ones, dikes do not reduce the probability of such floods occurring, but eliminate the damages that they may cause in a certain area (CIRIA, 2013). However, dikes are not able to protect areas against floods that are stronger than those they were intended for. Moreover, frequent exposure to water overflows means that dikes require constant maintenance.

Additional case study evidence comparing the cost-efficiency of dike heightening as a grey measure with its possible green alternatives is provided in Box 4.5.

Box 4.5 Additional cost-efficiency evidence comparing dike-heightening and green alternatives

A German case illustrates how these indirect benefits are important for choosing in favour of greener options (Dehnhardt et al., 2008). Two alternatives for reducing flood risks in the municipality of Mohnheim (on the Rhine) were considered: either (1) reinforcing and elevating current dikes (a 'grey' measure); or (2) retreating the dike and leaving a larger green area for the flood to overflow (a 'green' measure). The latter measure was found to cost almost four times the net present cost of the grey measure for the same degree of flood protection. However, when accounting for monetised values of indirect effects, the benefits of the green project were 33 times higher than the benefits of the purely grey measure. The benefit-cost ratio of retreating the dike was estimated at 1.96, whereas strengthening the old dike had a ratio of 0.24, which implies that retreating the dike was the more cost-efficient solution compared with strengthening the old dike. Similar results were found for the Netherlands when comparing the benefit-cost ratio of building higher dikes and creating green retention areas around the Rhine. The detailed cost-benefit assessment found that, for the same level of benefits, the grey measure was almost twice as expensive as the green measure (CPB, 2000). The benefit-cost ratio of the green measure was estimated to be between 4.6 and 10.8, whereas the grey alternative had ratios between 2.1 and 5.1, depending on the flood scenario considered. The green measure was therefore found to be almost twice as cost-efficient as its grey alternative.

4.7 Grey infrastructure — Longitudinal barriers

Dams are longitudinal barriers on a river that block the flow of water and regulate the amount of water that flows downstream of the barrier. Thus, in contrast to dikes, which are built parallel to the river, longitudinal barriers are usually built across the river, blocking its passage. This implies another significant difference between the two kinds of protective structures: while dikes are only temporarily subject to water pressure, dams and barriers are constantly opposing hydraulic loads (CIRIA, 2013).

The construction of dams is thus an effective way to protect downstream areas from floods, since it prevents large discharges of water from becoming river overflow. Upstream of the dam, however, an area must be permanently flooded, displacing people and activities. Besides flood control, dams can be used for agricultural irrigation, household and industrial water use and electricity generation (Wong, 2013).

Building dams requires complex engineering and large investments. The infrastructure must be continually maintained, to avoid breaches, which can be catastrophic for the downstream areas. A study of 46 dam failures in the last 150 years found that they caused the deaths of at least 1 000 people around the globe (Brown et al., 2009). Large dams are consistently faced with cost overrun during the construction process, which undermine their preliminary cost-benefit assessments (Ansar et al., 2014).

However, for the purposes of flood protection, other kinds of barriers may be sufficient. Longitudinal barriers such as small dams and storm surge barriers are abundant in Europe. The difference between these barriers and dikes is that they directly oppose the flow of the river, whereas dikes contain overflows on the river sides. Dam construction, that is, blocking river flow and flooding areas, is in general extremely expensive. Usually the word 'dam' is associated with megaprojects with various functionalities, notably electricity generation. These megaprojects are increasingly met with scepticism due to their immense and unpredictable construction and maintenance costs (Ansar et al., 2014).

A study by Hillen et al. (2010) collected costs and technical information on nine projects, in Europe (Germany, Italy, the Netherlands and the United Kingdom) and the USA (New Orleans), where barriers and gates were built. The evidence on the costs of the seven EU projects was transformed to costs per metre of longitudinal barrier and has been included in Table 4.15. Since the original source does not separate the cost data according to land acquisition costs and construction costs, a joint figure for both is reported in Table 4.15. They are all large-scale projects where costs ranged from EUR 115 million (a vertical lifting gate in New Orleans) to EUR 4 billion (the Eastern Scheldt Barrier in the Netherlands). On average, for each square metre of barrier these projects cost EUR 111 700, and for each metre of longitudinal width the average cost amounted to EUR 1.6 million. The height of the barriers ranged from 8 to 22 m, with the Maeslant Barrier near Rotterdam being the highest.

Table 4.15 Costs of longitudinal barriers

			Costs		
Longitudinal barriers			Land acquisition and compensation	Construction and rehabilitation	Operation and maintenance
Case	River/Location	Source	EUR/m		EUR/m/y
1	Maas (NL)	Hillen et al. (2010)	1.82 M		
2	Hartel (NL)	Hillen et al. (2010)	0.84 M		
3	Scheldt (NL)	Hillen et al. (2010)	1.68 M		
4	Ramspol (NL)	Hillen et al. (2010)	0.55 M		
5	Ems (DE)	Hillen et al. (2010)	1.02 M		
6	Thames (UK)	Hillen et al. (2010)	2.73 M		
7	Venice Lagoon (IT)	Hillen et al. (2010)	1.46 M		
8	Europe	Linham and Nicholls (2010)			5–10 % of investment

Note: DE, Germany; IT, Italy; NL, the Netherlands; UK, United Kingdom.

Source: Hillen et al. (2010); Linham and Nicholls (2010).

Table 4.16 Effects of longitudinal barriers

	Storing and slowing run-off	Storing and slowing river water	Reducing run-off	Water storage	Fishstocks and recruiting	Natural biomass production	Biodiversity preservation	Climate change adaptation	Groundwater recharge	Erosion control	Filtration of pollutants	Recreational opportunities	Aesthetic/cultural value
Longitudinal barriers	**Direct effects**				**Indirect effects (eco-system benefits)**								
0 = None, 1= Low, 2 = Medium, 3 = High	n.a.	3,0	n.a.	3	0	0	0	0	0	2	0	1	0

Note: N.a., not applicable.

Source: Author's expert judgement.

While this study does not provide an estimate of the maintenance costs, these are often seen as a major disadvantage of longitudinal barriers such as storm surge barriers. A study calculated them at 5-10 % of investment costs in the case of movable barriers for coastal floods (Linham and Nicholls, 2010).

Like dikes, longitudinal barriers have the purpose of directly blocking water from passing into a specific area. Again, the effects illustrated in Table 4.16 show only the direct flood risk reduction in terms of the blocking of river water ( ), and no negative values for ecosystem services are given in order to maintain the impact scores (low-high; 0–3). Still, studies have documented the negative effects of dams, which can reduce water quality, reduce fish populations, etc. In terms of the provided flood control benefits, dams and barriers oppose water flow frontally, which is different from dikes. This requires more resistant infrastructure and costlier maintenance, as longitudinal barriers are permanently under water pressure, whereas with dikes this only happens occasionally.

The advantage of longitudinal barriers compared with dikes is that they control the downstream flow of water. Dams, for example, may control how much water flows downstream through the barrier. The same can be said for movable barriers, such as the Maeslant Barrier in the Netherlands, which allows for active control over the water flow.

In many cases, notably in the Netherlands, longitudinal barriers are made to prevent seawater from raising the level of rivers, causing floods. In most cases, however, these barriers control the flow of the water downstream, thus flooding an area upstream of the barrier to reduce and control the downstream water flux.

5 Potential for further green infrastructure implementation in case study areas

The recent EEA (2015b) report *Exploring nature-based solutions: The role of GI in mitigating the impacts of weather- and climate change-related natural hazards* notes that, although research indicates that GI solutions are less expensive than grey infrastructure and provide a wide array of co-benefits for local economies and the broader environment, GI is not yet fully recognised among policymakers and planning authorities. The report thus highlights that there is still a lack of awareness about the fact that GI can provide benefits comparable with those of grey infrastructure, at reduced costs in the long term. Having quantitative figures would better enable decision-makers to compare grey and GI solutions in order to potentially invest in the conservation, sustainable management and/or restoration of natural ecosystems. It is thus necessary to develop, for each management plan, a separate financial case for GI, taking into account all costs and benefits related to it (supported by the ecosystem services approach).

Various case studies around the world (such as CPB, 2000; Gauderis et al., 2005; Turner et al., 2007; Dehnhardt et al., 2008; Grossmann et al., 2010) illustrate the benefits of using GI for flood protection (see Box 5.1 for an illustrative example). This is in line with the results from this study (although recognising that this study is based on a limited number of cases), indicating that GI solutions are generally more cost-efficient than grey infrastructure alternatives, especially because they generate indirect co-benefits that are generally absent in grey infrastructure developments. Moreover, GI also appears to be less costly than grey infrastructure for similar levels of flood protection.

It is therefore important that planners compare green with grey and identify new opportunities for investing in nature, including a combination of green and grey approaches when nature-based solutions alone are insufficient (EEA, 2015b).

In order to illustrate the additional future potential (in terms of available suitable space) of GI measures for flood risk management, this analysis has delineated suitable floodplain areas in the selected case study regions. The purpose of this modelling exercise is to assess the available 'space' or 'potential' for further GI (in this case, floodplains) implementation within these case study areas (the Elbe in Germany, the Rhône in France and the Vistula in Poland). The modelling is based on the initial research carried out in relation to the vulnerability of cities to floods, the review of the implementation of the RBMPs and FRMPs, and the integration of GI measures within these plans for the selected set of case studies. While the exercise is carried out for the case-specific situations, lessons learned are valuable for furthering the understanding of decision-makers as regards the future opportunities and spatial perception of GI solutions (floodplains) for flood management.

5.1 Case study specific identification of the potential for additional floodplains

One important large-scale green solution for flood management is the restoration of floodplains. These actions have significant potential for absorbing water

Box 5.1 Illustration of existing literature findings on the potential of floodplains

A study (Williams et al., 2015) of the European Parliament also assessed potential gains from restoring floodplains in Europe, estimating them to be approximately EUR 39.3 billion, with costs of EUR 24.1 billion per year for 8.8 million ha in Europe over the period 2015–2030. The large benefits are due not only to the reduced flood risk but also to the indirect benefits, such as the potential for recreation and tourism, and environmental services.

Source: Williams et al., 2015.

overflow and avoiding floods. Floodplains exist in several locations along a river, and the potential for additional floodplains can be identified by modelling exercises. The tabular results (Table 5.1) are the outcome of a modelling exercise (for the methodology see Annex 4), aimed at showing the potential for future implementation of GI measures along river sections upstream of cities that are identified as being vulnerable to flood risk.

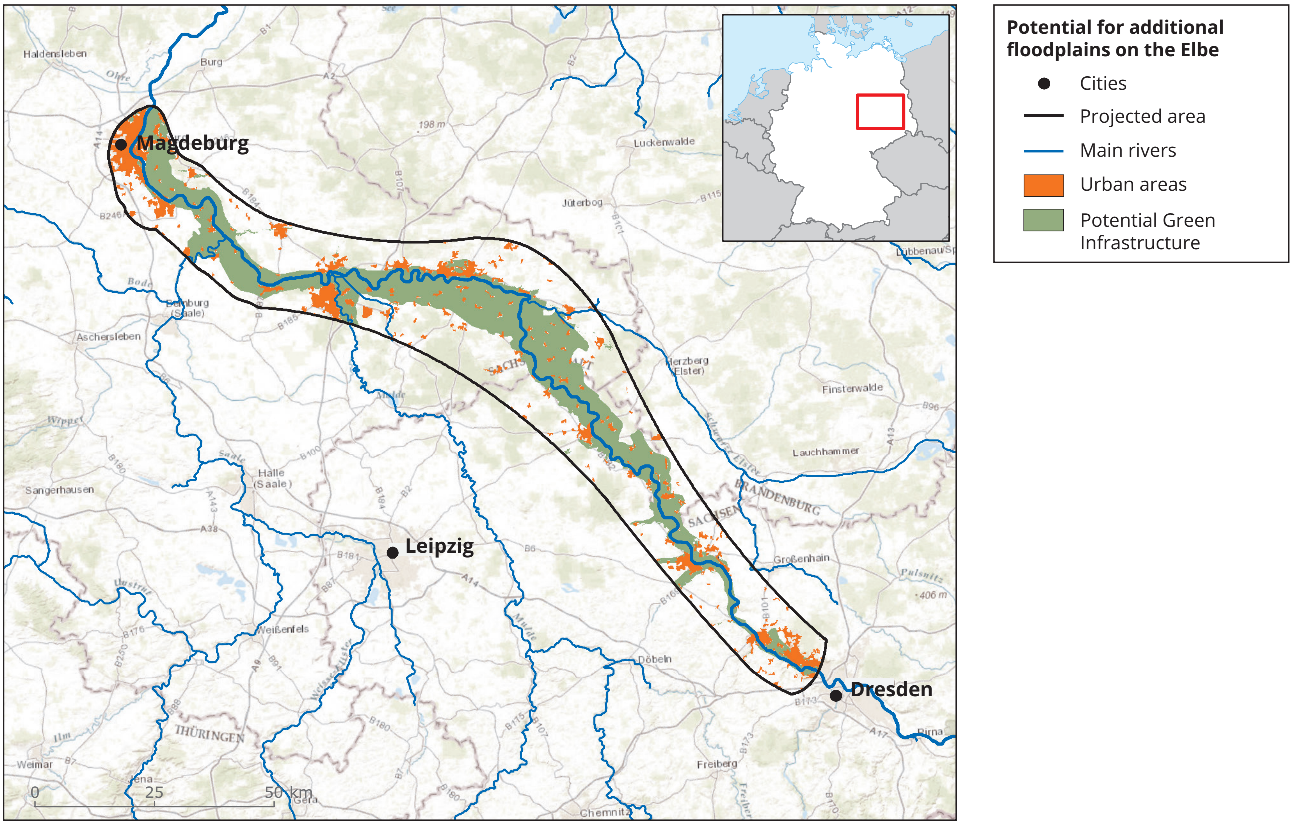
Table 5.1 depicts the modelled results of the potential (in terms of suitable space) for additional floodplains — both in volume and in surface area — for stretches of the Elbe, Rhône and Vistula. Maps 5.1–5.3 depict this potential for additional floodplains visually, in maps of the selected river stretches. The tabular results indicate the urban area currently flooded in a 1 in a 100 peak flow scenario, in comparison with the potential floodplain area available in the area upstream

Table 5.1 Tabular results (by volume and by surface area) of the potential for additional floodplains in the Elbe, Rhône and Vistula case study river stretches

	Elbe	Rhône	Vistula
Peak volume (million m³)			
Urban area flooded	155.83	71.56	43.36
Potential floodplain	2 293.25	1 408.76	2 048.82
Surface area (km²)			
Urban area flooded	137	121	89
Potential floodplain	1 188	794	1 751

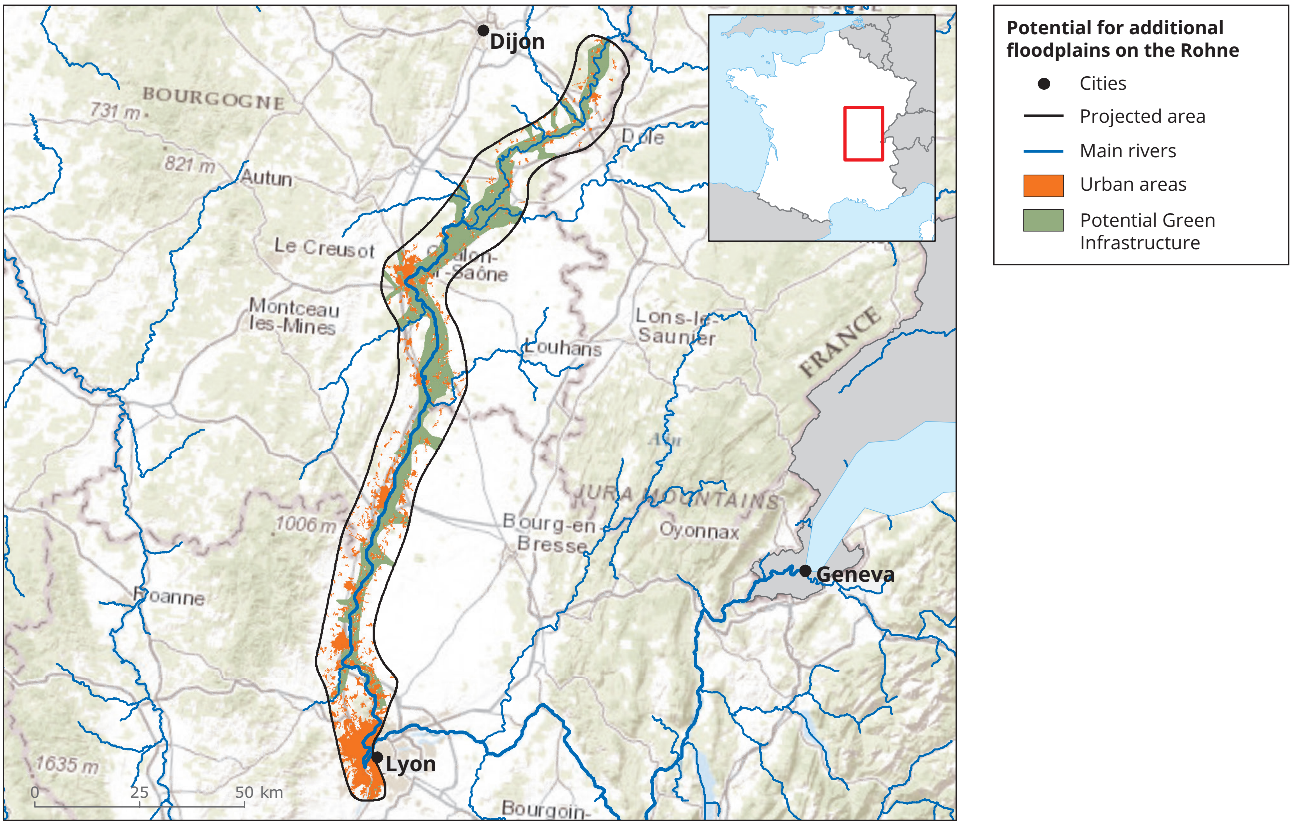
Source: Own analysis; for details see Annex 6.

Map 5.1 Potential for additional floodplains on the Elbe (selected stretch)



Source: Arcadis, 2016.

Map 5.2 Potential for additional floodplains on the Rhône (selected stretch)



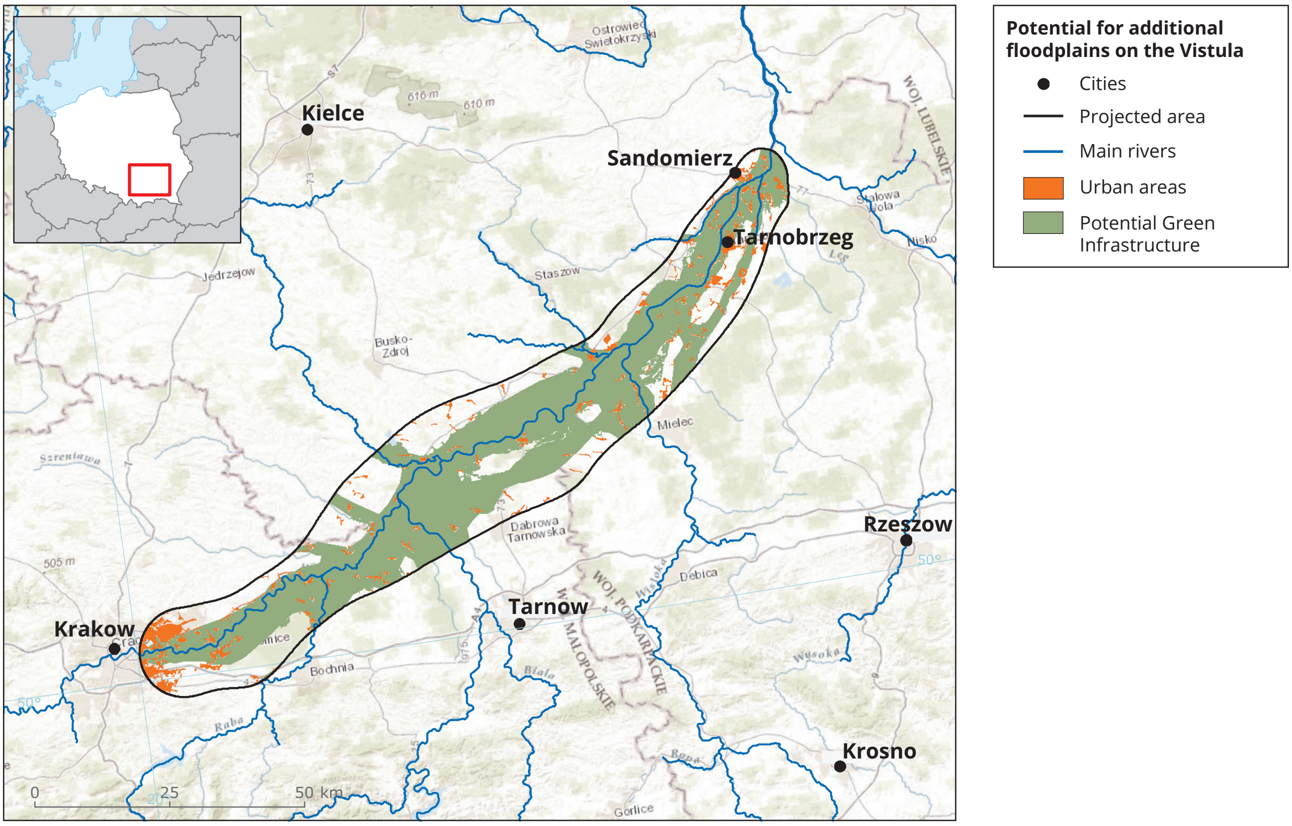
Source: Arcadis, 2016.

(minus the urban area) for absorbing peak flows. For every river basin stretch, sufficient capacity is available to absorb peak flows, currently already affecting urban areas, by creating additional floodplains.

The current potential floodplain area is made up of the EEA floodplain layer (potential area for alluvial forest calculated) and the Corine land use layer, as only agricultural and nature areas have been allocated as potential GI areas within the EEA floodplain layer. Topographic conditions are used to calculate the volume of water that can be 'absorbed' when filling the river floodplain area. It is a hypothetical scenario, does not include current 'structures' in the river built for flood protection, and does not take into account agricultural or natural land to be excluded from the floodplain. Essentially, it is a theoretical exercise and needs to be taken up further with the relevant river basin managers. As a result, the green shaded areas depicted in Maps 5.1–5.3 indicate the most suitable space for additional floodplains to be created in the future — keeping in mind the methodological limitations of the modelling exercise. The orange-shaded areas show the urban areas that can be protected via these potential floodplains.

The results of this modelling exercise show that relatively large areas (ranging from 794 km² for the Rhône's selected river stretch to 1 751 km² for the Vistula's selected river stretch) of suitable land exist to further increase the use of floodplains as a GI tool for flood risk reduction. In reality, however, the decision by policymakers to make use of this opportunity depends on a multitude of decision factors, including cost-benefit considerations, conflicting land use such as urban settlements, competition for the same space in spatial planning, availability of funding for alternative types of measures, potential stakeholder resistance and agricultural use of land, as well as previous hydromorphological terrain transformation and an unfavourable regulatory environment, may prevent authorities from restoring floodplains in these areas.

Map 5.3 Potential for additional floodplains on the Vistula (selected stretch)



Source: Arcadis, 2016.

The following observations should be kept in mind when interpreting the results:

- The potential floodplain area in each of the river basins is sufficient to 'absorb' the extra volume of peak flows derived from a 1 in 100-year event in the river basins upstream of the cities.
- Climate projections in the river basins, through the different IPCC scenarios, give very large ranges of expected volumes in the river basins at the cities selected. There is great uncertainty on the outcome of climate change in relation to peak flow changes.
- The potential floodplain areas are sufficient to 'absorb' the extra volume through peak flows projected to 2050, in the river basins (modelled projections versus baseline).
- River basin authorities would need a case-by-case assessment on what is needed and to evaluate each specific part of the floodplain in terms of GI potential and its cost-efficiency over the long term.
- These results do not mean that local or national authorities in the respective river basins are not already planning to perform flood prevention measures in these floodplains. As shown in Annex 5, all selected river basins do already take GI measures into account in their RBMPs and FRMPs.

In a modelling exercise taking into account climate change projections as an influencing factor for establishing additional floodplains, seven scenarios have been selected, each derived from a global circulation model and a regional circulation model as shown in Table 5.2 (also see Annex 6). This is building on the EURO-CORDEX climate change scenarios (Jacob et al, 2014), which calculate expected flood volume increases by 2050, as compared with a baseline of daily peak flows in a 1 in 100-year event derived for the period 1990-2013 (see Annex 4 and Annex 6 for more detailed information) (Alfieri et al., 2015).

Table 5.2 Climate change projections for flood volume increases in the selected river basins by 2050

Scenario	Climate projection		River basins					
	Global circulation model	Regional circulation model	Elbe		Rhône		Vistula	
			m³	%	m³	%	m³	%
Baseline 1990–2013			155.83		71.56		43.36	
1	EC-EARTH	RACMO22E	4.46	2.86	9.45	13.21	12.70	29.30
2	HadGEM2-ES	RCA4	66.13	42.43	4.72	6.60	13.66	31.50
3	EC-EARTH	RCA4	8.69	5.58	− 5.08	− 7.09	6.59	15.20
4	MPI-ESM-LR	REMO2009	− 15.58	− 10.00	− 2.61	− 3.65	−3.66	− 8.44
5	MPI-ESM-LR	CCLM4-8-17	0.62	0.40	12.59	17.60	5.72	13.20
6	MPI-ESM-LR	RCA4	−15.58	−10.00	−0.39	0.54	− 4.25	9.80
7	EC-EARTH	CCLM4-8-17	12.81	8.22	13.00	18.16	− 0.56	1.30
Largest expected volume			221.96		84.56		57.02	

Source: Own calculations.

Table 5.2 illustrates the increases in flood volumes when taking into account climate change projections for the Elbe, Rhône and Vistula river basins compared with their baselines. Expected changes are shown as a percentage (%) change and as additional volume in cubic metres (m³). When comparing the highest estimates for expected flood volume increases with the spatial area that has been modelled as suitable for creating floodplain areas (shown in Table 5.1), the results indicate that even the increased flood volumes under any of the climate change scenarios still amount to fewer cubic metres than the indicated potential floodplain areas could absorb. Hence, it can be concluded that only a fraction of the modelled suitable floodplain area must be created to safeguard against potential future flooding, even when accounting for climate change scenarios. This indicates that floodplains alone can provide sufficient flood protection for the assessed urban areas. However, due to the uncertainty factors involved, it would be useful to have a more detailed analysis on the likelihood of the IPCC scenarios for the projections in the selected river basin districts (RBDs).

Moreover, as has been highlighted in Chapter 4, the economic benefits (both direct and indirect) from implementation of floodplain restoration are potentially large. Besides being cost-efficient, such measures meet regulatory requirements on flood protection, biodiversity conservation and water quality, among others, stipulated in the Water Framework Directive and Floods Directive. As demonstrated by the modelling exercise, the potential (i.e. suitable space) for restoring additional floodplains in the case study areas is large. Recognising the limitation of generalising the findings from the three case studies, they nonetheless indicate that restoration of floodplains can be an efficient and feasible measure to fight flood risks in Europe today and in the future.

6 Conclusion

6.1 Opportunities for GI exist in European floodplains

All case studies were found to include planned GI measures for flood prevention. The Member States involved have employed GI measures, mainly de-poldering, restoring wetland areas and restoring floodplains over the years. The case of the Scheldt is particularly interesting, as the Belgian authorities carried out a detailed cost-benefit assessment in the scope of Sigmaplan, exploring the possibilities for floodplain restoration, and compared these solutions with grey and hybrid alternatives. The Sigmaplan assessment favoured the adoption of hybrid solutions. Similar assessments were performed by authorities in the river basins of the Vistula and Elbe, reaching similar conclusions: greener solutions bring about greater benefits and often have lower costs.

The modelling exercise, which looks into potential opportunities for future floodplain restoration in the areas surrounding the river in the basins of the Elbe, Rhône and Vistula, shows that the mapped areas with the right characteristics for serving as floodplains would be able to cope with the excess of floodwaters for 1 in 100-year events, even with future climate change scenarios up to 2050 taken into account. In the current situation, the spatial areas of the river basins are only partially used, and/or existing dikes do not use the floodplains for water retention, resulting in significant flood hazards for certain peak floods at the downstream level.

However, due to the study's limited scope, its conclusions regarding the spatial/mapping assessment identifying the future floodplain potential must be qualified by further research that accounts for various issues, including:

- Technical assessment of the RBMPs and FRMPs: The management plans are often an abstraction of the information available. The scale of GI implementation for the selected river basins versus the potential floodplain area available needs to be considered through a separate detailed analysis, together with the river basin authorities.

- Assessment of climate change impacts: Climate change may have a large effect on the peak flows that can be expected and the storage needed, and more research is needed to advise RBDs and authorities of the most likely scenarios and the capacity needed. No-regret measures should be key here.

- Assessment of importance of size and terrain: This study focused on large rivers. It is unclear, however, if the same conclusions would hold for smaller rivers. Moreover, diversity in soil types was not explicitly dealt with here, whereas it may be of crucial importance for determining technical feasibility and benefit-cost ratios of projects.

6.2 Cost-efficiency ratio of GI solutions for flood management compared with grey alternatives

The figures from the case studies suggest that, where a GI measure is technically feasible, its benefit-cost ratios are greater than those of its grey counterpart for the same degree of flood protection. It should be noted that the cost-efficiency calculations of individual measures (Box 6.1) provided in this report are not directly comparable with one another, as both costs and benefits are highly dependent on the geographical location of the measure (e.g. altitude, land use).

In terms of their cost-benefit assessments, the case studies show that grey and GI solutions differ in several fundamental ways.

- Firstly, GI solutions help prevent floods from happening, whereas grey solutions typically serve as a defence protecting areas from the effects of higher water levels. Grey flood protection infrastructure, such as dams and dikes, may also provide inhabitants of a protected area with a false sense of security, which is shattered when a flood overwhelms the protection, typically causing great damage. On the other hand, by altering hydromorphological ([37]) aspects of a river basin, GI measures change the behaviour and frequency of water overflows. However, this is done at a high cost in terms of land acquisition, since such GI measures often require re-naturalisation of areas and relocation of human dwellings and activities outside a flood risk area.

- Secondly, GI solutions do not interrupt river flows in the way that their grey alternatives do (e.g. interposing barriers to its course). This means that GI solutions are less prone to being worn out or damaged. Therefore, compared with grey infrastructure solutions, green measures have in general lower maintenance costs.

- Thirdly, there are many co-benefits of GI solutions besides flood protection, which grey infrastructure solutions do not offer. Grey infrastructures are engineered solutions often serving a single purpose, mostly fine-tuned to the needs of the site, so that the effectiveness can be maximised in the design of the structure. GI (e.g. NWRMs), on the other hand, contributes to multiple purposes at the same time, so that many additional indirect benefits ([38]) related to biodiversity, water quality, recreation and other ecosystem services can be realised. In contrast, grey infrastructure in some cases even diminishes or damages ecosystem service delivery. Therefore, when taking into account indirect co-benefits for the cost-efficiency assessment, these often tilt the balance in favour of green solutions (Box 6.1).

The results from the cost-efficiency analysis have to be interpreted with caution: making general conclusions on the relative cost-efficiency of the individual measures is not possible because of the limited number of cases analysed. Infrastructure measures are often implemented jointly in a project (particularly green measures), in which cases the joint benefits and costs are more advantageous than the sum of their individual parts, as they reinforce one another.

Accurate assessments of costs and benefits require site-specific analyses, with considerations taking into account the technical feasibility of one project as opposed to another. Some examples of such assessments are provided in this report, using case studies for the Elbe, Scheldt and Vistula. Due to the significance of the value of the indirect benefits for the outcome of cost-efficiency analyses of green, grey and hybrid flood protection infrastructure options, more research should be conducted into developing a reliable methodology for valuing indirect benefits of flood protection infrastructure measures, which need to take the unique characteristics of affected local communities into account.

Nevertheless, the summary matrix (Box 6.1) above offers a good starting point for investigating what types of costs and effects to take into account in location-specific evaluations and for making a preliminary selection of feasible green, grey and hybrid options to reduce flood risks.

6.3 There is a need for better coordination and cooperation between authorities

One of the key challenges and barriers to making progress with the implementation of GI has been identified as the level of coordination between upstream and downstream areas of river basins. A screening of 32 draft FRMPs covering 15 Member States, indicate that twenty-five of the plans differentiate the measures by type but there is no specific distinction made concerning GI measures. Furthermore, the reported information in the draft FRMPs for the selected four river basins (Elbe, Rhône, Scheldt and Vistula) show that objectives are established for management of flood risk. The review suggests that there is an increase in NWRMs except for the Scheldt. Creating space for water through land use change and spatial planning is clearly visible for the Elbe and Rhône whereas this is not the case for Scheldt and unclear for Vistula.

Overviews of the current status of the harmonisation and coordination of planning instruments between FRMPs and RBMPs per selected river basin can be found in Annex 5. On the basis of the analysis undertaken in Annex 5, there are clear arguments for improved coordination (in particular between upstream and downstream areas) to enhance the decision-making process, as well as the implementation of GI for flood risk management. The analysis show that aspects covering coordination are limited in most of the reviewed RBMPs and FRMPs.

([37]) For a definition of 'hydromorphological', see terminology table on page 8.
([38]) For a definition of 'indirect benefits', see terminology table on page 8.

Box 6.1 Summary overview of detailed results: cost-efficiency of reviewed green and grey infrastructure measures

The summary matrix combines the information of all reviewed measures on the standardised evaluation criteria in the categories of costs, direct effects and indirect effects. The overview matrix (Table 6.1) summarises the average unit costs in the EU for implementing **green** and **grey** flood protection infrastructure solutions based on the average for the three categories of costs displayed in the matrix. The infrastructure measures have been rated on three typical biophysical characteristics that provide flood protection (their **direct effects**) as well as on their characteristics that provide additional **indirect effects** (ancillary benefits) in the form of the provision of different types of ecosystem services. In a cost-efficiency comparison of green and grey infrastructure measures it is crucial to include in the assessment both direct benefits (effects) as well as indirect benefits (effects) in order to take into account all the benefits that each type of infrastructure measure provides to society. This overview matrix shows how the NWRM project scored GI measures (NWRMs) ([39]) in these different categories, where a '0' in the table represents 'no effect', '1 = low effect', '2 = medium effect' and '3 = high effect'.

'Wetland restoration' and 'floodplain restoration' infrastructure measures seem particularly attractive because of the high degree of flood risk protection offered and the provision of many additional ecosystem services. On the basis of the data gathered in this study, wetlands can be very cost-efficient flood risk reduction solutions thanks to their low per unit investment and maintenance costs. A case in the city of Nummela in Finland illustrates this high cost-efficiency ratio for wetlands well, as the restoration costs for 1 ha of wetland totalled EUR 62 000, providing cost savings of approximately EUR 50 000 per 100 m of grey infrastructure solutions (Naumann et al., 2011).

Table 6.1 Overview matrix and ranking of green versus grey infrastructure measures

Costs data represent an average of the standardised unit costs for different GI projects realised across the EU.

Direct effects represent biophysical characteristics of infrastructure measures that provide protection to flooding.

Indirect effects represent ancillary benefits that the infrastrcuture measure provides in terms of additional eco-system services. Effect scores range from 0 (no effect), 1 = low effect, 2 = medium effect and 3 = high effect, which are sourced from the NWRM project.

	Costs		Direct effects			Indirect effects (eco-system benefits)									
	Land acquisition & Compensation / Construction & rehabilitation	Operation and maintenance	Storing and slowing run-off	Storing and slowing river water	Reducing run-off	Water storage	Fish stocks and recruiting	Natural biomass production	Biodiversity preservation	Climate change adaptation	Groundwater recharge	Erosion control	Filtration of pollutants	Recreational opportunities	Aesthetic/cultural value
	EUR/ha (m)	EUR/ha/y	0/1/2/3			0/1/2/3									
Wetland restoration and management	13 302	348	3,0	2,0	1,7	2	3	2	3	2	2	1	2	2	2
Re-meandering	92 592	2	2,0	2,5	1,7	2	2	3	3	2	3	3	2	3	3
Stream bed re-naturalisation	20 114	*n.a.*	0,0	2,5	1,7	1	1	2	3	0	1	3	2	2	2
Floodplain restoration	153 279	2 412	3,0	3,0	2,3	3	3	3	3	2	3	3	2	3	3
Dike building or reinforcement	**2 283a**	**1 %**	*n.a.*	*3,0*	*n.a.*	*0*	*0*	*1*	*0*	*0*	*0*	*0*	*0*	*2*	*1*
Longitudinal barriers	**1 440 000a**	**5–10 %**	*n.a.*	*3,0*	*n.a.*	*3*	*0*	*0*	*0*	*0*	*0*	*2*	*0*	*1*	*0*

Note: n.a., not applicable.

([a]) Costs in euros per metre of dike or longitudinal barrier (assuming a 1 m elevation).

([39]) http://nwrm.eu/catalogue-nwrm/benefit-tables

Box 6.1 Summary overview of detailed results: cost-efficiency of reviewed green and grey infrastructure measures (cont.)

Wetlands are often smaller in size than floodplains or re-meandering projects, which means on the one hand that economies of scale cannot be achieved for their construction, but on the other that overall costs for the project are likely to be lower. Therefore, the overall cost-efficiency of wetland restoration could increase even further if it is executed as part of a larger project, either in hybrid form or in combination with other green measures, as fixed costs for such projects (such as costs of research, planning, obtaining licences) can then be shared.

Among the green measures, differences in scale and applicability can be seen. Whereas re-meandering and floodplain restoration projects are typically conducted at a large scale, their benefits in terms of flood protection and additional ecosystem services are high, but so are their costs. A smaller scale measure such as streambed re-naturalisation offers fewer biophysical flood reduction characteristics and also, because of its focus on the river itself, fewer ecosystem services, but the costs of streambed re-naturalisation are typically lower, and the feasibility of realising these projects is higher, as they do not require land acquisition, for example. Streambed re-naturalisation therefore works particularly well in combination with other GI measures.

From the Scheldt (Belgium) experience, the following factors have been concluded as key to successful coordination:

- the coordinated identification of suitable areas for the development of controlled flood zones, providing increased safety with limited damage caused to agriculture, land use and the economy;
- the integration of climate change and sea level rise predictions;
- the integration of compensation for areas lost by port expansion and the dredging of the Scheldt in the plan's overall objectives, strengthening its profile in negotiations with local governments and stakeholders;
- the availability of areas for the compensation of natural habitats lost due to infrastructure works in the Scheldt Estuary;
- the ability to expropriate the land necessary for the controlled flood areas (CFAs) — landholders are compensated for the existing price of the land plus 20 % (where feasible, expropriation can be delayed to the time when a farmer retires or is near to retirement);
- the ongoing engagement of plan managers with stakeholders during the phases of each project and in the overall decision-making process — this has addressed initial opposition (see limiting factors below);
- application of cost-benefit analysis and environmental impact assessment to strengthen plan and project design.

Factors threatening and/or limiting success in the Scheldt (Belgium) experience are:

- stakeholder opposition, which has been an issue for the construction of the Kruibeke CFA and also in the Netherlands for the Hedwige Polder project;
- budget restrictions that slow implementation of the plan, which could push its completion beyond the intended date of 2030.

The Elbe (Germany) case study illustrated good practice for integration of GI (i.e. floodplains) into the overarching national zoning regulation, which in turn helps clarify any possible conflicts between upstream and downstream stakeholders. In addition to local and regional measures identified in the PFRA, the plan also embedded national legislation for the establishment of floodplain locations via the integration of floodplains in land use planning regulations. This integration requires respecting the assigned land use restrictions of these floodplains and drainage areas for all other land use planning purposes in the area. This may result in land use changes and/or restrictions in the zoning of new constructions, because identified floodplains have legal priority over new land use planning for the identified areas.

Similar to the findings of EEA Report No 1/2016, the findings of this study also indicate that the better the coordination across the various levels of planning and management, the more attention can be given to reducing vulnerability and employing integrated measures that will be sustainable over the long term. Combining efforts on the WFD and the Floods Directive is expected to be beneficial. However, these processes can only be driven at the European level and yet need to be implemented at the river basin district level.

The analysis further illustrates that planning and coordination between flood and climate change adaptation policy measures is important. For example, 23 out of 28 EU Member States have adopted national adaptation strategies or plans which, for example, include measures such as adapting building regulations and building flood defences. However, in many of these countries, there is insufficient knowledge, experience and capacity to put adaptation into practice in various sectors. Across scales, a majority of reported GI initiatives for tackling climate change adaptation and disaster risk challenges are implemented at different scales without full coordination between Member States at local, regional and national levels.

6.4 There is a need for developing a common understanding that can guide decision-makers on green versus grey infrastructure solutions

Some of the main barriers perceived by decision-makers in the decision-making processes for selecting GI solutions include:

- uncertainties about required coordination efforts in the decision-making process as well as during implementation;
- a lack of information on GI funding opportunities; and
- overall limited knowledge and awareness of decision-makers about the advantages, costs and benefits of GI measures, despite more and more information being available on various information platforms and outlets.

Implementing GI requires coordination and management efforts with other sectors, as well as decision matrices and tools to better compare green, grey and hybrid infrastructure solutions, information on which remains scattered and difficult to locate and apply during decision-making processes. Hence, there is a need for building a coherent analytical framework to better support decision-makers. In support of such a framework this study points out that:

- The modelling of the additional floodplain potential shows that, in all case studies considered, the restoration of floodplains would be able to address current as well as future flood risks.
- The general cost-efficiency assessment provides new insights as regards cost and benefit considerations of green and grey measures, indicating that the benefit-cost ratios for these cases are greater than for their grey counterparts, for the same degree of flood protection.
- The case-specific cost-efficiency analysis demonstrates how such generic data can be applied on a location-specific level, revealing trade-offs that decision-makers must deal with.

Further research should be considered to investigate in more detail (via stakeholder engagement) how the existing knowledge could be drawn up in a more user-friendly way to assist decision-makers. While a checklist-type matrix can be useful for decision-makers to see the pros and cons of both green and grey measures in an organised way, such tools do not yet incorporate the spatial dimension of the decision-making process, which plays an important role when discussing infrastructure solutions for reducing flood risks.

6.5 EU-level approach and investment in green infrastructure solutions

Investing in GI can achieve significant cost savings for both the public and private sectors. Investors and institutions have to be more innovative and not necessarily stick to the traditional solutions in a sector. Traditional solutions can turn out to be systemic, as they also produce benefits elsewhere in the socio-economic system, for example for industry or for businesses with significant interest and investments in grey infrastructure production. Therefore, existing technologies/production systems often have significant 'sunk costs' from earlier investments, meaning that industries and investors can be reluctant to invest in more sustainable alternatives. In order to leapfrog these technological and institutional 'lock-ins' there is a need for transition in common practices, with hardwired emphasis on investment, innovation and exploration of alternative products and solutions, e.g. an increased focus where possible on green and more sustainable solutions and the co-benefits these provide.

Transition towards more sustainable solutions has thus received increasing attention and appreciation among policymakers. It is being recognised in the EU policy domain that investing in GI does not just protect natural capital. It is a big step towards smart, sustainable and inclusive growth, which is one of the EU's priority objectives. It is becoming evident that there is a need to tackle environmental and socio-economic challenges in a more integrated manner (as most environmental issues are cross-cutting, affecting water, air, soil, etc.). To this end, various overarching European policy objectives already encourage decision-makers to think outside the local, regional or even national box, and across different policy areas and sectors, to find the optimal path and solutions that deliver multiple benefits for both society and nature.

GI solutions can offer cost-efficient ways of addressing regulatory requirements. Therefore, many countries in the EU have already taken GI on board and have prepared national guidance documents and/or strategies to actively encourage investments in GI as an essential part of sustainable spatial planning. Member States can further support GI through programmes integrated into their development strategies. Co-financing opportunities currently available are:

- structural funds (ERDF and European Social Fund)
- Cohesion Fund
- EMFF
- European Agricultural Fund for Rural Development
- LIFE+
- research funding programmes
- European Fund for Strategic Investment
- Horizon 2020 and nature-based solutions.

There is a wide variety of funds available, which mirrors the wide cross-sectoral applicability of GI solutions. The analysis indicates that available funds are widespread across the various EU funds and often they provide only indirect indications as to whether or not a GI project is eligible. This is a constraint, as it is might not be entirely clear to implementers whether or not the funds are directly targeting GI.

Lack of (easy access to) finance has also been identified by experts as a specific challenge for restoring floodplains and for improving hydromorphological conditions affected by existing grey infrastructure, such as dams and dikes. This issue can be tackled in two ways:

- by reviewing the current funding approach and considering the possibility of either increasing the clarity of eligibility criteria or pooling all GI-related budgets under a dedicated fund; or
- by investing in awareness-raising and capacity-building efforts on Member State, regional and local level in order to better equip GI implementers with the know-how they need.

Furthermore, the European Commission and the EIB have established the NCFF to finance investments in natural capital projects, including GI, which generate revenues or save costs and contribute to nature, biodiversity and climate change adaptation objectives. The NCFF is open to public and private entities, where appropriate cooperating in partnerships. Investments could, for example, focus on floodplain (ecosystem) restoration projects as insurance against floods.

Lastly, the European Commission Action Plan for nature, people and the economy (EC, 2017) aims to provide guidance to support the deployment of GI, including identifying projects to be prioritised with appropriate funding, at a scale that transcends administrative boundaries, so as to enhance the delivery of essential ecosystem services throughout EU territory. Beyond 2020, the 7th EAP also sets out a vision of Europe in 2050:

> ... we live well, within the planet's ecological limits. Our prosperity and healthy environment stem from an innovative, circular economy where nothing is wasted and where natural resources are managed sustainably, and biodiversity is protected, valued and restored in ways that enhance our society's resilience. Our low-carbon growth has long been decoupled from resource use, setting the pace for a safe and sustainable global society (EU, 2014).

This underlines the importance of solving problems in new ways and aiming for solutions delivering multiple benefits for both society and nature.

References

Acreman, M. and Holden, J., 2013, 'How wetlands affect floods', *Wetlands* 33(5), pp. 773-786.

Alfieri, L., Salamon, P., Bianchi, A., Neal, J., Bates, P. and Feyen, L., 2014, 'Advances in pan-European flood hazard mapping', *Hydrological Processes* 28, pp. 4067-4077.

Alfieri, L., Burek, P., Feyen, L. and Forzieri, G., 2015, 'Global warming increases the frequency of river floods in Europe', *Hydrology and Earth System Sciences* 19, pp. 2247–2260 (doi: 10.5194/hess-19-2247-2015201).

Alfieri, L., Feyen, L. and Di Baldassarre, G., 2016, 'Increasing flood risk under climate change: a pan-European assessment of the benefits of four adaptation strategies', *Climatic Change* 136, pp. 507-521 (https://link.springer.com/article/10.1007/s10584-016-1641-1) accessed 17 August 2017.

Ansar, A., Flyvberg, B., Budzier, A. and Lunn, D., 2014, 'Should we build more large dams? The actual costs of hydropower megaproject development', *Energy Policy* 69, pp. 43-56.

Barredo, J., 2009, 'Normalised flood losses in Europe: 1970-2006', *Natural Hazards and Earth System Sciences* 9, pp. 97-104.

Barredo, J. I., 2010, 'No upward trend in normalised windstorm losses in Europe: 1970-2008', Natural *Hazards and Earth System Sciences* 10(1), pp. 97-104.

Beaufils, M. F., 2014, 'Réconcilier aménagement durable de nos territoires et inondations: l'opportunité d'un nouveau cadre d'actions', *Risques Infos* 33, pp. 8-9.

Belgian Science Policy, 2008, ADAPT — *Towards an integrated decision tool for adaptation measures — Case study: Floods*, Final Report, Belgian Science Policy.

Benedict, M. A. and McMahon, E. T., 2002, 'Green infrastructure: Smart conservation for the 21st century', *Renewable Resources Journal* 20(3), pp. 12-17.

Blackwell, M. S. A. and Maltby, E., 2006, *How to use floodplains for flood risk reduction*, Ecoflood Project, European Commission, Brussels.

Bočkarjova, M., 2007, 'Thinking about imbalances in post-catastrophe economies: An input-output based proposition', *Economic Systems Research* 19(2), pp. 205-223.

Bočkarjova, M., Steenge, A. E. and Van der Veen, A., 2004, 'On direct estimation of initial damage in the case of a major catastrophe: derivation of the basic equation', *Disaster Prevention and Management: An International Journal* 13, pp. 330-337.

Bouwer, L.M., Bubeck, P. and Aerts, J.C., 2010, 'Changes in future flood risk due to climate and development in a Dutch polder area', *Global Environmental Change*, 20(3), pp. 463-471.

Broekx, S., Smets, S., Liekens, I., Bulckaen, D. and de Nocker, L., 2011, 'Designing a long-term flood risk management plan for the Scheldt estuary using a risk-based approach', *Natural Hazards* 57(2), pp. 245-266.

Brown, P., Tullos, D., Tilt, B., Magee, D. and Wolf, A., 2009, 'Modelling the costs and benefits of dam construction from a multidisciplinary perspective', *Journal of Environmental Management* 90, pp. 303-311.

Burek, P., Mubareka, S., Rojas, R., de Roo, A., Bianchi, A., Baranzelli, C., Lavalle, C and Vandecasteele, I., 2012, *Evaluation of the effectiveness of Natural Water Retention Measures: Support to the EU Blueprint to Safeguard Europe's Waters*, JRC Scientific and Policy Reports, European Commission, Brussels.

Capon, S. J., Chambers, L. E., Mac Nally, R., Naiman, R. J., Davies, P., Marshall, N., Pittock, J., Reid, M., Capon, T., Douglas, M., Catford, J., Baldwin, D. S., Stewardson, M., Roberts, J., Parsons, M. and Williams, S. E., 2013, 'Riparian ecosystems in the 21st century: Hotspots for climate change adaptation?', *Ecosystems* 16, pp. 359-381.

Cardinale, B. J., Duffy, J. E., Gonzalez, A., Hooper, D. U., Perrings, C., Kinzig, A. P., Daily, G. C., Loreau, M., Grace, J. B., Larigauderie, A., Srivastava, D. and Naeem, S., 2012, 'Biodiversity loss and its impact on humanity', *Nature* 486, pp. 59-67.

CARMEN, 2015, 'Cartographie informative des surfaces inondables et des risques: TRI de Lyon — Rhône, Saône, Morgon, Nizerand, Azergues Brévenne, Turdine, Yzeron, Garon, Gier' (http://carmen.developpement-durable.gouv.fr) accessed 21 December 2015.

CEREMA, 2014, *Coût des protections contre les inondations fluviales*, CEREMA, Lyons, France.

Chambers, R., 1989, 'Editorial introduction: Vulnerability, coping and policy', *IDS Bulletin* 20(2).

CIRIA, 2013, *The international levee handbook*, CIRIA, London.

ClimateCost, 2016, 'Project home page' (http://www.climatecost.cc/) accessed 11 February 2016.

Comité de Bassin Rhône-Méditerranée, 2012, *Synthèse de la mise en oeuvre à mi-parcours (2012) du programme de mesures*, Commission Territoriale Rhône-Moyen, Lyons(http://www.rhone-mediterranee.eaufrance.fr/docs/dce/sdage/docs-complementaires/PdM_mi-parcours/PdM_bilan-mi-parcours_14dec2012_VF.pdf) accessed August 2017.

Comité de Bassin Rhône-Méditerranée, 2014, *Projet de programme de mesures 2016-2021: Bassin Rhône-Méditerranée, Comité de Bassin Rhône Méditerranée*, Lyons (http://www.rhone-mediterranee.eaufrance.fr/docs/sdage2016/consultation/20141114-RAP-ProjetDePdm-v0.pdf) accessed 24 August 2017.

Commission Territoriale Rhône-Moyen, 2012, *Etat d'avancement de la mise en oeuvre du programme de mesures 2010-2015*, Séminaire des Commissions Territoriales, Lyons (http://www.artois-picardie.eaufrance.fr/actualites/article/etat-d-avancement-de-la-mise-en) accessed 22 August 2017.

CPB, 2000, *Ruimte voor water: Kosten en baten van zes projecten en enige alternatieven*, Working Document 130, CPB, The Hague, Netherlands.

CRUE, 2008a, *Effectiveness and efficiency of non-structural flood risk management measures, final report*, CRUE Flooding ERA-NET.

CRUE, 2008b, *Flood risk reduction by preserving and restoring river floodplains*, ERA-NET CRUE Funding Initiative Research project fact sheet. (http://www.crue-eranet.net/calls/crue_projectfactsheet_pro_floodplain.pdf) accessed 17 December 2015.

De Nocker L., Broekx S., Liekens I., 2011, *Economische waardering van verbetering ecologische toestand oppervlaktewater op basis van onderzoeksresultaten uit Aquamoney*, Report 2011/RMA/R/248, VITO, Mol, Belgium.

Dehnhardt, A., Hirschfeld, J., Drünkler, D., Peschow, U., Engel, H. and Hammer, M., 2008, *Kosten-Nutzen-Analyse von Hochwasserschutzmaßnahmen*, Report to the Federal Environment Agency, Dessau-Roßlau, Germany.

Deltawerken, 2015, 'Het Deltaplan' (http://deltawerken.com/het-deltaplan/26.html) accessed 16 December 2015.

DG ENV, 2011, Note by DG Environment 'Towards better environmental options for flood risk management', European Commission, DG ENV D.1 236452, Brussels (http://ec.europa.eu/environment/water/flood_risk/pdf/Note%20-%20Better%20environmental%20options.pdf) accessed December 2015.

DHI Polska, 2013, *Raport z opracowania programu działań dla Regionu Wodnego Górnej Wisły*, Report KZGW/DpiZE-op/POPT/1/2013, DHI Polska, Warsaw, Poland.

Direction Régionale de l'Environnement, de l'Aménagement et du Logement Rhône Alpes, 2014, Projet de PGRI: *Territoires à risqué important d'inondations: Riverains du fleuve Rhône*, Lyons (http://www.rhone-mediterranee.eaufrance.fr/docs/dir-inondations/pgri/05_PGRI_volume2_afflRhon.pdf) accessed 24 August 2017.

EauFrance, 2015, 'L'eau dans le bassin Rhône-Méditeranée — Programme de mesures: Référentiel des mesures' (http://www.rhone-mediterranee.eaufrance.fr/docs/sdage2016/consultation/20141114-RAP-ProjetDePdm-v0.pdf) accessed 21 August 2017.

EC, 2004, Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions 'Flood risk management — Flood prevention, protection and mitigation' (COM(2004) 0472 final of 12 July 2004) (http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52004DC0472) accessed 15 December 2015

EC, 2010, Communication from the Commission, 'A strategy for smart, sustainable and inclusive growth' (COM(2010) 2020 final of 3 March 2010) (http://ec.europa.eu/eu2020/pdf/COMPLET%20EN%20

BARROSO%20%20%20007%20-%20Europe%20 2020%20-%20EN%20version.pdf) accessed 14 December 2015.

EC, 2011a, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions 'A resource-efficient Europe — Flagship initiative under the Europe 2020 Strategy' (COM(2011) 21 final of 26 January 2011) (http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52011DC0021) accessed 8 December 2015.

EC, 2011b, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions 'A Roadmap for moving to a competitive low carbon economy in 2050' (COM(2011) 112 final of 8 March 2011) (http://eur-lex.europa.eu/resource.html?uri=cellar:5db26ecc-ba4e-4de2-ae08-dba649109d18.0002.03/DOC_1&format=PDF) accessed 15 December 2015.

EC, 2011c, Communication from the Commission to the European Parliament, the Council, the Economic and Social Committee and the Committee of the Regions 'Our life insurance, our natural capital: an EU biodiversity strategy to 2020' (COM(2011) 0244 final of 3 May 2011) (http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52011DC0244) accessed 16 December 2015.

EC, 2011d, 'Towards better environmental options for flood risk management', Note D.1236452, European Commission Directorate-General of the Environment, Brussels (http://ec.europa.eu/environment/water/flood_risk/pdf/Note%20-%20Better%20 environmental%20options.pdf) accessed 16 December 2015.

EC, 2012, *Evaluation of the effectiveness of natural water retention measures*, JRC Scientific and Policy Report JRC25551, European Commission, Brussels.(http://www.researchgate.net/publication/263806285_Evaluation_of_the_effectiveness_of_Natural_Water_Retention_Measures_-_Support_to_the_EU_Blueprint_to_Safeguard_Europes_Waters) accessed 8 December 2015.

EC, 2013a, *Building a Green Infrastructure for Europe*, European Commission Directorate-General of the Environment, Brussels (http://bookshop.europa.eu/en/building-a-green-infrastructure-for-europe-pbKH0113599/;pgid=y8dIS7GUWMdSR0EAlMEUUsWb0000oy1hnZ8A;sid=0Z4DKVgP_VsDKQr-zm2djjoq1k0F-vrMrc4=?CatalogCategoryID=h2YKABstrXcAAAEjXJEY4e5L) accessed 15 December 2015.

EC, 2013b, *Guidance for reporting under the Floods Directive (2007/60/EC)*, Technical Report 2013-071, European Commission, Brussels (https://circabc.europa.eu/sd/a/acbcd98a-9540-480e-a876-420b7de64eba/Floods%20Reporting%20guidance%20 -%20final_with%20revised%20paragraph%204.2.3.pdf) accessed 11 December 2015.

EC, 2013c, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions 'Green Infrastructure (GI) — Enhancing Europe's Natural Capital' (COM(2013) 0249 final of 6 May 2013) (http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A52013DC0249) accessed 14 December 2015.

EC, 2013d, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions 'An EU Strategy on adaptation to climate change' (COM(2013) 216 final of 16 April 2013) (http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52013DC0216&from=EN) accessed 10 August 2017.

EC, 2014a, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions 'Towards a circular economy: A zero waste programme for Europe' (COM(2014) 398 final of 2 July 2014) (http://eur-lex.europa.eu/resource.html?uri=cellar:50edd1fd-01ec-11e4-831f-01aa75ed71a1.0001.01/DOC_1&format=PDF) accessed 16 December 2015.

EC, 2014b, *Natural water retention measures*, Technical Report No 2014-082, Publications Office of the European Union, Luxembourg. (https://circabc.europa.eu/sd/a/2457165b-3f12-4935-819a-c40324d22ad3/Policy Document on Natural Water Retention Measures_Final.pdf) accessed 10 December 2015.

EC, 2015, Report from the Commission to the European Parliament and the Council 'The mid-term review of the EU Biodiversity Strategy to 2020' (COM(2015) 0478 final of 2 October 2015) (http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52015DC0478) accessed 17 February 2016.

EC, 2016a, 'Nature-based solutions', European Commission, Brussels. (https://ec.europa.eu/research/environment/index.cfm?pg=nbs) accessed 10 December 2015.

EC, 2016b, 'Adaptation to climate change' (http://ec.europa.eu/clima/policies/adaptation/) accessed 8 February 2016.

EC, 2016c, 'LIFE financial instruments: Natural Capital Financing Facility', European Commission, Brussels. (http://ec.europa.eu/environment/life/funding/financial_instruments/ncff.htm) accessed 8 February 2016.

EC, 2016d, 'Horizon 2020 Work Programme for 2016-2017' (https://ec.europa.eu/programmes/horizon2020/en/news/horizon-2020-work-programme-2016-2017-published) accessed 11 February 2016.

EC, 2017, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions 'An Action Plan for nature, people and the economy' (COM(2017) 198 final of 27 April 2017) (http://ec.europa.eu/environment/nature/legislation/fitness_check/action_plan/communication_en.pdf) accessed 14 August 2017.

EC SWD, 2012, Impact assessment accompanying the document Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions 'A Blueprint to Safeguard Europe's Water Resources', COM(2012) 673 final. Staff Working Document. (http://ec.europa.eu/environment/water/blueprint/pdf/SWD-2012-382_EN_impact_assessment_part1.pdf) accessed 8 February 2016.

EEA, 2006, 'Corine Land Cover 2006 raster data' (http://www.eea.europa.eu/data-and-maps/data/corine-land-cover-2006-raster-3) accessed 5 December 2015.

EEA, 2010, Mapping the impacts of natural hazards and technological accidents in Europe, Technical Report No 13/2010, European Environment Agency.

EEA, 2011, *Green infrastructure and territorial cohesion*, Technical Report No 18/2011, European Environment Agency.

EEA, 2012a, *Climate change impacts and vulnerabilities in Europe*, Technical Report No 12/2012, European Environment Agency (http://www.eea.europa.eu/publications/climate-impacts-and-vulnerability-2012) accessed 10 December 2015.

EEA, 2012b, 'Water assessments 2012', European Environment Agency (http://www.eea.europa.eu/themes/water/water-assessments-2012) accessed 10 December 2015.

EEA, 2012c, *Challenges and opportunities for cities together with supportive national and European policies*, EEA Report No 2/2012, European Environment Agency (https://www.eea.europa.eu/publications/urban-adaptation-to-climate-change) accessed 13 September 2017.

EEA, 2015a (updated version in 2017), *Draft indicator assessment report on damages from weather and climate-related events*, European Environment Agency (https://www.eea.europa.eu/data-and-maps/indicators/direct-losses-from-weather-disasters-3/assessment) accessed 10 August 2017.

EEA, 2015b, *Exploring nature-based solutions: The role of green infrastructure in mitigating the impacts of weather- and climate change-related natural hazards*, Technical Report No 12/2015, European Environment Agency.

EEA, 2015c, Technical background document for the map book Urban vulnerability to climate change in Europe (http://climate-adapt.eea.europa.eu/tools/urban-adaptation/introduction) accessed 10 August 2017.

EEA/ETC-ULS, 2015d, Reported green infrastructure (GI) initiatives across EU-28 by Member State (MS) for the Green Infrastructure Implementation and Restoration Working Group, European Commission, 2015.

EEA, 2016a, *Flood risks and environmental vulnerability: Exploring the synergies between flood plain restoration and water, nature and thematic policies*, Technical Report No 1/2016, European Environment Agency.

EEA, 2016b, 'Reported flood phenomena' (https://www.eea.europa.eu/data-and-maps/daviz/reported-flood-phenomena/#parent-fieldname-title) accessed 13 September 2017.

EEA, 2016c, 'Reported flood phenomena per capita' (http://www.eea.europa.eu/data-and-maps/figures/reported-flood-phenomena-per-country) accessed 14 December 2015.

EEA, 2016d, *Urban adaptation to climate change in Europe 2016 — Transforming cities in a changing climate*, EEA Report No 12/2016, European Environment Agency (https://www.eea.europa.eu/publications/urban-adaptation-2016/at_download/file) accessed 5 August 2017.

EEA, 2017, *Climate change, impacts and vulnerability in Europe 2016*, EEA Report No 1/2017, European Environment Agency (http://www.eea.europa.eu/publications/climate-change-impacts-and-vulnerability-2016) accessed 8 August 2017.

EEA, 2017, *Climate change adaptation and disaster risk reduction in Europe — Enhancing coherence of the knowledge base, policies and practices*, EEA Report No

15/2017, European Environment Agency, https://www.eea.europa.eu/publications/climate-change-adaptation-and-disaster) accessed 14 November 2017

EHF, 2015, Environment and Health Fund draft text of letter for EU Water and Nature Directors, EU Working Group Green Infrastructure and Restoration, internal draft for Working Group.

ESPON, 2013, *Natural hazards and climate change in European regions*, Territorial Observations No 7, Publications Office of the European Union, Luxembourg.

ETC/ICM, 2015, *European freshwater ecosystem assessment: Cross-walk between the Water Framework Directive and Habitats Directive types, status and pressures*, ETC/ICM Technical Report 2/2015, Magdeburg: European Topic Centre on inland, coastal and marine waters.

EU, 1998, Directive 98/83/EC of the European Parliament and of the Council on the quality of water intended for human consumption (OJ L 330, 05/12/1998, p. 32-54) (http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:31998L0083) accessed 4 December 2015.

EU, 2006, Directive 2006/118/EC of the European Parliament and the Council on the protection of groundwater against pollution and deterioration (OJ L 372, 27.12.2006, p. 19-31) (http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32006L0118) accessed 11 December 2015.

EU, 2014, Decision No. 1386/2013/EU of the European Parliament and of the Council of 20 November 2013 'Living well, within the limits of our planet' (http://bookshop.europa.eu/en/general-union-environment-action-programme-to-2020-pbKH0113833/) accessed 8 December 2015.

Feyen, L., R. Dankers, K. Bódis et al., 2012, 'Fluvial flood risk in Europe in present and future climates', *Climate Change* 112, pp. 47–62 (doi: 10.1007/s10584-011-0339-7).

FGG Elbe, 2004, *Bericht über die Umsetzung der Anhänge II, III und IV der Richtlinie 2000/60/EG im Koordinierungsraum Mittlere Elbe/Elde (B-Bericht*, Flussgebietsgemeinschaft Elbe, Magdeburg (http://www.fgg-elbe.de/berichte.html) accessed 10 December 2015.

FGG Elbe, 2011, *Information der Öffentlichkeit gemäß § 79 WHG über die Umsetzung der Hochwasserrisikomanagement-Richtlinie (Richtlinie 2007/60/EG) für den deutschen Teil der Flussgebietseinheit Elbe*, Flussgebietsgemeinschaft Elbe, Magdeburg, Germany.

FGG Elbe, 2014, *Entwurf des Hochwasserrisikomanagementplans gem. §75 WHG bzw. Artikel 7 der Richtlinier 2007/60/EG über die Bewertung und das Management von Hochwasserrisiken für den deutschen Teil der Flussgebietseinheit Elbe*, Flussgebietsgemeinschaft Elbe, Magdeburg, Germany.

FGG Elbe, 2014, 'Hochwassergefahren- und Hochwasserrisikokarten: Informationen für die Öffentlichkeit' (https://www.fgg-elbe.de/dokumente/oeffentlichkeitsmaterialien.html?file=tl_files/Download-Archive/Oeffentlichkeitsmaterialien/Flyer_broschueren/Broschuere_HWG_HWR_14-03-2014.pdf) accessed 10 August 2017.

FLOODsite, 2006, *Flood risk analysis for the River Scheldt Estuary*, Integrated Flood Risk Analysis and Management Methodologies, Contract No GOCE-CT-2004-505420, Sixth Framework Programme (http://www.floodsite.net/html/partner_area/project_docs/T25_06_01_Scheldt_risk_analysis_D25_1_v1_0_P01.pdf) accessed 5 December 2015.

FNFRMS, 2014, 'French National Flood Risk Management Strategy' (http://www.developpement-durable.gouv.fr/IMG/pdf/French_Flood_Strategy.pdf) accessed 11 December 2015.

Gauderis, J., de Nocker, L. and Bulckaen, D., 2005, *Sigmaplan: Maatschappelijke Kosten-Baten Analyse*, Synthesis Report 4024-060, Waterwegen en Zeekanaal NV Afdeling Zeeschelde, Antwerp, Belgium.

Grossmann, M., Hartje, V. and Meyerhoff, J., 2010, *Ökonomische Bewertung naturverträglicher Hochwasservorsorge an der Elbe — Naturschutz und Biologische Vielfalt*, Federal Agency for Nature Conservation, Bonn, Germany.

Grossmann, M. and Hartje, V., 2012, 'Strategic cost-benefit analysis of an integrated flood plain management policy for the River Elbe', in: Grossmann, M. (2012), *Economic valuation of wetland ecosystem services: Case studies from the Elbe River Basin*, Technical University Berlin, Berlin, Germany.

Hallegatte S., 2008, 'An adaptive regional input-output model and its application to the assessment of the economic cost of Katrina', *Risk Analysis* 28(3), pp. 779-799.

Hallegatte S., Hourcade J. C. and Dumas, P., 2007, 'Why economic dynamics matter in assessing climate change damages: illustration on extreme events', *Ecological Economics* 62, pp. 330-340.

Hamburg, 2007, *Hochwasserschutz in Hamburg. Bauprogramm 2007*, Landesbetrieb Straßen, Brücken und Gewässer, Hamburg, Germany.

Hattermann, F., Krysanova, V., Post, J., Dworak, T., Wrobel, M., Kadner, S. and Leipprand, A., 2008, 'Understanding consequences of climate change for water resources and water-related sectors in Europe', in: Timmerman, J. G., Pahl-Wostl, C. and Moltgen, J. (eds), *The adaptiveness of IWRM — Analysing European IWRM research*, IWA Publishing, London, UK, pp. 89-112.

Hillen, M., Jonkman, S., Kanning, W., Kok, M., Geldenhuys, M. and Stive, M., 2010, *Coastal defence cost estimates: Case study of the Netherlands, New Orleans and Vietnam*, Communications on Hydraulic and Geotechnical Engineering, Delft University of Technology, Delft, Netherlands.

Horwood, K., 2011, 'Green infrastructure: reconciling urban green space and regional economic development: lessons learnt from experience in England's north-west region', *Local Environment* 16(10), pp. 963-975.

Hugin, 2013, 'Classifying ecosystem services' (http://openness.hugin.com/example/cices) accessed 16 February 2016.

IBI Group, 2015a, *Benefit/cost analysis of flood mitigation projects for the City of Calgary: Springbank off-stream flood storage*, Report prepared for Government of Alberta, IBI Group, 18 February 2015.

IBI Group, 2015b, *Benefit/cost analysis of flood mitigation projects for the City of Calgary: McLean Creek flood storage*, Report prepared for Government of Alberta, IBI Group, 18 February 2015.

IBI Group, 2015c. *Benefit/cost analysis of flood mitigation projects for the City of Calgary: Glenmore Reservoire diversion*, Report prepared for Government of Alberta, IBI Group, 18 February 2015.

Igigabel, M., Chaouch V. and El Fadili, M., 2014, *Coût des protections contre les inondations fluviales*, Collection Connaissances, CEREMA.

ICPR, 2006, Nachweis der Wirksamkeit von Massnahmen zur Minderung der Hochwasserstaende im Rhein infolge Umsetzung des Aktionsplans Hochwasser bis 2005. vol Report Number 157. International Comission for the Protection of the Rhine, Koblenz.

IKSE, 2016, 'Internationale Kommission zum Schutz der Elbe' (http://www.ikse-mkol.org/) accessed 16 February 2016.

IPCC, 2014, *Climate change 2014: Impacts, adaptation, and vulnerability — Part B: Regional aspects — Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, UK and New York, NY, USA.

Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O. B., Bouwer, L. M., Braun, A., Colette, A., Déqué, M., Georgievski, G., Georgopoulou, E., Gobiet, A., Menut, L., Nikulin, G., Haensler, A., Hempelmann, N., Jones, C., Keuler, K., Kovats, S., Kröner, N., Kotlarski, S., Kriegsmann, A., Martin, E., Meijgaard, E. van, Moseley, C., Pfeifer, S., Preuschmann,S., Radermacher, C., Radtke, K., Rechid, D., Rounsevell, M.,Samuelsson, P., Somot, S., Soussana, J.-F., Teichmann, C.,Valentini, R., Vautard, R., Weber, B., and Yiou, P., 'EUROCORDEX: New high-resolution climate change projections for European impact research', *Regional Environmental Change*, 14, pp. 563–578 (doi:10.1007/s10113-013-0499-2, 2014).

Joint-Industry White Paper, 2013, 'The case for green infrastructure' (http://www.nature.org/about-us/the-case-for-green-infrastructure.pdf) accessed 15 December 2015.

Jongepierová, I., Pesouet, P., Jongepier, J. W. and Prach, K., 2012, *Ecological restoration in the Czech Republic*, Nature Conservation Agency of the Czech Republic, Prague (http://chapter.ser.org/europe/files/2012/12/Ecological-Restoration-in-the-Czech-Republic1.pdf) accessed 5 February 2016.

Jongman, B., Hochrainer-Stigler, S. and Feyen, L, 2014, 'Increasing stress on disaster-risk finance due to large floods', *Nature Climate Change* 4, pp. 264-268.

JRC, 2011, *A European assessment of the provision of ecosystem services: Towards an atlas of ecosystem services*, JRC Scientific and Technical Reports, Publications Office of the European Union, Luxembourg.

JRC, 2012, *Evaluation of the effectiveness of natural water retention measures*, JRC Scientific and Policy Reports, Publications Office of the European Union, Luxembourg.

JRC, 2013, 'European soil portal — Soil data and information systems' (http://eusoils.jrc.ec.europa.eu/esdb_archive/ESDB/Index.htm) accessed 7 December 2015.

JRC, 2015, 'LISFLOOD Model and data' (http://floods.jrc.ec.europa.eu/lisflood-model.html) accessed 6 October 2015.

Kohler, Y., Heinrichs, A.K., 2011, Ecological Continuum Initiative – Catalogue of Possible Measures to Improve Ecological Connectivity in the Alps (http://www.alpine-ecologicalnetwork.org/information-services/publications/4034) accessed 13 September 2017.

Landeshauptstadt Magdeburg, 2015, 'Hochwasserschutz/ Hochwassernachsorge im ostelbischen Stadtgebiet' (http://www.magdeburg.de/Start/BürgerStadt/index.php?La=1&NavID=37.367&object=tx|37.7339.1&kat=&kuo=2&sub=0) accessed 10 December 2015.

Ließmann, P., 2012, 'Hochwasser 2002: Die Stadt hat gelernt' (http://www.volksstimme.de/nachrichten/magdeburg/915895_Hochwasser-2002-Die-Stadt-hat-gelernt-bis-7-Meter-Pegelhoehe-die-Nerven-zu-behalten.html) accessed 15 December 2015.

Linham, M. and Nicholls, R., 2010, 'Storm surge barriers and closure dams' (http://www.climatetechwiki.org/content/storm-surge-barriers-and-closure-dams) accessed 16 November 2015

Lucius, I., Raluca D., Caratas, D., Mey, F. Steinert, J. and Torkler, P., 2011, 'Green infrastructure: Sustainable investments for the benefit of both people and nature', *SURF Nature* (http://www.surf-nature.eu/uploads/media/Thematic_Booklet_Green_Infrastructure.pdf) accessed 6 December 2015.

Liekens, I., Schaafsma, M., Brouwer, R. , Broekx, S., Aertsens, J., Staes, J., Meire, P. and De Nocker, L., 2010, 'Spatial elements in a valuation function for nature development', Proceedings of 12th Annual BIOECON conference 'From the wealth of nations to the wealth of nature: Rethinking economic growth', Venice, Italy, 27-28 September 2010.

Maaskant, B., Jonkman S.N., and Bouwer L.M., 2009, 'Future risk of flooding: an analysis of changes in potential loss of life in South Holland (the Netherlands)', *Environmental Science & Policy*, 12(2), pp. 157-169.

Mayors Adapt, 2016, 'About', Covenant of Mayors Initiative on Adaptation to Climate Change (http://www.covenantofmayors.eu/Adaptation.html) accessed 13 September 2017.

Mazza, L., Bennett, G., De Nocker, L., Gantioler, S., Losarcos, L., Margerison, C., Kaphengst, T., McConville, A., Rayment, M., ten Brink, P., Tucker, G. and van Diggelen, R., 2011, *Green infrastructure implementation and efficiency: Freshwater and wetlands management and restoration*. Published by IEEP, 2011. (http://ec.europa.eu/environment/nature/ecosystems/docs/implementation_efficiency.pdf) accessed 7 August 2017.

MDR, 2015, 'Hochwasserschutz Magdeburg: Naturschutz lässt nicht alle Maßnahmen zu', Mitteldeutscher Rundfunk.

Ministère de l'Écologie, 2011a, 'EPRI: Évaluation préliminaire des risques d'inondation 2011: Bassin Rhône-Méditerrannée' (http://www.RhôneRhône-mediterranee.eaufrance.fr/gestion/inondations/epri.php) accessed 8 December 2015.

Ministère de l'Écologie, 2011b, 'EPRI: Évaluation préliminaire des risques d'inondation sur le bassin Rhône-Méditerrannée: Partie V: Unité de Présentation Rhône-Moyen' (http://www.rhone-mediterranee.eaufrance.fr/gestion/inondations/epri.php) accessed 10 August 2017.

Ministère de l'Écologie, 2012, 'Fiche de caractérisation du TRI de Lyon' (http://www.rhone-mediterranee.eaufrance.fr/docs/dir-inondations/cartes/lyon/FicheConsultation_TRI_Lyon.pdf) accessed 12 August 2017.

Morris, J. and Camino, M., 2011, *Economic assessment of freshwater, wetland and floodplain (FWF) ecosystem services*, UK National Ecosystem Assessment Working Paper (http://uknea.unep-wcmc.org/LinkClick.aspx?fileticket=lVLEq%2BxAI%2BQ%3D&tabid=82) accessed 8 December 2015.

Munich Re, 2016, 'NatCatService database' (www.munichre.com/natcatservice) accessed 16 August 2017.

Naumann, S., Davis, M., Kaphengst, T., Pieterse, M. and Rayment, M., 2011, *Design, implementation and cost elements of green infrastructure projects: Final report to the European Commission*, Directorate-General of the Environment, Contract No 070307/2010/577182/ETU/F.1, Ecologic and GHK (http://ec.europa.eu/environment/enveco/biodiversity/pdf/GI_DICE_FinalReport.pdf) accessed 14 December 2015.

NWRM, 2013a, 'Case study: Seymaz River renaturation', Natural Water Retention Measures, Service contract 07.0330/2013/659147/SER/ENV.C1, European Commission, Brussels. (http://nwrm.eu/sites/default/files/case_studies_ressources/cs-ch-01-final_version.pdf) accessed 14 December 2015.

NWRM, 2013b, 'Individual NWRM: Floodplain restoration and management', Natural Water Retention Measures, Service contract 07.0330/2013/659147/SER/ENV.C1, European Commission.

NWRM, 2013c, 'Individual NWRM: Re-meandering', Natural Water Retention Measures, Service contract 07.0330/2013/659147/SER/ENV.C1, European Commission.

NWRM, 2013d, 'Individual NWRM: Wetland restoration and management', Natural Water Retention Measures, Service contract 07.0330/2013/659147/SER/ENV.C1, European Commission.

NWRM, 2013e, 'Individual NWRM: Streambed re-naturalization', Natural Water Retention Measures, Service contract 07.0330/2013/659147/SER/ENV.C1, European Commission.

NWRM, 2014a, 'Synthesis Document 5 — Costs of natural water retention measures: What are the costs of NWRM?', European Commission.

NWRM, 2014b, 'Synthesis document 2 — Biophysical impacts and effectiveness of natural water retention measures and their contribution to policy objectives'

NWRM, 2014c, 'Synthesis document 4 – Benefits of natural water retention measures, What are the benefits of NWRM?'

NWRM, 2015, 'Natural Water Retention Measures' (www.nwrm.eu) accessed 8 December 2015.

NWRM, 2016a, 'Ecosystem services of hydro morphology benefit table' (http://nwrm.eu/catalogue-nwrm/benefit-tables) accessed 9 December 2015.

NWRM, 2016b, 'Policy objectives of hydro morphology benefit table' (http://nwrm.eu/catalogue-nwrm/benefit-tables) accessed 8 December 2015.

NWRM, 2016c, 'NWRM catalogue' (http://nwrm.eu/measures-catalogue) accessed 8 December 2015.

Préfecture du Rhône, 2009, *Plan de Prévention des Risques Naturels pour les inondations du Rhône et de la Saône sur le territoire du Grand Lyon: Note de Présentation Secteur Lyon-Villeurbanne*, Préfecture du Rhône, Lyon(http://www.RhôneRhône.gouv.fr/Politiques-publiques/Securite-et-protection-de-la-population/La-securite-civile/Les-risques-majeurs/Les-risques-majeurs-dans-le-RhôneRhône/Risques-inondations-PPRi/PPRi-du-Grand-Lyon) accessed 15 December 2015.

Rojas, R., Feyen, L. and Watkiss P, 2013, 'Climate change and river floods in the European Union: Socioeconomic consequences and the costs and benefits of adaptation', *Global Environmental Change* (doi:10.1016/j.gloenvcha.2013.08.006).

Schindler, S., Sebesvari, Z., Damm, C., Euller, K., Mauerhofer, V., Schneidergruber, A., Biró, M., Essl, F., Kanka, R., Lauwaars, S. G. and Schulz-Zunkel, C., 2014, 'Multifunctionality of floodplain landscapes: Relating management options to ecosystem services', *Landscape Ecology* 29, pp. 229-244, (doi:10.1007/s10980-014-9989-y).

Schwarz, U., Batrich, C., Hulea, O., Moroz, S., Pumputyte, N., Rast, G., Bern, M. R. and Siposs, V., 2006, *Floods in the Danube River Basin: Flood risk mitigation for people living along the Danube — The potential for floodplain protection and restoration*, WWF, Geneva(http://assets.panda.org/downloads/2006_floods_in_the_danube_river_basin_wwf_working_paper.pdf) accessed 6 December 2015.

Shaver, E, 2009, *Low impact design versus conventional development: Literature review of developer-related costs and profit margins*, Prepared by Aqua Terra International Ltd for Auckland Regional Council, Auckland Regional Council Technical Report 2009/045.

Sigmaplan, 2015, 'What is the Sigma Plan?' (http://www.sigmaplan.be/en/sigma-plan/what-is-the-sigma-plan) accessed 9 December 2015.

Smithers, J. and Smit, B., 1997, 'Human adaptation to climatic variability and change', *Global Environmental Change: Human and Policy Dimensions* 7(2), pp. 129-146.

Steenge, A. E. and Bočkarjova, M., 2007, 'Thinking about imbalances in post-catastrophe economies: An input-output based proposition', *Economic Systems Research* 19(2), pp. 205-223.

Stella, 2012a, *Costs, benefits and climate proofing of natural water retention measures (NWRM)*, Final Report to DG Environment, Contract 07037/2010/581332/SER/D1, European Commission, Brussels.

Stella, 2012b, *Costs, benefits and climate proofing of natural water retention measures (NWRM): Annex 7: Report on Wetland restoration and Creation*, Final Report to DG Environment Contract 07037/2010/581332/SER/D1, European Commission, Brussels.

Stella, 2012c, *Costs, benefits and climate proofing of natural water retention measures (NWRM): Annex 8: Report on floodplain restoration*, Final Report to DG Environment, Contract 07037/2010/581332/SER/D1, European Commission, Brussels.

Stella, 2012d, *Costs, benefits and climate proofing of natural water retention measures (NWRM): Annex 9: Report on Re-Meandering*, Final Report to DG Environment Contract 07037/2010/581332/SER/D1, European Commission, Brussels.

Sylwester, 2009, *Green infrastructure: Supporting connectivity, maintaining sustainability presents a longer discussion of the origins and various definitions of green infrastructure.*

Taylor, 2012, 'The regulation of stream water quality and flow by a forested wetland Kylmäojankorpi, Vantaa', University of Helsinki, Helsinki, Finland.

te Linde, A. H., Bubeck P., Dekkers J. E. C., De Moel H., and Aerts J. C. J. H., 2011, 'Future flood risk estimates along the river Rhine', *Natural Hazards and Earth System Sciences*, 11(2), pp. 459-473.

TEEB, 2010, *The economics of ecosystems and biodiversity: Mainstreaming the economics of nature: A synthesis of the approach, conclusions and recommendations of TEEB*, United Nations Envrionment Programme, Nairobi, Kenya.

Trinomics, 2015, Climate extremes Defining a pilot approach on estimating the direct and indirect impacts on economic activity, Final Report (unpublished: CLIMA.C.3/SER/2013/0019).

Trinomics, 2016, Supporting the Implementation of Green Infrastructure, Final Report(http://ec.europa.eu/environment/nature/ecosystems/docs/green_infrastructures/GI%20Final%20Report.pdf) accessed 8 August 2017.

Tröltzsch, J., Görlach, B., Lückge, H., Peter, H., Sartorius, C., 2012, *Kosten und Nutzen von Anpassungsmaßnahmen an den Klimawandel: Analyse von 28 Anpassungsmaßnahmen in Deutschland*, Report for Umweltbundesamt, Ecologic Institute, INFRAS and Fraunhofer Institut.

Turner, R. K., Burgess, D., Hadley, D., Coombes, E. and Jackson, N., 2007, 'A cost-benefit appraisal of coastal managed realignment policy', *Global Environmental Change Part A: Human & Policy Dimensions* 17(3-4), pp. 397-407.

Umweltministerien der Länder Schleswig-Holstein, Brandenburg, Niedersachsen, Sachsen-Anhalt und Mecklenburg-Vorpommern, 2004, *Bericht über die Umsetzung der Anhänge II, III und IV der Richtlinie 2000/60/EG im Koordinierungsraum Mittlere Elbe/Elde (B-Bericht*, Herausgegeben durch die Umweltministerien der Länder Schleswig-Holstein, Brandenburg, Niedersachsen, Sachsen-Anhalt und Mecklenburg-Vorpommern. (http://www.wrrl-mv.de/doku/2004/Elbe_B_MEL_Bericht.pdf) accessed 8 December 2015.

UNEP-DHI Partnership, IUCN and the Nature Conservancy, 2014, 'Green infrastructure guide for water management: Ecosystem-based management approaches for water-related infrastructure projects' (https://portals.iucn.org/library/efiles/documents/2014-026.pdf) accessed 7 December 2015.

UNISDR, 2009, '2009 UNISDR Terminology on Disaster Risk Reduction' (http://www.unisdr.org/files/7817_UNISDRTerminologyEnglish.pdf) accessed 12 August 2017.

Visser, H., Bouwman, A., Petersen, A. and Ligtvoet W., 2012, *Weather-related disasters: past, present and future*, PBL publication, Netherlands Environmental Assessment Agency, The Hague/Bilthoven.

(http://www.pbl.nl/sites/default/files/cms/publicaties/PBL_2012_Weather%20Disasters_555076001.pdf) accessed 11 December 2015.

WGF, 2012, *Flood risk management, economics and decision making support*, Final Report, ARCADIS, WGF Thematic Workshop.

Williams, R., Scheuer, S., Eichler, L. and Gancheva, M., 2015, *Study on existing and future water legislation*, European Parliament, Brussels.

Wong, E., 2013, 'Damning the dams: a study of cost benefit analysis in large dams through the lens of India's Sardar Sarovar Project', *Scripps Senior Theses*, Paper 169.

Annex 1 An introduction to the cost-efficiency of green versus grey infrastructure

To provide a comparative review of the cost-efficiency ([40]) of green versus grey infrastructure measures in the EU, there is a need to collect evidence on the costs and effects of the application of the individual measures and to provide insights into the relative advantages and disadvantages of green versus grey solutions. Advancing natural solutions for flood management often boils down to discussion on the costs of GI and whether or not these measures provide sufficient 'value for money' in comparison with the traditional grey alternatives. As for any investment decision, the exact return on investment is a crucial factor in deciding which investment option to choose.

As experience of applying GI solutions for flood risk management is limited, relatively little is known about their cost-efficiency compared with more traditional grey alternatives. Cost-efficiency here refers to the maximisation of effects per unit cost of investment. In other words, the intention is to explore what level of protection has been achieved and possibly what other types of services the measure provides for the amount of money invested in the measure.

Cost-efficiency analysis carefully distinguishes between the magnitude and type of costs made and all benefits achieved. In extensive cost-efficiency analyses, the aim is to quantify all direct and indirect effects in order to weigh these over a future time horizon against one-off costs and ongoing maintenance costs that need to be incurred.

In-depth cost-efficiency analysis for the specific cases is not conducted in this analysis. Rather, the study provides available evidence on the different types of costs and benefits related to green, grey and hybrid solutions, to allow comparative analysis in general across Europe. It is problematic to assess the precise cost-efficiency of infrastructure measures — especially when more general conclusions are called for — since the precise magnitude of costs and benefits related to the solutions always depends on a range of defining characteristics that are especially location specific, such as:

- the geographical characteristics of the area in which the measure is planned (the costs in rocky, hilly or otherwise difficult-to-access areas will be higher compared with those in flat plains);
- the hydromorphological characteristics of the river(s) in the area;
- the population density/urbanisation of the area (with costs increasing for land compensation, but also with increased benefits or reduced flood risk and aesthetic improvements to the landscape);
- the size of the project (economies of scale could be realised for larger projects);
- synergistic effects with other measures that could be implemented in one project (different types of green or green/grey combinations could result in effects larger than the sum of the individual measures);
- local price levels, capital and labour costs.

Approaching cost-efficiency of GI from either a general or a case-specific perspective therefore presents inherent limitations. From a general perspective, the assessment of costs and effects or benefits cannot be made specific or precise because of the lack of detail on geographical and site characteristics.

It is therefore not possible to present precise (or monetised) cost and effect data at an aggregate level and also to compare green versus grey measures on a one-to-one basis, as this would be misleading because of, for example, the risk of comparing a green solution used in an 'expensive' area (e.g. urban setting) with a grey solution in a 'cheap' area (e.g. in a rural setting). Cost-efficiency of green versus grey infrastructure solutions is hence provided on the basis of general cost and effect information, as well as detailed case-specific data.

([40]) For a definition of 'cost-efficiency', see terminology table on page 8.

Cost-efficiency approached from two perspectives

Cost-efficiency is approached from two perspectives: a more general perspective at individual measure level, based on case study evidence from Europe on the application of that particular measure, and a case-specific perspective based on the detailed cost-benefit assessments conducted for the four selected case study areas (Elbe, Rhône, Scheldt and Vistula).

Since the likelihood of receiving precise cost and benefit figures at the detailed case study level is more promising, realistic combinations of green, grey and green-grey (hybrid) solutions can be estimated. As GI measures often provide social and environmental benefits in addition to their direct purpose (flood protection), green and grey measures are also included with respect to their 'ancillary' benefits. To make green and grey measures as comparable as possible, a general categorisation of costs, direct benefits and ancillary benefits is introduced. This further consists of:

1. A generic cost-efficiency comparison per measure — evaluate the cost-efficiency of green and grey infrastructure measures designed for flood-risk prevention per measure at an aggregate level, using representative cases from across Europe. The different costs incurred for realising the specific measure in those cases are reported. Only individual green and grey solutions are considered, as hybrid solutions per definition are site-specific combinations of green and grey solutions, and therefore not possible to review in general.

2. Detailed site-specific cost-efficiency illustrations are included with detailed information on costs and effects of several proposed green, hybrid and grey flood prevention infrastructure investment options. Detailed information from available cost-benefit assessments are included in the selected case study areas (Elbe, Rhône, Scheldt, Vistula). As the case studies are site-specific, cost-benefit assessments also allowed the effects of different flood risk prevention options to be quantified, as well as providing exact comparisons on the cost-efficiency of the green, hybrid and grey solutions.

General categorisation of costs and effects

Flood prevention infrastructure measures are hardly implemented in isolation (especially green measures), as their effectiveness increases exponentially when multiple measures are combined. This makes their individual benefits (in isolation) difficult to judge when they are not modelled in the overall infrastructure project. Moreover, the marginal costs of a single GI measure can also decrease with the number of other GI measures implemented in the same project, as certain overall costs can be shared across a larger number of measures. An accurate ranking of green, grey and hybrid infrastructure solutions is therefore only possible at site-specific level.

Comparing benefits of green versus grey infrastructure solutions is also difficult without a fixed time horizon, as the benefits of GI measures tend to increase over time as ecosystems adjust. In contrast, grey solutions often reach their desired benefit level immediately after construction. These factors show that generating an accurate and reliable comparison at EU level is challenging.

In order to facilitate the comparison of costs incurred for the realisation of inherently different infrastructure projects, a general classification is adopted of the most common types of costs and effects that are typically incurred while realising these types of projects. Realising a project requires direct costs (relating to the construction of the project) as well as indirect costs (costs that go beyond the costs associated with construction of the project). The latter are not necessarily taken into account in the costs of realising the project and can in the case of a negative externality represent economic losses to society. Equally important in this context are opportunity costs in the form of foregone incomes and benefits of the original purpose of the land that will be converted for the realisation of the infrastructure project.

Farmers, for example, might no longer be able to farm their land when it is converted to wetland. Since these indirect costs are by definition site specific, it is difficult to include an accurate estimate of these indirect costs in the overall cost comparison of different infrastructure measures. To accommodate these types of costs at the general level, it is assumed that the costs of foregone revenues are included in land acquisition and compensation costs related to a project. The price for the land should theoretically reflect (at least to some extent) the foregone revenues from exploiting it.

The direct costs related to realising a project are labelled as construction and rehabilitation costs. Apart from these one-off costs at the start of the project, maintenance and operation costs are distinguished in relation to the infrastructure project, since both green and grey infrastructure solutions must be regularly maintained in order to keep fulfilling their purpose. Table A1.1 presents these categories and the related symbols, which are used in the analysis.

Table A1.1 Description of types of costs considered in the analysis

Costs	Description
Land acquisition and compensation	The financial expenditures incurred from buying land needed for the construction of the measure or compensation of landowners for externalities associated with the construction of the measure.
Construction and rehabilitation	Referring to all costs incurred during the construction phase of the measure, including the investments in equipment, infrastructures and other assets required as well as the associated labour and management costs.
Operation and maintenance	Including financial costs such as depreciation allowances, maintenance expenditures and operational expenditures.
Foregone benefits	Relating to the foregone incomes and benefits to the stakeholders in the area of not implementing the measure (e.g. from all future earnings from agricultural land that would be converted).

Source: NWRM (2014a); own interpretation. Icons obtained from icons8.com.

As to the effects (or benefits, as it is expected that they are positive in the context of flood protection measures), the analysis distinguishes between direct effects relating to the degree of flood protection offered and indirect additional effects provided to the ecosystem. Since the distinct feature of GI measures is that they provide additional social and environmental benefits beyond the direct purpose of the measure (flood protection), the analysis also reviews green and grey measures with respect to their 'ancillary' benefits. In the case of green flood protection measures, these ancillary benefits relate mostly to additional ecosystem services that the measures provide, for example in terms of biodiversity, rural development and climate change adaptation.

For the classification of the most common types of indirect benefits ([41]) related to flood protection measures, the earlier work of the JRC for The Economics of Ecosystems and Biodiversity (TEEB) assessment is followed. This work lists 22 ecosystem services and is also used by the NWRM project to classify the benefits of the NWRMs that are subject to cost-efficiency analysis (TEEB, 2010; JRC, 2011). Only the most relevant indirect effect categories in relation to flood protection infrastructure measures have been selected.

An alternative option was to use the Common International Classification of Ecosystem Services (CICES). This classification slightly differs from the ecosystem services categories used in the NWRM project. Since the NWRM project provides the most important source of benefit data for the GI measures considered in this study, the analysis follows the NWRM-JRC-TEEB classification in order to capitalise on the original data on ancillary benefits as much as possible. A correspondence table between the JRC-TEEB and the CICES classifications is available online (Hugin, 2013).

Table A1.2 presents the description and the types of effects (benefits) that have been used in the evaluation of the measures. The category codes used in the NWRM projects have been added ([42]). The ecosystem service 'Flood risk protection' (ES7 in the NWRM project) is not included in this table, as it has been used as a selection criterion for establishing the shortlist of GI measures being assessed (see Table A1.3). Since the green and grey infrastructure measures are primarily reviewed for their flood risk protection characteristics (as direct effects), it is considered methodologically inaccurate to score them again for their flood risk protection potential (as indirect effects) because of the risk of 'double counting'.

Selection of relevant green and grey infrastructure measures

As detailed and comparable cost and effect data are scarce, the analysis will focus only on a number of representative green and grey infrastructure measures. The relevant selection of GI measures is based on the NWRM catalogue of GI measures, which classifies the measures in agricultural, urban, hydromorphological and forest categories. The final selection considers a list of hydromorphological infrastructure measures that are close to their grey alternatives in terms of application (close to rivers), and selects four GI measures for more detailed review. From the longlist of hydromorphological measures, three selection criteria are used to select the relevant green measures:

([41]) For a definition of 'indirect benefits', see terminology table on page 8.
([42]) See NWRM (2014b, 2014c) for a complete overview of all biophysical and ecosystem service effects of NWRMs.

Table A1.2 Description of type of direct and indirect effects considered

Effects	Description
Storing and slowing runoff	Capturing the features of water retention relating to storing surface run-off (and releasing it back to surface water or infiltrating to groundwater) and slowing run-off through slowing movement of surface water without storage.
Storing and slowing river water	Capturing the features of water retention relating to storing or slowing river water through e.g. open or controlled connectivity of plains or increasing bed roughness
Reducing run-off	Reducing runoff through increasing evapotranspiration, increase infiltration and/or groundwater recharge and increasing soil water retention.
Water storage	The potential to store water during floods and to it available for other purposes (e.g. agriculture) by offering moister soils or by storing water for irrigation after the flooding has ceased.
Fish stocks and recruiting	Commercially valuable fish will indirectly benefit from restoration and pollution load reductions. Fishing can be stimulated by ensuring sufficient environmental flows in surface waters, which will maintain migration pathways.
Natural biomass production	In general, referring to additional increases in flora and fauna. Now especially related to vegetation stimulation along banks, on flood plains and other habitats.
Biodiversity preservation	Relating to both terrestrial and aquatic biodiversity and implying the number of species naturally active in the catchment area. Impacts can be both positive and negative depending on how the regulation of the flow is managed and how the indicated measures are implemented.
Climate change adaptation	Largely referring to combating greenhouse gas reductions, for example through carbon sequestration, which can be e.g. obtained through land management and riparian buffer zones.
Groundwater recharge	Horizontal connectivity in rivers through which plains are flooded regularly will increase the recharge of aquifers and incerase groundwater levels and more groundwater exchange.
Erosion control	Controlling the extent of erosion can have significant eco-system benefits through reducing the consequences of erosion to the river system.
Filtration of pollutants	Pollutants (e.g. nutrients/pesticides) can be absorbed and/or degraded before ending up in the water body through careful design and management of the areas.
Recreational opportunities	Providing the public acces to new or restored areas for leisure activities, such as walking, hiking, outdoor sports, bird watching and relaxation.
Aesthetic/cultural value	Relating to the improvement of the aesthetic value of the landscape also strongly linked to property values in the area.

Source: NWRM (2014b, 2014c); own interpretation. Icons obtained from icons8.com.

1. Potential to reduce flood risk as an ecosystem service (ES7), as scored by the NWRM project. The summary benefit tables have been used to select the most relevant GI measures from a flood protection perspective (NWRM, 2016a). Flood risk is used as an ecosystem service to select the most relevant GI measures, but is not included in the list of indirect effects that is used for the detailed evaluation of the selected green and grey infrastructure measures, as mentioned above, because of the risk of 'double counting' (Table A1.2).

2. Applicability to addressing the EU policy objective of taking adequate and coordinated measures to reduce flood risk (PS9) (NWRM, 2016b). According to the NWRM project, this indicator represents the extent to which the GI measure (NWRM) contributes to meeting the objectives of the EU Floods Directive (2007/60/EC).

3. Presence as green solutions in the reviewed case study areas.

Table A1.3 presents the list of hydromorphological measures taken from the NWRM catalogue (NWRM, 2016c). Based on the three selection criteria above, four measures have been selected and are shaded light green. The GI measures with 'high' potential for flood risk reduction such as floodplain restoration and management (N03) and re-meandering (N04), and also featuring in the case studies, have been selected. As wetland restoration (N02) was conducted in all case study areas, this measure has also been selected. Riverbed material re-naturalisation (N08) together with elimination of riverbank protection (N11) will be reviewed jointly under stream bed re-naturalisation (N05). This is because riverbed material re-naturalisation (N08) has insufficient cost and effect data and the elimination of riverbank protection (N11) is effectively covered by stream bed re-naturalisation (N05), which also includes the naturalisation of riverbanks.

For grey infrastructure, different types of measures can be envisaged, depending on the specificities of the location. Based on a list of representative grey flood protection infrastructure solutions (Table A1.4) acknowledged by the WGF under the Common Implementation Strategy of the WFD and the Floods Directive, their scale and presence were assessed in the selected case study areas (WGF, 2012). Table A1.4 lists the selected measures and classifies their scale in the relevant categories (small, medium and large).

Two grey measures that are large scale and present in the case study areas have been selected for in-depth analysis (and will be compared with the GI measures selected in Table A1.3). The two grey measures 'riverbank protection' and 'longitudinal barriers' are shaded light red in Table A1.4 and will be subject to more in-depth review.

Table A1.3 Selection of relevant green infrastructure (GI) measures

NWRM code	Name of GI measure (based on the NWRM catalogue)	ES7 — Flood risk reduction	P9 — Take adequate and coordinated measures to reduce flood risks	Vistula	Rhône	Elbe	Scheldt
N01	Basins and ponds	High	High				
N02	Wetland restoration and management	Medium	Medium	✓	✓	✓	✓
N03	Floodplain restoration and management	High	High			✓	✓
N04	Re-meandering	High	High		✓		
N05	Stream bed re-naturalisation	Medium	Medium			✓	
N06	Restoration and reconnection of seasonal streams	Medium	High				
N07	Reconnection of oxbow lakes and similar features	Medium	High				
N08	Riverbed material re-naturalisation	Medium	Medium		✓		
N09	Removal of dams and other longitudinal barriers	Low	Low			✓	
N10	Natural bank stabilisation	Medium	Medium				
N11	Elimination of riverbank protection	High	Medium			✓	
N13	Restoration of natural infiltration to groundwater	Low	Low				
N12	Lake restoration	Medium	Medium		✓		
N14	Re-naturalisation of polder areas	Medium	High				✓

Source: NWRM (2016a, 2016b).

Table A1.4 Selecting relevant grey infrastructure measures

Name of grey infrastructure measure	Scale	Vistula	Rhône	Elbe	Scheldt
Riverbank protection (dikes, floodwalls)	Large	✓		✓	✓
Longitudinal barriers (dams, storm surge barriers, breakwaters)	Large			✓	✓
Sewerage capacity (e.g. tunnels)	Large				
Straightening watercourse	Large				
Building reservoirs	Medium				
Sandbagging	Small				
Pumping and dredging	Small				

Source: WGF (2012); own illustration.

Cost-efficiency comparison (43)

The four selected GI measures and two grey infrastructure measures (see Table A1.4) are reviewed with respect to their costs and effects in Chapter 4. The most important information on which the analysis is based are the cost data included in the large repository of case studies presented in Stella (2012a) and the NWRM (2014a) project. All relevant cases referred to in these projects have been individually studied for this project, to distil the relevant cost data in line with the standardised cost categories presented in Table A1.1. The sources and references used for each of the different GI measures are mentioned in the detailed cost tables included in Chapter 4. Additional literature and relevant reports have been reviewed and taken into consideration, in particular in cases where GI measures were implemented and costs reported. In such cases, the individual references and source information have been included in the detailed cost tables.

The analysis aims to select a representative set of cases where different parts of Europe are covered and where the data on costs for the specific GI measures are most accurate (preferably from projects that split costs per measure, or for projects where the GI measure considered comprised the greater part of the overall project). The information is aggregated in the synthesis section with a derived aggregate cost figure. Since the original data on costs are gathered on a case-by-case basis from studies that were conducted at different points in time, the presented cost prices in this section refer to nominal values (44), as not all prices could be converted to a standard year. Where standardised cost data were presented across several cases (e.g. Stella, 2012), those values were selected. Where cost data were combined with data from other sources, only case studies from relatively recent years were used to ensure that the inflation effect is insignificant.

Information on the direct and indirect effects (benefits) is sourced from the NWRM project, illustrated with additional literature and case study evidence. The NWRM project contains a description for each measure, including a score (none-low-medium-high) for each of the ecosystem services we consider in the detailed assessment (those introduced in Table A1.2). The NWRM project submitted each measure in the NWRM catalogue to an expert panel in each scientific field to score the measures (none-low-medium-high). The final choice for the score of each measure was made by the NWRM project team on the basis of expert judgement, information from a literature review, data collected from case studies and a third-party expert workshop review. These scores have in this analysis been converted to 0 ('none'), 1 ('low'), 2 ('medium') and 3 ('high'), to be able to generate average scores for aggregate ecosystem or biophysical impact categories.

As Stella (2012) and NWRM (2014a) do not include cost and effect information on grey infrastructure measures, the costs and benefit data for the two selected grey infrastructure measures (see Table A1.4) have been sourced from other existing literature and reports referred to in Chapter 4. In turn, the costs were converted to a comparable unit of measurement, to ensure that the costs for realising the projects are

(43) The icons used for the cost and effect summary tables in this section were obtained from icons8.com
(44) Nominal prices have not been converted to a given reference year by adjusting them for inflation over time. Therefore nominal prices reflect contemporary prices at that time.

more or less comparable. The general classification of direct and indirect benefits, as included in the introduction, has also been used (see Table A1.2). As grey infrastructure measures are specifically designed with the single purpose of preventing river water run-off, certain biophysical characteristics that prevent flood risk do not apply to grey measures. Notably, reducing flood risk through storing and slowing run-off () and through reducing run-off () are marked 'not applicable', as the two grey measures considered (riverbank protection and longitudinal barriers) do not possess the biophysical characteristics that are associated with these direct effect categories (such as reducing run-off by increasing evapotranspiration or storing run-off in detention ponds). The information on the indirect effect categories (the ecosystem services introduced in Table A1.2) has been sourced from additional existing literature, as referred to in Chapter 3, on the basis of qualitative assessment of the associated score of 'none', 'low', 'medium' or 'high'. Since this process of scoring the indirect effects of grey infrastructure measures is different from that of the GI measures, these scores have been marked in italics in the benefit tables.

Annex 2 Overview of the methodologies used per research question

Identification of flood risk in selected river basin districts

The methodology used for determining flood risk in the four selected river basins is set up in four steps.

It should be noted that various datasets (including climate change data) used in this study have been obtained from the JRC (see Annex 4 for further details). More information on the hydrological simulations and on the ensemble of climate projections can be found in Alfieri et al. (2015).

A. Selection of river basins of interest for case study analysis

Four European basin districts have been selected for the analysis that will serve as an illustration of the possibility of implementing natural solutions for cost-efficient flood protection. The selection was based on the following criteria:

1. the incidence of flood events historically (based on 'River catchments affected by flooding 1998–2005' — EEA, 2016d);

2. the magnitude — large basins preferred (FHRMs, available for 12 EU Member States);

3. an international character, with cross-border issues;

4. the presence of alterations, in particular levees/ dikes/embankments, or drained wetlands (information from draft RBMPs and draft FRMPs);

5. types of flooding: fluvial flooding (in relation to floodplains);

6. availability of data: in general, information in draft RBMPs (2015) and draft FRMPs (2015), as well as the RBMP of 2009;

7. data from FHRMs;

8. potential for introducing floodplains to reduce flood risk — lowland areas to create floodplains;

9. the delineation of potential floodplains by the EEA or using FHRMs;

10. vulnerable cities located downstream (FHRMs and expert input); and

11. overall, good representation of the difference in types of flooding (pluvial, riverine, coastal) and climatological conditions.

Based on the most favourable outcomes for the various river basins (see Annex 3 for the selection matrix), the Elbe (Germany), Rhône (France), Scheldt (Belgium) and Vistula (Poland) have been selected as RBDs of interest for the scope of analysis of this study, with Magdeburg, Lyon, Antwerp and Sandomierz as the respective cities of interest. The analysis carried out for this report focused on screening river stretches upstream of these cities on their potential floodplains.

B. Analysis of potential floodplains

The flood management and protection requirements that are in need of flood risk mitigation solutions are screened. The idea is to have a very general estimate of where nature-based solutions or GI, such as floodplains, can be used. Within this study, potential areas of floodplain restoration are delineated, based on a very general GIS (geographic information system)-based analysis (see Annex 4). These potential floodplains are thought to deliver a significant contribution to water storage in the river system and to protect downstream urban areas, which have been affected by flooding in recent years. It is thought that the restoration of these floodplains can be an important measure to mitigate increased flood risk caused by urbanisation, intensive land use and climate change. The GIS analysis results delineating potential floodplains will be compared with planned and implemented measures in the river basins (in RBMPs and FRMPs), and will be repeated with relevant climate change scenarios (see next section).

The assessment will result in a 'GI potential floodplain layer'. This layer, as can be seen from Annex 4, consists of the flood hazard map (FHM) layer merged with the

EEA floodplain layer minus the urban area (Corine), where it is expected that floods should be avoided.

- The FHM layer indicates the potential flood hazard for a 1 in 100-year event, as is reported by the Member States through the Floods Directive. It includes the Member State mitigation measures that are currently present and gives the contour of the floods (taking into account existing protection measures).
- The EEA floodplains layer is based on land use, soil and floods modelling data. It includes the natural flood area in areas with no flood mitigation, it and takes into account the natural alluvial plains of the river.
- The urban area is defined as the built area with social and economic purposes.

The potential space for floodplain creation/restoration, a possible GI measure, is as such a union between the flood hazard area (a real context, i.e. the contours of a 1 in 100-year event when mitigation measures are taken into account) and the floodplains layer, which is based on the original alluvial grounds of the river. When one 'deletes' the existing urban area from this, the resulting map indicates the potential space suitable as a floodplain area. It should be noted, however, that this represents a rough estimate of currently non-built area that could be targeted for the purpose of 'flood retention basins'.

C. Impact of climate change and other pressures

In order to add the dimension of potential future changes to flood vulnerabilities caused by various climate change scenarios/projections, the following approach is applied: the latest climate change projections on river discharges on a regional basis (JRC, 2012) are retrieved, depending on the locations of the selected river basins, and a percentage change in peak discharges and water stages is used, to ensure inclusion of climate change projections in the overall analysis. Other pressures causing flood risk hazard include certain soil management practices, spatial planning measures, urbanisation, transport, etc.

D. Vulnerability screening and implementation of green infrastructure versus its full potential

It should be noted that this step was carried out once information from other methodological steps was also available, as described in Sections 2.3, 2.4 and 2.5. The screening needed to provide information for analysing the vulnerability to flood risk of several cities in the selected river basins:

- What large-scale natural measures (solutions) are implemented?
- What are the current strategies at the river basin level, and existing coordination mechanisms between FRMPs and RBMPs on flood risk management (with a focus on natural solutions and the decision-making process)? (See Section 2.3 for further information.)
- How do Member States and regional/local authorities take into account climate, soil protection and sustainable land use?
- How do Member States consider cost-efficiency of NWRMs? (See Section 2.4 for further information.)
- How do Member States fund NWRMs? (See Section 2.5 for further information.)
- In reality, how much of what has been found is actually being implemented (using mid-term review of the PoM from the first cycle of RBMPs, and the latest PoM from the draft RBMP 2009 report)?
- In future, will Member States have more opportunities regarding their GI potential than at present?

Review of current flood risk management strategies

A general overview of the status of implementation of Flood and Water Directive-related plans has been provided in Chapter 2. Building on this broad overview, the study also assessed in more detail the current status of flood risk management strategies in the selected case study RBDs, namely the Elbe (Germany), the Rhône (France), the Scheldt (Belgium) and the Vistula (Poland).

The description and assessment of the current status and level of implementation per RBD was based on the available literature, including primarily the draft RBMPs and draft FRMPs, as well as mid-term reviews or accompanying documents where available. In addition, the information has been combined with data and maps collected during the previous methodological step. In particular, the review also aimed to highlight the current application of GI measures as compared with grey infrastructure alternatives in the selected RBDs.

Review of barriers to decision-making processes

In order to improve the uptake of GI across Europe and across all levels (local, regional, EU) and sectors, it is important to gain a clear understanding of the relevant decision-making processes, and to assess how — and if — awareness-raising, training and decision-making tools could help support them.

The assessment carried out in this report is based on a review of relevant available literature in combination with interviews and feedback gathered via the researchers' involvement in various relevant professional working groups and other conferences/ events. Data and information gathering was also based on parallel research carried out for the European Commission in relation to supporting their implementation efforts of the EU GI Strategy. This review of barriers contributes to the overall study goal of facilitating the implementation of GI, in the sense that it allows one to combine the mapped opportunities resulting from this study on how to overcome the existing barriers to facilitate implementation.

Annex 3 River basin selection matrix

Seven potential RBDs were identified for more detailed assessment as regards their suitability as case studies: the Danube, Elbe, Rhine, Rhône, Scheldt, Thames and Vistula. The preliminary selection of these seven RBDs was based on the following criteria:

1. the historical incidence of flood events;
2. the magnitude — large basins preferred;
3. international character, with cross-border aspects;
4. the presence of alterations, and in particular:
   a. levees/dikes/embankments;
   b. drained wetlands;
5. types of flooding: fluvial flooding (in relation to floodplains);
6. availability of data:
   a. in general: information from RBMPs and (draft) FRMPs;
   b. data from FHRMs.
7. potential for introducing floodplains to reduce flood risk — lowland areas to create floodplains;
8. language coverage.

Table A3.1 Selection matrix for river basin districts (RBDs)

Name RBD	Unique code WFD	(1) Incidence	(2) Magnitude	(3) Cross-border	(4) Alterations	(5) Types: fluvial	(6a) Data available	(6b) Data from FHRMs	(7) Potential	(8) Language coverage	Cities of interest	Preference
Scheldt	BEScheIde_VL			+	+	+	+	+	+	++	Antwerp, etc.	++
Elbe	DE5000	+	++	++		+	+	+	++	+	Hamburg, Magdeburg, Dresden, etc.	+
Vistula	PL2000 (Lower Vistula RBD)	+	+	+		+	+	+	++	+	Gdansk, Wloclawec, Warsaw, etc.	+
Rhône	FRD (Rhône and Coastal Mediterranean)	++	+	+		+	+	–	+	+	Lyon, etc.	+
Danube	HU1000, DE1000, SK40000	++	++	++		+	+	+/–	+	– –	See historic floods*	
Rhine	DE2000	+	+	++		+	+	+	+	+	Koblenz, etc.	
Thames	UK06	+	+			+	+	–	–	+	Oxford, Reading, Slough, London, etc.	–

Note: Pros and cons:

Pros: +

Cons: –

Clarification and comments:

(1) Incidence

Based on:

- 'River catchments affected by flooding 1998–2005' — Figure 3.1 in proposal. Source: EEA report *Urban adaptation to climate change in Europe* (EEA, 2016d).

(2) Magnitude

Based on:

- FHRMs (available for 12 countries).

(3) Cross-border

Based on:

- RBDs.

(4) Alterations

Based on:

- information from RBMPs and FRMPs (to be undertaken in more detail).

(5) Types:

Less important criterion; focus on fluvial floods.

6(a) Data availability — general

- Data from EEA.
- RBMPs: downloaded via internet.
- (Draft) FRMPs: downloaded via internet.
- 'Known' data/national data:
  - data from 'Sigmaplan' — Scheldt — BE Fl.
- Data of International River Basin Commissions:
  - Danube, Elbe, Rhine, Scheldt, Vistula, etc.

6(b) Data from FHRMs:

- FHRMs available for 12 countries; see EEA document 'EU overview of FHRM reporting' — Table 1.
- FHRM not available for France (Rhône).

(7) Potentials

The opportunity to implement floodplains for mitigating flood risks.

Based on:

- the delineation of potential floodplains, made by EEA;
- FHRMs.

(8) Language coverage

Language coverage within the consortium Trinomics-ARCADIS.

Preference of RBD selection:

- Scheldt: downstream reach, Sigmaplan already implemented for many stretches, cross-border river basin.
- Elbe: mid-reach, the historical floods and main cities affected, cross-border river basin.
- Vistula: eastern Europe, mid- to upper reach and various smaller sized cities affected, cross-border river basin.
- Rhône: more upstream, large city (Lyon) affected, cross-border river basin.
- All: geographical spread across Europe.

Selection of 'areas of interest':

The analysis of potential floodplains will focus on areas of interest within the RBD.

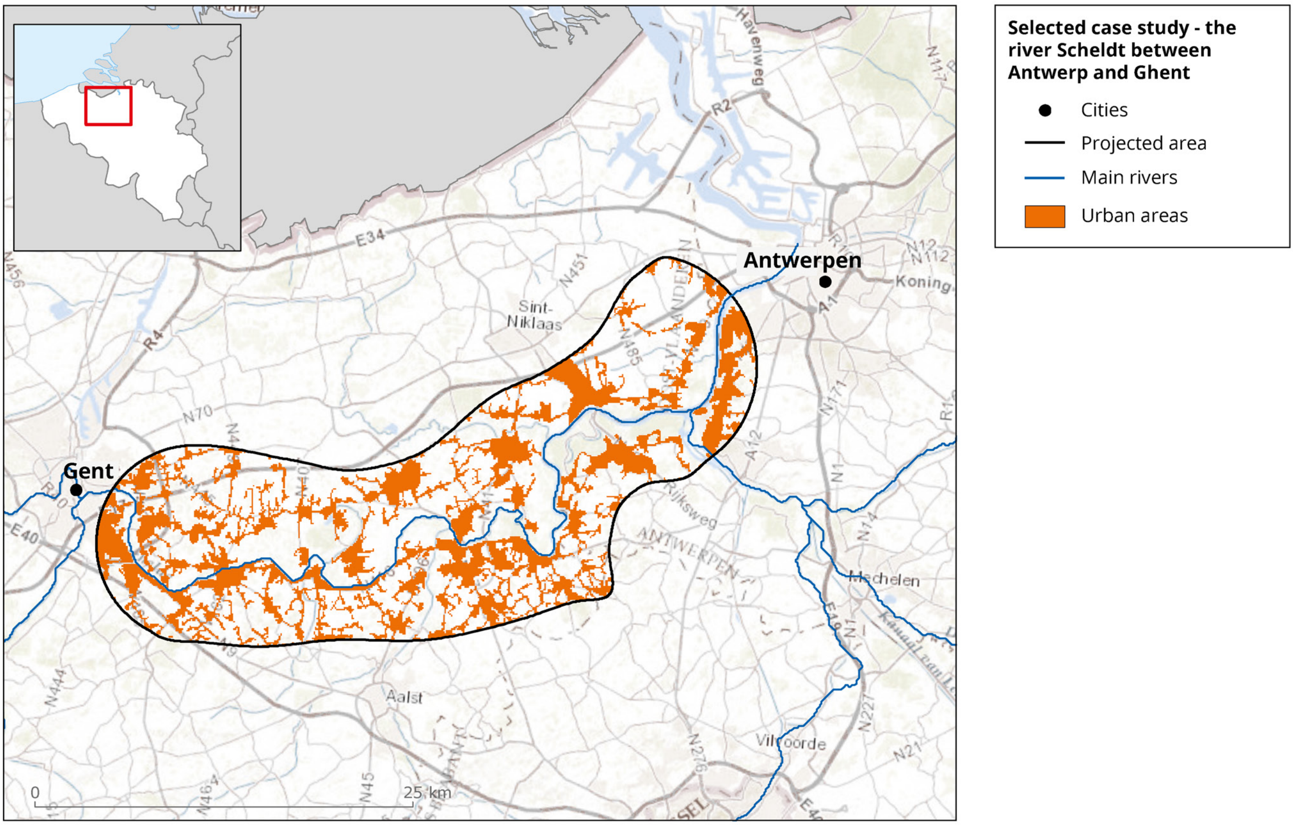
The selection of areas of interest is based on:

- floodplains, delineated floodplains by the EEA;
- FHRMs;
- information from experts with knowledge of flood issues in the river basin;
- general information from flood-related websites.

Scheldt

Area of interest will be the valley of the River Scheldt between Antwerp and Ghent.

Map A3.1 Scheldt river basin district — selected case study

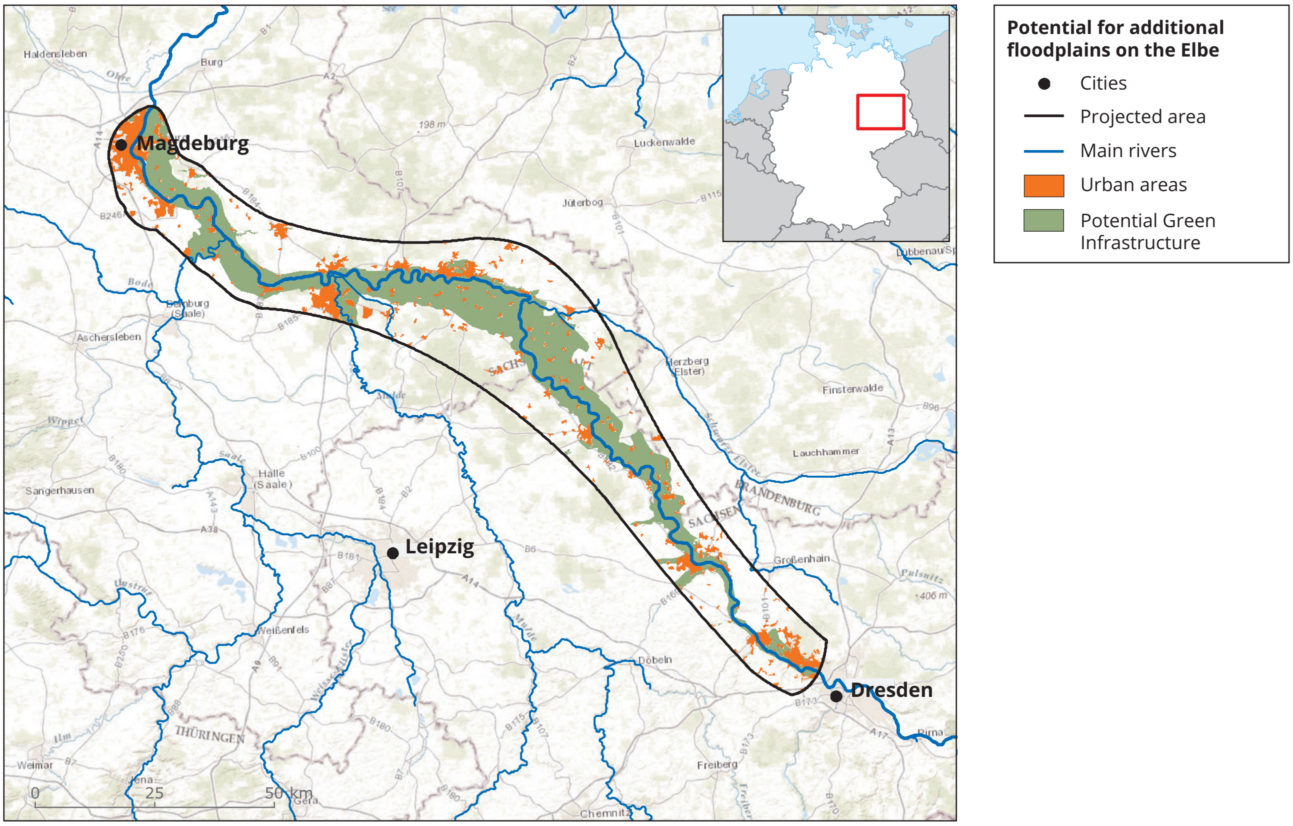


Source: Arcadis.

Elbe

Area of interest will be the valley of the River Elbe between Magdeburg and Dresden.

Map A3.2 Elbe river basin district — case study selection

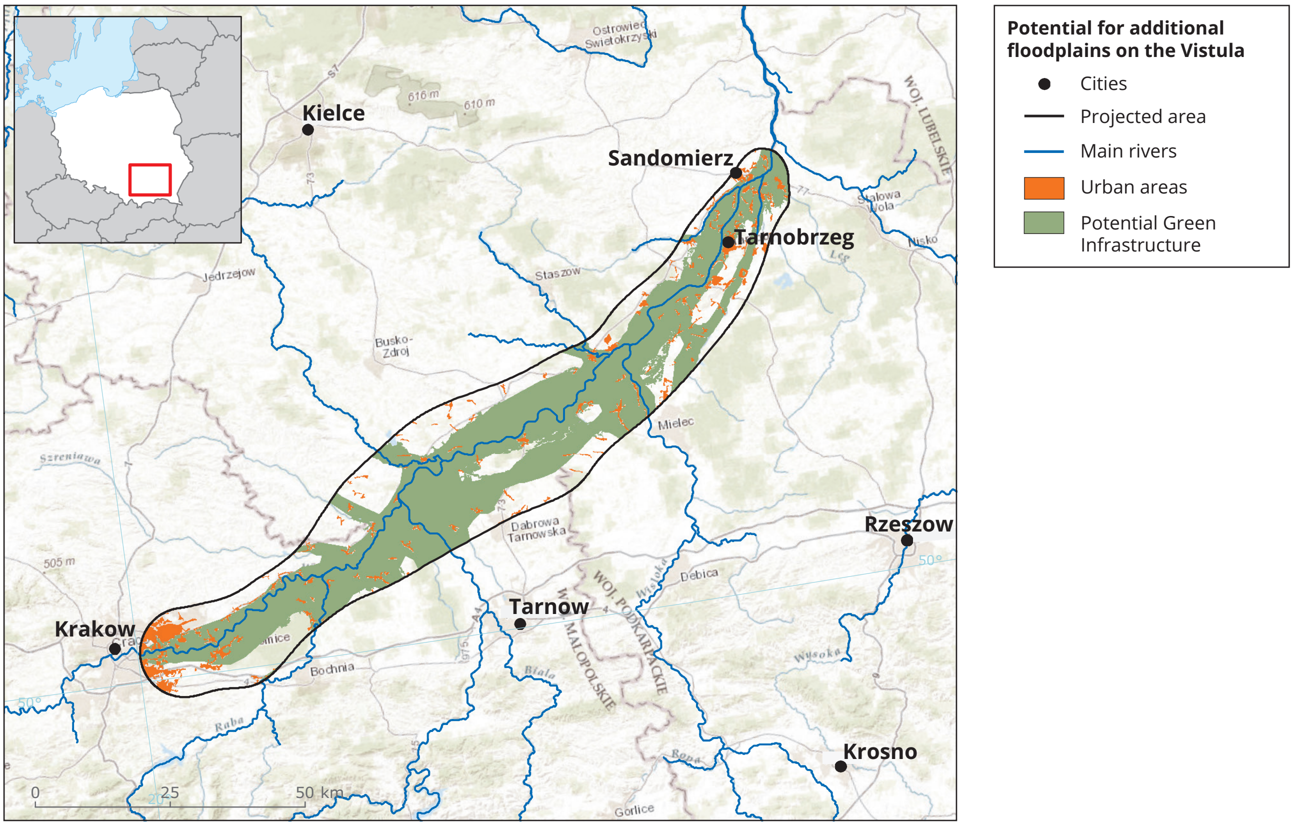


Source: Arcadis.

Vistula

Area of interest will be the valley of the River Vistula above Krakow (between Krakow and a place to be identified).

Map A3.3 Vistula river basin district — selected case study

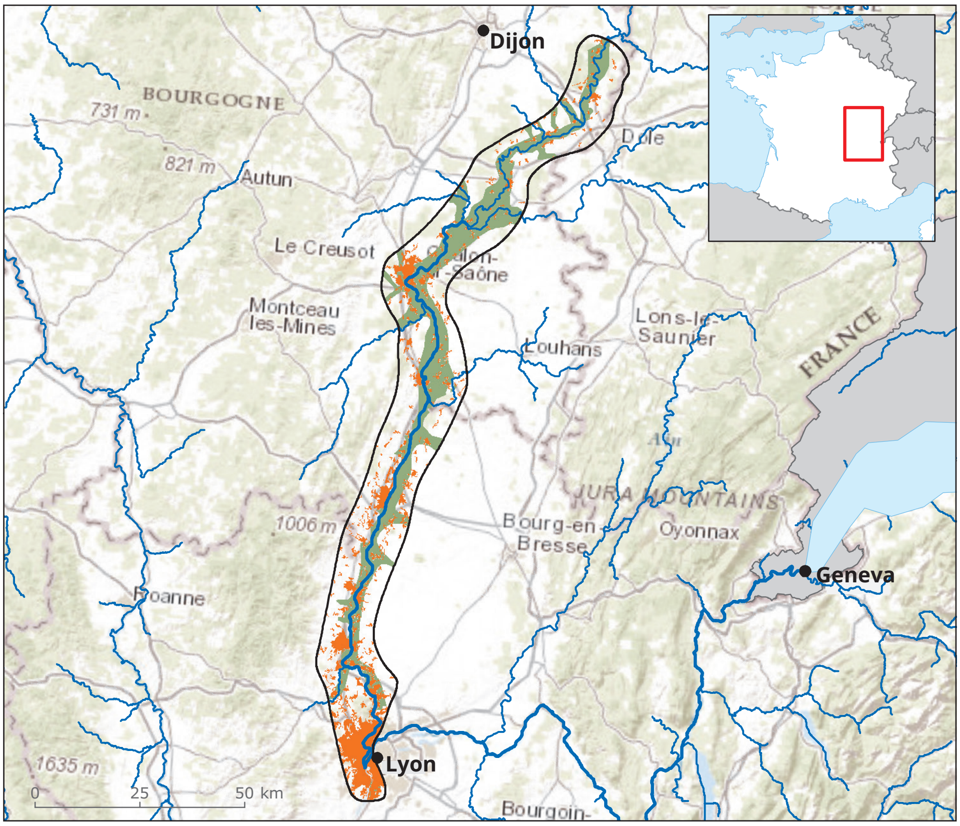


Source: Arcadis.

Rhône

Area of interest will be the valley of the River Rhône between Dijon and Lyon.

Map A3.4 Rhône river basin district — case study selection



Potential for additional floodplains on the Rohne

- Cities
- Projected area
- Main rivers
- Urban areas
- Potential Green Infrastructure

Source: Arcadis.

Table A3.2 Summary of selection criteria scores per river basin district (RBD)

RBD		Fluvial flood hazard and flood risk — seriousness					Data availability for analysis		Potential	City
Name RBD	**Code RBD (WFD)**	**(1) Historical incidence**	**(2) Magnitude**	**(3) Cross-border**	**(4) Alterations**	**(5) Types: fluvial**	**(6) Data available**	**(7) Data from FHMs via EEA**	**(8) Potential**	**(9) Possible city of interest (historic flooding)**
Scheldt	BEScheldе_VL			+	+	+	+	–	+	Antwerp, etc.
Mittel-Elbe	DE5000	+	++	++	+	+	+	+	++	Hamburg, Magdeburg, Dresden, etc.
Upper Vistula	PL2000, Vistula RBD	+	+	+	+	+	+	+	++	Gdansk, Wloclawec, Warsaw, Sandomierz, Krakow, etc.
Rhône	FRD	++	+	+	+	+	+	–	+	Lyon, smaller cities along Rhône and Saône
Danube	HU1000, DE1000, SK40000	++	++	++	+	+	+	+/–	+	Historic floods
Rhine	DE2000	+	+	++	+	+	+	+	+	Koblenz, etc.
Thames	UK06	+	+	/	+	+	+	–	–	Oxford, Reading, Slough, London, etc.

Annex 4 Detailed methodology for mapping the additional floodplain potential

Approach as applied by using the data

The GIS analysis aimed to delineate potential floodplains for the baseline scenario and the relevant climate change scenarios. The detailed methodology is given below, using FHMs as delivered by the Member States, land use maps and the EEA floodplain layer.

Table A4.1 Detailed methodology for delineating potential floodplains

Step	Description
Step 1 — Gathering and mapping basic data	• Gathering basic data, assuming this is available: – flood hazard maps, return period = 100 years – Corine land cover maps – digital elevation models (DEMs) (if readily available) • Mapping these data in a GIS environment.
Step 2 — Overlay and analysis	• GIS overlay of FHMs and Corine land cover maps: The FHMs are merged with the potential floodplain maps made up by the EEA, minus the urban areas results in the 'capacity for implementation of GI) in order to protect the city from floods'. For the Rhône river basin, no FHM was available, and only the floodplain layer was used. This resulted in the layer 'potential GI'. The urban and economic areas clipped off were: – continuous urban fabric – discontinuous urban fabric – industrial or commercial units – road and rail networks – port areas – airports – mineral extraction sites – dump sites – construction sites – green urban areas – sport and leisure facilities • Areas for implementation of GI in potential flood: – Vistula: 1 751 km² – Elbe: 1 188 km² – Rhône: 794 km² • The urban and economic areas covered by the FHMs merged with the potential floodplain maps were also computed. Urban and economic areas with potential flood risk: – Vistula: 89 km² – Elbe: 137 km² – Rhône: 121 km² As a percentage in relation to the potential areas for the implementation of GI: – Vistula: 5 % – Elbe: 11 % – Rhône: 15 % • Result: A revised and 'approved' delineation of potential floodplains (see Map 5.1).

Table A4.1 Detailed methodology for delineating potential floodplains (cont.)

<table>
<tr><th>Step</th><th>Description</th></tr>
<tr><td>Step 3 — Water storage</td><td>

The approximation of maximum water depth and determination of the average water depth of the potential floodplains and the storage volume is based on LISFLOOD data from the JRC. These are floods data but do not take into account any existing measures alongside the river course.
The computations of the water depth (maximum and average) are made for the areas covered by the layer described in step 2.

Water depth:
<table>
<tr><th>River basin</th><th>Maximum water depth (m)</th><th>Average water depth (m)</th></tr>
<tr><td>Vistula</td><td>10.6</td><td>1.8</td></tr>
<tr><td>Elbe</td><td>12.43</td><td>2.47</td></tr>
<tr><td>Rhône</td><td>18.8</td><td>3.02</td></tr>
</table>

Water storage:

Vistula: 2 048.82 × 10^6 m^3
Elbe: 2 293.25 × 10^6 m^3
Rhône: 1 408.76 × 10^6 m^3

The computation of the maximum and average water depth, and water storage, were also made for the urban and economic areas. Therefore the overlay between the LISFLOOD data and the urban and economic areas (Corine) was made.

Water depth:
<table>
<tr><th>River basin</th><th>Maximum water depth (m)</th><th>Average water depth (m)</th></tr>
<tr><td>Vistula</td><td>5.18</td><td>1.16</td></tr>
<tr><td>Elbe</td><td>13.09</td><td>1.75</td></tr>
<tr><td>Rhône</td><td>10.8</td><td>1.87</td></tr>
</table>

Water storage:

Vistula: 43.36 × 10^6 m^3
Elbe: 155.83 × 10^6 m^3
Rhône: 71.56× 10^6 m^3

As a percentage in relation to the volume stored within the areas for potential implementation of GI:

Vistula: 2 %
Elbe: 7 %
Rhône: 5 %

</td></tr>
</table>

Table A4.1 Detailed methodology for delineating potential floodplains (cont.)

Step	Description
Step 4 — Discharge/ stage analysis (including climate change)	Hydrogram: • The flows and hydrograms for the 1 in 100-year (Q100) event were computed based on JRC data (Alfieri et al., 2014): Daily peak flow of a 1 in 100 year event derived from historical simulations (1990-2013), based on an observed meteorological database used to force the hydrological model LISFLOOD. The peak flow of the Q100 event and the time of concentration allow the Q100 hydrograms to be computed. Climate change: • The climate change scenarios are based on an ensemble of seven EURO-CORDEX climate scenarios (Alfieri et al., 2015), received from the JRC. • The computations were based on: – Daily peak flow of a 1 in 100-year event derived for the baseline window (1976-2005) (Q100_baseline) and for the time slice (2036–2065) (Q100_2050) from an ensemble of seven EURO-CORDEX climate scenarios. The time slice (2036–2065) means that the climate projections are carried out for 2050. – Daily peak flow of a 1 in 100-year event derived from historical simulations (1990–2013). • For each climate scenario, the relative differences between Q100_2050 and Q100_baseline were applied as a multiplicative factor to Q100 to obtain the prediction. • Results: – The river basins are differently affected by the climate projections. – The flood volume increase and the flood volume for the baseline Q100 in urban areas are given in tables for the seven EURO-CORDEX climate scenarios. The first (Table 5.1) gives the volume increase as a percentage in relation to the baseline Q100. The second (Table 5.2) gives the volume increase of the stored water in urban and economic areas, which comes in supplement to the volume computed under step 3. The water volume stored on urban and economic areas for Q100 is also given in the table.

Annex 5 Case study reports

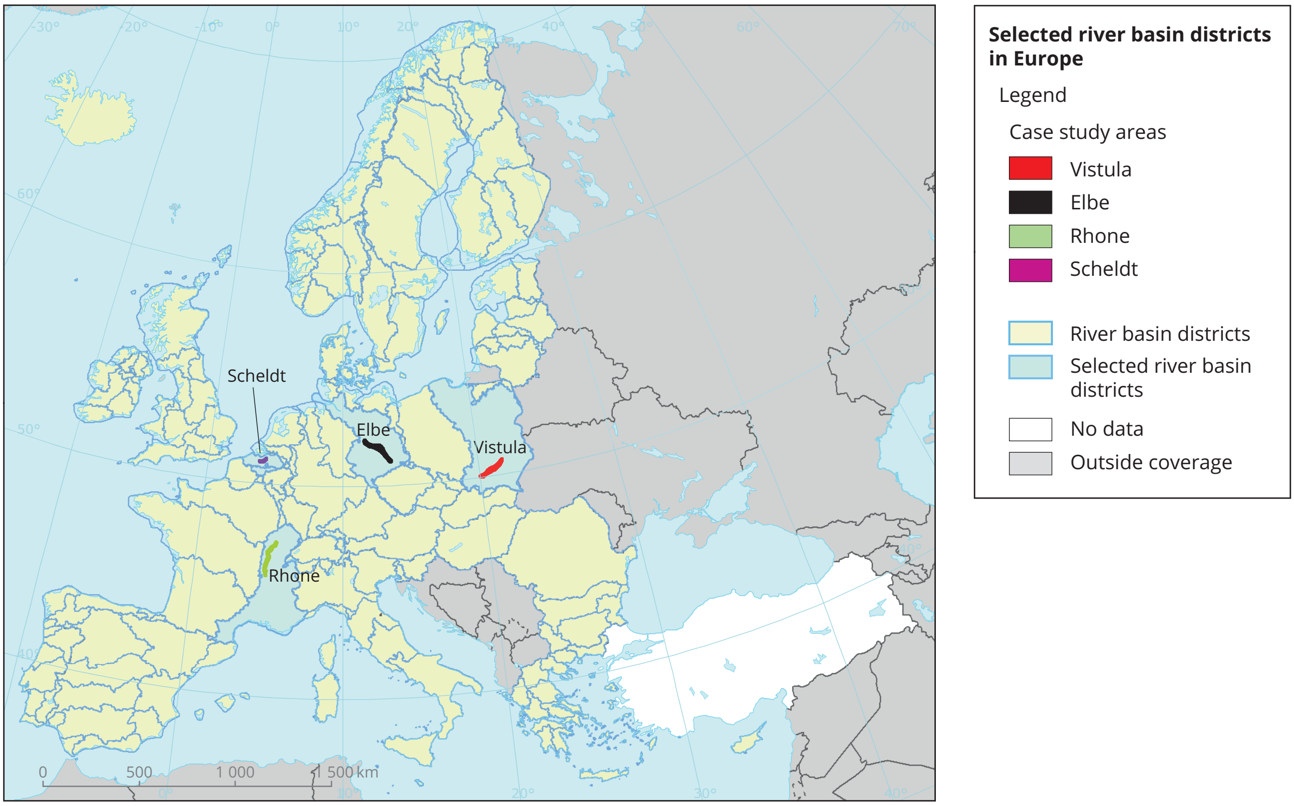
This annex provides a detailed description of the case studies in the four selected river basins: the Elbe (Germany), the Rhône (France), the Scheldt (Belgium) and the Vistula (Poland).

Each case study identifies:

- flood risk;
- the vulnerability of the main city of concern;
- the existence of FRMPs; and
- their current status of implementation.

Chapters in the main report refer to these in-depth case studies, highlighting additional insights into the cost-efficiency assessments of the chosen flood protection measures (Chapter 4) and the potential for additional floodplains (Chapter 5).

Map A5.1 Selected river basin districts in Europe



Source: Arcadis, based on EEA data.

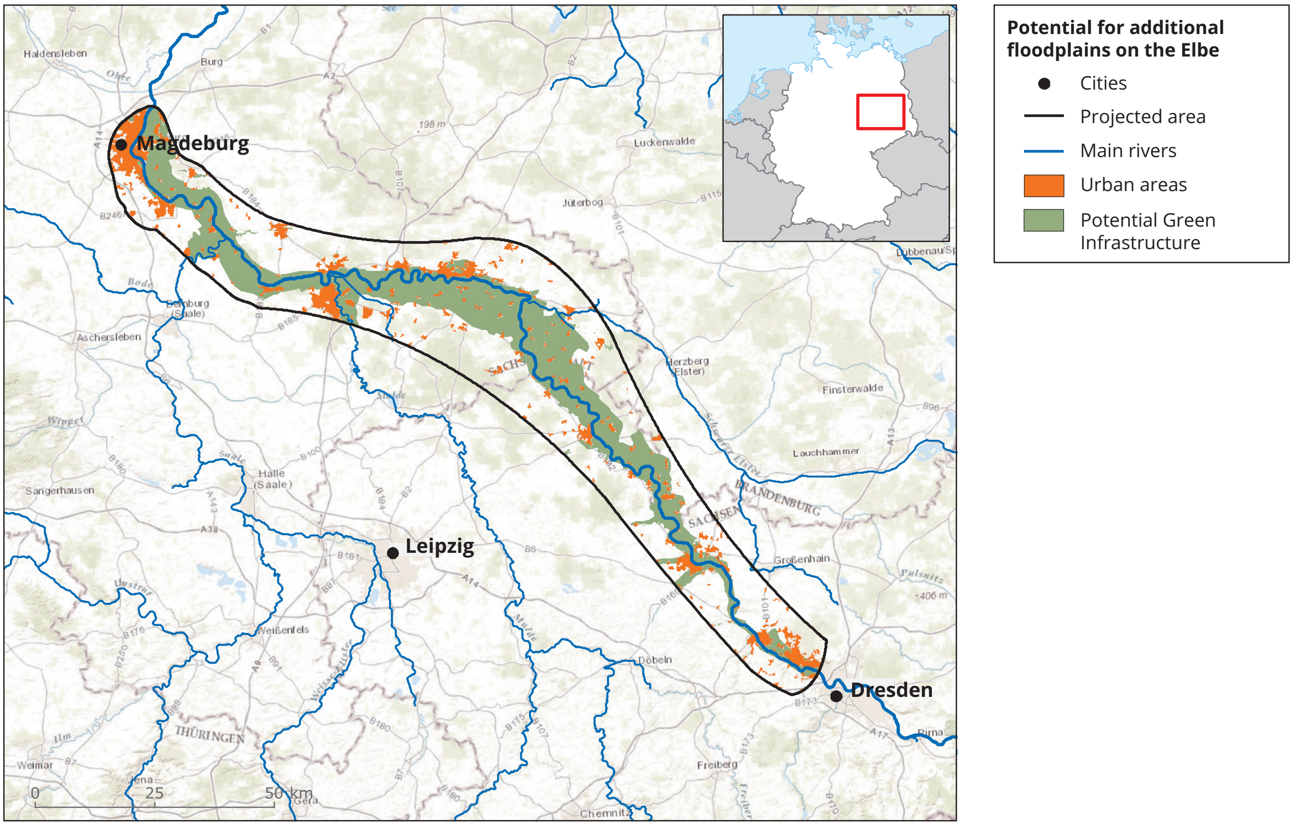
Elbe, Germany

Identification of flood risk

The Elbe starts in the Czech Republic and crosses around 1 100 km before reaching the sea in Cuxhaven, northern Germany. More than two thirds of its length, as well as two thirds of the basin's 150 000 km^2 area and three quarters of its 24 million inhabitants, are in German territory. The Elbe flows through 10 German states and many important cities, such as Leipzig, Dresden, Hamburg and Magdeburg. The latter, which will be analysed in more detail in this study, has 250 000 inhabitants and is the capital of Sachsen-Anhalt. Magdeburg is located in Mittlere Elbe/Elde, one of the five regions into which the river basin is divided.

The Mittlere Elbe/Elde region, located in the middle of the Elbe river basin, is spread over 16 500 km^2 in central and northern Germany, and it contains two important cities: Magdeburg and Schwerin, the former located on the river and the latter approximately 65 km away from it. Mittlere Elbe/Elde has 34 areas of potential significant flood risk, four of which are in the immediate vicinity of Magdeburg: Schrote, Polstrine, Elbumflut and Ehle/Ehleumflut.

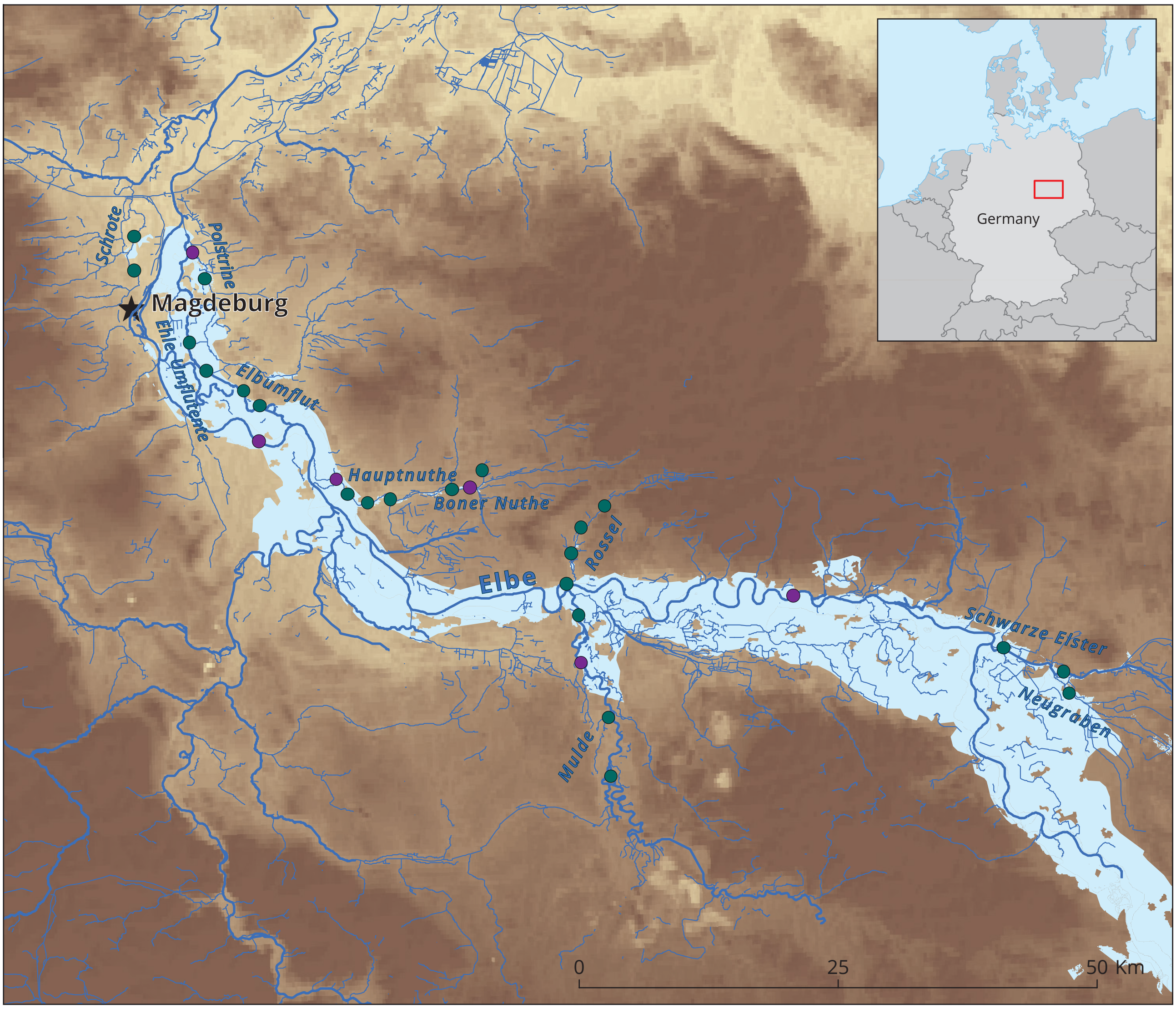
Map A5.2 **Elbe river basin district — case study selection**



Source: Arcadis.

Around 54 % of the area of the Mittlere Elbe/Elde region is used for agriculture, with a further 15 % being pastureland. Approximately 24 % of the territory is occupied by forests and 3 % by water bodies, such as rivers and lakes. The remaining 4 % is used for human occupation (FGG Elbe, 2004). Many risk areas contain industrial facilities, agricultural crops and provide cultural services, all of which require measures for protection against eventual floods. In Mittlere Elbe/Elde, the draft FRMP estimates that up to 289 industrial facilities could be affected by an extreme flood (FGG Elbe, 2014). Such a catastrophic scenario would also affect 210 000 inhabitants in the region. In a high-probability scenario, around 3 500 people

Map A5.3 Location of existing GI measures (planned and/or implemented) in the selected Elbe river basin district



Note:
Locations of measures are estimates based on the number of measures per river segment according to the national draft RBMP.

Source: Trinomics, based on location estimates of measures in national draft RBMP.

and four industrial facilities would be hit by floods in this region. The whole Elbe region has a significant number of sites recognised by Unesco as Cultural World Heritage Sites. These sites include the palaces, churches, museums and gardens of Potsdam and Berlin, as well as the towns of Quedlinburg, Wittenberg, Eisleben, Weimar and Dessau.

Vulnerability of the main cities

The Magdeburg region is vulnerable to river floods, and was strongly affected by major floods on the Elbe in 2002. Since then, some preventive measures have been taken to make the city better prepared for such events. The levee around Magdeburg has been rebuilt and strengthened, and a large number of sandbags (153 000 jute sacks, 200 000 plastic sacks and 80 000 large bags) are readily available to protect the levee (Ließmann, 2012). Other measures are improvements in the drainage system in Pechau/Zipkeleben (2007), the expansion of a trench system in Furtlake (2012), construction of the Furtlake Canal and a pumping station at Steingrabensiel, and work on the Elbe's riverbed to increase flow rate (Landeshauptstadt Magdeburg, 2015). Floods hit the city in 2003, 2006 and 2013. Currently Magdeburg's authorities are willing to proceed with projects to reduce vegetation in the river and in the canal around Magdeburg (*Umflutkanal*), increasing the space available for water, but this is currently impossible because the vegetation in the area is protected under European legislation (MDR, 2015).

Management plans and status of implementation

Map A5.3 (and corresponding Table A5.1) depict the GI measures already implemented and/or planned in the selected case study area of the Elbe river basin.

Summary of the consideration of land use, soil management and climate change in relation to flood risk management

In the general area of the Elbe basin (which extends beyond the Mittlere Elbe/Elde case study area), the distribution of land use is as follows: 45 % agricultural farmland, 15 % pasture, 27 % forests, 8 % human occupation and the rest is basically occupied by water bodies (rivers and lakes). The following map is based on the PFRA (*Vorläufige Bewertung des Hochwasserrisikos*) and depicts the whole Elbe basin within Germany (FGG Elbe, 2011).

The PFRA for the Elbe identifies land use planning and construction planning measures as key aspects for the management of flood risk and prevention in the German parts of the Elbe. For the German catchment areas of the Elbe, almost all flood risk areas have set measures to avoid flood risks via land use planning and the identification of floodplains. For the case study area of Mittlere Elbe/Elde, the identified land use planning measures include 18 measures involving regional land use regulation, 32 measures for the identification of floodplains, 32 measures to guide construction planning and zoning, and three measures involving changes in or adaptation of current land use. In addition to these regional or local measures, an example of a wider measure applicable for all areas (embedded in national legislation) is the establishment of floodplain locations and the embedding of these in land use planning regulations. This requires following the assigned land use restrictions for these floodplains and drainage areas. This may result in land use changes and/or restrictions in the zoning of new constructions, as identified floodplains have legal priority over new land use planning for the identified areas.

Regarding climate change, the Elbe river basin has been identified as one of the German areas under particular threat of future climate change, and in particular changes in rainfall and temperature (Hattermann et al., 2008). This in turn will trigger changes in the Elbe's water cycles. Flood risks may be affected because of changes in the height, duration and frequency of flood run-off. The Elbe's 2015 draft RBMP and FRMP also identify that climate change will have indirect consequences on water management due to potential changes in land use. The climate change assessment carried out under the Elbe's 2015 draft RBMP concludes that all identified measures will still contribute to improved water management even under conditions of climate change. The 2015 draft RBMP highlights the important contribution of rivers with good ecological status towards climate change adaptation, given that they are more resilient to extreme climate events, e.g. floods or droughts. Building on this, the Elbe's FRMP incorporates the conclusion of the Sixth Elbe Ministerial Conference (5 December 2013) that additional floodplains and — if needed — infrastructure-based reservoirs for flood management installations should be prioritised and extra financial resources provided.

Table A5.1 Elbe — existing/planned GI measures

Name of measure	Type of measure	Part of strategic approach?	Planned/ implemented	Timing	Location/ extent of measure	By who? Responsible body	Funding	Coordination	Cost-efficiency, benefits calculated/ reported?	Reference	Impact on main city
Protection/ restoration of flood areas	Green: N02 Floodplain restoration	Mittlere Elbe/Elde-Elbumflut, DEST_ RG_5746	Planned			State government				Hochwassermanagementplan Elbe	High
Clear out river flow cross-section	Green: N05 Stream bed re-naturalisation	Mittlere Elbe/Elde-Elbumflut, DEST_ RG_5746	Planned			State government				Hochwassermanagementplan Elbe	High
Protection/ restoration of flood areas	Green: N02 Floodplain restoration	Mittlere Elbe/Elde-Hauptnuthe/Lindauer Nuthe, DEST_RG_572	Started			Communal government				Hochwassermanagementplan Elbe	High
Restoration of flood areas	Green: N02 Floodplain restoration	Mittlere Elbe/Elde-Hauptnuthe/Lindauer Nuthe, DEST_RG_572	Planned			State government				Hochwassermanagementplan Elbe	High
Restoration and expansion of river flow cross-section	Green: N05 Stream bed re-naturalisation	Mittlere Elbe/Elde-Hauptnuthe/Lindauer Nuthe, DEST_RG_572	Planned			State government				Hochwassermanagementplan Elbe	High
Clear out river flow cross-section	Green: N05 Stream bed re-naturalisation	Mittlere Elbe/Elde-Hauptnuthe/Lindauer Nuthe, DEST_RG_572	Planned			State government				Hochwassermanagementplan Elbe	High
Protection/ restoration of flood areas	Green: N02 Floodplain restoration	Mittlere Elbe/Elde-Boner Nuthe, DEST_ RG_5724	Started			Communal government				Hochwassermanagementplan Elbe	High
Restoration and expansion of river flow cross-section	Green: N05 Stream bed re-naturalisation	Mittlere Elbe/Elde-Boner Nuthe, DEST_ RG_5724	Planned			State government				Hochwassermanagementplan Elbe	High
Clear out river flow cross-section	Green: N05 Stream bed re-naturalisation	Mittlere Elbe/Elde-Boner Nuthe, DEST_ RG_5724	Planned			State government				Hochwassermanagementplan Elbe	High
Protection/ restoration of flood areas	Green: N02 Floodplain restoration	Mittlere Elbe/Elde-Ehle/Umflutehle, DEST_RG_574	Planned			State government				Hochwassermanagementplan Elbe	High
Clear out river flow cross-section	Green: N05 Stream bed re-naturalisation	Mittlere Elbe/Elde-Ehle/Umflutehle, DEST_RG_574	Planned			State government				Hochwassermanagementplan Elbe	High
Protection/ restoration of flood areas	Green: N02 Floodplain restoration	Mittlere Elbe/Elde-Polstrine, DEST_ RG_5748	Started			State government				Hochwassermanagementplan Elbe	High

Table A5.1 Elbe — existing/planned GI measures (cont.)

Name of measure	Type of measure	Part of strategic approach?	Planned/ implemented	Timing	Location/ extent of measure	By who? Responsible body	Funding	Coordination	Cost-efficiency, benefits calculated/ reported?	Reference	Impact on main city
Clear out river flow cross-section	Green: N05 Stream bed re-naturalisation	Mittlere Elbe/Elde-Polstrine, DEST_RG_5748	Planned			State government				Hochwassermanagementplan Elbe	High
Protection/ restoration of flood areas	Green: N02 Floodplain restoration	Mittlere Elbe/ Elde-Schrote, DEST_RG_5768	Planned			State government				Hochwassermanagementplan Elbe	High
Clear out river flow cross-section	Green: N05 Stream bed re-naturalisation	Mittlere Elbe/ Elde-Schrote, DEST_RG_5768	Planned			State government				Hochwassermanagementplan Elbe	High
Protection/ restoration of flood areas	Green: N02 Floodplain restoration	Mittlere Elbe/Elde-Mulde, DEST_RG_54	Planned			State government				Hochwassermanagementplan Elbe	Medium
Restoration of flood retention areas	Green: N02 Floodplain restoration	Mittlere Elbe/Elde-Mulde, DEST_RG_54	Started			State government				Hochwassermanagementplan Elbe	Medium
Clear out river flow cross-section	Green: N05 Stream bed re-naturalisation	Mittlere Elbe/Elde-Mulde, DEST_RG_54	Planned			State government				Hochwassermanagementplan Elbe	Medium
Restoration and expansion of river flow cross-section	Green: N05 Stream bed re-naturalisation	Mittlere Elbe/Elde-Mulde, DEST_RG_54	Planned			State government				Hochwassermanagementplan Elbe	Medium
Protection/ restoration of flood areas	Green: N02 Floodplain restoration	Mittlere Elbe/ Elde-Rossel, DEST_RG_5398	Planned			State government				Hochwassermanagementplan Elbe	Medium
Restoration of wet areas	N03 Wetland restoration	Mittlere Elbe/ Elde-Rossel, DEST_RG_5398	Planned			State government				Hochwassermanagementplan Elbe	Medium
Removal of barriers	Green: N09 Removal of dams and other longitudinal barriers	Mittlere Elbe/ Elde-Rossel, DEST_RG_5398	Planned			State government				Hochwassermanagementplan Elbe	Medium
Restoration and expansion of river flow cross-section	Green: N05 Stream bed re-naturalisation	Mittlere Elbe/ Elde-Rossel, DEST_RG_5398	Planned			State government				Hochwassermanagementplan Elbe	Medium
Clear out river flow cross-section	Green: N05 Stream bed re-naturalisation	Mittlere Elbe/Elde-Neugraben, DEST_GR_53892	Planned			State government				Hochwassermanagementplan Elbe	Low

Table A5.1 Elbe — existing/planned GI measures (cont.)

Name of measure	Type of measure	Part of strategic approach?	Planned/ implemented	Timing	Location/ extent of measure	By who? Responsible body	Funding	Coordination	Cost-efficiency, benefits calculated/ reported?	Reference	Impact on main city
Removal of barriers	Green: N09 Removal of dams and other longitudinal barriers	Mittlere Elbe/Elde-Schwarze Elster, DEST_RG_538	Planned			State government				Hochwassermanagementplan Elbe	Low
Removal of barriers	Green: N09 Removal of dams and other longitudinal barriers	Mittlere Elbe/Elde-Schwarze Elster, DEST_RG_538	Planned			State government				Hochwassermanagementplan Elbe	Low
Clear out river flow cross -ection	Green: N05 Stream bed re-naturalisation	Mittlere Elbe/Elde-SNL Elbe 2 + Gew1O, DENS_RG_5_2	Finished			State government				Hochwassermanagementplan Elbe	Low
Restoration of flood retention areas	Green: N02 Floodplain restoration	Mittlere Elbe/Elde-Elbe, DEBB_RG_5_1	In progress			State government				Hochwassermanagementplan Elbe	Low
Improvement of water retention infrastructure	Grey measure	Mulde-Elbe-Schwarze Elster — Elbe, DEBB_RG_5_1	Work in progress							Hochwassermanagementplan Elbe	Low
Improvement of water retention infrastructure	Grey measure	Mulde-Elbe-Schwarze Elster — Mulde, DEST_RG_54	Not yet started							Hochwassermanagementplan Elbe	Medium
Maintenance of water retention infrastructure	Grey measure	Mulde-Elbe-Schwarze Elster — SNL Elbe 2 + Gew1O, DESN_RG_5_2	Finished							Hochwassermanagementplan Elbe	Low
Maintenance of water retention infrastructure	Grey measure	Mulde-Elbe-Schwarze Elster — Rossel, DEST_RG_5398	Not yet started							Hochwassermanagementplan Elbe	Medium
Maintenance of water retention infrastructure	Grey measure	Mulde-Elbe-Schwarze Elster — Mulde, DEST_RG_54	Not yet started							Hochwassermanagementplan Elbe	Medium
Maintenance of water retention infrastructure	Grey measure	Mittlere-Elbe/Elde — Ehle/Umflutehle, DEST_RG_574	Not yet started							Hochwassermanagementplan Elbe	High

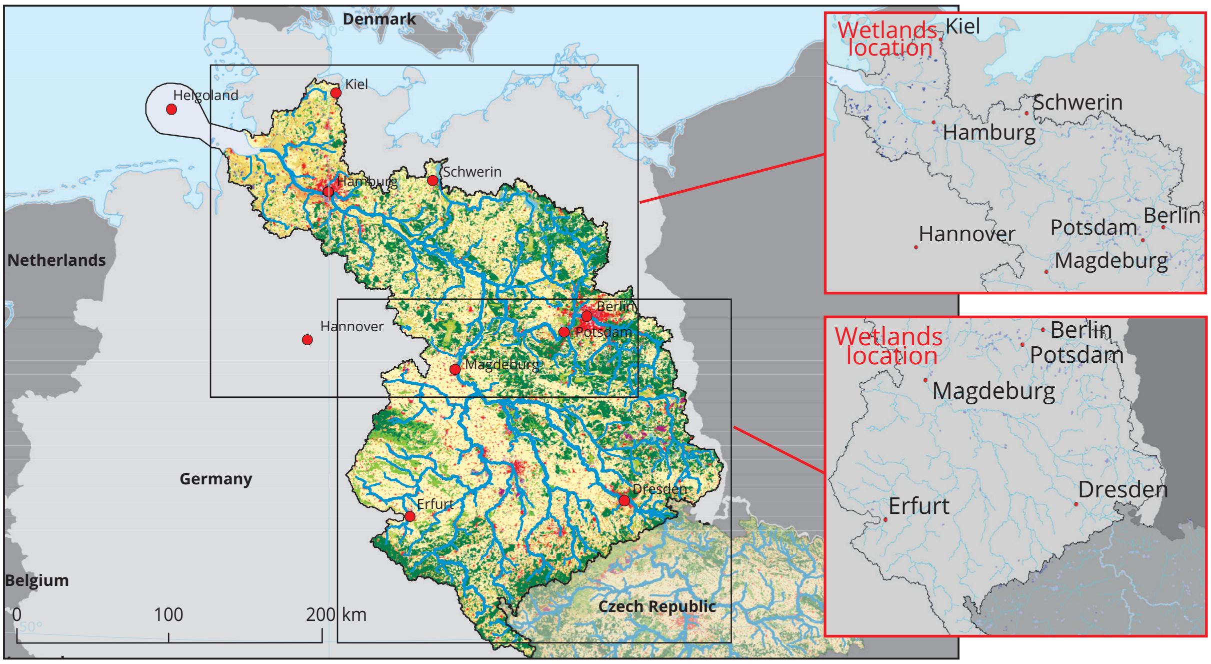
Table A5.1 Elbe — existing/planned GI measures (cont.)

Name of measure	Type of measure	Part of strategic approach?	Planned/ implemented	Timing	Location/ extent of measure	By who? Responsible body	Funding	Coordination	Cost-efficiency, benefits calculated/ reported?	Reference	Impact on main city
Maintenance of water retention infrastructure	Grey measure	Mittlere-Elbe/Elde — Schrote, DEST_ RG_5768	Not yet started							Hochwassermanagementplan Elbe	High
Build water retention infrastructure	Grey measure	Mulde-Elbe-Schwarze Elster — Elbe, DEBB_ RG_5_1	Work in progress							Hochwassermanagementplan Elbe	Low
Build water retention infrastructure	Grey measure	Mulde-Elbe-Schwarze Elster — Elbe, DEBB_ RG_ 5_1	Unknown							Hochwassermanagementplan Elbe	Low
Build water retention infrastructure	Grey measure	Mulde-Elbe-Schwarze Elster — SNL Elbe 2 + Gew1O, DESN_ RG_5_2	Finished							Hochwassermanagementplan Elbe	Low
Build water retention infrastructure	Grey measure	Mulde-Elbe-Schwarze Elster — SNL Elbe 2 + Gew1O, DESN_ RG_5_2	Started							Hochwassermanagementplan Elbe	Low
Build water retention infrastructure	Grey measure	Mulde-Elbe-Schwarze Elster — Schwarze Elster, DEST_RG_538	Not yet started							Hochwassermanagementplan Elbe	Low
Build water retention infrastructure	Grey measure	Mulde-Elbe-Schwarze Elster — Neugraben, DEST_RG_53892	Not yet started							Hochwassermanagementplan Elbe	Low
Build water retention infrastructure	Grey measure	Mulde-Elbe-Schwarze Elster — Mulde, DEST_RG_54	Not yet started							Hochwassermanagementplan Elbe	Medium
Build water retention infrastructure	Grey measure	Mittlere Elbe/Elde — Boner Nuthe, DEST_RG_5724	Not yet started							Hochwassermanagementplan Elbe	High
Maintenance of protection infrastructure	Grey measure	Mulde-Elbe-Schwarze Elster — SNL Elbe 2 + Gew1O, DESN_ RG_5_2	Finished							Hochwassermanagementplan Elbe	Low
Maintenance of protection infrastructure	Grey measure	Mulde-Elbe-Schwarze Elster — SNL Elbe 2 + Gew1O, DESN_ RG_5_2	Started							Hochwassermanagementplan Elbe	Low

Table A5.1 Elbe — existing/planned GI measures (cont.)

Name of measure	Type of measure	Part of strategic approach?	Planned/ implemented	Timing	Location/ extent of measure	By who? Responsible body	Funding	Coordination	Cost-efficiency, benefits calculated/ reported?	Reference	Impact on main city
Maintenance of protection infrastructure	Grey measure	Mulde-Elbe-Schwarze Elster — Schwarze Elster, DEST_RG_538	Not yet started							Hochwassermanagementplan Elbe	Low
Maintenance of protection infrastructure	Grey measure	Mulde-Elbe-Schwarze Elster — Neugraben, DEST_RG_53892	Not yet started							Hochwassermanagementplan Elbe	Low
Maintenance of protection infrastructure	Grey measure	Mulde-Elbe-Schwarze Elster — Mulde, DEST_RG_54	Not yet started							Hochwassermanagementplan Elbe	Medium
Maintenance of protection infrastructure	Grey measure	Mittlere Elbe/Elde — Elbumflut, DEST_RG_5746	Not yet started							Hochwassermanagementplan Elbe	High

Map A5.4 Land use in the German Elbe basin (2006)



Landuse in the German Elbe basin

- Cities
- Elbe basin in Czech Republic and Austria

Artificial surfaces

Urban fabric
- Continuous urban fabric
- Discontinuos urban fabric

Industrial, commercial and transport units
- Industrial or commercial units
- Roas and rail networks and associated land
- Port areas
- Airports

Mine, dump and construction sites
- Mineral extraction sites
- Dump sites
- Construction sites

Artificial, non-agricultural vegetated areas
- Green urban areas
- Sport and leisure facilities

- Outside coverage

Forests and semi natural areas

Forests
- Broad-leaved forest
- Coniferous forest
- Mixed forest

Scrub and/or herbaceous vegetation associations
- Natural grasslands
- Moors and heathland
- Transitional woodlands-shrub

Open spaces with little or no vegetation
- Beaches, dunes, sands
- Sparsely vegetated areas

Wetlands

Inland wetlands
- Inland marshes
- Peat bogs

Maritime wetlands
- Salt marshes
- Intertidal flats

Agricultural areas

Arable land
- Non-irrigated arable land

Permanent crops
- Vineyards
- Fruit trees and berry plantations

Pastures
- Pastures

Heterogeneous agricultural areas
- Complex cultivation patterns
- Land principally occupied by agriculture, with significant areas of natural vegetation

Water bodies

Inland waters
- Water courses
- Water bodies

Marine waters
- Estuaries
- Sea and ocean

Source: Trinomics, based on preliminary flood risk assessment and EEA Corine 2006 land use data.

Reality check

The mid-term review for the Elbe river basin (submitted in 2012) provides an overview of progress towards the implementation of the 2009 RBMP and other related EU water regulation. As can be seen in Figure A5.1, for the entire river basin, about 20 % of measures have been completed, 10 % have been started, 40 % are under implementation and the remaining 30 % have not yet been started. With respect to GI and flood management in particular, measures falling under the category of 'improvement of river flow' (*Längsdurchgängigkeit*) and the 'improvement of water circulation' (*Gewässerstruktur*) involve relevant measures. For these two types of key measures, about 20 % of measures have been completed, about 35 % have not yet been started, and 45 % are currently being implemented. In the PoM implementation report, published in 2015, it is stated that authorities in the Elbe river basin have not yet started 7 % of supplementary measures, indicating that further progress was made between the 2012 mid-term review and 2015.

Figure A5.1 depicts the level of implementation for measures on river flow in more detail. As can be seen from the figure, a few measures fall within the defined case study area (also listed in the measures catalogue above).

The mid-term review does not provide any conclusions on whether or not this is considered good progress. However, given the fact that well over 50 % of the total measures have either been completed or are ongoing, progress is being made towards the implementation of measures. However, it is concluded for some RBDs in Germany (including the Elbe) that ambitions were too high and that it was unrealistic to finish planning and implementing measures by 2015.

Actions in the plans for the Elbe include:

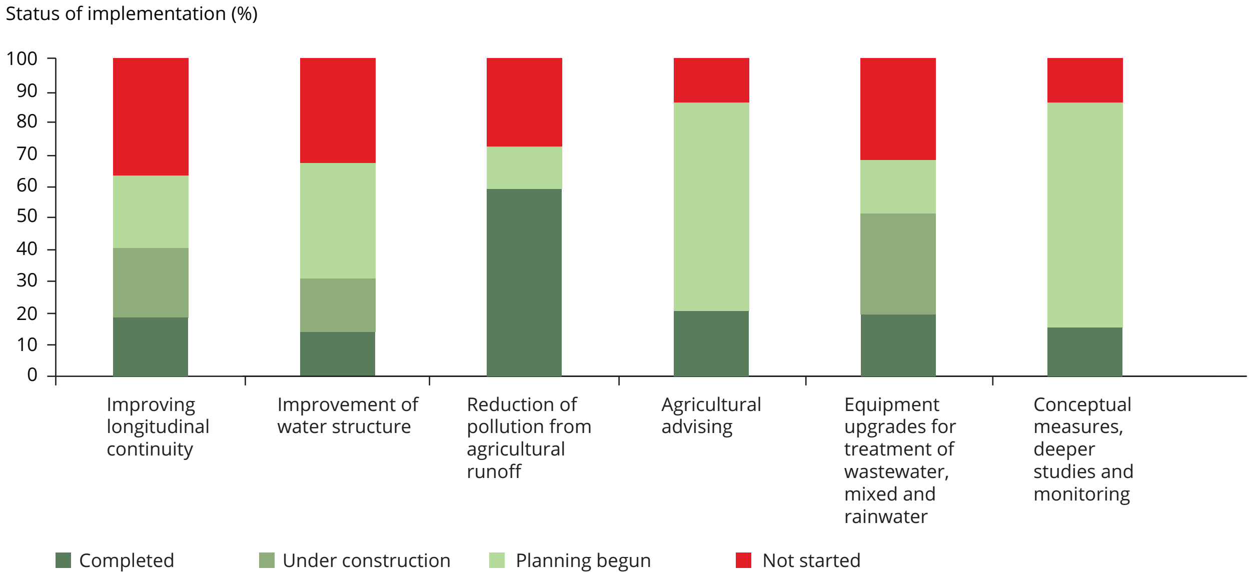
- restoration and protection of flood areas, including morphological alterations to improve hydraulic conditions (most actions);
- restoration of wetlands; and
- removal or setback of levees.

Overview of current coordination between upstream and downstream areas

International coordination

The river basin of the Elbe extends over several EU Member States, namely Austria, the Czech Republic, Germany and Poland. These countries have agreed to coordinate all activities and responsibilities stemming from the EU's Floods Directive under one common coordination group, IKSE. IKSE is responsible for coordination on an international level, while each national authority (Austria, the Czech Republic, Germany and Poland) feeds into this international cooperation structure (IKSE, 2016)

Figure A5.1 Status of implementation of the listed key measures for FGG Elbe



Source: Mid-term assessment of river basin management plan implementation on the Elbe (2012).

Coordination between RBMP and FRMP

All measures are coordinated under the 'LAWA' catalogue of measures which is jointly developed and managed by relevant national and regional authorities under a jointly established management umbrella organisation, 'FGG Elbe'. Urgency of measures, synergies and timing are cross-checked between the two plans.

FGG Elbe works closely with IKSE. The content discussions and coordination of measures take place in the working group on flood protection.

Other relevant EU policies are also taken into account, e.g. all regulation falling under the European WFD, such as the Drinking Water Directive. In addition, the EU Guidelines on Environmental Impact Assessment for public and private projects, plans and programmes (2011/92/EU and 2001/42/EG), as well as SEVESO-III (2012/18/EU) are taken into account in all measures carried out under FGG Elbe.

Several synergistic measures have been identified between the FRMP and RBMP, including the protection of natural floodplains from construction, as well as the improvement of natural water retention. Potentially conflicting results as regards goals within the RBMP and FRMP relate to technical infrastructure measures for flood protection preventing a more natural development of the river.

Rhône, France

Identification of flood risk

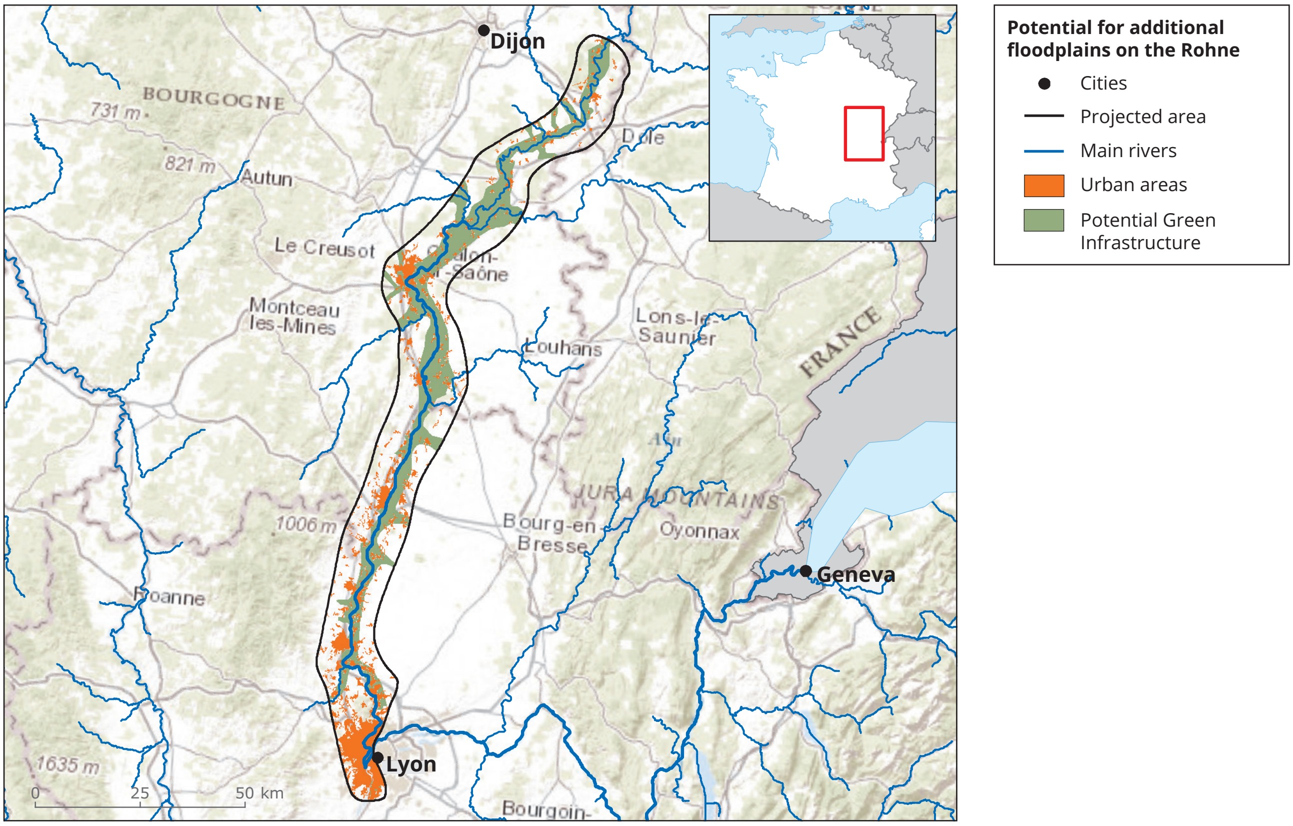
The Rhône-Méditerranée basin is located in southern France, comprises approximately one quarter of France's territory (127 000 km^2) and is home to approximately one quarter of its population (14.8 million in 2008), therefore having a population density close to the national average (Ministère de l'Écologie, 2011a). However, this population is not evenly distributed in the territory, and many locations with important human occupation face serious risk of natural disasters. The region also contains three major cities: Grenoble, Annecy and Lyon. This study will focus on Lyon, and the areas of interest will be those around Lyon (e.g. the rivers Azergues, Brévenne, Garon).

Vulnerability of main cities

Around 1.5 million people live in the area of significant flood risk around Lyon (*Territoire à Risque Important*), with 570 000 (38 %) living in very high risk zones. Lyon is the third largest French city, representing an important urban and economic centre. Around 50 % of jobs in Lyon are located in areas of significant flood risk (Ministère de l'Écologie, 2012). The area is important for its industrial activity in the urban agglomeration around Lyon and also for its agricultural activities. In the north-west of the Rhône-Moyen, on the Beaujolais, there is an important wine producing area. Together with the risks associated with the dense demographic occupation of the area, the plains located to the east of Lyon are perceived as being particularly vulnerable to river floods (Direction Régionale de l'Environnement, de l'Aménagement et du Logement Rhône Alpes, 2014).

The region around Lyon can be affected by three kinds of floods: pluvial flooding from excessive run-off water, slow fluvial floods of the Rhône, Saône and affluent rivers (Gier, Garon, Yzeron, Azergues, etc.) and rising groundwater (*remontée de nappe phréatique*). Groundwater flooding, a phenomenon more common in the urban areas of Lyon, is associated with floods on the Rhône. In the 1990s, six major floods in the Rhône and Saône affected the region of Lyon, causing economic damage and interruption of activities. Cars and parking lots have been the most frequent assets affected by recent floods in Lyon (Préfecture du Rhône, 2009). Important recent floods occurred in affluent rivers of the Rhône in 2003 (mainly the River Gier), 2005 and 2008 (mainly the Brévenne and Turdinne) (Direction Régionale de l'Environnement, de l'Aménagement et du Logement Rhône Alpes, 2014), with the floods of 2003 and 2008 causing significant damage to economic activity and infrastructure (Ministère de l'Écologie, 2011b).

Map A5.5 Rhône river basin district — case study selection



Source: Arcadis.

Management plans and status of implementation

Map A5.6 (and corresponding Table A5.2) depict the GI measures already implemented and/or planned in the selected case study area of the Rhône river basin. The sources of the measures listed below are the draft second RBMP (*Projet de SDAGE*) (Comité de Bassin Rhône-Méditerranée, 2014).

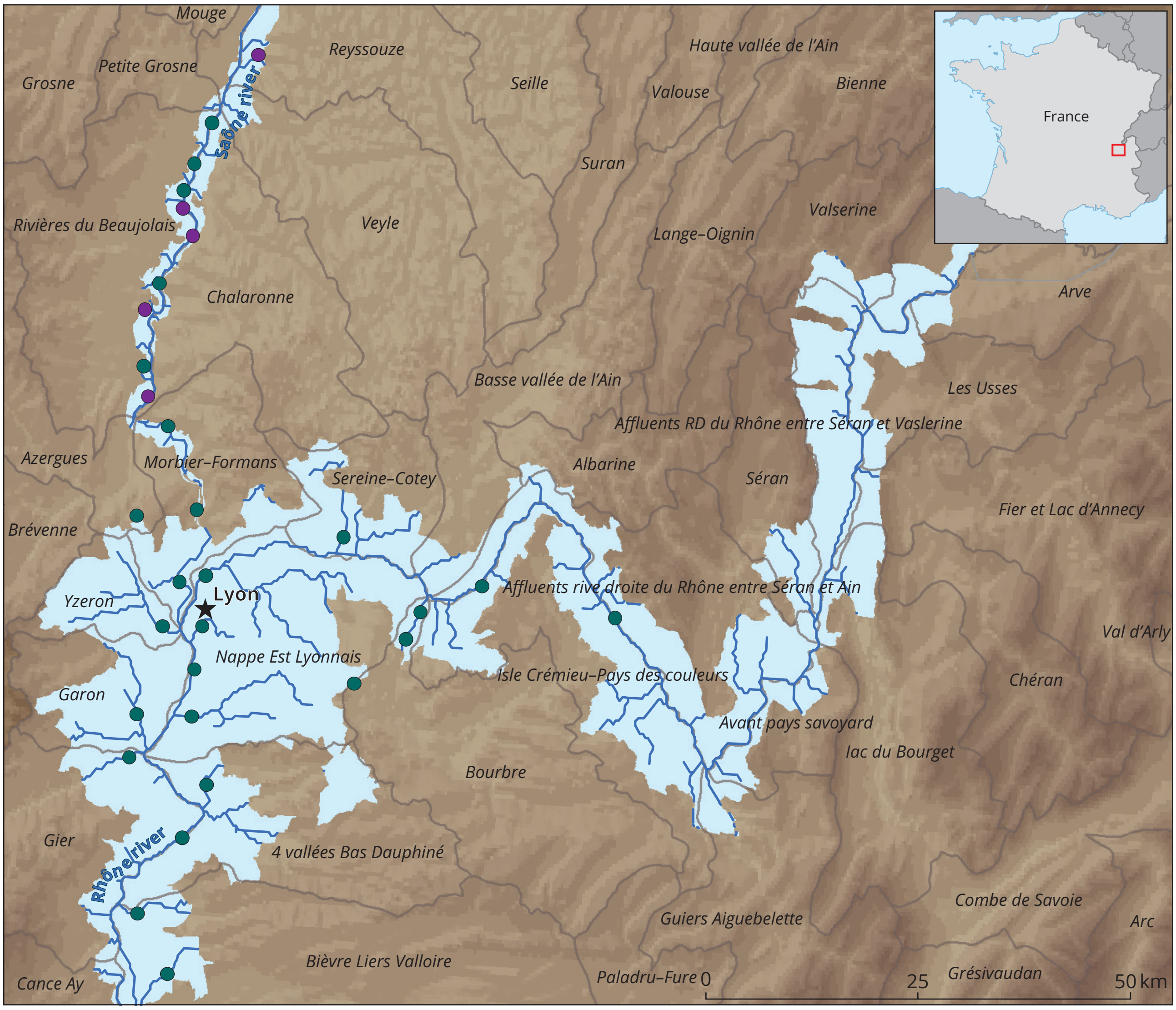
Summary of the consideration of land use and soil management in relation to flood risk management

In the FRMP for the Grand Lyon (region around Lyon), authorities were called to divide the areas into 'blue' areas and 'red' areas. The latter represent those areas with high risk of flooding, on which nothing could be built. These areas should be used to allow the natural expansion of floods without having a negative impact on human activity. There are three types of red area, with different levels of restrictions. The blue areas represent those areas with minor flood risks, but which still require some adaptability measures. There are two types of blue areas. This division of the areas as defined in the FRMP must be incorporated into the local urbanism plan (*Plan Local d'Urbanisme*) and the soil occupation plan (*Plan d'Occupation du Sol*) of each district.

Reality check

According to data available on the RBMP 2009 website (EauFrance, 2015), projects related to hydromorphological alterations in the Rhône-Moyen (among which are most of the GI projects listed) cost a total of EUR 10.6 million over 2010–2015, of which around half went to projects in the Gier area (RM_08_08). A mid-term assessment of the projects planned in the 2009 RBMP was performed in 2012 (Comité de Bassin Rhône-Méditerranée, 2012). According to this evaluation, there were 41 actions in the Rhône-Moyen related to restoring hydromorphological features and sedimentary transport. By 2012, around two thirds of these works had not been initiated, and three had been completed. In general, actions taken on hydromorphology and sediment transport went slowly in the Rhône-Moyen, due to the high complexity of these operations (Commission Territoriale Rhône-Moyen, 2012).

Map A5.6 **Locations of planned and implemented flood management measures near Lyon, France**



Locations of Planned and Implemented Flood Management Measures near Lyon

- ★ Cities
- Implemented measures
- Planned measures
- Rhône and Saône rivers
- Floodplain

Note:
Locations of implemented and planned measures are estimates based on number of measures per municipality or watershed, respectively, from National draft RBMP (Project de SDAGE).

Source: Trinomics, based on floodplain and watershed data from CARMEN, 2015 and Projet de SDAGE.

Table A5.2 Rhône — existing/planned GI measures

Name of measure	Type of measure	Part of strategic approach?	Planned/ implemented	Timing	Location/ extent of measure	By who? Responsible body	Funding (EUR)	Coordination	Cost-efficiency, benefits calculated/ reported?	Reference	Probable impact in the main city (Lyon)
Restoration of floodplain at Dracé	Green: N02 Floodplain restoration	Saône-aval, Moyen, Rivières du Beaujolais, RM_08_12	Implemented	2004-2005	Local	Commune de Dracé	125 000			PAPI Saône	Low
Restoration of floodplain at Taponas	Green: N02 Floodplain restoration	Saône-aval, Moyen, Rivières du Beaujolais, RM_08_12	Implemented	2004-2005	Local	Commune de Taponas	125 000			PAPI Saône	Low
Restoration of floodplain at Saint Georges de Reneins	Green: N02 Floodplain restoration	Saône-aval, Moyen, Rivières du Beaujolais, RM_08_12	Implemented	2004-2005	Local	Commune de Saint Georges de Reneins	170 000			PAPI Saône	Low
Restoration of floodplain at Sermoyer à Feillens	Green: N02 Floodplain restoration	Saône-aval , Moyen, Rivières du Beaujolais, RM_08_12	Implemented	2005-2006	Local	Sybdicat des digues de Pont de Vaux à Feillens	624 500			PAPI Saône	Low
Restoration of floodplain at Anse, Pommier, Limas	Green: N02 Floodplain restoration	Saône-aval, Moyen, Rivières du Beaujolais, RM_08_12	Implemented	2005-2006	Local	Syndicat des praiories ou collectivités	180 000			PAPI Saône	Low
Restore the course of a river	Green: N04 Re-meandering	Rhône-Moyen, 4 vallées Bas Dauphiné, RM_08_01	Planned	2016-2021	Local					Projet de SDAGE- Rhône-Méditerranée	None (downstream of Lyon)
Restore a wet zone	Green: N02 Wetland restoration	Rhône-Moyen, 4 vallées Bas Dauphiné, RM_08_01	Planned	2016-2021	Local					Projet de SDAGE- Rhône-Méditerranée	None (downstream of Lyon)
Restore the course of a river	Green: N04 Re-meandering	Rhône-Moyen, Azergues, RM_08_02	Planned	2016-2021	Local					Projet de SDAGE- Rhône-Méditerranée	Low
Restore the course of a river	Green: N04 Re-meandering	Rhône-Moyen, Bièvre Liers Valloire, RM_08_03	Planned	2016-2021	Local					Projet de SDAGE- Rhône-Méditerranée	None (downstream of Lyon)
Restore the sedimentary balance and the long profile of a river	Green: N05 Stream bed re-naturalisation	Rhône-Moyen, Bièvre Liers Valloire, RM_08_03	Planned	2016-2021	Local					Projet de SDAGE- Rhône-Méditerranée	None (downstream of Lyon)
Restore the course of a river	Green: N04 Re-meandering	Rhône-Moyen, Bourbre, RM_08_04	Planned	2016-2021	Local					Projet de SDAGE- Rhône-Méditerranée	Low

Table A5.2 Rhône — existing/planned GI measures (cont.)

Name of measure	Type of measure	Part of strategic approach?	Planned/ implemented	Timing	Location/ extent of measure	By who? Responsible body	Funding (EUR)	Coordination	Cost-efficiency, benefits calculated/ reported?	Reference	Probable impact in the main city (Lyon)
Large-scale restoration of the functionalities of a river and its tributaries	Green: various	Rhône-Moyen, Bourbre, RM_08_04	Planned	2016-2021	Local					Projet de SDAGE- Rhône-Méditerranée	Low
Restore a wet zone	Green: N02 Wetland restoration	Rhône-Moyen, Bourbre, RM_08_04	Planned	2016-2021	Local					Projet de SDAGE- Rhône-Méditerranée	Low
Restore the course of a river	Green: N04 Re-meandering	Rhône-Moyen, Brévenne, RM_08_05	Planned	2016-2021	Local					Projet de SDAGE- Rhône-Méditerranée	Medium
Restore the course of a river	Green: N04 Re-meandering	Rhône-Moyen, Garon, RM_08_07	Planned	2016-2021	Local					Projet de SDAGE- Rhône-Méditerranée	None (downstream of Lyon)
Restore the course of a river	Green: N04 Re-meandering	Rhône-Moyen, Gier, RM_08_08	Planned	2016-2021	Local					Projet de SDAGE- Rhône-Méditerranée	None (downstream of Lyon)
Restore the course of a river	Green: N04 Re-meandering	Rhône-Moyen, Isle Crémieu- Pays des couleurs, RM_08_09	Planned	2016-2021	Local					Projet de SDAGE- Rhône-Méditerranée	Medium
Restore a wet zone	Green: N02 Wetland restoration	Rhône-Moyen, Isle Crémieu- Pays des couleurs, RM_08_09	Planned	2016-2021	Local					Projet de SDAGE- Rhône-Méditerranée	Medium
Restore the course of a river	Green: N04 Re-meandering	Rhône-Moyen, Morbier — Formans, RM_08_10	Planned	2016-2021	Local					Projet de SDAGE- Rhône-Méditerranée	High
Restore the sedimentary balance and the long profile of a river	Green: N05 Stream bed re-naturalisation	Rhône-Moyen, Morbier — Formans, RM_08_10	Planned	2016-2021	Local					Projet de SDAGE- Rhône-Méditerranée	High
Restore a wet zone	Green: N02 Wetland restoration	Rhône-Moyen, Morbier — Formans, RM_08_10	Planned	2016-2021	Local					Projet de SDAGE- Rhône-Méditerranée	High
Restore the course of a river	Green: N04 Re-meandering	Rhône-Moyen, Rivières du Beaujolais, RM_08_12	Planned	2016-2021	Local					Projet de SDAGE- Rhône-Méditerranée	Low
Restore the course of a river	Green: N04 Re-meandering	Rhône-Moyen, Sereine — Cotey, RM_08_13	Planned	2016-2021	Local					Projet de SDAGE- Rhône-Méditerranée	Medium

Table A5.2 Rhône — existing/planned GI measures (cont.)

Name of measure	Type of measure	Part of strategic approach?	Planned/ implemented	Timing	Location/ extent of measure	By who? Responsible body	Funding (EUR)	Coordination	Cost-efficiency, benefits calculated/ reported?	Reference	Probable impact in the main city (Lyon)
Restore the course of a river	Green: N04 Re-meandering	Rhône-Moyen, Territoire Est Lyonnais, RM_08_11	Planned	2016-2021	Local					Projet de SDAGE- Rhône-Méditerranée	High
Large-scale restoration of the functionalities of a river and its tributaries	Green: Various	Rhône-Moyen, Territoire Est Lyonnais, RM_08_11	Planned	2016-2021	Local					Projet de SDAGE- Rhône-Méditerranée	High
Restoration of a water surface	Green: N12 Lake restoration	Rhône-Moyen, Territoire Est Lyonnais, RM_08_11	Planned	2016-2021	Local					Projet de SDAGE- Rhône-Méditerranée	High
Restoration of a wet zone	Green: N02 Wetland restoration	Rhône-Moyen, Territoire Est Lyonnais, RM_08_11	Planned	2016-2021	Local					Projet de SDAGE- Rhône-Méditerranée	High

Actions in the management plan for the Rhône around Lyon include:

- restoration of the floodplain at various locations;
- restoration along the course of the river;
- restoration of a wet zone;
- restoration of the sediment balance and the profile of the river; and
- large-scale restoration of the functionalities of the river and its tributaries.

Overview of current coordination between upstream and downstream areas

Coordination of RBMP and FRMP and other policies

The Floods Directive was transposed into French law in 2010 ([45]). It integrated existing tools for risk prevention, namely the Prevention Plan for Natural Risks (*Plans de Prévention des Risques Naturels*) and the Local Protection Plan (*Plan Communal de Sauvegard*), into the floods instruments, namely the PFRA, the division of territory in areas of significant flood risk and the elaboration of FRMPs. The FRMPs are designed for each hydrographical district, and they are harmonised nationally by the National Flood Risk Management Strategy (*Stratégie National de Gestion des Risques d'Inondation*), a French innovation (Beaufils, 2014).

The FRMP explicitly derogates the dispositions in the RBMP regarding flood prevention. Under the French system, public authorities have to design Schemes for Territorial Coherence, which take into account various kinds of risks. Since the FRMP was designed, the Schemes for Territorial Coherence are not obliged to seek compatibility with the RBMP ([46]).

This legal rule is to some extent merely precautionary, for the FRMP deals with a degree of detail that is not seen in the RBMP. The FRMP is more specific in themes such as use of territory, vulnerability of buildings, territory resilience and awareness raising on flood risks. The clearest synergies in the two management plans occur in the interaction between flood prevention and water management.

International coordination

The FRMP for the basin Rhône-Méditerranée requires international coordination with four countries: Italy, Monaco, Spain and Switzerland. The Monegasque authorities are concerned with one specific aspect of the plan in the coastal region of Provence-Alpes-Côte d'Azur. The region of interest in this case study, Lyon, is not concerned with any of these international coordination arrangements. Since the source of the Rhône is located in Switzerland, the themes in common with this country are the ones that require more attention for international policy coordination.

In principle, it would be possible to create an international RBD with a single policy framework. However, this was not possible because Switzerland is not an EU Member, thus not subject to the Floods Directive. Coordination with this country occurs at a site-specific level and takes place in the area of significant flood risk of Belfort-Montbéliard and Annemasse-Cluses. No international commission has been created between France and Switzerland for the implementation of the Floods Directive and management of French-Swiss floods.

As for Spain, a French-Spanish cooperation agreement was signed in 2006 for the implementation of the WFD. Under this agreement, French and Spanish authorities are commonly involved in the implementation of RBMPs. No specific arrangement was settled for the implementation of FRMPs. In Italy, an intentions protocol was signed in 2013 for cooperation on the River Roya, but no agreement was signed.

([45]) Law 2010-788 of 12 July 2010.

([46]) Direction Régionale de l'Environnement, de l'Aménagement et du Logement Rhône Alpes (2014). 'Dès lors, une fois le PGRI approuvé, en dérogation à l'article L.111-1-1 du code de l'urbanisme, les SCOT n'auront plus à être compatibles avec les orientations fondamentales du SDAGE relatives à la prévention des inondations' (p. 12).

Scheldt, Belgium

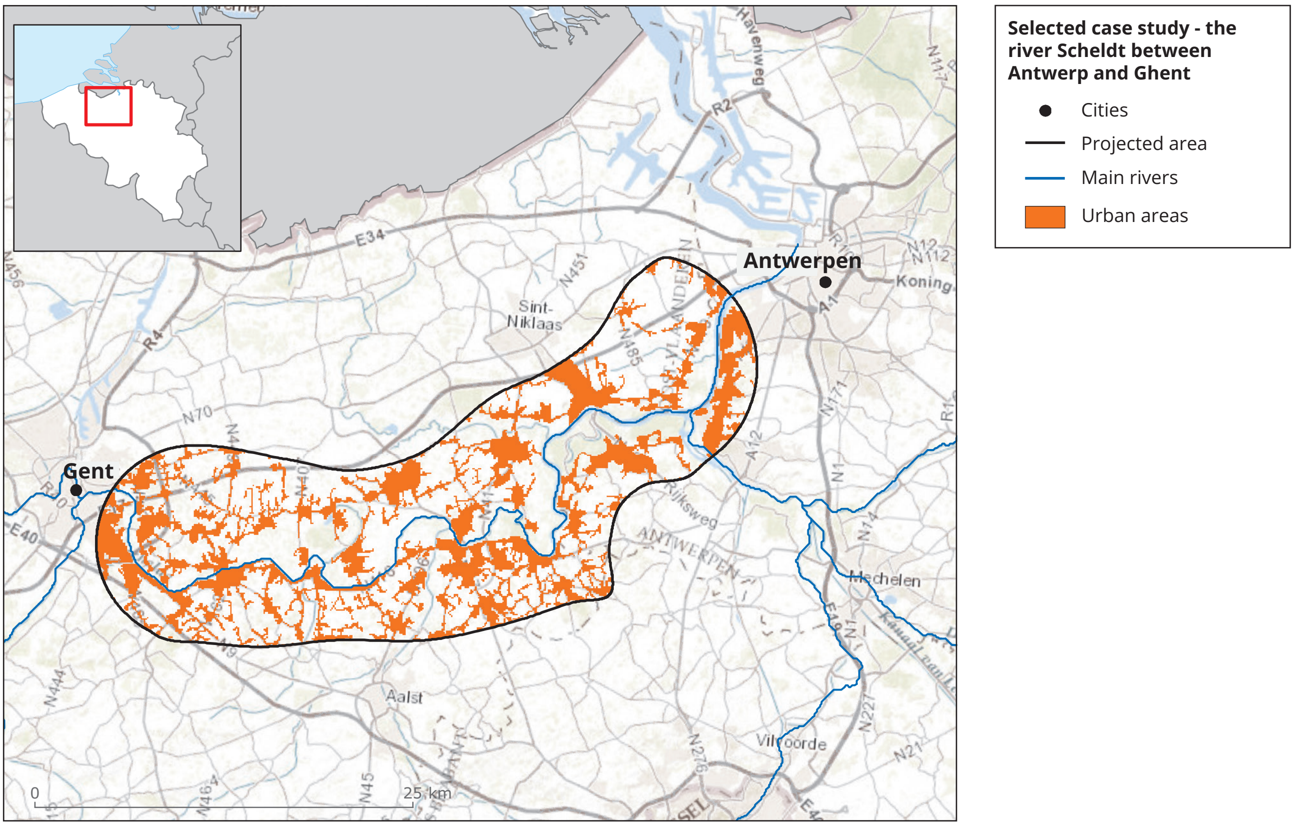
Identification of flood risk

The Scheldt estuary extends from the upper reaches near Ghent in Belgium to the lower reaches and the mouth at Vlissingen in the Netherlands. In its Belgian part, called Zeeschelde, the estuary is a single meandering channel, with intertidal areas at the inner part of bends, but without intertidal islands. The study area considered here is the Belgian part of the estuary, running through the major city of Antwerp and reaching up to Ghent.

The estuary is of economic importance as a major shipping artery, hosting the harbour of Antwerp. This area includes the city of Antwerp, with a current population of around 0.5 million. The 1976 flood in Flanders triggered the Belgian Sigmaplan, which used the same design level of 1:10 000 each year as that of the Dutch Delta Project. Flooding incidents during 1993-1994 prompted an emergency plan for flood management, which initially called for an accelerated execution of the ongoing Sigmaplan. But soon it became clear that the original form of the Sigmaplan could not meet the multiple objectives of integrated water management that became the new paradigm. This resulted in a new Sigmaplan taking an explicit risk approach using risk maps. It should also be noted that the average tidal amplitude of the river has increased significantly during the past century (56 cm in Antwerp). These changes are largely due to human interventions affecting the flow of water in the Scheldt. Changes include the diverting of water to feed into canals, the removal of river meanders by straightening the river and increasing the depth of shipping channels. These changes exacerbate the impacts from climate change (FLOODsite, 2006).

This study will focus on the implementation of Sigmaplan in a specific area of the Scheldt RBD (between the Dutch border and Ghent, on the main river section), with a specific focus on ongoing GI measures to protect Antwerp and its downstream area.

Map A5.7 Scheldt river basin district — selected case study



Source: Arcadis.

Vulnerability of main cities

The Beneden-Zeescheldt area is considered a 'pluvial river'. The flow varies significantly over the year. During winter months, a very high flow can occur. The average yearly flow downstream of Antwerp is around 100 m^3 per second. In periods of extreme precipitation, this can be six times as high. The increasing population of the city and consequently of hard surface in the area causes a shortened period of downstream transport of water and, as such, high peak flows. The effect is highest in the tributaries of the Scheldt. The more downstream, the smaller the contribution of these flows to the river level, as there is a tidal current that determines the level of the Zeeschelde, Rupel and Durme.

Historically, there have been major floods. For that reason, several measures have been taken, and large works have been carried out through the Sigmaplan. These are:

- development of CFAs or flood retention basins;
- building of weirs and pumping stations; and
- building of dikes.

The Scheldt river basin is an international river basin going through the Netherlands, Belgium and France. In Belgium, it covers the Walloon, Brussels and Flanders regions. There are already CFAs installed and planned through **Sigmaplan between Antwerp and Ghent**; see map below (2010–2050).

As reported through the RBMP and FRMP, in the Beneden-Scheldt (border with Netherlands upstream towards the city of Ghent), 1 100 people would potentially be affected by floods with a high degree of probability, and 3 900 by floods with a medium to high degree of probability. For floods with a low degree of probability, 48 000 people would potentially be affected. This is because of the consequences of rare flood events in the very densely populated area of Antwerp.

Management plans and status of implementation (47)

Sigmaplan is a project in Flanders intended to make the Scheldt river basin more flood resilient. Its competent authority is the Flemish government. Sigmaplan is coordinated by De Vlaamse Waterweg, which is the waterway administrator for the western and central parts of Flanders. W&Z (Waterwegen en Zeekanaal NV), the main implementing body, works in close cooperation with the Agency for Nature and Forest (*Agentschap voor Natuur en Bos*) on the nature-related parts of the project. Other partners, such as Vlaamse Landmaatschappij, Departement Ruimtelijke Ordening (Departement Omgeving) and Woonbeleid en Onroerend Erfgoed, are also consulted based on their expertise. The initial Sigmaplan was launched in 1977. It was based on the *Ontwikkelingsschets 2010* (Development Draft for 2010), which was approved by both the Flemish and Dutch governments. The revised Sigmaplan was approved by the Flemish government in 2005. The first projects commenced in 2010, with new projects starting every 5 years. For all five of the Sigmaplan clusters, work has now started. These are Hedwige-Prosperpolder, Kalkense Meersen, Vlassenbroek, Wal-Zwijn and Dijlemonding en Durmevallei. The execution of the complete plan is intended to be completed in 2030.

The main objectives of the updated Sigmaplan are: to protect the land bordering the Scheldt river and its tributaries such as the Rupel, the Nete and the Durme from storm surges and river flooding; and to help Belgium meet its EU obligations for nature protection. The following information has been summarised by the main leading and implementing body W&Z to include this information on the Climate-ADAPT website, which is a joint initiative between the European Commission and the EEA.

Solutions

While the Sigmaplan's main purpose is flood control, it is based on an integrative perspective on river management that acknowledges various river functions and their importance for society. These include shipping, nature development, landscape values, cleansing functions, fish nurseries and more. Sigmaplan was originally conceived in 1977 with flood control as its main purpose; since then, perspectives on water management have evolved. An updated Sigmaplan was adopted in 2005. It was based on three main pillars: flood protection, access to the Scheldt ports and a natural functioning of the physical and ecological system.

The original Sigmaplan called for dikes stretching a total length of 512 km to be raised and strengthened, the establishment of 13 CFAs covering a total of 1 133 ha, and the construction of a storm surge barrier. Plans for the storm surge barrier were later suspended after

(47) The information for this subsection is available in the Climate-ADAPT and SIGMA brochures, and reports at http://www.sigmaplan.be

analysis showed that the benefits did not outweigh the costs. The realisation that the storm surge barrier was prohibitively expensive, together with an increased demand for a healthier river ecosystem, led to greater application of a concept called 'room for the river'. The revision also took into account projected climate change impacts. The revised plan gives a greater role to CFAs and de-poldered areas that counter storm surges by temporarily storing excess water.

CFAs have low dikes, called overflow dikes, along the river, and higher dikes on the inland side to maintain flood protection: the overflow dikes allow water to flood during storm surges; after high water levels have receded, drainage outlets allow water to exit. The CFAs help attenuate the impacts of flooding events by increasing the river catchment area, thus reducing upstream water levels. The volume of many CFAs has increased, as their ground levels are below the average water level due to historical compacting of the soil and loss of natural sedimentation processes. These low ground levels, however, mean that overflow dikes and artificial water regulation are needed. The predominant use for land within CFAs has been as natural areas that contribute to achieving conservation objectives and improving water quality. Under EU nature legislation — in particular, requirements to compensate for the loss of natural areas taken by the expansion of the Port of Antwerp — the total area set aside as flooding areas was increased for the purpose of nature development: by 2030, a total of 2 458 ha will have been created. Another 656 ha have been indicated as possible future flood zones to be constructed after 2030, if necessary, to guarantee flood safety beyond 2050.

Some CFAs also include controlled tidal areas, where a regular, reduced tide is produced through an adjustable weir system in the overflow dike. During high tide, water from the Scheldt flows into the area through a weir, and during low tide it flows out through a low weir. The controlled tidal areas allow for the creation of tidal habitats while maintaining the CFA's functions.

Other Sigmaplan projects consist of de-poldering areas, where dike protection is moved inland, once again exposing a former polder (land reclaimed from the water) to tidal influences. De-poldered areas provide room for river water during high water levels, and thus they, like the CFAs, attenuate storm surge levels. They also provide room for estuarine nature.

The updated Sigmaplan also calls for raising an additional 24 km of dikes and increasing the land set aside solely for flood protection to 1 523 ha (390 ha more than in the original plan).

Table A5.3 Scheldt — existing/planned GI measures

Name of measure	Type of measure	Part of strategic approach?	Planned/ implemented	Timing	Location/ extent of measure (in hectares)	Funding (EUR)	Coordination	Cost-efficiency, benefits calculated/ reported?	Reference
Sigmaplan		Sigmaplan	Ongoing			Annual amount for investment of 50 million Total costs (2005 to 2030) are estimated at 830 million + 40 million for supporting measures (Source: http://www.vlaanderen.be/nl/vlaamse-overheid/persberichten/goedkeuring-geactualiseerd-sigmaplan)	Coordinator Sigmaplan: Waterwegbeheer Waterwegen & Zeekanaal (W&Z) Samenwerking met Agentschap voor Natuur en Bos Inbreng expertise vanuit diverse partners, zoals Vlaamse Landmaatschappij, Departement Ruimtelijke Ordening, Woonbeleid en Onroerend Erfgoed	Costs and benefits taken into account: Execution costs Safety benefits (avoided costs and avoided risks) Effects on agriculture Effects on forestry Effects on shipping Ecosystem benefits Recreational benefits Visual hindrance for surrounding community	Syntheserapport 4024-060-10
Potpolder of Lillo	Green: N02N02 Wetland restoration and management/ *Afwerkte dijkwerken*	Sigmaplan	Implemented	2010	17,03 ha				
Fort Filip 1	Grey measure: *Afwerkte dijkwerken*	Sigmaplan	Implemented	2015	11,66 ha				
Fort Filip 2	Grey measure: *Afwerkte dijkwerken*	Sigmaplan	Implemented	2015	31,27 ha				
Grensgebied ('border area')				2020	15,38 ha				
Cluster Durme en haar vallei	Green: N03 Floodplain restoration and management Green: N14 Re-naturalisation of polder areas	Sigmaplan, changed in 2000: 3 additional floodplains instead of storm surge barrier				100 million for realisation of 3 floodplains			
Potpolder IV				2020	43,03 ha				
Potpolder IV				2020	7,87 ha				
Potpolder IV				2020	26,06 ha				
Potpolder V				2020	39,6 ha				
Bulbierbroek	Green: N02 Wetland restoration and management	Sigmaplan	Implemented	2010	19,14 ha				
Polder van Waasmunster				2020	10,55 ha				

Table A5.3 Scheldt — existing/planned GI measures (cont.)

Name of measure	Type of measure	Part of strategic approach?	Planned/ implemented	Timing	Location/ extent of measure (in hectares)	Funding (EUR)	Coordination	Cost-efficiency, benefits calculated/ reported?	Reference
Weijmeerbroek	Green: N02 Wetland restoration and management	Sigmaplan	Implemented	2010	50,52 ha				
Klein Broek	Green: N14 Re-naturalisation of polder areas	Sigmaplan	Ongoing	2010	32,78 ha				
Groot Broek	Grey measure: *Dijkwerken & inrichting van het binnengebied*	Sigmaplan	Ongoing	2010	64,24 ha		Agreement for cooperation between the municipality of Temse and W&Z on a new Speelbos (play wood) in 2014, to replace the playground that will be lost as a result of the creation of a floodplain		
Hof ten Rijen	Green: N02 Wetland restoration and management	Sigmaplan	Not specified	2020	26,37 ha				
Zuidelijke Vijver Hof ten Rijen				2010	11,97 ha				
Nonnengoed				2015	5,5 ha				
Oude durme				2020	32,71 ha				
Putten van Ham				2025	65,1 ha				
Potpolder I				2020	82,34 ha				
Hagemeersen	Green: N02 Wetland restoration and management	Sigmaplan	Not specified	2010	11,53 ha				
De Bunt	Green: N03 Floodplain restoration and management/ *Aanleg gecontroleerd overstromingsgebied*	Sigmaplan	Not specified	2010	99,37 ha				
Zennegat	Green: N03 Floodplain restoration and management/ *Aanleg gecontroleerd overstromingsgebied*	Sigmaplan	Ongoing	2010	61,85 ha				

Table A5.3 Scheldt — existing/planned GI measures (cont.)

Name of measure	Type of measure	Part of strategic approach?	Planned/ implemented	Timing	Location/ extent of measure (in hectares)	Funding (EUR)	Coordination	Cost-efficiency, benefits calculated/ reported?	Reference
Heindonk - Tien Vierendelen, deel 1	Green: N03 Floodplain restoration and management/ *Aanleg gecontroleerd overstromingsgebied*	Sigmaplan	Not specified	2010	37,29 ha				
Grote Vijver, deel 1	Green: N03 Floodplain restoration and management/ *Aanleg gecontroleerd overstromingsgebied*	Sigmaplan	Implemented	2010	24,49 ha				
Grote Vijver, deel 2	Green: N03 Floodplain restoration and management/ *Aanleg gecontroleerd overstromingsgebied*	Sigmaplan	Implemented	2010	79,45 ha				
Oude Dijlearm									
Cluster Kalkense Meersen									
Paardeweide	Green: N03 Floodplain restoration and management/ *Aanleg gecontroleerd overstromingsgebied* Green: N02 Wetland restoration and management	Sigmaplan	Implemented	2010	84,73 ha		W&Z and the municipality of Wichelen signed an agreement for cooperation on water-related projects in 2015		
Wijmeers, deel 1	Green: N02 Wetland restoration and management/*Aanleg meerdere dijken*	Sigmaplan	Ongoing	2010	158,75 ha		W&Z and the municipality of Wichelen signed an agreement for cooperation on water-related projects in 2015		
Wijmeers, deel 2	Green: N14 Re-naturalisation of polder areas	Sigmaplan	Ongoing	2010	27,85 ha		W&Z and the municipality of Wichelen signed an agreement for cooperation on water-related projects in 2015		
Paardebroek	Green: N02 Wetland restoration and management	Sigmaplan	Implemented	2010	27,77 ha				

Table A5.3 Scheldt — existing/planned GI measures (cont.)

Name of measure	Type of measure	Part of strategic approach?	Planned/ implemented	Timing	Location/ extent of measure (in hectares)	Funding (EUR)	Coordination	Cost-efficiency, benefits calculated/ reported?	Reference
Bergenmeersen	Green: N03 Floodplain restoration and management/ *Aanleg gecontroleerd overstromingsgebied*	Sigmaplan	Implemented	2010	41,37 ha		W&Z and the municipality of Wichelen signed an agreement for cooperation on water-related projects in 2015		
Kalkense meersen	Green: N02 Wetland restoration and management	Sigmaplan	Implemented	2010	606,16 ha		W&Z and the municipality of Wichelen signed an agreement for cooperation on water-related projects in 2015		
GOG Grote Wal-Kleine Wal-Zwijn									
Grote Wal-Kleine Wal-Zwijn	Green: N03 Floodplain restoration and management/ *Aanleg gecontroleerd overstromingsgebied Green: N02 Wetland restoration and management*	Sigmaplan	Planned	2010	148,64 ha				
Groot Schoor (Hamme)	Green: N14 Re-naturalisation of polder areas	Sigmaplan	Planned	2020	23 ha				
GOG Vlassenbroekse Polder									
Vlassenbroekse Polder, deel 1	Green: N03 Floodplain restoration and management/ *Aanleg gecontroleerd overstromingsgebied*	Sigmaplan	Implemented	2010	101,85 ha				
Uiterdijk				2015					
Vlassenbroekse Polder, deel 2	Green: N03 Floodplain restoration and management/ *Aanleg gecontroleerd overstromingsgebied*	Sigmaplan	Implemented	2010	137,58 ha				
Spierbroekpolder									

Table A5.3 Scheldt — existing/planned GI measures (cont.)

Name of measure	Type of measure	Part of strategic approach?	Planned/ implemented	Timing	Location/ extent of measure (in hectares)	Funding (EUR)	Coordination	Cost-efficiency, benefits calculated/ reported?	Reference
Hingene Broekpolder									
Blankaart									
Battenbroek									
Heindonk-Tien Vierendelen, deel 2	Green: N03 Floodplain restoration and management/ *Aanleg gecontroleerd overstromingsgebied*	Sigmaplan	Not specified	2030	108,86 ha				
Tielrode Broek				2025	96,46 ha				
GOG Oudbroekpolder-Schellandpolder									
Groot Schoor (Bornem)	Green: N14 Re-naturalisation of polder areas	Sigmaplan	Planned	2020	23 ha				
Schellandpolder	Green: N03 Floodplain restoration and management/ *Aanleg gecontroleerd overstromingsgebied* Green: N02 Wetland restoration and management	Sigmaplan	Planned	2015	54,74 ha				
Oudbroekpolder	Green: N03 Floodplain restoration and management/ *Aanleg gecontroleerd overstromingsgebied* Green: N02 Wetland restoration and management	Sigmaplan	Planned	2015	131,96 ha				
Stort van Hingene	Green: N14 Re-naturalisation of polder areas	Sigmaplan	Planned	2025	7,73 ha				
Stort Ballooi	Green: N03 Floodplain restoration and management/ *Aanleg gecontroleerd overstromingsgebied*	Sigmaplan	Ongoing	2025	12,08 ha				

Table A5.3 Scheldt — existing/planned GI measures (cont.)

Name of measure	Type of measure	Part of strategic approach?	Planned/ implemented	Timing	Location/ extent of measure (in hectares)	Funding (EUR)	Coordination	Cost-efficiency, benefits calculated/ reported?	Reference
Schouselbroek	Green: N03 Floodplain restoration and management/ *Aanleg gecontroleerd overstromingsgebied*	Sigmaplan	Ongoing	2015	127,04 ha				
Stort van Burchtse Weel				2025	1,95 ha				
Burchtse Weel				2010	67,83 ha				
Schonenberg									
Schonenberg 1				2020	4,72 ha				
Schonenberg 2				2020	13,99 ha				
Dorent									
Dorent Zuid-oost	Green: N02 Wetland restoration and management	Sigmaplan	Planned	2015	29,53 ha				
Dorent Noord-west	Green: N02 Wetland restoration and management	Sigmaplan	Planned	2015	25,87 ha				
Doelpolder Noord en Midden									
Doelpolder-Validatiedecreet				2010	144,45 ha				
Hedwige-Prosperpolder							Flanders and the Netherlands agreed to re-naturalise the Hedwige-Prosperpolder		Selection not advised: controversy/ discussion on de-poldering
Prosperpolder	Green: N14 Re-naturalisation of polder areas	Sigmaplan	Planned	2025	458,1 ha				
Hedwigepolder-Noordelijk deel Prosperpolder	Green: N14 Re-naturalisation of polder areas	Sigmaplan	Ongoing	2010	458,42 ha				

Reality check

The state of implementation of Sigmaplan is depicted in Map A5.10. The colouring indicates the deadline for the implementation for measures: dark green, 2010; light green, 2015; yellow, 2020; orange, 2025; and pink, 2030.

In addition, the implementation of the RBMP of the Scheldt (not only the stretch considered but the entire RBMP) can be reviewed to set its ambitions in the context of the real world. Figure A5.3 and the text come from the RBMP 2016–2021.

At the end of 2012, the progress of basic and supplementary measures under the first PoM was reported to the European Commission. The following description of the implementation rates of the measures therefore covers the period from 2010 until the end of 2012, and only in relation to the priority areas. By the end of 2014, an update on the level of implementation of the full PoM had been organised. This information will be included in the final second RBMP (not available at the time of writing this report).

With respect to the basic measures, three have been completed. There was no substantial delay for basic measures in the period 2010–2012. Of the 170 additional steps, eight were completed, 119 measures were in progress and 43 measures had not started yet. A series of measures was delayed in the period 2010–2012. **A frequently mentioned reason is the severe flooding in 2010, which has shifted the priority to measures to prevent flooding. Other reasons that have led to delays include political decisions, uncertainty about the initiator and limited resources.**

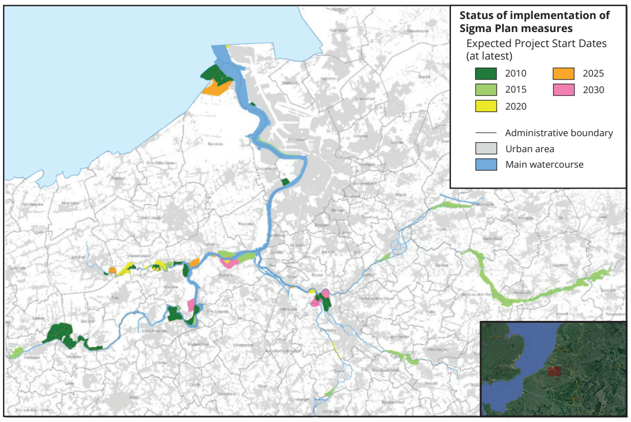
In 2013, for the 62 actions in the priority areas, the following was reported:

- 10 actions have not yet been started;
- 49 actions are to a greater or lesser extent in implementation;
- three actions are completed.

The implementation of 18 actions has suffered a considerable delay.

Due to flooding in recent years, decision-makers have decided to prioritise some measures, while delaying others.

Map A5.10 Status of implementation of Sigmaplan measures



Source: Waterwegen en Zeekanaal NVNV.

In Flanders, the implementation of measures is mainly ongoing and the financing mechanisms are in place. The PoM implementation report for Belgium indicates that implementation of some measures was facing delay because priority was given to actions related to the severe flooding event of 2010 ([48]). Current flood risk measures are planned to be implemented by 2021, so there is still quite a long time before these come into effect and implementation can be evaluated through the second RBMP, which integrates the FRMP. The measures are diverse and focus on, for example, flood-proof buildings, a review of restrictions on building in flood-prone areas, protective measures and measures to provide greater buffer capacity. As a programme including green-grey infrastructure measures for the Scheldt river basin, Sigmaplan is mentioned.

For the Scheldt river basin (selected stretch), the majority of existing and planned GI measures fall within the following categories:

- floodplain restoration and management (controlled flooding areas);
- re-naturalisation of polder areas; and
- wetland restoration and management.

([48]) Assessment of Member States' progress in the implementation of PoMs during the first planning cycle of the WFD. Member State Report: Belgium.

Overview of current coordination between upstream and downstream areas

Coordination

Flanders has followed a strategy of open communication to implement the Sigmaplan in a way that maximises public acceptance and support. The communication strategy is coordinated by W&Z (Waterwegen en Zeekanaal NV, 'Waterways and Sea Channels'), a department of the regional government, with consultation at ministerial level and under the oversight of a steering group (*stuurgroep Sigmaplan*) that includes various authorities.

The steering group includes representatives of W&Z, Department of Mobility and Public Works, Agency for Nature and Forests, Department for Land Use Planning, Department for Housing Policy and Heritage Buildings, Department of Environment, Nature and Energy, Department for Agriculture and Fisheries, Flemish Land Agency, the Executive Secretariat of the Flemish-Dutch Scheldt Commission and the OS2010 working group.

Stakeholder participation

Communication is carried out using various tools including brochures, newsletters and educational materials for children, as well as meetings to disseminate information and discuss key issues with stakeholders. Specific types of stakeholders have been actively involved in planning, including agricultural organisations, environmental NGOs, hunters, fishers, and the tourism and hospitality industry.

The communication strategy focuses on three outcomes from the Sigmaplan. The first and primary pillar is increased flood safety; the other two pillars are recreation and nature protection. Each project is extensively communicated to the public, and focus groups are organised at both regional and local levels. In Belgium, the Kruibeke project was the only project that saw significant opposition, and support there has now increased as it nears completion. A transboundary project involving the de-poldering of the Hedwige Polder, located in the Netherlands, has resulted in stakeholder and public opposition.

Vistula, Poland

Identification of flood risk

The Vistula starts in southern Poland, in the Beskidy Mountains, and crosses around 1 047 km before reaching Gdańsk Bay, part of the Baltic Sea. The Vistula is divided into three major regions: lower region, middle region and upper region. In this study the upper region of Vistula will be analysed. The **upper Vistula region** covers over 43 000 km^2 in southern Poland. The major cities in the region are Krakow (capital of Malopolskie voivodeship), Tarnow, Kielce, Nowy Sacz, Rzeszow, Przemysl and Krosno. The length of the Vistula in the upper region is 290 km. The biggest tributaries of the upper Vistula are the San (basin area 16 861 km^2) and Dunajec (6 804 km^2), which cover almost half of the region. Other large tributaries are the Wisłoka, Raba, Soła and Skawa.

The upper Vistula region is vulnerable to the occurrence of floods for several reasons. For example, factors such as precipitation and run-off of 15 % and 50 %, respectively, above average for Poland increase the risk of flooding. A serious threat is posed by flash floods. This threat is caused by a dense and concentric hydrographical network, steep slopes and troughs, the oval shape of the catchment, and high road density and saturation of the catchment area.

The main flood types in the summer are:

- freshets pose a risk of flooding in both winter and summer, and are characteristic of the mountains and uplands (summer freshets occur in the upper Vistula from May to October and are classified depending on rainfall type);
- flash floods occur because of heavy and sudden rain;
- pluvial floods are caused by long-term, heavy rainfall covering a large area.

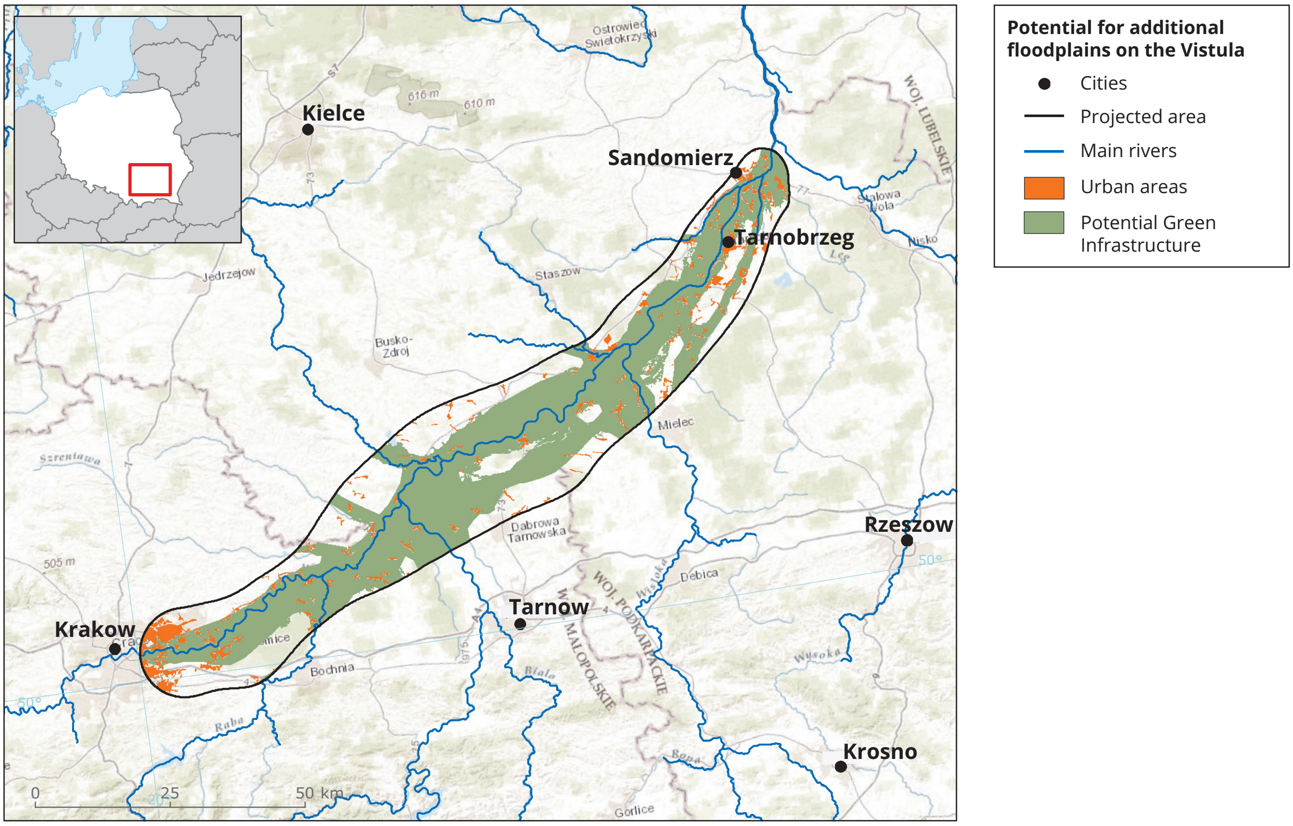
Freshets occurring from November to April (winter) are typical of lowland areas, but they are still a risk in the upper Vistula region. Winter floods are divided into:

- snowmelt floods caused by rapidly melting snow;
- flooding caused by ice dams on rivers.

Vulnerability of main cities

The city of Sandomierz is located in Swietokrzyskie voivodeship in the northern part of the upper Vistula region, on the Vistula river and its tributaries, the Koprzywianka and the Trześniówka. The city of Sandomierz has an area of over 28 km^2 and is inhabited by 24 731 residents (2013). The main cause of flooding

Map A5.11 Vistula river basin district — selected case study



Source: Arcadis.

in the upper Vistula region is rainfall of various intensities: long-term (widespread) rainfall can cause river floods, as can intense and short-lived downpours, which cause sudden freshets, especially at a local level. Less frequently, freshets are caused by melting snow (snowmelt floods).

Historical floods in the municipality of Sandomierz include:

- floods in 2003, in which there were four deaths and 3 000 people were injured;
- floods in 2010, caused by heavy rainfall in the second half of May and early June, which caused levees to collapse in the vicinity of a glass factory in the village of Koćmierzów, next to Sandomierz, which in turn led to flooding parts of Sandomierz, Tarnobrzeg and the municipality of Gorzyce.

Flood risk around Sandomierz is created by the Vistula, Koprzywianka and Trzesniowka rivers. Within the area of the highest flood hazard are located a window glass factory, an industrial plant, hundreds of residential buildings, a church, cemeteries, a water intake and a waste landfill.

In 2010 a Vistula dike collapsed in Kocmierzów, which caused flooding in parts of Sandomierz, Tarnobrzeg and Gorzyce. An area of 1 154 ha on the right bank was flooded (40 % of total city area). The flood covered 390 ha of the built-up area. Parts of Sandomierz, including Kocmierzów, Powisle, Wielowiejska and Vitrum-Zarrzekowice, were most affected. The losses caused by the flood cost approximately EUR 100 million; 3 000 people were evacuated and four people died. The evacuation action cost more than EUR 500 000.

Photo A5.1 Panoramic view of a flooded Sandomierz city and glassworks (centre)

Source: Poland, Sandomierz, 2010 fot. Kacper Kowalski/ forum http://www.990px.pl/index.php/2010/08/13/czlowiek-vs-zywiol/

Heavy rainfall in late July 2011 caused damage to the old town, road infrastructure, the sewerage network and recreational areas. Total losses added up to almost EUR 2 million.

According to the currently published **FHRM** the biggest risk is on the right bank of the Vistula, in the districts of Zarzekowice and Kocmierzow.

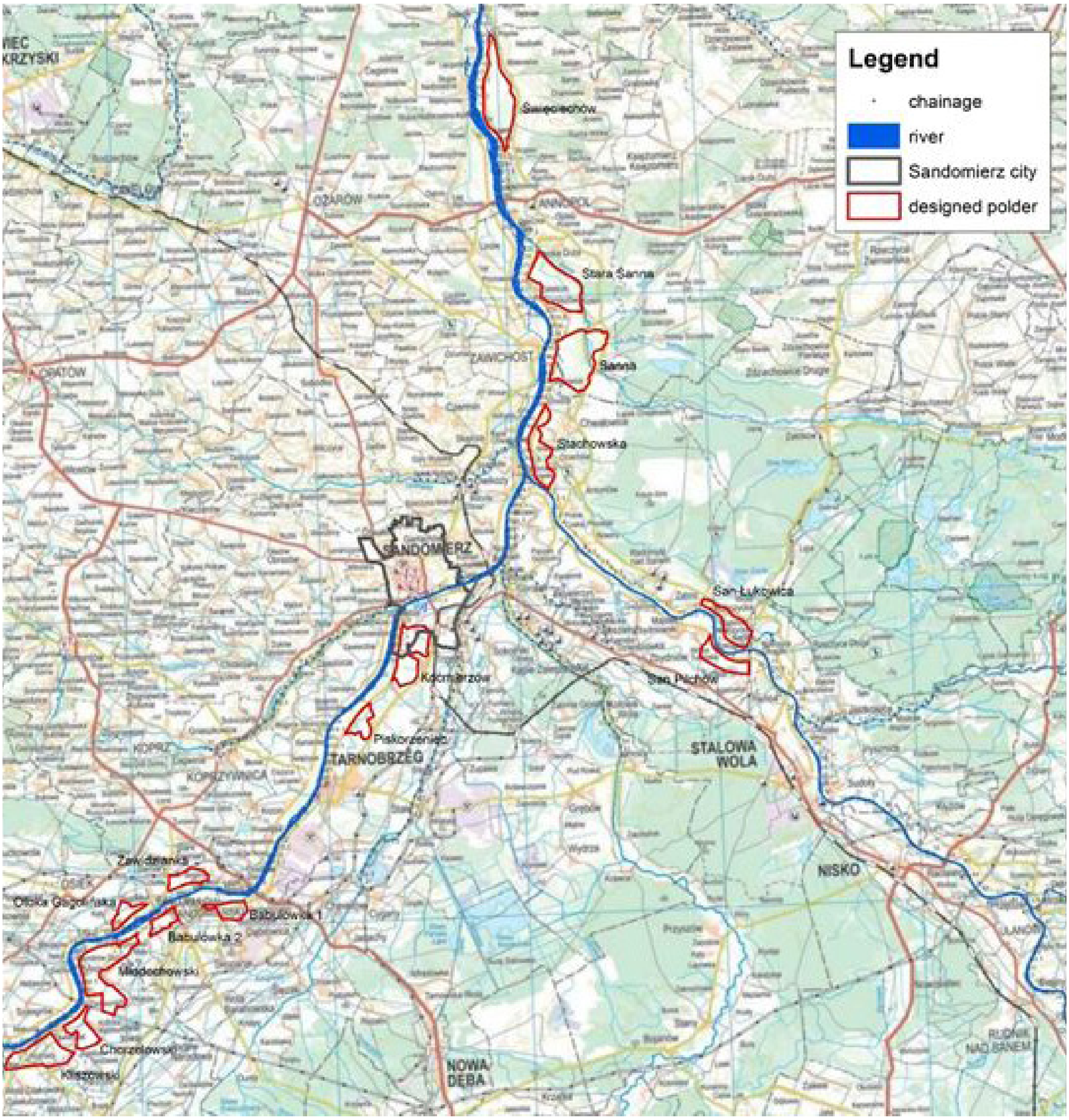
Management plans and status of implementation

For the Vistula, the type of GI measures currently implemented include:

- improving the hydraulic conditions of embankments;
- improving polder areas; and
- improving embankment structures and felling of trees.

Table A5.4 and map A5.12 below depict the GI measures already implemented and/or planned in the selected case study area of the Vistula river basin.

Map A5.12 Overview of designed polders along the Vistula (selected stretch)



Source: Arcadis

Table A5.4 Vistula — table of existing/planned GI measures

Name of measure	Type of measure	Part of strategic approach?	Planned/ implemented	Timing	Location/ extent of measure	By who? Responsible body	Funding	Coordination	Cost-efficiency, benefits calculated/ reported?	Reference
Implementation of new measures in catchment of Vistula Sandomierska	Green: N02 Wetland restoration Phase 1: expansion of the right embankment of the Vistula river from Tarnobrzeg to Koćmierzowo (10 km)	Upper Vistula region — RBMP	Planned	To 2021	Local	RZGW w Krakowie; PZMiUW w Rzeszowie; ŚZMIUW w Kielcach	-	RZGW w Krakowie; PZMiUW w Rzeszowie; ŚZMIUW w Kielcach	Cost of project: PLN 859 272 348	-
Implementation of reconstruction measures in catchment of Vistula Sandomierska Project ID: 77162	Green: N02 Wetland restoration Technical — felling of trees and shrubs in Vistula embankments	Upper Vistula region — RBMP	Planned	To 2021	Local	RZGW w Krakowie	-	RZGW w Krakowie		-
Implementation of non-technical measures in catchment of Vistula Sandomierska Project ID: 77136; 77152	Green: N02 Wetland restoration Non-technical — construction of polders along the riverbank from estuary of Dunajec to Sandomierz, and improving hydraulic conditions between embankments	Upper Vistula region — RBMP	Planned	To 2021	Region of upper Vistula	RZGW w Krakowie	-	RZGW w Krakowie		-
Investments specified for implementation in second round in the event of availability of funds Project ID: 77165; A_145_W; A_148_W;A_166_W; 77166	Grey measure: Reconstruction and modernisation of the river embankments	Upper Vistula region — RBMP	Planned	To 2021	Local	MZMiUW w Krakowie, ŚZMIUW w Kielcach, PZMiUW w Rzeszowie	-	MZMiUW w Krakowie, ŚZMIUW w Kielcach, PZMiUW w Rzeszowie		-
Analytical studies and conceptual design to prepare solutions and actions to update RBMP, including analysis of resettlement	Grey measure: Analysis of the possibility of changing the function, or adapting the construction, of buildings and public facilities in environmentally hazardous locations	Upper Vistula region — RBMP	Planned	To 2021	Sandomierska Vistula catchment	RZGW w Krakowie	-	RZGW w Krakowie	PLN 3 690 000	

Summary of the consideration of land use and soil management in relation to flood risk management

During the evaluation of various measurements, the impact on strategic environmental protection objectives was considered. Eight main objectives were taken into account: (1) protection of public health and safety; (2) biodiversity protection; (3) supporting environmental objectives for water bodies; (4) reducing vulnerability and preparing for climate change; (5) protection of the earth's surface and soil; (6) protection and if possible improvement of landscape features; (7) protection of cultural heritage; and (8) economic objectives and protection of material goods of high value. The influence of considered measurements has been evaluated by specialists, based on criteria set. For the upper Vistula region, analysis shows that proposed measures would have a positive influence on objectives (1) 'protection of people health and safety' and (8) 'economic objectives and protection of material goods of high value', a potentially positive influence on (7) 'protection of cultural heritage', a neutral influence on (4) 'reducing vulnerability and preparing for climate change' and (6) 'protection and if possible improvement of landscape features', and a negative influence on (2) 'biodiversity protection', (3) 'supporting the environmental objectives for water bodies' and (5) 'protection of the earth's surface and soil'. As the most invasive the following measures were highlighted: water reservoirs, dikes and polders, river regulation, and maintenance works on the riverbed.

Climate change was taken into consideration in evaluating various measures. Measures that could be adapted to climate change were preferred. The most suitable variants for the environment were selected. Where there was a lack of suitable variants, or variants were ineffective for environmental objectives, a technical variant was selected. The impact of flooding on soil protection has not been considered in RBMPs. Ecological corridors and other forms of nature protection were analysed while selecting the variants.

Reality check

Benefits: polders significantly reduce the volume and height of the culminating wave. It is assumed that this solution will eliminate the risk of water overflowing embankments in the event of a 1 % probability flood. There are 5 632 protected buildings in flood hazard areas. In terms of status of implementation, most of the measures in the first RBMP related to environmental quality, sewage treatment, etc. There is no information about measures connected with flood risk management. Current flood risk measures are planned to be implemented by 2021, so there is still quite a long time before these come into effect and implementation can be evaluated through the second RBMP, which integrates the FRMP. Actions included in the management plan for the Vistula contemplate:

- improving the hydraulic conditions of the embankment;
- improving polder areas; and
- improving the embankment structures and felling of trees.

Overview of current coordination between upstream and downstream areas

International coordination did not take place with regards to the upper Vistula region. The whole catchment of the upper Vistula is located within Poland. Cooperation took place at local level. In accordance with Polish water law, international cooperation takes place only on rivers that have cross-border watersheds. The executory act relating to the regulations of the Water Law Act on RBDs and water region borders is the Regulation of the Council of Ministers of 27 June 2006 (OJ of 2006 No 126, item 878 as amended).

The national body for water management is responsible for international cooperation on transboundary waters. Furthermore, the Minister for Water Management is responsible for the implementation of water management policy, in accordance with the provisions of the Water Act of 18 July 2001. Every 2 years, and no later than 30 June, the minister is required to give the Polish parliament information on water management involving international cooperation on boundary waters and the implementation of agreements.

International cooperation and the Regional Water Management Authority (RZGW) in Krakow

International cooperation in the area of the upper Vistula region is implemented within the framework of the statutory tasks of the Regional Water Management Authority in Krakow, and focuses on two principal divisions:

- cooperation on water borders (mainly Ukraine, Slovakia);
- the remaining issues of cooperation in the field of water management.

According to the current legal order, international cooperation led by the Regional Water Management

Authority in Krakow is based on the provisions of international conventions and intergovernmental agreements. This cooperation is also based on the findings of agreements on mutual cooperation in the introduction and implementation of EU water policy, established by the Regional Water Management Authority in Krakow with foreign partner institutions in the framework of institutional cooperation with:

- the Office of Water Management in Hof (Wasserwirtschaftsamt Hof) and the Bavarian State Office for the Environment, Hof (Bayerisches Landesamt für Umwelt Dienststelle Hof), Germany;
- Bjørnsen Beratende Ingenieure GmbH, Koblenz (Germany);
- Water Agency Artois, Picardy (France); and
- membership in the International Network of Basin Organizations (INBO).

International cooperation with Ukraine

An agreement between the Government of Poland and the Government of Ukraine on cooperation in the field of water management on boundary waters was signed in Kiev on 10 October 1996. In 1999 the Polish-Ukrainian Commission for Transboundary Waters was established, and annual meetings review the implementation of the agreement.

International cooperation with Slovakia

Cooperation on boundary waters between the Polish Republic and the Slovak Republic continues on the principle of succession. The responsibilities of the committee include in particular:

- solving hydrological problems relating to boundary waters;
- systematic examination of the quality of boundary waters and the implementation of projects related to the protection of water against pollution;
- developing methods for performing common measurement criteria for assessment and classification of water quality limits, and maintaining the list of pollutants;
- developing the principles of cooperation and control systems in the field of preventing and removing the effects of cross-border pollution;
- coordinating activities related to the improvement of groundwater and cross-border watersheds;
- securing the output data, test and measurement relating to the work of hydropower and water management facilities;
- determination of guidelines for the design and implementation of projects, maintenance of watercourses and water management facilities, as well as other necessary guidelines;
- supervision, technical and financial control, and accounting operations;
- solving problems related to forest- and water-related tourism.

International cooperation with Belarus ([49])

On 27 January 2010 a conference was held in Lvov on a cross-border programme of cooperation between Poland, Belarus and Ukraine between 2007 and 2013. This was attended by representatives of the regional water management authority in Krakow. The Conference was attended by representatives of the central authorities of Belarus, Poland and Ukraine, as well as local authorities, NGOs and universities.

([49]) Arcadis project 'Flood risk management plan for the Upper Vistula water region'.

Annex 6 Modelled approach for determining floodplain potential

The GIS analysis aimed to delineate potential floodplains for the baseline scenario and the relevant climate change scenarios. The outcome of the volume in the urban area flood versus the potential floodplain in a 1 in 100-year flood event is given in Table A6.1 (both in volume and surface area).

Table A6.2 depicts the modelling results (in percentage change and volume increase) when taking into account various climate change scenarios.

Table A6.1 Results of volume and area estimated of flooded area and area potentially available in the floodplain areas of the three river basins

Urban area flooded	89 km²	137 km²	121 km²
Potential floodplain	1 751 km²	1 188 km²	794 km²

Table FA6.2 Additional volume (in percentage change and cubic metres) as modelled through climate projections that needs to be allocated in the floodplain area, based on the volume expected in urban areas

	Climate projection		**Percentage change**		
	Global circulation model	**Regional circulation model**	**Elbe**	**Rhône**	**Vistula**
1	EC-EARTH	RACMO22E	2.86	13.21	29.30
2	HadGEM2-ES	RCA4	42.43	6.60	31.50
3	EC-EARTH	RCA4	5.58	−7.09	15.20
4	MPI-ESM-LR	REMO2009	−10.00	−3.65	−8.44
5	MPI-ESM-LR	CCLM4-8-17	0.40	17.60	13.20
6	MPI-ESM-LR	RCA4	−10.00	−0.54	−9.80
7	EC-EARTH	CCLM4-8-17	8.22	18.16	−1.30

	Climate projection		**Volume increase (10 million m³)**		
	Global circulation model	**Regional circulation model**	**Elbe**	**Rhône**	**Vistula**
	Baseline 1990-2013		155.83	71.56	43.36
1	EC-EARTH	RACMO22E	4.46	9.45	12.70
2	HadGEM2-ES	RCA4	66.13	4.72	13.66
3	EC-EARTH	RCA4	8.69	−5.08	6.59
4	MPI-ESM-LR	REMO2009	−15.58	−2.61	−3.66
5	MPI-ESM-LR	CCLM4-8-17	0.62	12.59	5.72
6	MPI-ESM-LR	RCA4	−15.58	−0.39	−4.25
7	EC-EARTH	CCLM4-8-17	12.81	13.00	−0.56

European Environment Agency

Green Infrastructure and Flood Management
Promoting cost-efficient flood risk reduction via green infrastructure solutions

2017 — 155 pp. — 21 x 29.7 cm

ISBN 978-92-9213-894-3
doi:10.2800/324289

TH-AL-17-013-EN-N
doi:10.2800/324289

European Environment Agency
Kongens Nytorv 6
1050 Copenhagen K
Denmark

Tel.: +45 33 36 71 00
Web: eea.europa.eu
Enquiries: eea.europa.eu/enquiries

Publications Office

European Environment Agency