OPERANDUM

OPEn-air laboRAtories for Nature baseD solUtions to Manage hydro-meteo risks

Critical evaluation of risks and opportunities for OPERANDUM OALs

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Short Description
The aim of this document is to critically analyse and document hydro-meteorological hazards, their negative consequences and good practice examples of NBS to manage the associated risks in OPERANDUM OALs. The outcomes of this deliverable serve as a foundation for the various tasks in other WPs of OPERANDUM. For instance, the evidence summarised from Section 3 to Section 7, feeds into WP2 to WP7 for design/co-design and implementation of NBS for flooding, droughts, salt intrusion, landslides, coastal erosion and storm surge, nutrients and sediment loading across OPERANDUM OALs. Overall, the reviewed documents showed that hydro-meteorological risks occur more regularly with a strong increase in intensity to cause significant loss of life and economic damage in OPERANDUM OAL countries and these hazards are projected to increase in severity and duration under future climate change scenarios. In response to this, in OPERANDUM OALs, different types of NBS such as green, blue and hybrid approaches were used and are under implementation.

Dissemination level		
PU	**Public**	**x**

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List of Acronyms and Abbreviations

ARPA-E	Advanced Research Projects Agency–Energy
BC	Before Christ
CA	California
CBAG	Local residents and stakeholder interest groups (CBAG)
CCA	Climate Change Adaptation
CCF	Continuous Cover Forestry
CCO	Channel, Coastal and Observatory
CCRM	Centre for Coastal Resources Management
CEDEX	Centre for Research and Experimentation of Public Works
CO	Confidential
CO_2	Carbon dioxide
COAWST	Coupled-Ocean-Atmosphere-Wave-Sediment Transport (COAWST) Modeling System
CRT	Climate Resilience Toolkit
CW	Constructed wetland
DCC	Dublin City Council
DPSIR	Drivers, Pressures, State, Impact and Response Model of Intervention
DRR	Disaster Risk Reduction
EC	European Commission
ECOBAS	Eco-engineered coastal defence integrated with sustainable aquatic food production
EEA	European Economic Area
EM-DAT	Emergency Events Database
EPA	Environmental Protection Agency
EU	European Union
EURO-CORDEX	Coordinated Downscaling Experiment – European Domain
FAO	Food and Agriculture Organization
FOS	Factor of safety
FGD	Focus Group Discussion
FP7	Seventh Framework Programme
FSC	Forest Stewardship Council
FSR	Flood Storage Reservoir
GA	Grant Agreement
GBP	Great Britain Pound
GCU	Glasgow Caledonian University
Geo-IKP	Geo-Information Knowledge Platform
GI	Green infrastructure
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
GR	Greece
GS	Geological survey
H2020	Horizon 2020
HMH	Hydrometeorological hazard
HZG	Helmholtz-Zentrum Geesthacht
IPCC	Intergovernmental Panel on Climate Change
IPR	Intellectual Property Rights
IT	Italy
IUCN	International Union for Conservation of Nature
KKT-ITC	Kentro Kainotomon Technologion Ae

KPI	Key Performance Indicators
MBASIN	MIKE BASIN
MSHE	MIKE SHE
NBS	Nature-based solutions
N	Nitrogen
NE	Not exist
NH4N	Ammonia-nitrogen
NO	(In NO Clear-cutting)
NO3N	Nitrate-nitrogen
NOAA	National Oceanic and Atmospheric Administration
NWRM	Natural Water Retention Measures
OAL	Open-air Laboratory
OEAW	Austrian Academy of Sciences
OLF	Overland Flow Area
OPERANDUM	OPEn-air laboRAtories for Nature baseD solUtions to Manage hydro-meteo risk
OR	Oregon
P	Phosphorus
PEFC	Programme for the Endorsement of Forest Certification
PESTEL	Political, Economic, Social-Cultural, Technological, Environmental and Legal
PFC	Peak Flow Control
PO4P	Phosphate-Phosphorus
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PU	Public
RCP	Representative Concentration Pathway
SAR	Synthetic Aperture Radar
SI	Salt intrusion
SLR	Systematic Literature Review
SME	Small and medium-sized enterprises
SWI	Salt-water Intrusion
UCD	University College Dublin
UK	United Kingdom
UNIBO	University of Bologna
UNISDR	United Nations Office for Disaster Risk Reduction
USD	United States Dollar
USGS	United States Geological Survey
WAMBAF	Water Management in Baltic Forests
WP	Work Package
WWAP	World Water Assessments Programme
WWDR	World Water Development Report
WWF	World Wildlife Fund
YPEKA	Hellenic Ministry of Environment and Energy

IPR: Intellectual Property Rights

Executive summary

Objectives: Changes have been observed in the risks associated with hydro-meteorological extreme events and they are projected to increase under climate change. Using a novel concept of Open-Air Laboratories (OAL), OPERANDUM intends to respond to these challenges through nature-based solutions (NBS). The information provided herein builds a strong foundation for project activities related to the design and implementation of NBS against floods, droughts and salt intrusions, landslides, coastal erosions and storm surges, and nutrients and sediment loadings. The aims of this document are to (i) to select an optimal NBS for each OAL via participatory approach, (ii) benchmark the performance and associated trade-offs of NBS, (iii) detect potential barriers that hinder NBS implementation, (v) analyse the enabling factors to overcome these barriers and (vi) test the outlined barriers on targeted stakeholders from OPERANDUM OALs and summarise the lessons learned.

Methods: A systematic literature review (SLR) methodology was used to include 275 out of 7000 peer-reviewed journal articles and reports considering the scope and keywords of the deliverable goal. The analysis of interviews and meetings with stakeholders were also inspired by the PESTEL (Political, Economic, Social, Technological, Environmental and Legal) framework.

Selection process of an NBS: Hydro-meteorological risk management is based on a deep understanding of the main physical phenomena that trigger the hazards and it is not sufficient without integrating with stakeholders' knowledge and risk perception. The effectiveness of NBS highly depends on stakeholders' perception and attitudes, which play a critical role on how individuals and institutions act to implement the solution and mitigate risks. In each OAL, stakeholders from different areas and sectors came together to distinguish and design an optimal NBS that integrates technical, social, environmental, economic, legal and institutional aspects while managing hydro-meteorological risks. During stakeholders' engagement following a participatory approach, each OAL's participants were asked to select a combination of measures for each hydro-meteorological hazard (at least one NBS measure and at most five measures altogether). The selection process was part of the co-creation framework developed in WP1 (Task 1.3) and the participants had to choose the best NBS based on: (1) predefined hydro-meteo hazards, (2) landscape features and climate conditions, (3) expected impacts (e.g., tailored to the local conditions at the floodplain, landslide slope; spatially limited field experiment), (4) the project time frame to allow for a reasonable monitoring period (accessibility; doability within the project's duration), (5) probability of permission (availability of green and blue spaces) and (5) costs to be covered by the project, such as costs of land,water, raw materials (e.g. sands, trees, etc), labour (skilled, unskilled) and capital (e.g. machinery, buildings). Following these, about 26 types of NBS were selected in OPERANDUM OALs from nine countries: 5 in Finland (FI), 4 each in Austria (AU) and Italy (IT), 3 each in United Kingdom (UK) and China (CH), 2 each in Germany (GER), Greece (GR) and Australia (AUS) and 1 in Ireland (IE).

Performance and associated trade-offs: The selected NBS are promising and expected to produce high performance against predefined hydro-meteo hazards. However, a crucial trade-off related to the size of the intervention, large enough to produce observable results, while not exceeding the limited funds allocated by the regional government.

Potential barriers: The successful implementation of NBS outlined above against hydro-meteorological hazards within OALs were hindered by a broad variety of gaps and barriers. For instance, flood tackling four OALs in FI, GER, IT, IE and GR, realised finance/funding and poor involvement of stakeholders throughout NBS projects life-cycle as the main barrier. In OAL-UK, the

spatio-temporal scale, lack of monitoring data and a standardised way of quantification of the benefits were identified as major barriers for NBS implementation against storm surge. Barriers of NBS upscaling from local to regional, attitude of landowners and climate change were identified in OAL-FI. In OAL-AU, long-term effectiveness of NBS was identified as a main barrier. Since the landslide hazard continuously damages buildings, therefore NBS with long-term effects (like changing forest management) does not have high priority. Discussions with the leaders of OPERANDUM OALs also reflected that there was very little scope of NBS options and their various trade-offs because they were either already in place or dominated by the use of other existing practices.

Enabling factors: Several lessons can be taken from stakeholders' engagements, in particular the enabling factors that can overcome the above-mentioned barriers. For instance, the main enabling factor of the project associated with poor involvement of stakeholders is continuous involvement of citizens and organizations throughout the life cycle of NBS projects as well the commitment of the main stakeholders. In four OALs, the availability of public funds was identified as an enabling factor to overcome the barriers associated with NBS against flooding. The co-creation on a local/pilot-scale and standardised procedures could solve the barriers associated with NBS implementation against soil erosion and storm surge in OAL-UK. The involvement of experts in designing NBS in OAL-FI was identified as an enabling factor to overcome barriers. NBS in OAL-AU are cost-efficient and work without synthetic materials. They may, therefore, be preferred over grey solutions and could solve the barriers associated with NBS implementation.

*Lessons learnt***:** During the co-creation process in each OALs, the following lessons were learnt: (1) the inclusion of environmental awareness (climate change, topography, etc) and impact modelling techniques in the design of NBS could increase the level of willingness and commitment of stakeholders towards the implementation of the NBS; (2) involving citizens in the co-creation process can boost the opportunities for operationalisation of NBS, and create trust and ownership; (3) involving and keeping in touch with funding agencies throughout the project life cycle and disseminating the results/achievement through deliverables and publications, are crucial to keep the stakeholders engaged; and (4) Co-creation process is quite easy; however, administrative problems due to the complicated bureaucracy made the process very complex. More lessons learnt will be presented in D1.3 (due on M24). Here, it is crucial to make lessons learned and data gathered in this report more widely available and disseminate through publications. As a result, the outcomes of the report were converted into three scientific papers published in top-ranked journals (Debele et al., 2019; Sahani et al., 2019; Kumar et al., 2020), which will support a larger uptake of NBS in practice.

Links to other WPs and contribution to specific objectives (SOs): The success factors in designing and operationalising the selected NBS in each OALs will be evaluated within other related OPERANDUM WPs based on the key performance indicators (KPIs) developed in other WPs, such as WP3, WP4 and WP6. Both spatial and temporal scales will be taken into account in these KPIs. Overall this deliverable directly (60%) and indirectly (40%) contributed to the achievement of OPEANDUM specific objectives (SOs). For example, this D1.2 directly contributed 28% of 25 (100%) OPERANDUM main results (R1-R4, R8, R9 and R23) by setting a foundation that will be used as background information for the other WPs in OPERANDUM.

Conclusions: The adoption of a participatory approach supported in increasing the available knowledge and awareness for the potential and uptake of NBS measures compared with traditional engineered (grey) approaches. The findings summarised in different sections of this deliverable will feed into recommendations for creating synergies within current policy process, scientific plans and practical deployment of NBS for hydro-meteorological risk reduction beyond OPERANDUM OALs.

1 Introduction

Hydro-meteorological hazards are defined as processes or phenomena of atmospheric, hydrological or oceanographic origin that may cause injuries or other health and social impacts, such as loss of lives, services and livelihoods, social and economic disruption or damage to properties and environment (UNISDR, 2009a). Hydro-meteorological extreme events, such as heavy precipitation, floods, heatwaves, droughts, landslides and storm surges have become more frequent and intense in Europe and worldwide. The increasing frequency and severity of hydro-meteorological extreme events is largely connected with climate change (Forzieri et al., 2016) and causing huge damage of the economy, human life and the environment (Section 1.2) each year in Europe. For example, about 618.5 billion USD worth of economic loss was caused by various types of natural hazards in Europe over the period 1980-2017. Approximately 502.56 billion USD of those damages was specifically caused by weather HMHs across Europe (EEA, 2019). The impact will be more pronounced in areas vulnerable to s (EEA, 2019), as can be seen in Figure 1. Disaster risks and losses are a current issue that concern societies and policymakers (e.g. European Commission, United Nations) since they have intensified in recent years and are anticipated to further increase as a result of the combination of urbanization, land-use change and projected climate change (EEA, 2019). For instance, most hydro-meteorological risks are projected to increase in severity, duration, and/or extent under future climate change, and to show strong regional variation across Europe (Forzieri et al., 2016; IPCC, 2018).

Forzieri et al. (2016) studied the overall exposure of European cities to multiple (independent) hazards using a comprehensive multi-hazard assessment throughout the 21st century. They analysed the trends in the frequency of six hydro-meteorological hazards (flooding, droughts, wildfires, windstorms, and heat and cold waves) using climate projections. The overall exposure of Europe to this multi-hazard scenario showed ‘a positive gradient’ that was even more pronounced than the exposure found for single-hazard scenarios. A progressive and strong increase in overall hydro-meteorological hazards will strongly impact regions in coastlines and floodplains of southern (the Iberian Peninsula, southern France, northern Italy and the Balkan countries along the Danube) and western Europe which are highly populated and economically pivotal. More specifically, the projections from most recent studies have pointed out the following:

- Future flood risks in western Europe were anticipated to rise as a result of a pronounced increase in heavy precipitation (see Section 3).
- Severe high coastal water levels have raisen in most regions along the European coastline. This rise appears to be mostly due to rise in mean local sea level rather than to changes in storm activity. Projected changes in the frequency and intensity of storm surges are expected to cause significant ecological damage, economic loss and other societal problems along low-lying coastal areas in northern and western Europe unless additional adaptation measures are implemented. Particularly in the northern Adriatic Sea, the projected changes in mean sea level under climate change becomes more consistent due to the well-known natural subsidence associated with the subduction of the Adriatic plaque under the Apennines, estimated at about 1mm per year (see Section 4).
- The magnitude and timing of extreme weather events also affect biogeochemical processes in surface waters. Because nitrogen (N) and phosphorus (P) are the limiting nutrient resources for plant and microbial growth in most boreal waters, their excess input into

watercourses due to forestry activities, such as tree cuttings; may lead to nutrient enrichment and eutrophication (see Section 5).

- The severity and frequency of droughts appear to have increased in parts of Europe, in particular in southern and south-eastern Europe. Droughts are projected to increase in frequency, duration, and severity in most of the Europe with the strongest increase projected for southern Europe (see Section 6).
- Since 2003, Europe has experienced several extreme summer heatwaves. Such heatwaves are projected to occur as often as every two years in the second half of the 21st century, under a high emissions scenario (RCP8.5). The damage will be particularly strong in southern Europe.
- Landslides are a natural hazard that cause fatalities and significant economic losses in various parts of Europe. Projected increase in temperature and changes in precipitation patterns will affect rock slope stability conditions and favour increase in the frequency of shallow landslides, especially in European mountains (see Section 7).

Seven OPERANDUM project countries are located in Europe and three are located outside of European territories (two in China and one in Australia) (Figure 1) and are mostly affected by single, inter-related or multiple hydro-meteorological hazards depending on their geographical, topographic and climatic conditions. Therefore, OPERANDUM project intends to respond to these challenges by the deployment of nature-based solutions (NBS) in ten selected Open-Air Laboratories (OALs) countries shown in Figure 1. The social-ecological elements of OALs are at risk due to the occurrence of natural hazards, often at the high magnitude, because of higher exposure and vulnerability of the elements. In this section, the core concepts and definitions used throughout this report are briefly presented. For the sake of clarity, we briefly summarise basic terminologies related to hydro-meteorological risks and its management from OPERANDUM D1.1.

A natural hazard is defined as a natural process or an incident that could induce destruction, injury to humans and damage their assets, economic losses or ecological degradation (Moos et al, 2017). They can normally be characterised by their magnitudes, such as volume and area or intensity (e.g. the destructive power) and probability of occurrence (Paton and Johnston, 2006; UNISDR, 2009). A disaster is a natural hazard event which causes serious problems to a society, damage assets and cause environmental losses (UNISDR, 2009). The risk resulting from potential hydro-meteorological hazard processes refers to the estimated negative consequences, such as to the number of loss of life, the number of people harmed, loss to property (houses and other infrastructures) and natural environments, the disruption of societal and economic activities (Moos et al., 2017). In the field of climate change adaptation (CCA) and disaster risk reduction (DRR), the risk is most commonly defined as the product of three factors (Equation 1):

$$Hydrometeorological\ risks = Hazard \times Exposure \times Vulnerability \qquad (1)$$

where the exposure is characterised by an aggregation of the likelihood that people and their assets are present at the time of the event; and the vulnerability is defined as the extent of an individual, social or ecological degradation arising from an hydro-meteorological hazard (UNISDR, 2009; IPCC, 2018), Figure 2.

In general risk assessment consist of three steps: (1) risk identification – finding, recognizing and describing risk; (2) risk analysis – estimation of the probability of its occurrence and the severity of the potential impacts and (3) risk evaluation – comparing the level of risk with risk criteria to determine whether the risk and/or its magnitude is tolerable. In the risk analysis step, a hazard analysis provides in-depth knowledge about the hydro-meteorological hazards process including its spatial extent, magnitude and frequency. Combining both the hazard and consequence analysis, the risk can be estimated in a qualitative or quantitative way. In the risk assessment, additional factors such as societal risk tolerance criteria and value judgements are considered to evaluate the actual risk. Finally, risk adaptation measures and control plan are then developed and implemented. Continuous monitoring and reviewing in the course of the disaster response cycle enhances the understanding and the effectiveness of each step undertaken (Dai et al. 2002, Fell et al. 2005, 2008).

NBS is defined as: '… actions to protect, sustainably manage and restore natural or modified ecosystems, which address societal challenges (e.g. climate change, food and water security or natural hazards) cost-effectively and adaptively, while simultaneously providing human well-being and biodiversity benefits' (Cohen-Shacham et al., 2016). The European Commission also understands: '… NBS to societal challenges as solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systematic interventions' (European Commission, 2016). For more theoretical details, we refer to OPERANDUM D1.1.

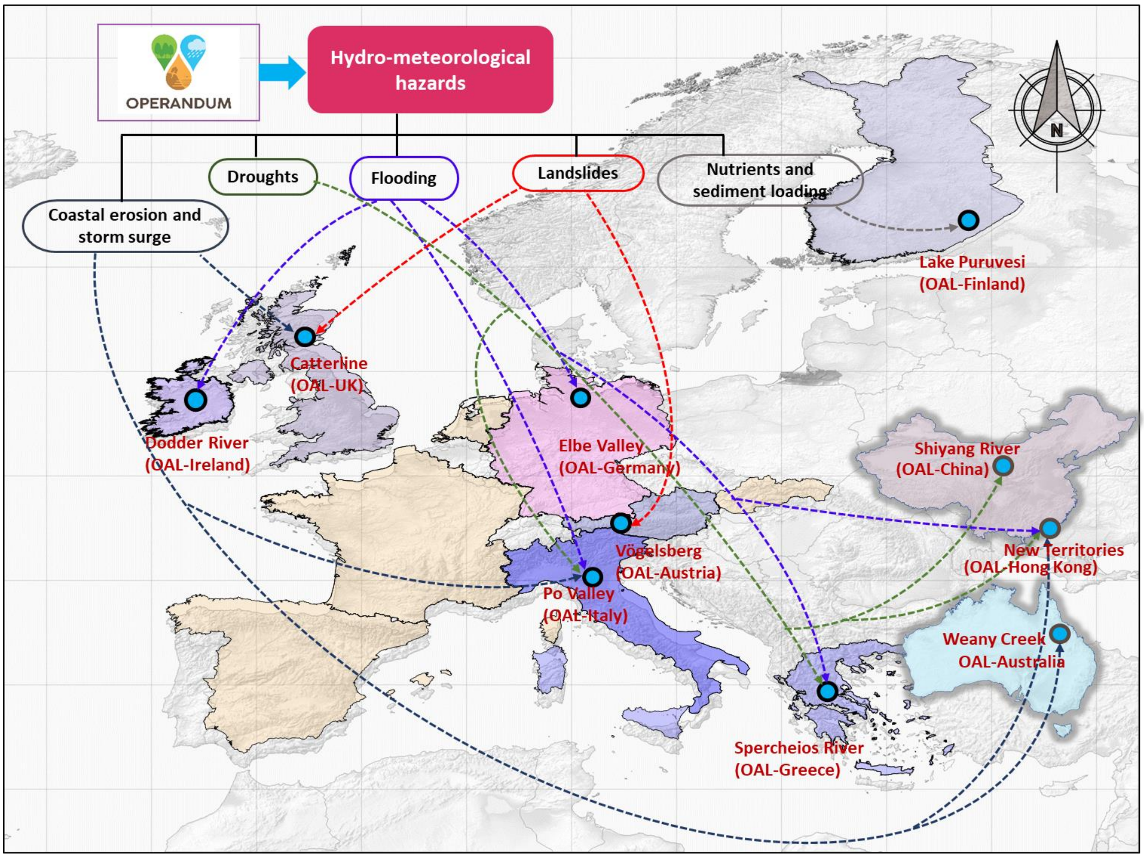

Figure 1: Location of OPERANUM OALs along with targeted hydro-meteorological hazards (Source: authors own figure).

1.1 Objectives

The general aim of this deliverable is to critically evaluate hydro-meteorological risks in OPERANDUM OALs, their management through NBS and create an opportunity for NBS deployment. This will enable leveraging the potential of NBS compared with traditional engineering (grey) approaches, which would likely accelerate and improve the implementation of NBS and make their uptake more efficient and effective. Based on the methodology outlined in Section 2, the key objectives of this deliverable will be:

1) To select an optimal NBS for each OAL via participatory approach,
2) Benchmark the performance and associated trade-offs of NBS,
3) Detect potential barriers that hinder NBS implementation,
4) To analyse the enabling factors to overcome these barriers and
5) Test the outlined barriers on targeted stakeholders from OPERANDUM OALs and summarise the lessons learned.

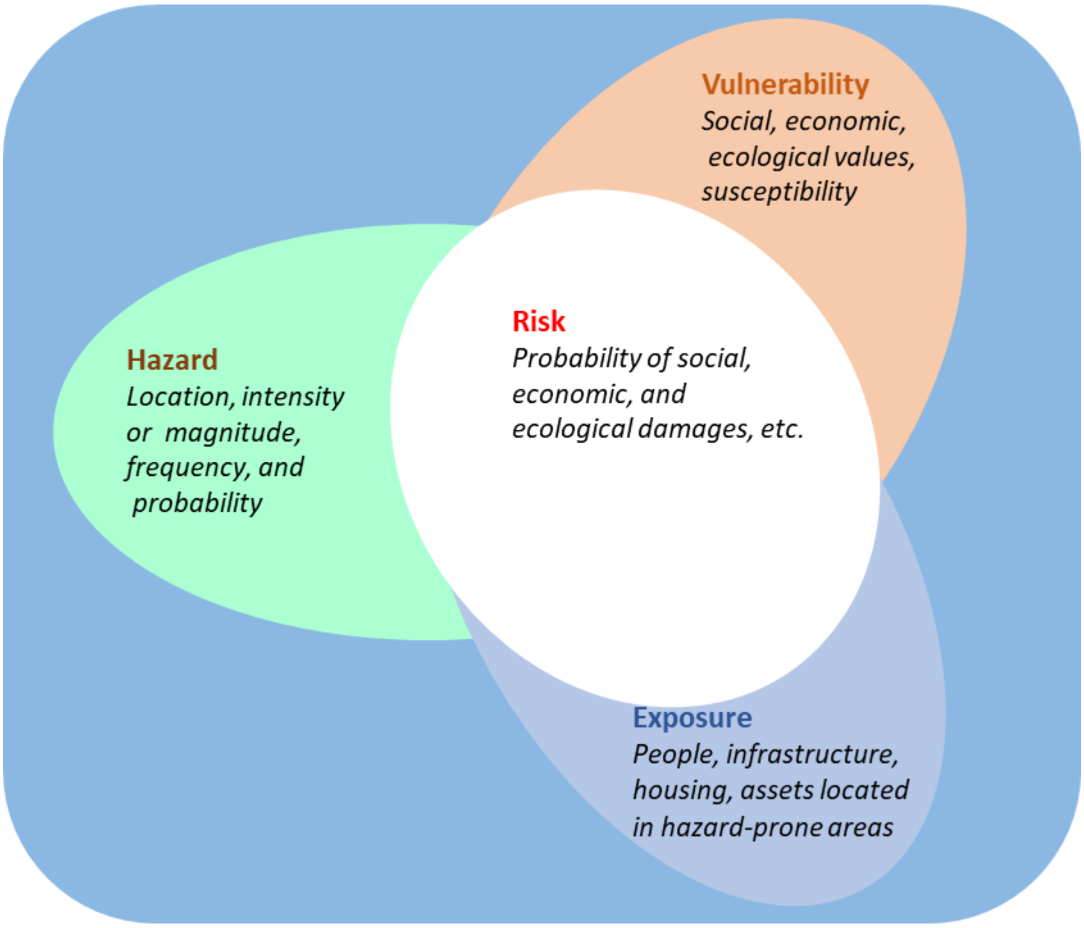

Figure 2: Conceptual framework of risks and the linkage between hazard, exposure and vulnerability (adapted from UNISDR, 2009).

1.2 Damages caused by hydro-meteorological hazards in OPERANDUM and other European countries

Climate-related extreme events have caused huge effects on human life, health and economy in Europe (Figure 3). Figure 3a and b show the distribution of loss of life and economic losses across the EEA member countries (EEA 33). The total reported economic damages caused by climate-related extreme events in the EEA 33-member countries over the period 1980-2017 amount to around approximately US$ 502.6 billion (Figure 3b). During this period (1980-2017), the loss of life caused by climate-related extreme events in the EEA33 countries was approximately 90,325 fatalities. France recorded the largest total loss of life (about 23,415), while Germany recorded the substantial amount of economic loss (about 107.2 billion US$) compared to other EEA countries (Figures 3a and b).

Table 1: Distribution of fatalities across OPERANDUM OALs countries per hydro-meteorological hazards types (data source: EM-DAT, 2019).

Countries	Loss of life (in %)				Economic damage (in %)				Total loss of life	Total economic damages
	Floods	Drought	Heatwave	Landslides	Floods	Drought	Heatwave	Landslides	in %	in %
Austria	0.032	-	0.351	0.293	2.615	-	0.159	0.024	0.676	2.79
Finland	-	-	-	-	-	-	-	-	0.00	0.00
Germany	0.061	-	9.559	0.005	16.51		1.155	0.004	9.63	17.67
Greece	0.095	0.0	1.140	-	0.733	0.569	0.002	-	1.24	1.304
Ireland	0.005	-	-	0.035	0.207	-		0.003	0.04	0.21
Italy	1.72	0.00	20.516	2.591	14.49	2.442	2.580	0.774	24.83	20.28
UK	0.091	-	1.098	0.143	12.51	-	0.00	0.00	1.33	12.51
Rest of EU	6.721	0.03	54.942	0.580	29.09	10.91	4.520	0.704	62.27	45.23
Total	8.73	0.03	87.606	3.647	76.15	13.93	8.416	1.509	100%	100%

The damages caused by specific hydro-meteorological hazards such as droughts, landslides, extreme temperatures and floods in seven OPERANDUM countries are presented in Table 3. Table 3 describes the sizeable and growing loss of life and economic damages caused by hydro-meteorological hazards across OPERANDUM countries over the last 120 years (1900-2019). As reported in Table 1, the largest economic damages in Europe was caused by flooding (76.2%), followed by droughts (13.9%), heatwaves (8.4%) and landslides (1.5%). Of these economic damages, 54.8% occurred in the OPERANDUM OALs countries. While flooding (47.1%) is responsible for the largest economic loss, the other hazards caused about 7.7% in total. In the same period, the deadliest among the hydro-meteorological hazards in Europe was heatwaves/extreme temperature (87.6%) followed by flooding (8.7%) and landslides (3.6%). During this period, OPERANDUM OALs countries accounted for 37.74% of all European fatalities (100%). Among the fatalities in OPERANDUM OALs countries, 32.7% is from heatwaves/extreme temperature, while the other hazards (landslides and flooding) accounted for 5.1% in total, Table 1. In general, the estimates for past losses in Europe vary substantially over time with average yearly economic losses ranging from US$15.5 billion to US$ 14.4 billion in the past 10 years (2010-2017). Estimates of total future losses in Europe could increase from current 14.4 billion

US$ per year to nearly 88.8 billion US$ per year by the end of the 21st century (Forzieri et al., 2015; Hallegatte et al., 2013). The use of a large database in OPERANDUM such as EM-DAT is mainly to provide the big-picture of our activities related to hydro-meteorological hazards and their associated damages rather than to be a source of data for detailed studies on OALs level, at least for the following three reasons:

1) Often the size of the OALs and the number of damages are of negligible size and impact at the country to global scales, and are not surveyed by large databases;
2) In some cases, the type of impact cannot be ranked in terms of common indicators (money or human life losses) since affecting environmental aspects are more difficult to evaluate, such as ecosystem health or the touristic exploitation of a natural area and
3) EM-DAT considers only very severe events (with a relatively high minimum threshold for money losses, injured people and casualties), so that midsize events, that could be relevant for OALs, are not reported.

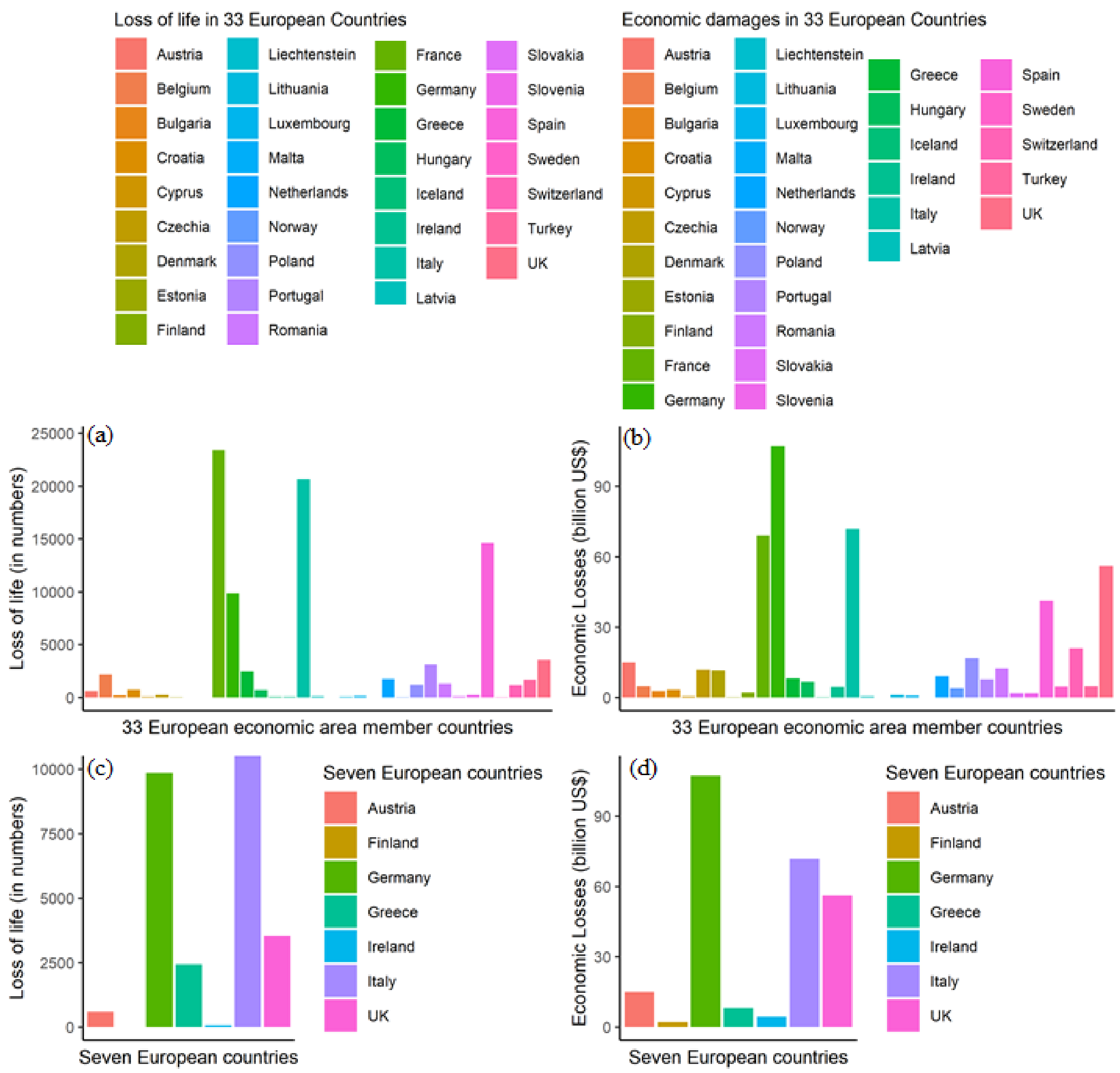

Figure 3: The impacts of extreme weather and climate-related events (1980-2017): (a) loss of life; (b) economic damages in the 33 European member countries; (c) loss of life and (d) economic damages in OPERANDUM OALs countries (Source: Kumar et al., 2020).

1.3 Hydro-meteorological risks and planned NBS in OPERANDUM OALs

1.3.1 Hydro-meteorological hazards focused in OPERANDUM OALs and their management

Flooding is more frequent hazards in five of the ten OALs (Table 2 and Figure 1): (1) OAL-Germany (Niedersächsische Elbtalaue, Biosphere Reserve) – is a flood-prone area along the Elbe river. During a high flood in the upper reaches of the Elbe river, part of the area gets inundated. Significant floods have occurred in this catchment in 2002, 2006, 2011 and 2013. The residual risks include potential damage to assets, dyke, loss of fodder production, disruption of ferry communication and tourism activities. The economic damages caused by the Elbe and Danube floods amounted to about 12.9 billion USD (in 2002) and 7.8 billion USD (in 2013) in Germany alone (Thieken et al., 2005; GVD, 2019). (2) OAL-Ireland (Dodder river) – this catchment gets impacted by flash floods and the downstream part of the river near estuary also experience tidal flooding and storm surges. Major flood events have occurred in this catchment in 1986, 2002 and 2011 (Steele-Dunne et al., 2008). Over 300 properties and 66 million USD economic losses have been caused by these floods (Pilla,2019). (3) OAL-Greece (region of Sterea Ellada) – heavy rainfall and riverbank overflow due to floodwater from upstream including snowmelt in the upstream mountainous areas cause flooding in the Spercheios catchment from October to May. Spercheios catchment has experienced four extreme flooding in 1993, 1997, 2012 and 2017. (4) OAL-Italy (Appennine's tributary of the Po river) – is a multi-hazard prone catchment, particularly in the city of Modena. Over the last 50 years, more than nine severe flood events have occurred. The most recent and devastating floods occurred in January 2014 when more than 50km^2 areas were inundated and more than 550 million USD economic loss occurred (Orlandini et al., 2015; Carisi et al., 2018). (5) OAL-China (Hong Kong New territories), a region between two major urban areas of Hong Kong and Shenzhen. According to hazard exposure and asset value in this catchment, flooding generated by heavy precipitation (flash flooding) and storm surge (coastal flooding) is the main hazards affecting human life and the environment. In response to this, hard measures (dykes) and soft measures, i.e. green approach, e.g. the renaturation of the Elbe tributary stream Rögnitz, natural drainage ditch systems, Elbe-groynes with different natural materials and clearing of meadowlands through cattle and renaturation of riparian forests are currently working in OAL-Germany while the other types of NBS against flooding shown in Table 2 are planned by OPERANDUM in respective OALs. Section 3 will introduce the best practices in the application of NBS against flooding hazards.

Storm surge can cause biodiversity loss by flooding of coastal habitats and eroding dune habitats and recreation areas, e.g. in OAL-Scotland, OAL-Italy and OAL-China (Hong Kong new territories) (Table 2). Coastal erosion caused by storm surge is a global phenomenon which leads to a loss of land or a long-term removal, transportation and deposition of sediment in the littoral zones, mainly due to the action of waves, currents and tides which often stem from hydro-meteorological phenomena, such as storm surges. The risks associated with this phenomenon include surface soil erosion, shallow and deep landslides, as well as changes in the associated ecosystems. In this document, we will introduce the best practices in the application of NBS against coastal erosion due to hydro-meteorological hazards with a view of potential application of some/any of them being applied in the OPERANDUM OALs, such as Scotland (Catterline), Italy (Po Valley) and OAL-China (Hong Kong new territories), Table 2. Gully erosion is also one of the hazards impacting OAL-Australia (Burdekin River Basin). For instance, gully erosion/soil erosion caused by runoff water is one of the most important land-degradation processes in Australia and worldwide. Gully erosion caused severe damage environmental impacts in OAL-Australia, such as destruction of agricultural lands, damages to roads etc. A list of potential NBS against this hazard planned by OPERANDUM project (2018-2022) is given in Table 2.

Nutrients and sediment loading - Lake Puruvesi, OAL-Finland is prone to increased nutrients and sediment loading (Table 2). Hydro-meteorological variables such as heavy precipitation and rapid snowmelt can cause high nutrient loading during winter and summer. Therefore, despite the excellent ecological status of Lake Puruvesi, there is a risk for eutrophication in many sub-catchments of Puruvesi. For instance, the extreme levels of eutrophication were evidenced in 1998 and 2012 when the whole Lake Puruvesi was affected. The responses to this hazard have been made via NBS and still in progress by OPERANDUM (Table 2). For instance, a survey of different NBS feasibility to prevent suspended solids and nutrient load to the recipient watercourses (caused by forest practices) indicated that the main knowledge gap and barrier for the NBS implementation is linked to the uncertainty on how the NBS will work in changed climate conditions. In addition, the effect of NBS was often too small, the flat landscape was challenging and lack of funding and limited time to plan NBS caused problems. To overcome these barriers, it was suggested to make a comprehensive plan for the focused area and not to build only one NBS structure, but to build several of them to have the maximum effect. It is also important to reserve enough time and funding to implement NBS. In addition, the models which will be developed in OPERANDUM (NutSpathy, Vemala, Rusle) will help to predict how the chosen NBS (Table 2) will work in different climate scenarios.

Drought is one of the hydro-meteorological hazards affecting life and ecosystems in four OPERANDUM OALs such as OAL-Greece in Sperheios valley, OAL-Italy in Po river, OAL-China in Hong Kong new territories and Shiyang River Watershed (Figure 1 and Table 2). The most common socio-economic impact concerns in these two OALs is water demand, especially during drought seasons in summer (e.g. Sperheios valley, Po river). Water used for irrigation makes this worse and leads to seawater intrusion in the groundwater table. The negative impact of the salt intrusion (SI) from the Adriatic Sea into the Po river mouth in OAL-IT is also one of the hydro-meteorological hazards focused upon here. For example, in the most extreme conditions, the effects of SI can go up to 15-20 km from the mouth. The sea penetration problem is even more severe if we consider the incoming sea level rise together with the known subsidence process affecting the Po valley coastal area thereby enhancing the adverse effects of salinity on crops. The NBS proposed or being implemented already (Table 2) will be evaluated by examining literature and by reviewing similar experiences; the co-design will be developed in close connection with the stakeholders and the local authorities since the selected areas, Sperchios and Po di Goro, are included in protected areas where any action can encounter several barriers to be identified, analysed and possibly overcome.

Landslides are one of the hazards that have continuously caused fatalities and economic loss in OAL-Austria (Vögelsberg) and OAL-Scotland (Figure 1). The major hazard in Vögelsberg, OAL-Austria is a continuously moving deep-seated landslide. The lower-lying part of the catchment is potentially affected by subsequent debris flows which can be caused by heavy rainfall events. The management cycle of landslide risk typically follows a framework with several stages (e.g. Fell et al., 2005 and 2008) as shown in **Figure 4**. It is of particular importance that both the potential hazard and its consequences are sufficiently understood before risk mitigation measures are designed and implemented. Similar to other hazards, adaptation measures against landslide risk can be hard measures (grey), non-structural and soft measures (NBS) or mixed/hybrid interventions and actions.

Structural measures are technical interventions which aim at minimizing the impact of landslides by actively reducing landslide hazard and/or decreasing the consequences. Such measures include active stabilization of slopes prone to failure, modifications of drainage systems and improvement of human-made objects to withstand the impact of landslides. Non-structural measures aim at reducing the impact of landslides by passively reducing their potential consequences. This includes temporary or permanent measures reducing the exposure of elements at risk by means of land-use planning, temporarily closing of infrastructure and by implementing warning systems for emergency evacuation (Popescu and Sasahara, 2009).

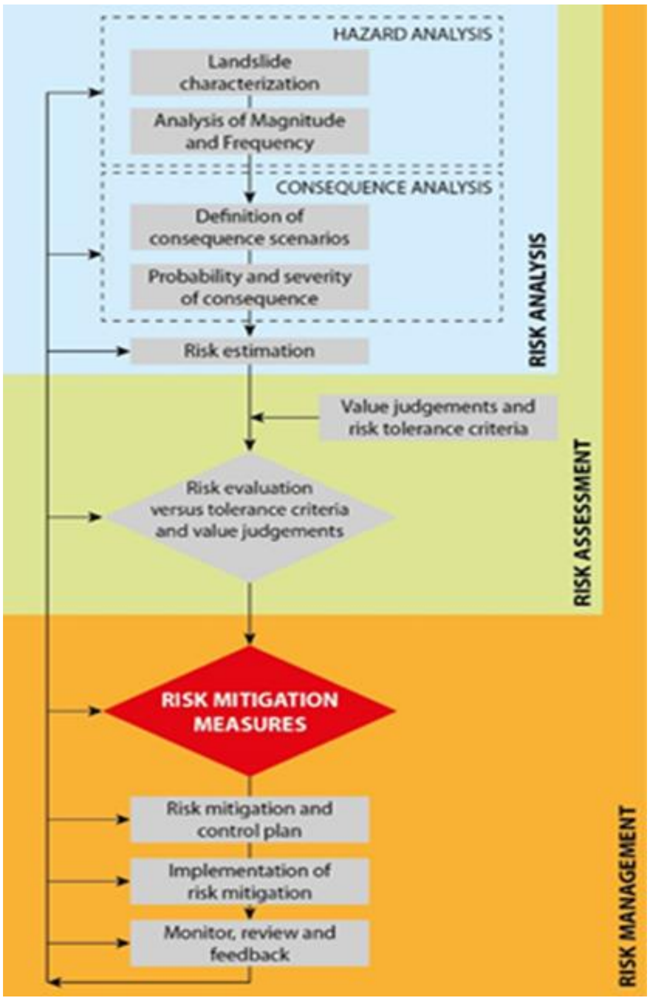

Figure 4: Framework for landslide risk management (modified after Fell et al., 2005, 2008).

Following Popescu and Sasahara (2009) and Vaciago (2013), structural landslide mitigation measures can be further classified into (i) modifications of the slope geometry, (ii) adaption of the drainage network, (iii) implementation of retaining structures and (iv) direct slope reinforcement. Non-structural measures for reducing landslide risk are typically part of spatial planning which may differ depending on national legislation (Greiving et al., 2006). NBS such as afforestation, live retention walls, fascines and drainage systems against landslides can help to build long-term resilience. Basically, the choice of suitable adaptation measures to reduce landslide risk must be (1) feasible from an engineering point of view, (2) economically meaningful and (3) socially and environmentally acceptable and in accordance with laws and regulations (Popescu and Sasahara, 2009). The applicability of adaptation measures strongly depends on the type of landslide. Key characteristics for a proper selection of measures depend on the involved material, the depth and rate of the landslide movement and its potential causes and trigger mechanisms. Moreover, the presence and type of elements at risk and their vulnerability as well as the accessibility of the unstable area may determine the type of adaptation measures.

Table 2: Summarising OPERANDUM OALs focused hazards, existing and planned NBS. All the catchmemnt names has been hyperlinked to their respected websites.

Catchment name	OALs countries	Coordinates		Hydro-meteorological hazards	Existing NBS	Planned NBS
		Longitude	Latitude			
Po Valley	Italy	11.5ºE	44.5ºN	Floods, Droughts., Coastal erosion and storm surge	Unsystematic	(1) deep-rooted herbaceous vegetation; (2) plantation of special plants; (3) artificial dune ad (4) plants combined with the dune.
Lake Puruvesi	Finland	29.5ºE	61.9ºN	Increased nutrients and sediment loading	Green/Blue/grey /hybrid	(1) riparian buffer zones; (2) constructed wetlands; (3) sedimentation ponds; (4) peak control structures; (5) continuous cover forest.
UNESCO/Biosphere Reserve Elbe Valley	Germany	11.5ºE	51.5ºN	Floods	Green	(1) Clearing of riparian woods and (2) Grazing management on meadows.
Spercheios River	Greece	22.2ºE	38.9ºN	Floods, Droughts	Unsystematic	(1) natural water retention measure and (2) planting trees and grass
Vögelsberg	Austria	14.6ºE	47.2ºN	Landslides	Green	(1) modify hillslope drainage system; (2) sealing of streams and channels; (3) modify snow accumulation and (4) optimize forest structure and management.
Catterline	Scotland	2.2ºW	56.9ºN	Coastal erosion and storm surge Landslides	Unsystematic	(1) Live crib walls, live drains, live palisades, wattle fences, tree plantation; (2) live lattices, brush layers, live ground anchors and (3) Shellfish reefs, live cobble berms.
Dodder River	Ireland	6.3ºW	53.3ºN	Floods	Unsystematic	Green roofs
Weany Creek	Australia	147.3ºE	19.4ºS	Gully erosion	Unsystematic	(1) restoration and (2) Trees and others
Shiyang River Watershed	China	100.6ºE	39..2ºN	Drought	Unsystematic	(1) restoration; (2) water harvesting; (3) Salt tolerant and (4) drought resistant crops.
Hong Kong New territories	China	114.2ºE	22.3ºN	Flooding, storm surge, extreme precipitation and heatwaves	Unsystematic	Green/Bluey/hybrid

1.3.2 Selection procedures of NBS for each OPERANDUM OALs

Selection of the most suitable sets of NBS for hydro-meteorological hazard requires greater collaboration amongst different policy areas, sectors and stakeholders. During stakeholder's engagement using a participatory approach, participants were asked to collectively select a combination of measures for each hydro-meteorological hazard in each OALs (at least one NBS measure and at most five measures altogether). The selection process was part of the co-creation framework developed in WP1 (Task 1.3) and the participants had to choose the best NBS for each OALs by taking into account the following selection criteria:

- The predefined hydro-meteo hazards (flood, drought, landslides, coastal erosions and storm surges, and nutrients and sediment loadings) at the proposal level,
- The stakeholders' engagement strategy in the context of developing a co-design framework,
- The OPERANDUM time frame to allow for a reasonable monitoring period,
- The availability of matching funds from the regional government,
- The relevance and science based effectiveness of NBS against predefined hydro-meteo hazards, and
- The implementation convenience of the selected NBS in the conditions which prevail in each OAL.

Following these criteria, about 26 types of NBS were selected in nine OPERANDUM OALs - OAL-AU (4-NBS), OAL-FI (5-NBS), OAL-GER (2-NBS), OAL-GR (2-NBS), OAL-IE (1-NBS), OAL-IT (4-NBS), OAL-UK (3-NBS), OAL-AUS (2-NBS) and OAL-CH (3-NBS) - as summarised in Table 2. The NBS selection procedures for each OAL are consistent and include transparent monitoring of NBS with time to facilitate comparison of NBS across different locations. In general, the decision-making has honoured the inevitable trade-offs for selecting an NBS in a particular OAL. The identified NBS in all the OALs are planned to be tested and verified through scenario analysis and impact modelling. An example of the process of co-design and co-deployment of NBS followed in OAL-UK is shown in Annex 1 (Figure 43).

NBS selection procedure in OAL-UK

The process of co-design and co-deployment of NBS followed in OAL-UK is illustrated in Annex 1 (Figure 43). The hydro-meteorological hazards of concern in OAL-UK include shallow landslides, storm surge and erosion. The local community came up with the problem of unstable coastal slope and the site was identified and visually inspected involving them. In collaboration with the local authority, we conducted stakeholder mapping to identify and establish strategy for their wider engagement. This allowed us to inform and consult stakeholders appropriately at each stage of this process and ensure that outcomes were reflective of their interests, views, requirements whilst establishing a partnership or collaboration with them. Then, the location of hazard-prone zones was identified through the implementation of the landslides detection module of Plant-Best (Gonzalez-Ollauri and Mickovski, 2017), followed by a ground validation process that consisted additional site visits and inspection of the zones detected by the model as hazardous. Once the model outcomes were verified, a hazard map was generated for OAL-UK. The stakeholders including the local authority, local interest groups, and local residents were informed at each step of this process and the outcomes were presented to the stakeholders.

Subsequently, a comprehensive investigation campaign was organised to retrieve site information related to the ground and environmental attributes of the OAL. Special emphasis was paid on the collection of information related to the soil hydrological and geo-mechanical properties, land cover and vegetation composition, and meteorological features of the OAL-UK (e.g. precipitation, air temperature). Local residents and stakeholder interest groups (CBAG) collaborated in this process by arranging site access, providing basic climate data and monitoring using own and GCU equipment.

In December 2018, a partnership was established with GCU, CBAG, and Naturalea Ltd. for the protection of the slope with mutual benefit to the community and academics to explore the science and engineering implications. This approach helped to define potential NBS for OAL-UK. Naturalea and the OAL-UK team inspected the zones-prone to landslides and erosion mapped at the OAL. In consultation with CBAG, Naturalea and the local authority, eleven hazard-prone zones were selected from the pool of hazardous zones identified at the OAL. These zones were selected on the basis of their hazard status (i.e. in progress, stable but prone to fail), their potential risk to property and infrastructure, as well as the accessibility to the hazard-prone zones and the stakeholders' human resource requirements which were deemed as essential feasibility indicators within the co-design process. Based on these, a specific NBS intervention was proposed for each hazard-prone zone, inspired by the soil and ground bioengineering principles and comprising an array of interventions that combined inert, timber-based structures with living vegetation to promote the stability and protection of the slopes comprising the OAL-UK and where landslide and coastal erosion hazards were identified.

In consultation with the CBAG, the feasibility of the identified potential NBS was assessed in terms of costs, local materials availability, deployment with low mechanical and machinery input, and perception by end-users. To explore the end-users' perception towards the proposed NBS, a face-to-face, informal meeting with the local OAL-UK residents was organised at the Creel Inn (Catterline, Aberdeenshire, UK) in February 2019. During this meeting, the stakeholders were informed of the proposed location and features of the NBS. The presentation of the proposed NBS included sketches, drawings, and method statements illustrating the evolution of the proposed NBS over time and also mapped the stakeholder involvement at each step of the process. The use of technical language was avoided wherever possible. The face-to-face meeting was supplemented with stakeholder consultation in form of a paper-based questionnaire in which the attendees were asked to rate the perception and preferences with regard to the proposed and presented NBS. The questionnaire also provided the participants with the opportunity to engage and suggest improvements to the specimen NBS designs presented at the meeting as well as means of getting a 'buy-in' for the next stage which is to help the co-deployment.

Using the above-mentioned criteria, out of the 11 NBS interventions proposed initially, 5 interventions comprising different NBS techniques were selected in the light of their feasibility, cost-effectiveness, ability to be implemented with the use of local materials and acceptance by the local and primary stakeholders. The selection of different NBS techniques intended to showcase multiple NBS examples at the OAL, bringing the opportunity to create an open-air NBS 'walk-through museum' (or 'gallery') at OAL-UK. The final detailed design of the selected NBS interventions was carried out by Naturalea in constant consultation with GCU and input from CBAG, which supplemented and adjusted the interventions designs on the basis of costing, further feasibility assessment, and the availability of local materials and other resources. For the latter, further engagement with secondary stakeholders and providers (e.g. Forestry Commission, Woodland Trust, Flooding Authority) was established through email and phone communications, as well as frequent site visits and informal interviews. Throughout the process, all stakeholders were kept informed on a regular basis.

The co-deployment of the NBS interventions at the OAL-UK was planned for spring 2020 with participation of a wide range of stakeholders but was postponed due to COVID-19 outbreak. The construction on site is expected to start as soon as the restrictions are lifted and the optimal period for NBS deployment (October to April) coincides.

1.4 Links to other OPERANDUM WPs and contribution to OPERANDUM specific objectives

The outcomes of this deliverable along with deliverable 1.1 (which was completed in M12) serve as a foundation for the various tasks in other WPs of OPERANDUM. For example, hydro-meteorological risks and their potential NBS critically surveyed in various Section (from Section 3 - Section 7) of this deliverable will be used in WP2- WP7 (Figure 5) for design/co-design and implementation of NBS for flooding, droughts, salt intrusion, landslides, coastal erosion and storm surge, nutrients and sediment loading in OPERANDUM OALs (Figure 1).

The fundamental concepts and the key technical features of past studies reviewed in this deliverable could be used as foundation in WP2 (task 2.2.1 to task 2.2.5), which aimed to successfully co-design NBS those are effective against flooding (task 2.2.1), coastal erosion (task 2.2.2), nutrient and sediment loading (task 2.2.3), drought (task 2.2.4) and landslides (task 2.2.5) in OPERANDUM OALs. WP3, particularly task 3.3 is about deployment and implementation of NBS for hydro-meteorological risks focused on OPERANDUM OALs. The reviewed resources in this deliverable will be used as a tool to implement and operationalise NBS across OPERANDUM OALs.

The targets of NBS and their potential for each hydro-meteorological risk, their cost-effectiveness, efficacy and monitoring techniques reviewed in various Section of this deliverable can be utilised in WP3 (task 3.4), and WP4 (task 4.5) to develop key performance indicators (KPI) for monitoring NBS in OPERANDUM OALs. The information addressed from Section 3 to Section 7 can be used as the basis in WP5 (task 5.2). The reviewed risks in all its dimensions of vulnerability, capacity, exposure of persons and assets, hazard characteristics and the environment in each OAL is utilised in WP6 (task 6.3, 6.4, 6.5 and 6.7), Figure 5. The list of hydro-meteorological hazards and their potential NBS developed in this deliverable is used in Geo-Information Knowledge Platform (GeoIKP) – in the components of risk, hazard and NBS (task 7.1), Figure 5. As shown in Figure 5, D1.2 contributed to the achievement of four OPERANDUM specific objectives (SOs) which are:

1) *SO1*: Integrate knowledge about NBS efficacy against hydro-meteorological risks particularly to;
    - *Result (R1 - new NBS developed in 7 EU Countries)* – D1.2 serves as background information for new NBS developed in European and other territories.
    - *Result (R3 - assessment of new NBS in OPERANDUM OALs) – to* consolidate the existing NBS through SLR, expert interviews and stakeholder involvement and paves a strong foundation for assessment of new NBS in OPERANDUM OALs and
    - *Result (R8 - guidelines for upscaling and replication of NBS)* – the reviewed documents also used to develop a guideline for upscaling and replication of NBS.
2) *SO2*: Strengthen technology innovation in the area of NBS, specifically to,

- *Result (R9 - co-designed, co-developed and implemented NBS from micro to landscape-scale)* – the results of stakeholder engagement discussed in a different Section of this deliverable can be used for co-design, co-developed and implementation of NBS in the different landscape such as micro and macro scales.

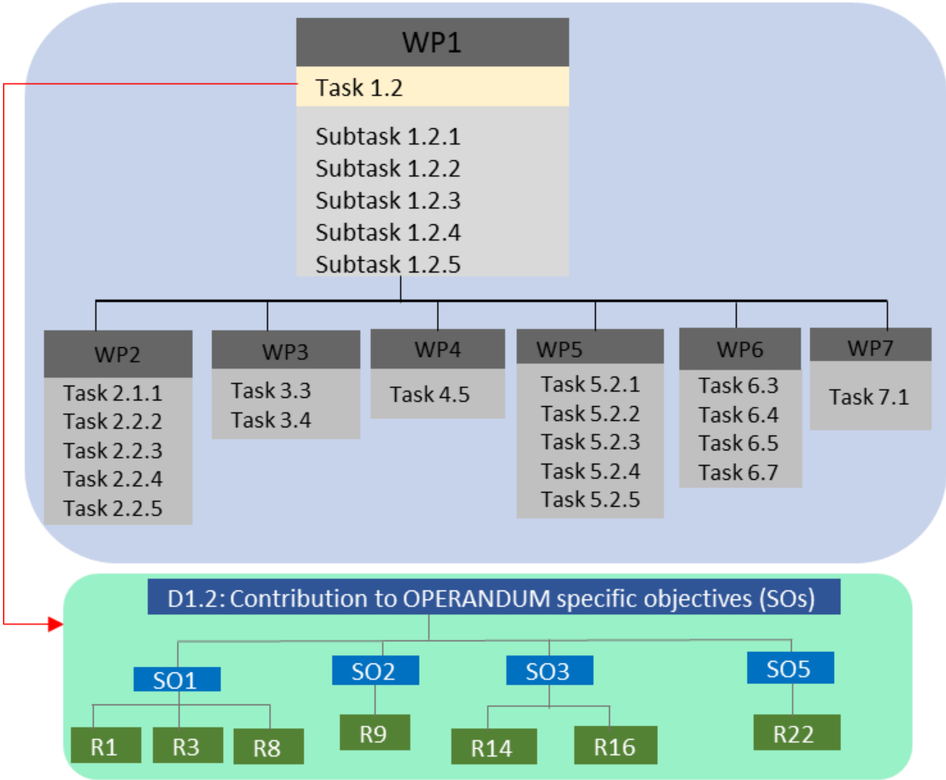

Figure 5: Link of task 1.2 to other OPERANDUM WP tasks and contributions to OPERANDUM SOs.

3) *SO3*: Improvement of acceptance of NBS based implementation, in particular to,
   - *Result (R14 - Communication framework for multi-scale stakeholdership including strategies to overcome socio, cultural and regulatory barriers at the local scale)* - the discussion with multidisciplinary stakeholders (Sections 3, 5 and 6) create trust, ownership, stewardship, including strategies to overcome socio, cultural and regulatory barriers at the local scale.
   - *Result (R16 - Protocols for the co-design and co-development of NBS as well as for their integrated design, taking into account land management and planning using OALs as strategic foci)* – the reviewed lists of NBS using OALs as showcases, i.e., by considering land management and planning of the OALS can be contributed to R16.
4) *SO5*: To strengthen the adoption of NBS in national policies for DRR land planning, EIP Water, more specifically to,
   - *Result (R22 - Guidelines for assessment of the effectiveness of NBS in wider lands (replication and scalability) as a measure of adaptation to the effects of climate change)* – The reviewed NBS in different Section of this deliverable (i.e., Sections 4 and 7), can be used to evaluate the cost-effectiveness and potentials of NBS against the rising impact of climate change.

1.5 Scope and outline of the report

The scope of this deliverable is limited to the following hydro-meteorological hazards – flooding, droughts, salt intrusion at river mouth due to drought, landslides, coastal erosion and storm surge, nutrients and sediment loading. The geographical coverage of the report includes mainly the seven European OALs countries, while the information is very limited for other three non-European OPERANDUM OALs which are located in Australia (OAL-Burdekin River Basin) and China (OAL-Hong Kong new territories and OAL-Shiyang River Watershed), see Figure 1.

The OALs were selected due to their climate differences and level of maturity with regard to NBS. These hazards were selected on the basis that: (1) they occur more regularly with strong increase in intensity to cause significant loss of life and economic damages; (2) under climate change scenarios these hazards are projected to increase in severity and duration and (3) the selected OAL countries were identified as most vulnerable areas with valuable ecological and cultural heritages and are suitable for the applicability of NBS under both current and future climate change scenarios.

The deliverable is structured as follows. Section 2 describes the methods applied in the systematic literature review (SLR) and the PESTEL (political, economic, social-cultural, technological, environmental and legal) framework. Section 3 gives the list of challenges/barriers and ways to overcome in designing and implementation of flooding NBS across Germany, Ireland, Greece, and Italy OALs (task 1.2.1). In particular, this Section will use the methodological approach given in Section 2 and organise meetings with stakeholders in the four OPERANDUM OALs to critically review and summarise lessons learned from the available project reports of past and current projects (including FP7 and H2020) and scientific publications. Section 4 starts with a detailed overview of coastal erosion and storm surge along with potential NBS across Scotland and Italy OALs (subtask 1.2.2). This Section will evaluate the long-term performance effectiveness, cost-effectiveness and and social perception of the specific NBS used against coastal erosion and storm surge.

Section 5 presents increase in nutrients and sediment loading (subtask 1.2.3) and the potential NBS in the Lake Puruvesi catchment (Finland-OAL), Europe and worldwide. By utilising the methodologies given in Section 2 and interviews and meetings with experts, this Section will start with a critical review of the available literature and expert surveys and collection of the planning tools and guidelines developed in the EU Baltic Sea Region Programme funded project Water management in Baltic forests (WAMBAF). By using the reviewed information, (i) the mapping NBS and their efficiency will be carried out; (ii) the identification and prioritisation of the gaps in the knowledge of the NBS efficiency will be carried out through an expert evaluation in the OAL countries; (iii) the environmental, economic and social factors and planning tools enabling or making barriers for NBS deployment and ways to overcoming the barriers will be identified (i.e. by interviewing experts in the OAL countries).

Section 6 focuses on droughts and salt intrusion by collecting the existing information on water availability and usage (e.g. Spercheios valley, OAL Greece and Po river, OAL Italy), identifying the critical parameters and developing best practice strategies for hydrological management (subtask 1.2.4). Using the methodological approach given in Section 2 interviews and meetings with experts, this Section will critically evaluate the impacts of droughts and saltwater intrusion from the Adriatic Sea into the Po river mouth and outline the best NBS against them. The design and co-designing of NBS will be developed in close collaboration with stakeholders and with the local authorities. Based on the methodology outlined in Section 2, Section 7 presents the long-term performance, cost-effectiveness and social perception of the specific NBS against landslides in Austria and Scotland OALs. Finally, Section 8 concludes the findings from the previous Sections and identifies specific opportunities for further enhancing the wider uptake of NBS against hydro-meteorological risks. The risk and opportunities identified and analysed in this deliverable are systematically summarized and presented in a form that can be easily utilized in a different part of OPERANDUM WPs.

2 Methods

We carried out a systematic literature review (SLR), which is a common method used for literature review in many fields of studies (Berrang-Ford et al., 2015; Frohlich et al., 2018; Pearce et al., 2018; Plummer et al., 2012). For the aim of this deliverable, we pursued the concept of 'Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)' approach for searching and choosing the literature sample (Moher et al, 2009; Shamseer et al., 2015), Figure 6. The string of keywords shown in Table 3 is applied to perform searches and compile a record of scientific papers and reviews deemed for full-text review in Web of Science, Scopus, Science Direct and PubMed databases. We have selected these scientific databases because they are comprehensive and covered a broad range of disciplines. The literature sample was limited to articles written in English and published between 1982 and 2019. We recognize that some relevant literature may be excluded from the study based on the search string adopted and/or the language of publication. This may introduce some limitations to the literature reviewed and analysed here. The search in these scientific databases returned over 7000 articles. To include peer-reviewed papers from a journal that might not be indexed in the these scientific databases, we repeated the search procedure in 'Google search engine and Google Scholar'.

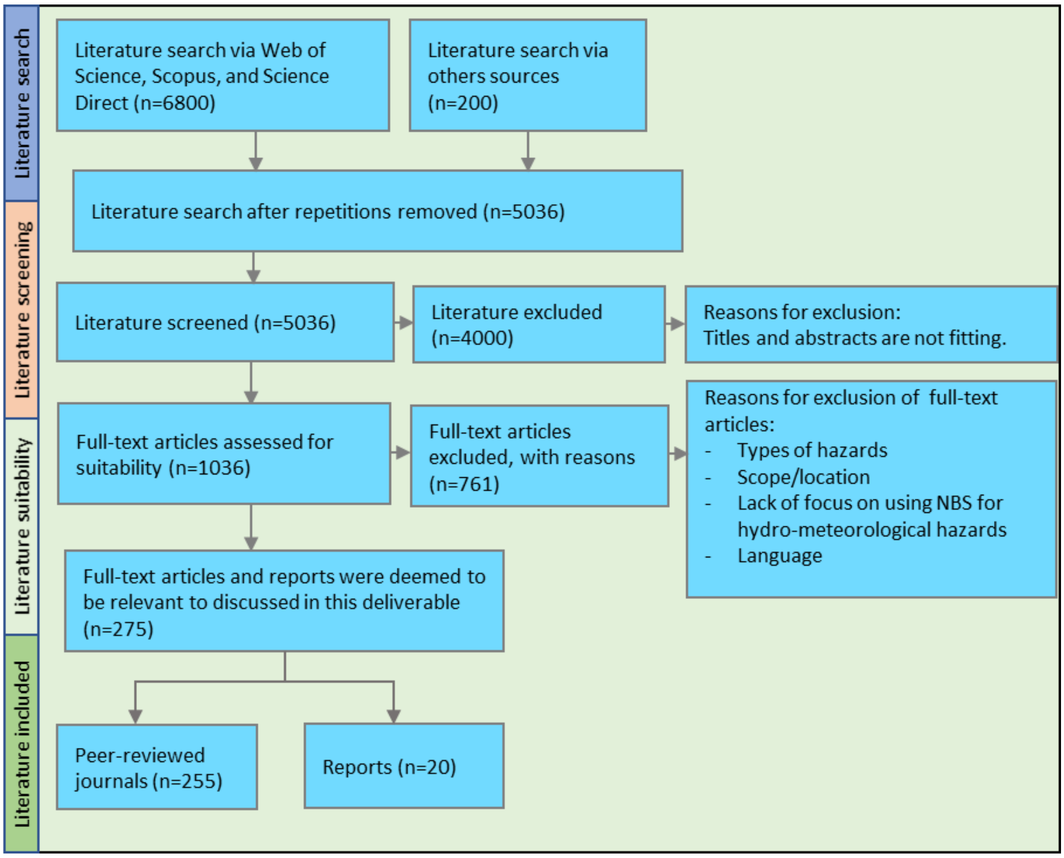

Figure 6: Schematic representation of a systematic literature review (SLR) and reasons for exclusions.

The search resulted in a total of 7000 articles and reports (Figure 6). In the screening procedure, we reviewed all titles, abstracts and keywords against lists of incorporation criteria, as shown in Figure 6. Of 5029 articles, 4000 articles were eliminated from full-text review based on titles and abstracts. We also carried out a further screening to identify the most suitable scientific papers/reports and eliminated 761 papers/reports from 1036 papers/reports based on types of hazards, application of NBS for hydro-meteorological risks management, location and language. Finally, about 275 articles and reports were relevant to analyse and discuss in this deliverable. The distribution of 275 articles among the five hydro-meteorological hazards and their respective NBS has shown the following: (i) 12% (33 of the 275 papers) covered Section 3 (floods and their NBS), (ii) 28% (78 of the 275 articles) covered Section 4 (coastal erosion and storm surge and their NBS), (iii) 18% (50 of the 275 articles) covered Section 5 (increase nutrients and sediment loading and their NBS), (iv) 15% (41 of the 275 articles) covered Section 6 (droughts and their NBS), (v) 15% (42 of the 275 articles) covered Section 7 (landslides and their NBS) and (vi) 11% (31 of the 275 papers) covered other concepts i.e. climate change, systematic literature review, etc. Figure 7 indicates the full-text articles and reports included in this deliverable by year of publication and 2018 was shown to be the year with the maximum number of publications. The SLR was also used to evaluate the reviewed materials according to predefined criteria. Scoring criteria was attended to the following drivers: (1) effectiveness of engineering solutions for hydro-meteorological hazards, and (2) sustainability and resilience of NBS. The former action will culminate with a meta-analysis that will allow evaluating the performance, trade-offs, enabling factors and potential barriers for implementation of existing NBS against hydro-meteorological risks reviewed in various Section of this deliverable.

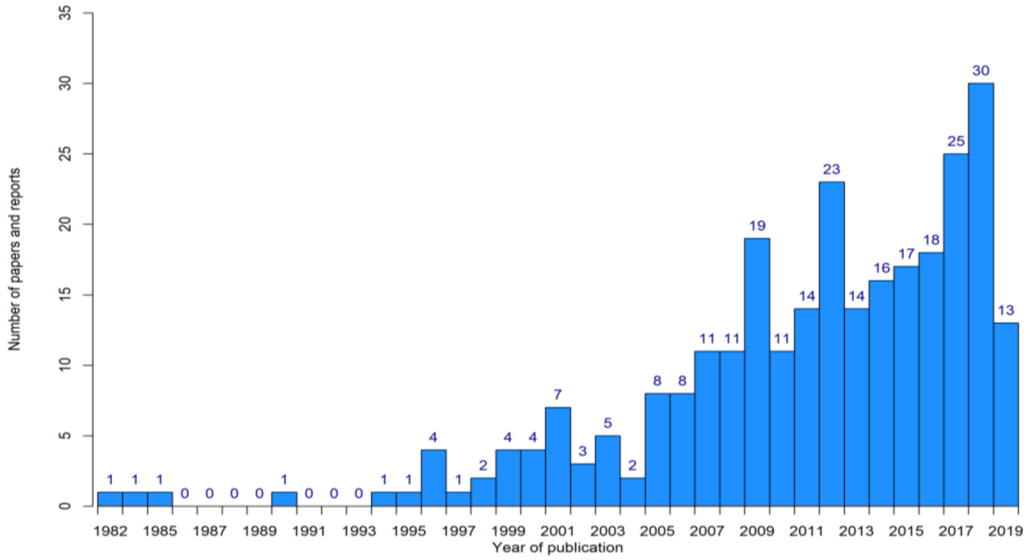

Figure 7: Full-text articles included in the deliverable by year of publication until 2019.

We conducted a comprehensive stakeholder analysis (Section 3, 5 and 6) that involved end users, investors, funders, policy makers, designers, delivery and maintenance bodies, suppliers and influencers. The methodology used to collect stakeholders (Table 3) and group them, foresaw the identification of specific keywords to be used for searches that included coarse level and secondary level keywords and, as a result, a total of 106 stakeholders, 38 classified as primary and 68 classified as secondary, were mapped at seven OPERANDUM OALs. Among them, 79% act at local level, 23% act at national level and 3% act at global level. The type, number and role of the stakeholders vary among the levels (local/national/global), context (e.g. urban/rural, small scale/large scale) as well as NBS specific issues (e.g. technology/method applied). The stakeholders were brought together in an interactive co-creation process combining elements of design-thinking and system-thinking. Ideally, the stakeholders are involved throughout the co-creation process from co-designing the project up to the dissemination including continuous reflection and monitoring.

Table 3: The string of keywords used to record literatures for the review.

Coarse level- keywords	Second level –keywords	
"Disaster prevention"	"Climate change "AND" disaster risk reduction"	"Co-creation "AND" disaster risk reduction"
"Disaster resilience"	"Eco-Disaster Risk Reduction"	"Co-development "AND" disaster risk reduction"
"Disaster risk management"	"Ecosystem-based "AND "disaster risk reduction"	"Coastal erosion "AND" risk management"
"Disaster risk reduction"	"Sustainable innovation "AND" Disaster risk reduction"	"Drought "AND" risk management"
"Ecosystem based adaptation"	"Climate Change "AND" nature-based solution"	"Flooding "AND" risk management"
"Ecosystem functions"	"Hydro-meteorological risk "OR "reduction"	"Increased nutrients "AND" risk management"
"Ecosystem services"	"Climate Change "AND "disaster risk reduction"	"Landslide "AND" risk management"
"Ecosystem-based mitigation"	"Nature conservation "AND" Disaster risk reduction"	"Salt intrusion "AND" risk management"
"Environment Risk Management"	"Environment Risk" AND "management"	"Sediment loading "AND" risk management"
"Green Infrastructure"	"Ecosystem services "AND "policy"	"Stakeholders" AND "perception"
"Hydro-meteorological hazards"	"Hydro-meteorological risk "OR "management"	"Storm surge "AND" risk management"
"Hydro-Meteorological risk"	"Spatial planning"	Blue AND "Nature based solution"
"Landscape quality"	"Environmental planning"	Green "Nature based solution"
"Living labs"	"Sustainable development "AND" disaster risk reduction"	"Hybrid" AND "Nature based solution"
"Natural infrastructure"	"Policy-science-society interface"	"Participatory innovation"
"Natural-Hazard risk"	"Disaster risk reduction "AND" rural areas"	"Participatory planning"
"Nature Based Solution"	"Natural hazard risks "AND "mitigation"	"Sustainable development planning"
"Quantitative risk analysis "	"Nature-based solution" AND "policy" OR "EU policy"	"End-user interest"
"Eco-engineering"	"Plant-soil interactions"	"Cost benefits of nature-based solutions"
"Nature-based solution"	"Quantitative risk analysis"	"Effectiveness of nature-based solutions"
"NBS potential barriers"	"NBS associated trade-offs"	"Interviews and meetings with experts"
"NBS enabling factors"	"Trade-offs evaluation"	"Political AND economic AND social-cultural"
Combined search string		
(TITLE-ABS-KEY ("hydro-meteorological hazards" OR "hydro-meteorological risks" OR "quantitative risk assessment" OR "quantitative risk analysis" OR "climate change" OR "damages caused by natural disasters") AND TITLE-ABS-KEY (flood* OR droughts OR landslides OR coastal erosion and storm surge OR nutrients and sediment loading) AND TITLE-ABS-KEY ("hydro-meteorological risk management" OR "hydro-meteorological risk adaptation/mitigation" OR "disaster risk reduction" OR "disaster management") AND TITLE-ABS-KEY ("nature-based solutions" OR "ecosystem-based adaptation" OR "ecosystem-basedmitigation" OR "ecosystem protection approaches" OR "ecosystem restoration approach" OR "ecosystem based management approaches" OR "ecosystem services" OR "ecological engineering" OR "green and blue infrastructure") AND TITLE-ABS-KEY ("assess (cost-) effectiveness of nature-based solutions" OR "stakeholder acceptance of nature-based solutions" OR "EU policy framework for hydro-meteorological risks and nature-based solutions" OR "political acceptance of nature-based solutions" OR "end-user interest and perception OR "NBS trade-offs evaluation" OR "potential barriers OR implementation") AND DOCTYPE (articles OR credible reports) AND (PUBYEAR > 1982)).		

To identify potential barriers for the implementation of NBS and develop strategies to overcome the barriers, this report applies the *PESTEL* framework. *PESTEL* is an acronym for political, economic, social, technological, environmental and legal factors in which interviews and meetings with experts were analysed in the context of NBS designing, co-design and implementation. The PESTEL framework which is a multifaceted approach in order to assess all the important components needed for a successful designing, implementation and continuity of NBS was discussed in more detail in Section 3. First, stakeholder engagement, interviews and meetings with experts in OPERANDUM OALs are summarized. Then, we analyse the PESTEL factors to assess the influences on projects, products or designing/implementation strategies of NBS in OPERANDUM OALs (e.g. OAL-Greece) including relevant regulations and policies, funds and awareness, the distribution and scale of investment, implementation, difficulties in NBS uptake and project continuity, public concerns, environmental protection issues and the existing shortcomings. In the following Section, we will present a critical review of flooding (Germany, Ireland, Greece, Italy), droughts (Greece, Italy), salt intrusion (Italy), landslides (Austria, Scotland), coastal erosion and storm surge (Scotland, Italy), nutrients and sediment loading (Finland) along with their potential NBS.

3 Flooding

This section aims to identify challenges in designing and implementing flooding NBS and points out the ways to overcome them. For this purpose, we applied SLR given in section 2 and discussed with stakeholders in OPERANDUM OALs to identify barriers and enabling factors that hinder the successful implementation and effectiveness of NBS against flooding. In Section 3.1, we briefly present background information for flooding and NBS from past projects and case studies. Section 3.2 is dedicated to challenges, barriers and gaps associated with the implementation of NBS against flooding. Co-creation and co-designing of NBS along with their challenges with stakeholders from three OPERANDUM OALs are given in Section 3.3.

3.1 Flooding and NBS

Flooding events have been found to have caused the largest annual financial losses globally in comparison to other natural hazards, such as earthquakes and cyclones (Green et al, 2013; Munich Re, 2012). Within EU member state nations (Figure 7), it has been observed that huge loss of life, injuries, damage to property, ecosystems and other significant infrastructure have been sustained due to flooding events (Debele et al., 2019; Sahani et al., 2019). Floods are expected to become more intense in the upcoming years due to future climate changes (Bouwer et al., 2010; Jonkman et al., 2008). NBS have a main advantage over other adaptation strategies to climate change since they have the capability to deliver multiple benefits by bundling ecosystem services and by doing so, generating various social, economic and environmental co-benefits (Martín, 2019).

Next to social factors, climatic factors such as changes in precipitation patterns, storms and changing temperatures and hydrological factors, such as soil moisture and groundwater levels contribute to the global increase in flooding (WWF, 2018). In general, there is an overwhelming dominance of grey approach for flood risk management in the current instruments of governance. Nevertheless, various NBS for flooding exist at different stages of development and implementation (WWDR, 2018).

Typically, the deployment of infrastructural practices due to growth in urbanization, such as channelization of natural streams, culverting of streams under roads and bridges and the construction of stormwater detention basins were utilized to prevent flooding. However, it has been found that NBS can provide equivalent services to grey infrastructure (Bautista and Peña-Guzmán, 2019). In contrast to grey approaches (i.e. dykes, levees, dams), NBS require more (and mostly privately owned) land and more diverse stakeholder engagement. Flood risk management is therefore not only an issue of technical expertise, but also land-use planning, economics, property rights and other disciplines (Hartman et al., 2019).

Examples of NBS for flooding are vegetation pruning, the creation and connection of floodplains, dyke relocation and the creation of storage areas and wetlands, which influences water quality, quantity and risks (WWAP, 2018). These approaches are intended to counter human intervention, restore natural processes and ensure sustainable flood protection (BFN, 2015).

The deployment of NBS such as grass covers and wetlands instead of concrete helps to increase surface roughness which can slow down the flooding waves by increasing the flood retention time. Also, the infiltration procedure can slow runoff velocity as water passes slowly through soil and can help in slowing erosion tendencies that can indirectly reduce flooding (Collentine and Futter, 2018).

In addition to improving biodiversity and ecosystems, NBS measures have an impact on social, economic and cultural sectors (Eggermont, 2015; IUCN, 2015). The success of NBS measures is linked with the environmental and socio-economic conditions of the area in which they will be applied. It is important to assess their long-term effectiveness under climate change projections also. But there is a real dearth of studies that assess the effectiveness of NBS in a climate change context (Martín, 2019). Therefore, the lack of studies and knowledge seems to be a barrier to the successful implementation of flooding NBS.

3.2 Challenges of flooding NBS

For the identification of challenges, NBS in river basins were considered in the three OPERANDUM OALs, Germany, Greece and Ireland. Discussions with OAL stakeholders in those countries can, therefore, be carried out on relevant NBS in the OALs. Beforehand, a strategic literature review was carried out and identified projects were reviewed regarding the type of NBS, expected functionality, expected efficacy, environmental and social benefits, challenges and implementation and stakeholder engagement. By doing so, three river flooding NBS cases were identified, where challenges in the design and implementation of flooding NBS are described.

3.2.1 Dyke relocation

The relocation of dykes is a common measure to reclaim flood plains (BFN, 2015). It increases the size of the floodplain ecosystem and gives the river more space. With dyke relocations, a larger natural area can be used for flooding. Natural processes, as well as the resilience of floodplains, can be improved locally (European Commission,2015, IUCN 2015, WWAP 2018).

Figure 8: Restored floodplain landscape in the OAL Germany in Lenzen (Source: Nabel, 2009).

One of the biggest dyke relocation measures (420 hectares) in Germany took place in Lenzen (Figure 8) which is located in Brandenburg, close to the borders of the states Niedersachsen and

Mecklenburg-Vorpommern. The project combines flood protection and nature conservation. The measures applied included construction of a new dyke, planting of alluvial forest, the establishment of half-open pasture landscapes and profiling of flood channels in the area of the relocated dyke (BAW 2013). The practical implementation began in 2005 and ended in 2009 (Schmidt, 2013). This dyke relocation is considered to be the most extensive at present in Germany. Over a length of 6.1km, 420 hectares of new floodplains were created, offering diverse living conditions for plants and animals (BMU, 2016). According to NWRM (2015), the project shows a successful combination of nature conservation, flood protection and other measures. Because the authorities provided a lot of information about the project, public acceptance was high. During flood events in 2011 and 2013, lower water levels up to 30km downstream could already be observed than during comparable previous events (NWRM, 2015).

During the implementation of NBS in Lenzen, substantial funding was identified as the main barrier. However, thanks to the multifunctionality of the NBS measures (nature conservation and flood protection), it was possible to finance the project through different sources. This was critical to getting the project implemented because the sum of funds from different sources made the project as a whole financially viable (NWRM, 2015). A further barrier to implementation was the public participation process. Mainly issues of hunting and fishing, as well as the accessibility of the area, have been controversial topics. By providing a lot of information about the project, those barriers could be overcome to a large extent(Henry, 2013; NWRM, 2015).

The main enabling factor of the project was the continuous commitment of the main stakeholders. The project was initiated by a few individual regional stakeholders and was then continuously extended. A further enabling factor was the high public and scientific interest in the project. A research project took place beforehand and the reallocation of farmland took place in a constructive way (NWRM, 2015).

3.2.2 Restoration and conservation

Land-use change for restoration or conservation is a common NBS (WWAP, 2018). A well-suited example of river restoration to tackle flooding is the Odense River in Denmark. The river in southern Denmark was channelized and deepened in the late 1940s to improve agriculture. In 2003, different measures (such as wetland restoration and management, floodplain restoration and management) were established to restore floodplain connectivity, as shown in Figure 9. These measures are helping to prevent flooding in downstream towns and cities, and reduce diffuse pollution resulting from flooding in general (Madsen and Debois, 2006; NWRM, 2015).

The project was highly subsidised by public funds and was met with landowner protest (Madsen and Debois, 2006). The unwillingness of the landowners to participate was the main barrier in the project. With several measures, such as land consolidation, these problems could be solved and voluntary agreements with and among the landowners were established (NWRM, 2015). A crucial enabling factor for the project was the financial support of the Danish Nature Agency. As time went by, land prices became much higher and the county had to hold the remaining financing of 50% (NWRM, 2015). For this project, stakeholder dialogue and the financing were the two crucial factors for the successful implementation of NBS.

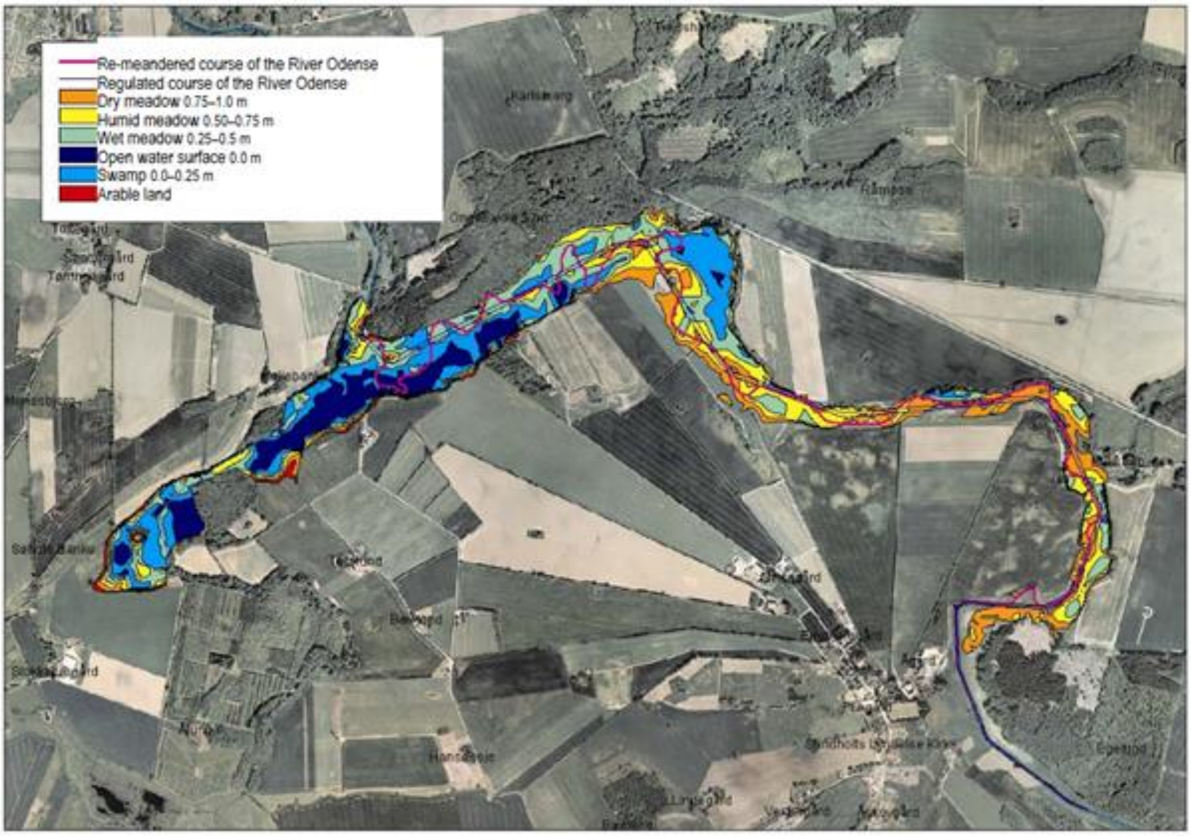

Figure 9: Different NBS measures for the restoration of the Odense River in Denmark (Source: Madsen and Debois, 2006).

3.2.3 Natural water retention

Natural water retention NBS are open areas in the landscape that can temporarily absorb water and thus reduce discharge peaks (WWAP 2018, WWF 2016). An example of a successful natural water retention project is the Fluvial and ecosystem restoration of the Arga-Aragón Rivers systems in Navarra, Spain, started in 2006 (Figure 10).

Due to economic growth and demographic change, the natural resources of the area have suffered over the last decades. The river was shortened by cutting through meanders and dykes and breakwater defences were built to protect agricultural and forestry plantations. Since the 1960s, the struggle against flooding had been getting more intense. To control the flooding and the risks, floodplains were restored, so that they can perform its main function, driving away from the energy of floodwaters by storing them during the flooding process (Magdaleno, 2016; NWRM, 2015). The main barriers to successful implementation were the missing knowledge of the river system, in particular about extreme hydro-meteorological events, the flora and fauna and the actual functioning of the river system. In addition, the coordination between the authorities posed a barrier. The project was still successfully implemented, mainly due to the attitude of the relevant stakeholders, the financing possibility and the “flexible and adaptive management to overcome uncertainties and unexpected deviations from original design” (NWRM, 2015).

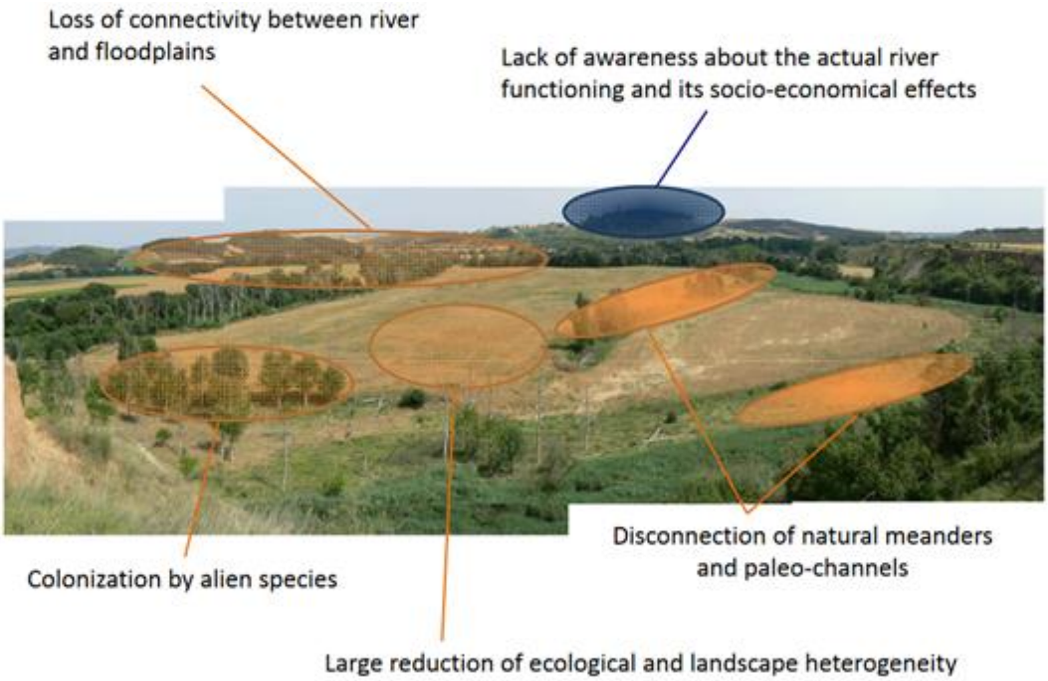

Figure 10: The challenges of the NBS implementation in the Arga-Aragón Rivers systems (Source: CEDEX, 2014).

3.3 Stakeholder discussions

In the Greece, Irish and Germaney OALs, stakeholder discussions about challenges in design and implementation of flooding NBS took place, since flooding is the main hazard under study in each of these OALs. Due to the different framework conditions in each OAL, the stakeholder discussions were carried out using various methods.

OAL-Greece used focus group discussions with stakeholders to reveal and validate barriers or opportunities. These discussions were followed by a workshop. During the discussions, qualitative and quantitative methods were used. In OAL-Germany, the stakeholder discussions took place with one main stakeholder (see Section 3.3.1). With this stakeholder, informal meetings and one risk-assessment workshop took place. OAL-Ireland has regular meetings every month. Additionally, they conducted interviews, surveys, focus group discussions and workshops where among other topics challenges in design and implementation of flooding NBS were discussed.

3.3.1 OAL Germany – Stakeholder discussions: Biosphere Reserve Niedersächsische Elbtalaue

In the OAL Germany, stakeholder discussions are done differently than in other OAL's of OPERANDUM, since for the OAL Germany there is one main stakeholder, who is working in the biosphere reserve management. Within the scope of the project "Kooperatives Auenmanagement", he is in engagement with the local stakeholders.

The biosphere Niedersächsische Elbtalaue is a near-natural and species-rich landscape in which floodplains with flood channels and old water lakes characterize the landscape. A flood protection dyke separates the Elbe floodplains from the Elbe marshland with its main features, such as seepage water and fields, woods and settlements. The expected output of the project "Kooperatives Auenmanagement" is to establish a long-term sustainable management plan which will, on the one hand, determine which parts of the territory - in particular the bank areas - fulfil which function (flood protection versus nature conservation). On the other hand, the management plan will determine which measures (grey vs. green) can secure and preserve the functions of each area permanently; therefore, this supports OPERANDUM goals as well.

A stakeholder in Germany (Dr Prüter) mentioned different challenges for the NBS. Farmers in the region have observed an increase in climatic variability of the seasons in recent years with seasons being drier or wetter than usual. Both anomalies reduce - for various reasons - the quantity and quality of the harvest but also influence flood protection measures such as floodplain management. Since floodplain management is a complex task, the involved persons and institutions have to network more effectively, and new cooperation structures have to be established.

Legal provisions of the various levels, as well as the subordinate state regulations and framework plans based on them, are subject to ongoing updating and revision so that in concrete cases the currently valid legal regulations have always to be applied. The ongoing revisions and updating are therefore a barrier to the implementation since they complicate the implementation.

Further challenges at the beginning of the project are the lack of funding, unclear responsibilities of different authorities, lack of coordination between upstream and downstream areas as well as the conflict between the farmers and government authority, which led to poor management of grasslands and floodplains. Furthermore, the isolation of a small number of plants and animals, wolves threatening livestock and soil contamination by dioxin are challenges for the implementation of the NBS.

3.3.2 OAL Ireland - Stakeholder Engagement: Dublin City Council (DCC)

Tidal flood defences are currently under development on the Dodder River by Dublin City Council's (DCC's) flood protection team. The on-going work is being conducted along the Dodder River basin and the DCC is working up to Donnybrook from the estuary at this moment. The DCC has planned out the framework of the operation, and currently, the plan is to extend the flood protection over a larger area. The DCC team plans to cover both riverine as well as tidal flooding. There is an acknowledgement of pluvial flooding, which has been attributed to an antiquated network. It has been observed that when there is a big flood on the river or tidal flood or heavy rainfall which tends to happen at the same time because of the formation of the low-pressure zone, effect of high tide is extremely critical. The DCC has designated to put in more flood prevention plans in Cabra where there are local areas that floods mainly because the builders squeeze more buildings in and the stormwater pipes are very flat. DCC plans to create a pipe network at the bottom of the hill where all the water will be going down as well as in Ringsend park as there is some flooding in that area from heavy rainfall and from tidal waves as water in those regions has nowhere else to go. The significance of the lands can be attributed to the fact that big monetary value is associated with many places in the region. The city council is planning to put a small defence on the road to the east link adjacent to Ringsend because of severe events of tidal flooding faced in the past. There have been tidal flooding just after the toll bridge on the south side. There is a low area there that floods and that means the whole east link is out of action for a certain amount of time during flooding.

The design and feasibility study was conducted by the DCC along with the talks with the consultants working on all those stages. Based on this study, DCC has identified a couple of preliminary locations to deploy the intervention. DCC has implemented or is currently working on deploying flood defences based on Grey infrastructure as well as NBS to prevent flood risk. One example is the Ashling hotel. However, their main focus at this stage is to treat the water before it gets to the river. They also want to focus on treating the tidal zone as it is heavily polluted.

One stakeholder gave the information that over the past few years he has been working on design, construction and monitoring of flood defence systems in several areas across Dublin. They have a water framework directive that specifically looks at the flooding aspect. The city council plans to use green infrastructure (GI) as NBS to reduce the run-off from sites. The types of GI that are in DCC's plan include bioswales, bioretention, infiltration trenches, stormwater wetlands, green roofs. Currently, Dublin exhibits 2 litres per second per hectare surface water discharge due to rainfall on average, but the goal is to reduce the flow down to zero for normal rainfall within a ten-year timeframe using GI as NBS. The city council is also looking at storing as much surface water in this new development as possible using tree pits and different types of NBS solutions. Also planting different types of trees increases the value of the properties by 10-15% as well, hence local community provide support in these types of solutions. DCC recently received 16.56 million euros for an urban redevelopment scheme and want to use a portion of it on developing flood protection for housing locality.

3.3.3 Stakeholder discussions - OAL Greece

The risks and opportunities relative to the area were first identified through an SLR (see also Section 6). This procedure was carried out through exhaustive research in several studies, scientific papers, reports and previous projects already conducted in OAL Greece. The concept was to focus on the most common hazards of the specific area which causes the hazards, as well as the elements that are exposed and vulnerable to the hazards. Additionally, through the research, the potential opportunities regarding the whole socio-ecological system in the OAL were identified. Thereafter, the plan was to discuss the findings with several groups of stakeholders, in order to validate them and reveal any barrier or/and opportunity concerning the OAL and the NBS implementation.

The strategy followed included a workshop in which a questionnaire with nominal and ordinal variables was distributed, two FGDs – the first one co-organized with WP6 - and several interviews with experts in the public and private sectors. The methods used were constructed with both qualitative and quantitative parts. Regarding the qualitative parts, we chose the FGD method and interviews, among several others, as the most suitable ones, because they help researchers understand how people think (Krueger and Casey, 2000) and why they think in the specific manner (Puchta and Potter, 2004).

It is worth mentioning that the place we decided to hold the FGDs, was a local coffee shop. In Greece, these places serve as enclaves of communal life where forms of collective memories and social representations emerge thus the researcher can derive opinions and views as in parallel the participants share experiences (Lidaki, 2012). Both methods help researchers to generalize conclusions because while people take part in the discussion, talk and interact with each other, the normality of everyday life is revealed (Bloor et al., 2002).

There has been an effort to adjust the research in the PESTEL framework in order to cover all the important components needed for successful project continuity. The discussions and the findings of the stakeholders consultation are analyzed according to the PESTEL Framework as described below.

Political factors

The fragmented and uncoordinated measures implemented by the Regional Government were discussed with experts and local community, and it was pointed out that people are hesitant against projects that study mitigation measures because usually, a top-down approach is followed and the results are limited up to now. When clarified that as opposed to the other projects, OPERANDUM will follow a holistic bottom-up approach and focus on delivering pragmatic results, there was a shift of attitude (Stefanopoulou et al., 2019).

Economical factors

The most important demand of the local community corresponds to irrigation. Their concern is about the cost of water in the process of climate change which is bound to affect the financial viability of their farming enterprises. Although they comprehend and know the multiple benefits of the river for the community, they only focused on economic losses when we talked about risk identification.

Social factors

The catchment basin of Spercheios River extends over a wide geographical area, hence one goal of the research was to consult the local stakeholders in order to limit down the research in specific areas that face the most severe HMRs. We organized a discussion in which we invited members of the local community in order to gather information about their perception of risks previously identified to occur in the area. The specific community residing in the downstream area confirmed what was originally identified by our research; the main risk perceived is flooding. As for seasonal drought, the community in which the FGDs were conducted does not face such hazard and our research will have to be redirected to other target groups that reside further downstream in the catchment (see also section 6.2.5).

Regarding water resources management, which is characterized by reckless use and uncontrolled water waste, the overall impression gathered from the interaction with the stakeholders was very encouraging as they repeatedly stated that it is the first time someone asked them for anything and that they were prompt to participate in all stages of a changing process. Another important remark was that they mentioned several times how important it was to them that scientific information was shared in an understandable manner. They were interested and willing to take part in the decision-making process regarding the design and implementation of measures to mitigate flooding as well as take part in the training process for sustainable water use.

Technological factors

Since there are many interdependent parameters that contribute to water shortages, in order to have a better understanding, we had several interviews with experts that have substantial knowledge of the Spercheios river. The scope of those interviews was to identify the best possible areas for the implementation of the NBS, especially in the case of NBS reconstruction/revival. We gathered detailed information of the sources, secondary/torrential network of Spercheios River and locations of interest concerning floods, and NBS positioning with characteristics that fit the needs of the NBS implementation as well as serve as contributors for irrigation purposes.

Environmental factors

Several semi-structured interviews with experts were conducted regarding the best possible location for the NBS due to actual risks, land use, NATURA area restrictions and land ownership. The experts interviewed were from different disciplines, e.g. hydrologists, meteorologists, the management body of the national park of Spercheios Valley and employees of the environmental office of the regional government.

From the discussion with the local community stakeholders, we came to the conclusion that the members know perfectly well how nature would work if there were no human interventions involved and they were quite sceptical of the measures that have been implemented in the area so far. They also mentioned that there used to be a significant culture of river maintenance by the local community before the implementation of such interventions that disfigured the landscape. This last observation is highly important from our point of view for OPERANDUM as it can generate a completely new perception of maintenance for the designed NBS and decrease the related costs.

Legal factors

Interviews were also conducted with experts and public bodies such as the Forest Service and the Technical Service of the regional government in order to assess the potential barriers as well as the enabling conditions in designing, licensing and implementing NBS. Those interviews proved to have a critical contribution in the optimal positioning of the NBS and in fact expediting considerably the implementation of OAL Greece NBS. The competent authorities have the best knowledge of the area and most of them are the key persons in issuing the work permits required which in OAL-Greece could otherwise have taken quite a long time.

After a brief presentation of OPERANDUM and the ways NBS would potentially improve water availability in the catchment, we had a series of thorough discussions. Those concerned mainly the ways of involving the public bodies' departments and the corresponding experts in the co-design and co-development of the best NBS to be applied in the area and the requirements for issuing the necessary permits. In most cases, we received a very positive attitude against the project as far as bureaucracy is concerned; proactive initiatives to resolve issues and a general willingness to contribute in any possible way as to overcome barriers.

4 Coastal erosion and storm surge

Using a SLR (Section 2), this Section will attempt to evaluate the long-term performance effectiveness, cost-effectiveness, and social perception of a series of ecosystem-specific NBS against coastal erosion due to hydro-meteorological hazards. These NBS include:

- Wetlands and marshes (Section 4.1)
- Oyster reefs (Section 4.2)
- Shoreline vegetation barriers (Section 4.3)
- Vegetated and artificial dunes (Section 4.4)
- Vegetation-induced wave damping (Section 4.5)
- Stone-filled and vegetated gabion baskets (Section 4.6)
- Cobble berms (Section 4.7)
- Beach nourishment and scraping (Section 4.8)

The above NBS have been identified as the best practices in terms of adaptation against risks of coastal erosion and storm surges, and have the potential to be applied at the OAL Scotland (UK) site.

4.1 Wetlands and salt marshes

A salt marsh (Figure 11) includes vegetated marsh plains and entire geomorphic complex. This complex includes marine seabed, marsh plain, marsh scraps and pools within the marsh plain (Ganju et al., 2017). A salt marsh is a relatively cheap NBS, provides eco benefits (flood prevention, trap sediments and filter pollutants) and adapts towards natural hazards effectively (Bacmeister et al., 2016). Salt marshes offer different type of ecosystem services such as buffering capacity. Prasetya et al. (2007) defines buffering capacity as the development of green belts around coast in the form of salt marsh etc. for the prevention of coastal erosion, estimated up to 5 million US$ per km^2 in the United States and 1014.4 million US$ per year for UK marshes (Foster et al., 2013).

Coastal flooding depends on the topography of a region. Coastal erosion potentially affects the storm surge proliferation. Storm surge and coastal erosion are interlinked to each other. Storm surges (and wave forces) lead to coastal erosion, while coastal erosion affects the broadcast of storm surge and consequently spreads the intensity of flooding. A salt marsh protects against floods, storm surge and coastal erosion; it stores sediments, pollutants, nutrients and significant amount of carbon at a geological time scale (Pendleton et al., 2012). Moreover, it is a habitat of plants and animal communities and a hub for recreational and touristic activities (Barbier et al., 2013).

The long-term effectiveness of salt marshes depends on the nutrient, sediment balance, wave energy, storm surges, tidal inundation and sea level rise. Figure 11 shows a sketch of some of the major physical and ecological processes acting on a salt marsh. The survival of a salt marsh is mostly related to sediment availability and management as sediments presence or absence decides the fate of erosion (Ganju et al., 2017).

Salt marshes and large salt marshes in particular are extremely vulnerable and losses have been recognized globally. For example, in England and Wales, salt marsh areal loss has been assessed to be around 83 ha per year (Foster et al., 2013), 105 ha per year for the period between 1993 and 2013 and is projected to be 349 ha per year for the period between 1998 and 2048 (Lee, 2001).

Furthermore, it has been shown that salt marsh erosion is mostly due to average monthly storms, while intense hurricanes contribute to less than 1% to long term salt marsh erosion rates (Leonardi et al., 2018). The storms can affect the salt marsh in short term but salt marsh upset erosion/deposition and sediment import/export within the marshes and surrounding areas in the long term. Furthermore, Zhang et al. (2012) demonstrated that the effectiveness of storm surge reduction depends on specific properties of (1) the storm forcing, such as storm intensity, duration, forward moving speed and storm track, (2) the marsh ecosystem, such as marsh size and soil elevation, vegetation density and continuity, within-marsh channel dimensions, and (3) larger-scale coastal landscape settings, such as off-shore bathymetry, shoreline shape, open coast, back-barrier, estuarine or deltaic setting, levees or dikes behind marshes (Leonardi et al., 2018).

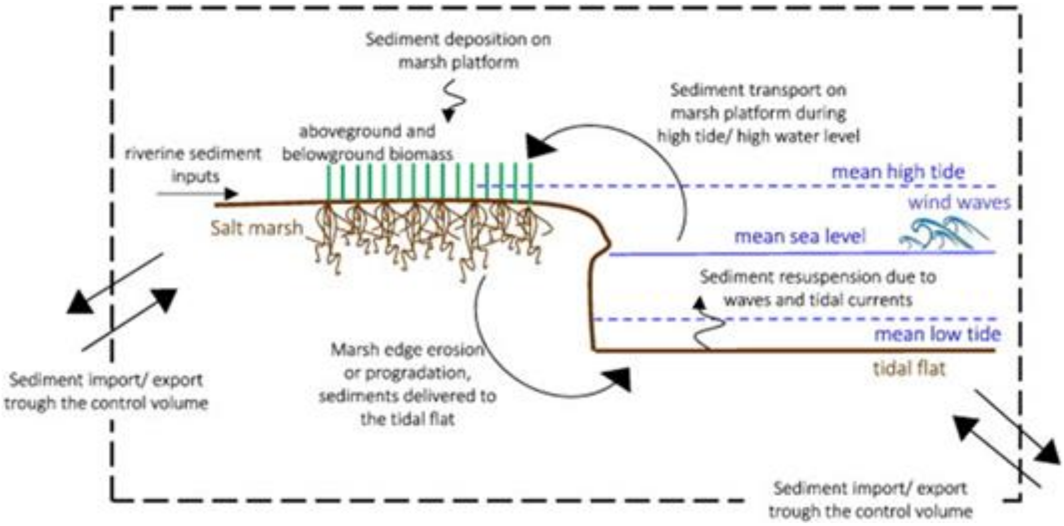

Figure 11: Physical and ecological processes on salt marsh (Source: Leonardi et al., 2018).

The effectiveness of salt marshes highly depends on storm characteristics, as marshes with higher soil elevation effectively reduce the storm speed, lose sediment balance and fail their efficiency towards storm surge (Temmerman et al., 2012). The efficiency of marshes decreases for storms with a longer duration, as the surge has more time to proliferate landward and to fill up the whole marsh area. In terms of marsh ecosystem properties, broader marshes, of at least 10 or more km wide, as well as marshes with a higher soil elevation, are more effective in disintegrating the overflow (Temmerman et al., 2012).

However, salt marshes are more cost-effective as compared to hard engineering structures, as they do not only provide flood risk mitigation but also valuable ecosystem services (Temmerman et al., 2013). Narayan et al. (2016) analysed the costs and benefits of fifty-two coastal erosion management ecosystem-based projects around the world and found that mangroves and salt marshes can be up to five times cheaper than a breakwater and could even become more economic than a series of groynes.

Wetlands can act as a green infrastructure barrier to minimize the risks of floods by storing and slowing down the flood water so that it reaches downstream progressively rather than in a single large flow. Wetlands are considered effective in reducing small and frequent flood events, whereas floodplains can reduce downstream peak flows for more severe events as well. Many climate scenarios indicate an increase in severe precipitation events and demands an increase in wetlands construction for human welfare. However, wetlands are largely neglected by preferring artificial engineered solutions through channelization of rivers (Watson et al., 2016). Wetlands are mostly located in flat plain areas to minimize the speed of flood (Watson et al., 2016). They provide ecosystem services such as carbon sequestration, water quality protection, coastal protection, groundwater level and soil moisture regulation, flood regulation and biodiversity support (Thorslund et al., 2017). They also have a potential to address a variety of environmental, social and economic challenges. There is a continuous decline in wetland areas worldwide, as in Europe and USA wetlands have been deteriorated over the past decade (Thorslund et al., 2017). Yet, wetlands contribute more than 20% of ecosystem services globally, higher than the contributions of terrestrial forests and coral reefs. This signifies the wetlands as a sustainable and cost-effective solution to future climate induced challenges (Thorslund et al., 2017).

4.2 Oyster reefs

Oyster reefs are considered ecosystem engineers, provide economic and aesthetic values to humans. They can provide potential benefits in the form of food (from aquatic habitat), increase in biodiversity, carbon sequestration and coastlines guard (Bayne, 2017). Coastal ecosystems such as oyster reefs are recognized as an important element of coastal defence, as they maintain their own habitat and grow with the sea level rise via biophysical feedback (Bayne, 2017).

A suitable substrate is vital for oysters to grow and protect coastal sites. For the oyster maintenance, shell material and substrate give birth to new self-sustainable generation. Long-term sustainability of oysters depends on the ecosystem engineering species (e.g. salt marsh plants, corals, oysters) and requires knowledge about the life history, population dynamics and habitat requirements of the species under consideration. Such knowledge is crucial to analyse both the predictability and reliability of their coastal protection function (Bouma et al., 2014). Extensive shellfish banks of reefs have the ability to minimize the impacts of direct water flow, extreme waves, storm surges, and can stabilize the shoreline (Bayne, 2017).

Coral Reefs act as a first line of defence from erosion and flooding through wave reduction (Figure 12) and the production and retention of sand (Pascal et al., 2016). Fringing natural reef crests function much like low crested breakwaters, dissipating wave energy and protecting the shoreline (Reguero et al., 2018). Living coral provides the reef with shallower geometrical complexity and more surface roughness that dissipate wave energy through friction and wave breaking (Quataert et al., 2015). Similarly, coral mortality increases the wave energy reaching shores as the reef gives lesser friction to waves and the removal of the coral skeletons increases the depth of water over the reef flat (Reguero et al., 2018).

The instalment of coral reef is a complex process; Figure 13 describes the whole mechanism to recruit reefs on a proposed site (e.g. Grenville waterfront, Grenada). Figure 13a gives an overview of the proposed site, Figure 13b shows custom made barge loaded with baskets and rocks for constructing the breakwater, Figure 13c shows building the reef breakwater, one stone at a time and packing the second layer of baskets at low tide with waves now breaking directly on the breakwater. Figure 13d and e presents submerged view of the pilot units on top of coral reef rubble right after installation with coral transplants evident in Figures 13 (d, f and g). These show details of coral recruitment on bars and fill materials 12 months after installation (Reguero et al., 2018).

Oysters bring many ecosystem services and are abundant and persistent structures of marine and estuarine ecosystems worldwide. Oysters formulate dense three-dimensional reef structures to alter water flow and minimize wave flow and trap sediments. They also provide other ecosystem services as they create a habitat in coastal environments on which complex food webs are based. Oyster reefs are mostly constructed for shoreline protection and erosion control (Walles et al., 2016). Reef building shellfish species such as oysters and mussels also have the ability to trap sediment, reduce current velocities and dampen waves (Borsje et al., 2011). These processes can enhance and maintain adjacent habitats such as salt marshes and seagrasses, further increasing shoreline stabilization (Spalding, et., 2014). The construction of artificial reefs and restoration of natural reefs is often complicated by several factors, including sedimentation, substrate limitation, degraded water quality, predation and diseases which affect the oyster population. Burial by sediment causes significant loss of reef habitat (Bouma et al., 2014).

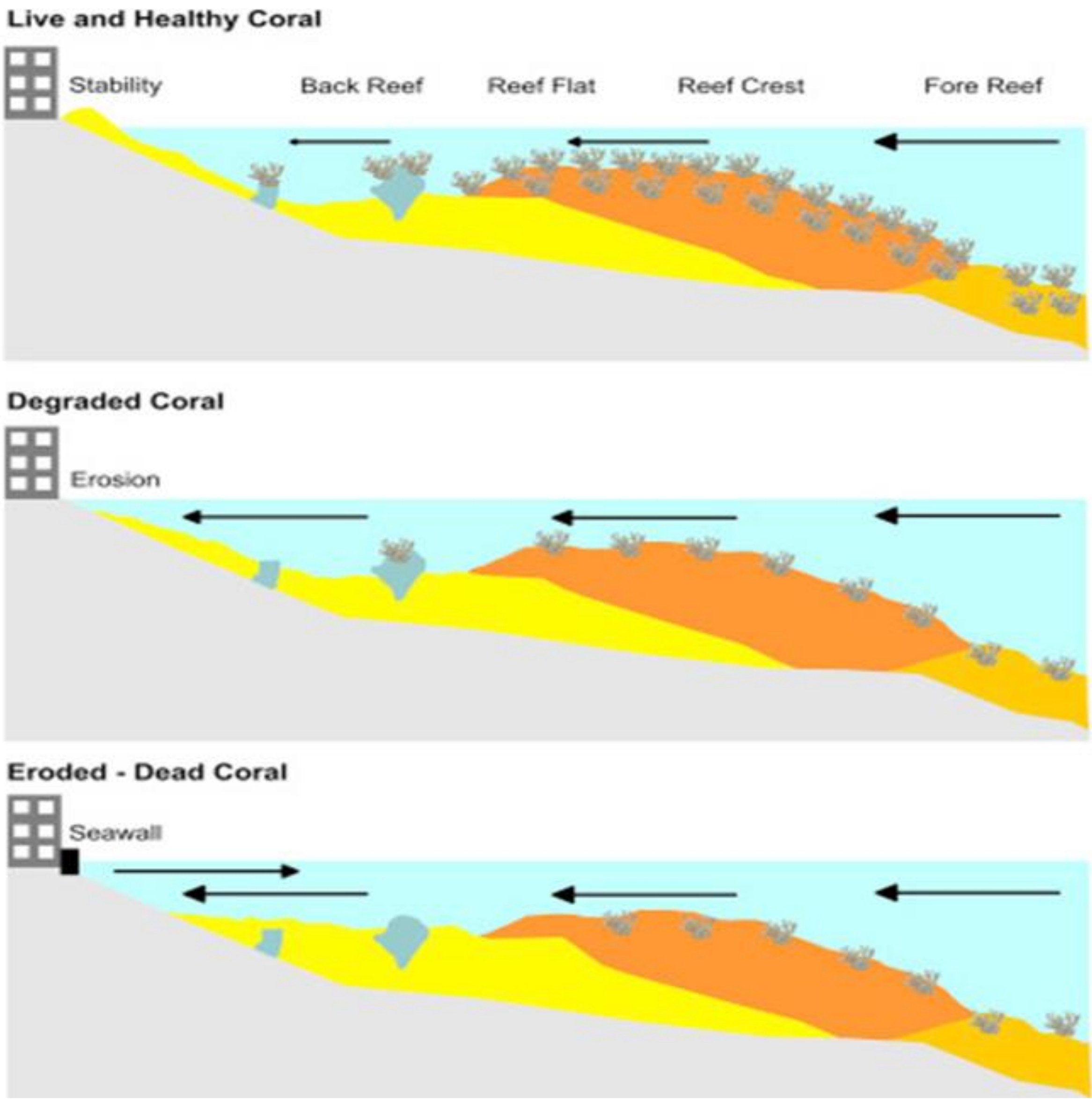

Figure 12: Wave attenuation and coastal erosion protection given by coral under different management scenarios (Source: Gracia et al., 2018).

To avoid sedimentation, constructed reef height needs to exceed a certain threshold. Substrate limitation can be attributed to construction/restoration material unsuitability (Nestlerode et al., 2007). Even after the death of oysters, their shell material acts as a substrate for another oyster's population. In this way, they have multiple natural benefits not only in their life but also after death. A multiple year living reef can buffer for annual recruitment variability. Luter et al. (2016) defines it as an analysis to determine the variation in the quantification of recruitment assemblage structure of corals over a range of spatial and temporal scales on an annual basis), as long-lived reefs add their shell material to reef structure (Walles et al., 2014).

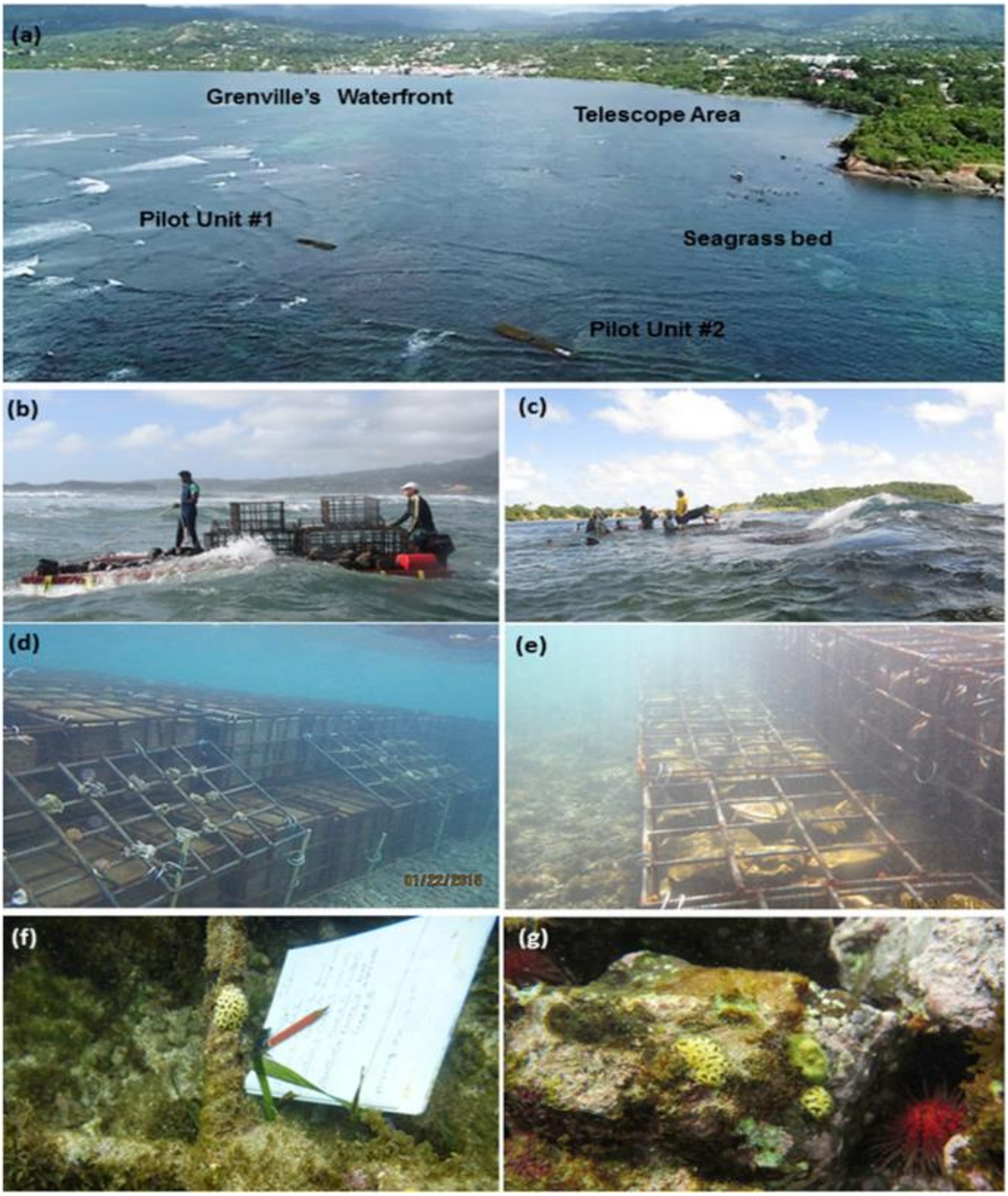

Figure 13: Process of instalment of coral reefs (Source: Reguero et al., 2018).

The long-term persistence of oyster reef determines its ability for incorporation against coastal erosion. In the Dutch innovation program "Building with Nature" five artificial oyster reef, consisting of gabions filled with oyster shells, were built on eroding tidal flats in the Oosterschelde estuary. The objective of this project was to identify reefs potential to reduce erosion on the site and support their own habitat (De Vriend and Van Koningsveld, 2012). This project found that the oysters performed positively on the artificial constructed reef and minimised coastal erosion (Walles et al., 2016).

The physical structure and natural growth of oyster reefs have led to the deliberation of oyster reef breakwaters as a cost-effective alternative to limestone rock breakwaters (Spalding et al., 2014). Living oyster breakwaters are an attractive alternative as they can be constructed using sustainable native materials, have the potential to increase in size over time, and are less likely to require long term replenishment to remain effective (Spalding et al., 2014). Therefore, it can be argued that the coral reefs are cost effective and long-term solution for and coastal adaptation schemes.

Oyster reefs can increase the biodiversity of the intertidal zone by forming a new hard substrate for other species in soft sediment environments. For example, In Bangladesh, oyster farming is used as a management strategy to combat coastal erosion (Walles et al., 2014). The ECOBAS project tested the oyster potential as a way to increase sedimentation, thereby helping to protect vulnerable sectors of coastline against erosion, and to determine their capacity as a sustainable aquatic food source for consumption and trade. The project demonstrated that oyster reefs can induce accretion of sediment on the lee side of the reef. As a result of this accumulation process, salt marsh and mangrove development have been enhanced (Walles et al., 2014).

4.3 Vegetated and artificial dunes

Coastal vegetated dunes are believed to have the capacity to manage and stabilize coastal erosion not only in Europe but also all over the world. Coastal vegetated dunes have the ability to modify and stabilize the physical environment (Gutierrez et al., 2011). For example, marram grass (Ammophila arenaria) triggers dune growth by trapping and stabilizing wind-moving sand as shown in Figure 14a by use of planting in Netherlands (Gracia et al., 2018). Similarly, Figure 14b shows that fencing is an effective approach against coastal erosion in Portugal. Moreover, Figure 14c illustrates the process of thatching in Spain to minimize coastal erosion and flooding. From the above discussion it is obvious that fencing, thatching and planting provide extra strength against waves and coastal erosion (Gracia et al., 2018).

Small plants located on the face of eroded dunes can enhance the natural development above the limit of direct wind or wave attack. Additionally, grasses can be transplanted to encourage the growth of new foredunes along the toe of existing dunes, as long as these species are tolerant to occasional seawater flood. Planting grasses from seed can be undertaken but will not usually be successful along the dynamic foredune environment (Gracia et al., 2018).

There are some significant examples of coastal sand dunes in the city of Natal (Figure 15), Brazil (Luna et al., 2011). The image shows dunes migrating from the beach into the continent. These dunes are classified as foredunes. Similarly, Figure 16 demonstrates a coastal dune field in the state of Maranhao, Brazil. Barchanoids and transverse dunes intercalated by freshwater lagoons extending over several kilometres form the characteristic pattern of this dune field (Luna et al., 2011).

Figure 14: Example of dune stabilization by the use of planting, fencing and thatching at (a) Netherlands, (b) Portugal, (c) Spain (Source: Gracia et al., 2018).

Figure 15: Coastal dunes in Natal and Brazil (Source: Luna et al., 2011).

Figure 16: Coastal dune field “Lençóis Maranhenses” in the State of Maranhão and Brazil (Source: Luna et al., 2011).

Sand deposition in dunes occurs by means of three clear mechanisms (Gracia et al., 2018).

a) Wind energy is dissipated due to a layer of formed vegetation,
b) Sand hits the surface of the plant and is trapped in the same dune and
c) The dense subsoil mat formed by the grass rootlet system tends to bind and stabilize trapped sediment.

Dune plant species, morphology, wind speed and wave action are some factors that affect the dune formation. Vegetation tends towards a natural recovery of resources to resist erosion (Gracia et al., 2018). Once vegetation is fully developed dunes may become self-sustaining, although any erosion damage will need to be rapidly repaired (Gracia et al., 2018).

A good example of dune vegetation as a coastal erosion management strategy is located at Papamoa, a coastal township located on the Bay of Plenty, New Zealand. In the early 1990's, storms severely eroded dunes within a few metres of some property boundaries (Jenks and Brake, 2001). In 1994, following concerns from local residents, a management programme was initiated to improve dune ecosystems. The work focused on restoration of a good cover of sand binding species on the seaward face of the dune, with plantings of several thousand shoots of Spinifex squarrosus and Ficinia spiralis and fertilizer application to existing stands of these species to assist in their recovery and spread. Dune access walk-overs were installed in high use areas to protect sensitive vegetation from human trampling. This management strategy has successfully reached a complete dune restoration, resulting in a seaward dune advance of 10–25m, providing a much wider dune with a more gentle, vegetated and resilient front slope to help buffer current and future erosion (Gracia et al., 2018).

Coastal sand dunes provide a wide range of ecosystem services, such as fresh water, food, fibre and fuel, mineral extraction, etc., regulatory (water storage, storm protection, purification of water, among others), cultural (cultural heritage, recreation and tourism, aesthetic value, social relations) and supporting (soil formation, nutrient cycling and provision of habitat) (Everard et al., 2010). During storms, the protective role of coastal dune vegetation has been acknowledged for almost 50 years (Silva et al., 2016). Beach–dune systems are widely recognized as a bio-structure that protects the coast by building up an elevated barrier and hence providing a buffer between the sea and the land (Silva et al., 2016). Increase in vegetation cover can play a crucial role to achieve long-term resilience against coastal erosion. However, if vegetation cover is abnormally high, it can be vulnerable to erosion, as the profile becomes too steep and near-shore scouring, and eventual sediment export occurs (Silva et al., 2016).

In addition to vegetated sand dunes, coastal erosion management is also accomplished through construction of temporary artificial dunes, which resist against high water levels and waves during the storm period. Moreover, these dunes are constructed on the basis of local experience and with little knowledge of their ability to sustain the effects of different storm types (Seok et al., 2018).

Traditionally, coastlines are protected by sea walls or embankments. During storm surges, the tops of hard engineering structures and top layer of sand are negatively affected (Seok et al., 2018). To minimize sand loss on the coast beaches, soft treatments are used. For example, sand nourishment and artificial sand dunes were used in Haeundae Beach (Korea) to reduce coastal erosion (Seok et al., 2018).

The typical sand-dune dimensions are shown in Figure 17a. To model the artificial dunes, a boundary-fitted orthogonal curvilinear grid with minimum spacing of 5m was used to adequately describe the concave-shaped beach layout and to effectively simulate dune breaching, as shown in Figure 17b and Figure 17c demonstrates rectilinear grid for real-time forecasting with grid size of 30m. This flexible grid structure can interpret beach modification with good accuracy, if reliable data is available. Seok et al. (2018), have reported that, despite some limitations, artificial dunes have great potential to minimize coastal erosion, withstand elevated water level and reduce storm damage.

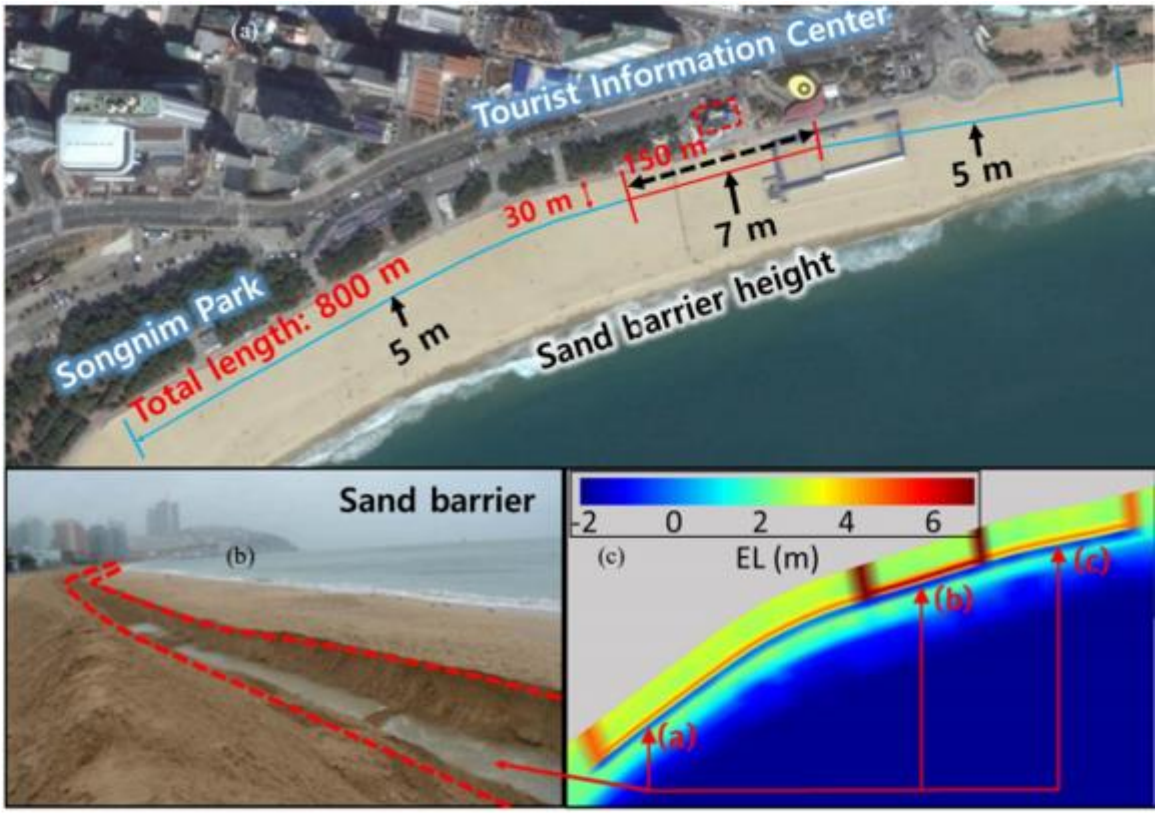

Figure 17: (a) Sand barrier specifications, (b) orthogonal curvilinear grid with minimum size of 5m for simulation of barrier breaching, and (c) rectilinear grid for real-time forecasting with grid size of 30m (Source: Seok et al., 2018).

4.4 Shoreline vegetation barriers

Shoreline vegetation barriers protects the land from coastal erosion and stabilize the shoreline. Vegetated shorelines often comprise an offshore sill (i.e. a low-rising breakwater) with existing, restored, or enhanced marsh plantings (Scyphers, 2015). The sill is typically constructed of marl, granite, or oyster shell and placed below the ordinary high-water mark. Vegetated shorelines can reserve and even improve the services of coastal ecosystems (Gittman et al., 2016); however, most living shoreline projects have been built within the last decade, so there is limited information on the most suitable protection measures for various shoreline energy regimes. There is a common perception that the hard-engineered shorelines are more durable than the vegetated shorelines; therefore, it is necessary for coastal managers to highlight the benefits of natural vegetation barriers over other engineering solutions (Scyphers et al., 2015).

Living shorelines are a green infrastructure technique using native vegetation alone or in combination with offshore sills to stabilize the shoreline (NOAA, 2018). Living shorelines provide a natural substitute to 'hard' shoreline stabilization methods like stone sills or bulkheads and provide several benefits (Figure 18) including nutrient pollution remediation, essential fish habitat provision, and protecting shoreline from waves and storms. Moreover, living shorelines also store carbon, hence, they not only provide protection against coastal erosion, also has the potential to mitigate the effects of climate change (NOAA, 2018).

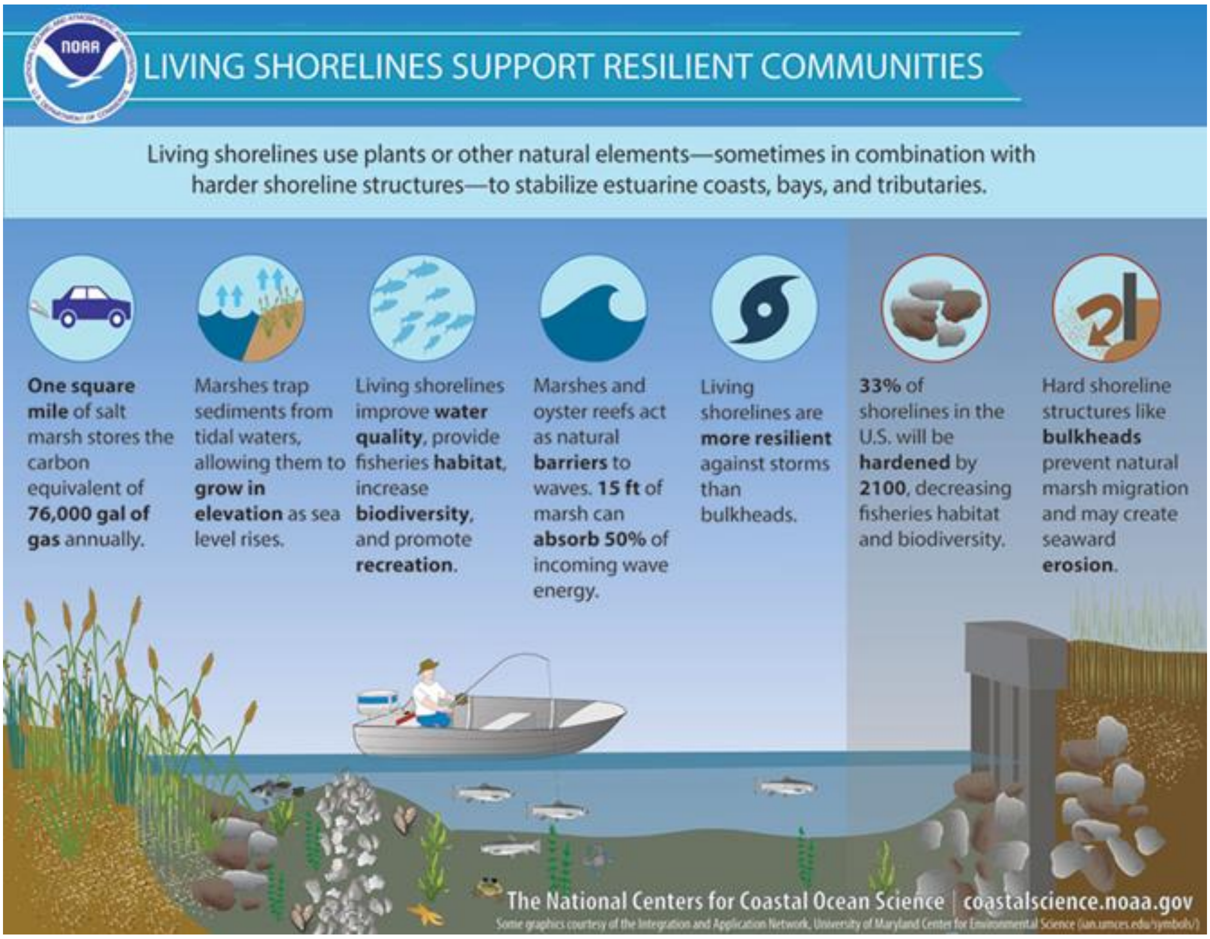

Figure 18: Benefits associated with living shorelines (Source: NOAA, 2018).

The cost of vegetated shoreline can range from 72 to 500 US$ per meter depending on the nature of construction, which is not higher than the hard engineering solutions. This means that the local communities can move towards the vegetated shorelines to achieve desired results at lower cost for better coastal management. Van Slobbe et al. (2013), found that ecosystem-based protection could provide a more sustainable and cost-effective option to flood protection than traditional hard engineered structures. However, some local communities prefer short term engineered solutions over long term sustainable vegetated solution, which not only provide protection but also enhances ecosystem services (reduce wave energy, flood protection, aesthetic value of ecosystem, and stability of land). To add in, vegetated barriers need less attention and maintenance without external inputs, once they are implemented. This type of immediate prioritization can threaten the future of coastal residents and NBS (Smith, 2017). However, Scyphers et al. (2015) revealed that local communities in Alabama, were ready to adopt eco-friendly approaches, if they would be feasible and cost effective. Similarly, Sutton-Grier et al. (2015) also suggested that management and legislation for vegetated alternatives to shoreline hardening could be helpful to enhance the knowledge of local people about NBS. Therefore, it is now imperative to not only conserve coastal habitats but also to adopt management schemes that enhance ecological system adaptability by incorporating living habitats into shoreline defense schemes (Smith, 2017).

Vegetation has been proven to be an effective landslide mitigation measures, as it enhances the soil shear strength via a series of mechanical and hydrological effects (Norris et al., 2008). Soil hydrology is one of the central drivers of shallow landslides, and although precipitation events are often linked to the cause of landslides, it is the change in pore water pressures that cause a slope to fail (Stokes et al., 2014). Moreover, vegetation affects slope hydrology by interrupting rainfall, changing hydraulic conductivity through physical transformation of the soil by roots and transpiring stored water. Root water uptake (transpiration) and evaporation are two main removers of water from the soil layers, with both processes tightly coupled to canopy properties (Stokes et al., 2014).

4.5 Vegetation induced wave damping

Wave attenuation by vegetation is a relatively recent field of study. For example, with respect to mangroves, it is only in recent times that field and laboratory studies have been conducted to study wave dissipation in mangroves (Suzuki et al., 2012). Aquatic vegetation (e.g., mangroves, salt marshes, and seagrasses) play an important role in estuarine ecosystems by acting as a seabed preservative, nutrient sink, and a home for aquatic habitat. They also termed as eco engineers, as they modify physical environment according to the needs of the system (Beudin, 2017). For instance, seagrasses can reduce sediment resuspension thereby increasing light penetration and potential growth (Carr et al., 2010). To analyse the resilience of aquatic vegetation a good understanding of the interactions between vegetation, currents, waves, and sediment transport (Temmerman et al., 2013) is required.

Water waves passing through the submerged vegetation (Figure 19) loses energy by performing work on the vegetation stems, hence it results in smaller wave heights (Anderson et al., 2011). Wave dissipation by vegetation is a function of vegetation characteristics such as geometry, resilience, density, toughness, and spatial coverage as well as wave conditions such as incident wave height, period, and direction (Anderson et al., 2011). Coastal vegetation vary from stands of near monoculture composition (e.g., mangroves, invasive phragmites) to diverse communities with many taxa (i.e., groups of plants, Figure 19) (Anderson et al., 2011). Vegetation-wave interactions are highly interconnected in that the vegetation field is open to variable wave forcing that changes with time as stems bend, flatten to the bed, or are washed out. Due to reliance on different types of coastal plants, the variability of wave damping by vegetation is huge (Mendez and Losada, 2004).

Dean and Bender (2006), applied linear wave theory in the shallow-water limit. This study found that a component of storm surge is minimized by two-thirds in the presence of vegetation as compared to without vegetation. Hence, it can be argued that the potential of vegetation to dissipate wave energy is obvious and Table 4 gives an overview of major coastal species and the wave attenuation perceived in these field experiments (Anderson et al., 2011).

Vegetation barriers have a dual function in terms of the benefits as they recover the riverine ecosystem, delay water flows and capture sediments coming from the hillslopes that needs to pass the riparian zone before entering the channel (Gracia et al., 2018). Coastal storms are generally a combination of extreme water levels, strong winds, large waves, and extreme rainfall. The simulation of these events require accounting for wind-wave-current interactions. The coupled Ocean-Atmosphere-Wave-Sediment Transport (COAWST) modelling system has been successfully applied under various storm conditions in several coastal and estuarine environments (Warner et al., 2010). The wave-flow-vegetation module now allows for quantification of the effects of emergent and submerged aquatic vegetation on storm surge, waves, and sediment transport, which can be used to inform ecosystem-based coastal risk management.

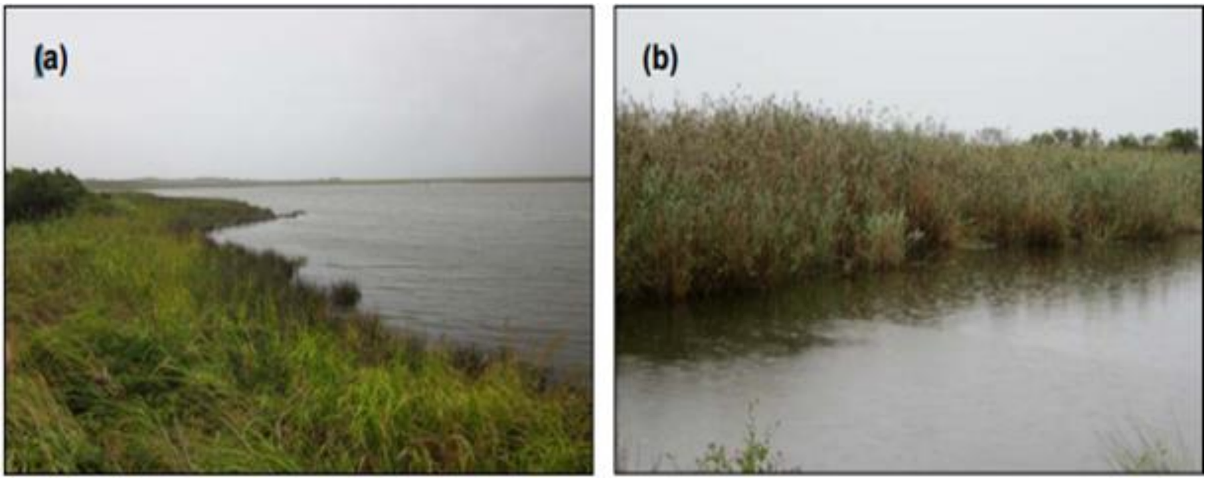

Figure 19: Two marsh plant communities in Currituck Sound, in North Carolina: (a) a diverse assemblage composed of Juncus romerianus, Spartina s , and numerous other taxa and (b) a near monospecific stand of Phragmites Australis (Source: Anderson et al., 2011).

COAWST also integrates a coupled biogeochemical-optical model based on a nutrient, phytoplankton, zooplankton, and a light attenuation model depending on concentrations of suspended sediment, organic material, and phytoplankton (Beudin, 2017). The wave-flow-vegetation module offers a new connection for assessing the hydrodynamic forces on a seagrass bed and the resulting sediment resuspension and mixing in and above the seagrass canopy that affect light availability, and in turn potential seagrass biomass production.

The coupled wave-flow-vegetation model shows that the vegetation modifies the wave characteristics (height, period, steepness, and direction) primarily by wave energy dissipation resulting from the work done by drag force on the vegetation stems, and secondarily by influencing the water level and current fields: (i) any (positive or negative) gradient of free surface elevation across the vegetation patch reduces vegetation-induced wave damping; (ii) wave dissipation rate decreases/increases when waves propagate along/against the current, while the (intrinsic) wave frequency increases/decreases to conserve wave action density which enhances/diminishes wave dissipation by bed friction and vegetation drag. In parallel, waves influence the flow; therefore, waves alter the capacity of vegetation to reduce current speed and adjust water level. This model contributes to an improved understanding of how aquatic vegetation influences the physical environment and, more generally, provides a multidisciplinary tool for informing decision-making of the potential ecological and economic benefits of aquatic vegetation (Beudin, 2017).

Table 4: Field studies of wave attenuation over vegetation (Source: Anderson et al., 2011).

Reference	Transect length (m)	Dominant plant species	Average wave reduction (% per m)
Wayne. (1976)	20	Spartina alterniflora	3.6
	20	Thalassia testudinum	2.1
Knutson et al. (1982)	30	Spartina alterniflora	3.1
Moeller et al. (1999)	180	Limonium vulgare, Aster tripolium, Atriplex portulacoides, Salicorina s , Spartina s , Suaeda maritima, Plantago maritimae, Puccinellia maritima	0.34
Moeller and Spencer. (2002)	163	Limonium s , Aster s , Salicorina s , Suaeda s , Puccinellia s	0.54
	10	Limonium s , Aster s , Salicomia s , Suaeda s , Puccinellia s	4.38
Cooper. (2005)	300	Puccinellia maritima, Salicorinia europaea	0.3
	250	Atriplex portulacoides, Spartina alterniflora	0.26
	110	Atriplex portulacoides, Salicorinia europaea	0.71
Moeller. (2006)	10	Spartina anglica, Salicornia s	1.8
	10	Spartina anglica, Salicornia s	1.4
	10	Salicornia s	1
Quartel et al. (2007)	100	Kandelia candel, Sonneratia sp., Avicennia marina	0.74
Bradley and Houser. (2008)	39	Thalassia testudinum	0.77
Loevstedt and Larson. (2009)	Over first 5-14m of vegetation	Phragmites australis	4.0-5.0

4.6 Stone-filled and vegetated gabion baskets

Wire mesh gabions structures have been applied in the civil engineering for more than 120 years due to their inherent properties (flexibility, permeability, environmental integration, ease of installation), especially in hydraulic applications (Vicari et al., 2013). They offer a technical, economical and esthetical alternative to more traditional solutions such as rip-rap protection, concrete or sheet pile walls and have shown an extraordinary capability for regeneration of the natural environment, since gabions and mattresses are filled with stones, soil and roots which eventually provide favourable developmental conditions (Vicari et al., 2013). Apart from the integration aspects, a recent study (Vicari et al., 2013) has demonstrated how the use of gabions and Reno mattresses is a solution which reduces the impact on climate change, having a lower carbon footprint than one of the equivalent traditional engineering solutions in terms of CO2 emissions (Vicari et al., 2013).

Moreover, compared with traditional rigid protective structure, gabions (Figures 20 and 21) or Reno mattresses have high ability on anti-erosion, better self-permeability, better integrity, better foundation adaptability, strong anti-wave, simple construction, while the multi-pore structure of biological easy to habitat, ecological landscape effect significantly, river training works have a huge promotional value (Vicari et al., 2013). They provide various types of ecosystem services such as restrict pollution, improve water quality, habitat for aquatic plants and animals, maintain the strength of the soil, and reduce the risk of landslides and coastal protection (Vicari et al., 2013). Hence, their ability of anti-water erosion, support in vegetation growth make an effective approach to reduce coastal erosion. Due to their simple construction and lower maintenance they can be an ideal choice for local communities (Vicari et al., 2013).

Figure 20: Gabion baskets installed for slope stabilization along a stream (Source: Freeman, 2000).

Sea walls provide vital flood protection for lowland coastal property. Transportation of sediments at the toe of sea defences weakens the structural integrity of sea walls and is a predominant, serious, and costly problem for coastal erosion in the U.K. and worldwide (Bradbury et al., 2012). Artificially creating narrow fringes of salt marsh in front of existing sea wall structures has shown to be effective in reducing wave energy. Salt marsh suburbs can be created through the installation of gabions (cages of wire mesh filled with stone) to protect the toe of existing sea walls. Positioned to form a solid margin which is then backfilled with clay or sediment to form a terrace (Figure 21) (i.e. a flat strip of raised ground on the seaward face of the sea wall), such terraces have the potential to enhance the local environment by creating new space which can be populated by salt marsh vegetation.

If successfully settled, vegetated terraces could contribute to the dissipation of wave energy and protect the sea wall (Cousins, 2017). Gabion terraces have similar preliminary installation costs; £660 per metre (Miller and Rella, 2009) compared to approximately US$ 701.9 per metre for the concrete blockwork and toe-board protection usually constructed for 'hard' engineered sea wall repairs. Through natural accretion and vegetation growth, the structural integrity of gabion terraces often increases with the passage of time, and they can survive relatively high velocity flows (Miller and Rella, 2009).

In the longer term, plant colonisation of the terraces could be considered successful if community composition were to meet with those found in existing marshes. However, recognising the considerable timescales (decades) required for stable communities of natural salt marsh vegetation to establish (Mossman et al., 2012), in the study it was the appearance of pioneer (e.g. Salicornia sp.) and early perennial (e.g. Atriplex portulacoides) species which were of particular interest. The outcomes of Mossman et al., 2012, could inform further trials of this approach to sea-wall repair, and determine whether gabion terraces can be helpful to identify cost-effective solution to sea-wall maintenance with the additional benefit of providing biodiversity gains for salt marsh communities.

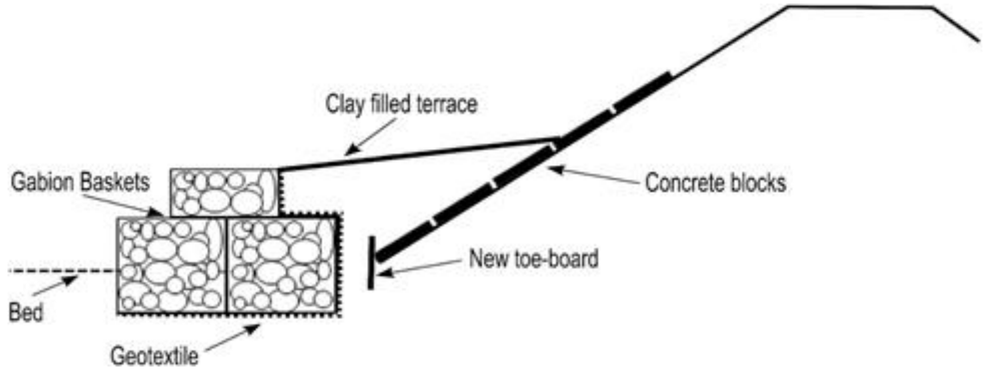

Figure 21: Schematic cross Section of new terraces, backfilled with clay behind stone filled gabions to protect the toe of the sea wall (Source: Cousins, 2017).

Moreover, these gabion – clay infill terrace installations can contribute towards achieving mitigation measure and therefore compliance with the European Directive, as well as being a cost-equivalent option for sea wall repair. Gabion method is one of a range of soft engineering solutions that can also enhance biodiversity as well as providing a sea defence function. The theoretical advantages of the gabion-terrace approach are in the double benefits of securing the defence of coastal land while providing additional habitat for wildlife (Cousins, 2017).

4.7 Beach nourishment and scrapping

Traditional coastal management methods in UK are expensive, time consuming and need proper maintenance mechanism (Frew, 2009). This situation has urged to move towards sustainable protection measures such as gabions, groynes and beach nourishment to reduce the negative impacts of wave storms (Frew, 2009). Beach nourishment can play a dual role in coastal protection such as major defensive way to nourish the beach or as a supplementary infrastructure to lessen maintenance costs and guarantee environmental sustainability (Walvin and Mickovski, 2015). Increment doses of beach nourishment improve coastal protection, with an increase in beach height and provides socio-economic benefits (recreational, tourism, income etc.). For example (Figure 22), Skegness, Ingoldmells, Mablethorpe (all in UK), Ter Heijde, Scheveningen and Zandvoort (all in South Holland) created better socio-economic conditions by using beach nourishment method. Moreover, it can be seen in Figure 22 that beach levels have been improved after four months of beach nourishment, which helped to dissipate wave energy (Walvin and Mickovski, 2015).

The use of groynes (Figure 23) can be helpful for sediment capture along the coast and to control wave currents (Walvin and Mickovski, 2015). Groynes are constructed from different simple material such as wood, rock (Figure 24), timber or bamboo and are normally used on sandy coasts (Prasetya et al., 2007). However, sediment deposition depends on the length of shore and wave speed, which determines the effectiveness of groynes (Dales et al., 2012). Moreover, regular maintenance of gryones is paramount for positive outcomes.

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et al., 2007). However, sediment deposition depends on the length of shore and wave speed, which determines the effectiveness of groynes (Dales et al., 2012). Moreover, regular maintenance of gryones is paramount for positive outcomes.

Figure 22: Beach nourishment sites in UK (Source: Walvin and Mickovski, 2015).

Figure 23: Sand beach with groynes (Source: CCO, 2018).

An offshore breakwater (Figure 25) is a structure across the coast, which functions as a wave absorber and with beach nourishment creates stable pockets along the coast (CCRM, 2018). To add in, it also attenuates wave energy and helps to deposit sediments along the coast (Prasetya et al., 2007). Submerged type break waters are most commonly used to reduce coastal erosion, can be multifunctional for water sport activities. However, breakwaters are large structures, complex to build, and vulnerable towards storm surge (Prasetya et al., 2007).

Coastal squeeze is the largest threat for sandy coastal areas. To mitigate seaward threats, erosion and sea level rise, sand nourishment is commonly applied. The largest threat facing coastal zones and sandy beaches is coastal squeeze (Lewis, 2012). Beaches are trapped between rising sea levels and erosion on the sea side and increasing coastal development on the land side. The resulting narrowed beaches leave no room for inland migration of sandy beaches that would occur as a natural process following sea level rise. Coastal squeeze amplifies the consequences of erosion for the same reasons. As a consequence, sandy beaches may possibly disappear, threatening the developed coastal inland areas. When erosion threatens the physical attributes of sandy beaches, it is often mitigated by beach nourishment. Beach nourishment is generally considered to be an environmentally friendly instrument to combat erosion (Lewis, 2012).

Figure 24: Rock groyne system (Source: CCO, 2018).

Figure 25: Breakwater system (Source: CCRM, 2018).

Beach nourishment is an ecologically sustainable approach, which uses natural material from sand deposits to mitigate beach erosion (Danovaro, 2018). Beach nourishment is a widely utilized solution to offset the erosion of shorelines (Danovaro, 2018). To add in small-scale beach nourishment, appear to be an eco-sustainable approach to contrast coastal erosion. It depends on different factors such as the quantity and typology of the material used, the location of the intervention, the hydrodynamic regime and the season when the replenishment is carried out (Danovaro, 2018).

Sandy beaches are of high socio-economic value. They provide recreational opportunities, are aesthetically valued, buffer the land against extreme wave events, and are the sites of water filtration and nutrient cycling (Cooke, 2012). Additionally, beaches support dense and diverse biological communities of ecological significance. The invertebrates that live under the sand surface provide food for surf fishes and shorebirds and, along with microphytobenthos, are critical in carbon and nutrient cycling. The beach also provides critical nesting habitat for turtles and seabirds (Cooke, 2012).

Many agencies regard soft engineering as the preferred management option since it avoids the negative effects of hard structures on public beach service and coastal ecosystems (Cooke, 2012). However, whether beach nourishment can be considered a long-term solution to shoreline erosion remains to be seen. Beach nourishment projects vary distinctly in their success, judged by volumetric loss, loss rates, planned versus required intervals between nourishment projects and ascertainment of specific project goals (Board, 1995). The effectiveness and impacts of soft engineering are likely to depend on the scale and timing of projects, as well as the source of sediment they use (Peterson et al., 2006). Beach scraping (also referred to in the literature as skimming, beach panning, nature assisted beach enhancement, assisted beach recovery and beach recycling and re-profiling) was the mechanical redistribution of sediment, without alteration of total volume, from the intertidal zone to the backshore (Cooke, 2012).

Over 20 years, consistent with the design life of De Zandmotor, smaller scale interventions are as efficient at reducing erosion as a mega-nourishment scheme, making them more cost-effective over shorter management time frames due to the lower implementation costs. Designing a nourishment scheme such that it works with the natural environment to maintain a high level of resilience ensures long-term costs associated with the intervention are minimised (Brown et al., 2016). The value of larger mega-nourishments is thus more likely to be appreciated beyond a 20-year timeframe. Over time different costs are associated with coastal schemes. Initially there is the build cost, which is followed by monitoring and maintenance costs (Brown et al., 2016). The frequency of maintenance will vary over the life of a scheme due to long-term degradation and/or changing storm impact. Where beaches are nourished recharge is often on an annual or 2–3-year timescale. With a changing climate the nourishment frequency (Cooke et al., 2012) and the need for defence is increasing.

Hard engineered structures can be built and raised in response to changing conditions, but they are environmentally and financially unsustainable. Mega-nourishment has the potential to maintain resilient beach levels as is evolves over time with the natural conditions, reducing wave impact on existing or new hard structures. However, the initial build cost will depend on the availability of large volumes of appropriate material. In locations where the appropriate material can be sourced this approach has the potential to be more cost-effective than hard engineering, with minimal maintenance costs as natural energy is used to redistribute the sediments. With beaches becoming squeezed softer interventions are also valuable in terms of socio economics (Cooke et al., 2012) and ecosystem services. With a low public 'willingness to pay' cost-effective solutions are required by local authorities, as found in the study area (Brown et al., 2016). Thus, there is a need to explore new alternative approaches to flood and erosion risk management that build with nature.

4.8 Cobble berms

Cobble berms (Figure 26) are mounds of rounded rock sorted and shaped by wave action (Hapke, 2006). They are most prevalent at river and creek mouths but also form at the base of cliffs, whether as lag deposits (typically below sandy beach and exposed when the sand scours away) or as higher, well-developed berms that extend to higher levels of wave run-up. Cobble berms have been successfully installed as Natural Shoreline Infrastructure at both Surfers Point, Ventura, and Chula Vista Bayfront in San Diego Bay. Where cobble deposits naturally occur, cobble is seasonally exposed or covered with a sand layer. In areas where cobble deposits are not naturally occurring, cobble berms are referred to as dynamic revetments. A few examples of where dynamic revetments have been successfully installed include: Ocean Beach (San Francisco, CA), Chula Vista Bayfront (San Diego Bay, CA) and Cape Lookout State Park (OR) (Hapke, 2006).

The use of cobble berms as Natural Shoreline Infrastructure is suitable on both open, swell exposed coasts and sheltered waters. Cobble berms provide shore protection for the backshore (e.g. bluff, shoreward natural habitat or human infrastructure) by dissipating wave energy and reducing overtopping events. During extreme events or particularly erosive conditions, cobble berms can also serve as a "backstop" in terms of limiting the landward extent of erosion (Hapke, 2006).

Cobble sediment size typically ranges from 150 to 600mm. Larger sediment sizes are associated with higher wave exposure, while smaller sizes, closer to gravel, can be used in berm formations for sheltered waters. The use of gravel on open coast environments would be considered more suitable for beach nourishment, rather than berm construction (Hapke, 2006). Sediment eroded during large storms typically gets deposited in protective offshore bars that cause waves to break farther away from vulnerable property and infrastructure. Deposited sediment then returns to the beach system over the summer season (Hapke, 2006).

Cobble berms have great potential for coastal management, as cobble-sand-gravel is highly absorbent and resists towards storm surge for a longer period of time (Frandsen et al., 2015). Beach morphology depends on the hydrodynamic conditions and developed under the regular constant waves. However, irregular wave conditions reduce the morphological features of cobble berms. A fully established cobble berm dissipates the wave energy over a longer distance by creating irregular water breaks (Frandsen et al., 2015). Hence, it can be argued that the tidal effect is beneficial for cobble berm morphology. The beach slope-change patterns are managed by high wave energy events and independent from the initial beach slope. Thus, nourished beaches (cobble berms) levels the wave tide by reducing the overall beach slope with a major reduction in beach width (Frandsen et al., 2015). However, beach width is stabilized with the passage of time with a significant reduction in coastal erosion (Frandsen et al., 2015).

The ecological functions of cobble berms vary by whether cobble is native or non-native to a project site (Hapke, 2006). Non-native cobble berms serve primarily as coastal defense mechanisms. Native cobble berms; however, provide habitat equivalency for marine invertebrates and other organisms while alluding to more natural landform. Traditional armoured approaches, such as rock rip rap or solid seawalls, provide neither of these benefits. They can be utilized with other natural shoreline infrastructure types in a “layered” approach, reducing wave energy and erosion at common water levels so that landward Natural Shoreline Infrastructure (e.g. sand/cobble berms on the beach, marsh sills) are able to function optimally during extreme events (Hapke, 2006). Overall, we reviewed the best practice of NBS implementation against coastal erosion and storm surge. Based reviewed studies and projects, a summary of some of addressed WP1 and task 1.1.2 objectives are presented in Table 5.

Figure 26: Cobble Berm Installed at Surfers' Point (Source: CRT, 2018).

Table 5: Summary of planned and achieved objectives in subtask 1.2.2.

WP1 objectives related to task 1.2.2	Mapping against this Section
To map existing NBS implemented in Europe and worldwide.	Eight the most common used NBS for coastal protection against erosion and storm surge have been critically reviewed based on a number of case studies worldwide.
To categorise the NBS according to specific hydro-meteorological risks.	All NBS reviewed in this Section are categorised for coastal protection against erosion and storm surge.
To identify, prioritise and assess data gaps in terms of parameters and spatial and temporal scales.	*Salt Marshes:* topographic survey (shape, elevation) and landscape settings; wave forces/energy/height; sea levels/bathymetry; short- and long-term efficiency; nutrient availability; sediment balance; tidal inundation; storm duration/intensity/speed/track; wetland size; vegetation density and continuity. *Oyster reefs:* substrate suitability and limitations; species suitability and limitations; life history, population dynamics, habitat requirements; surface roughness; wave height/energy/forces; bathymetry; storm duration/intensity/speed/track; sedimentation rate/intensity/location; water quality; predation rates; disease rates; reef structure in short- and long term. *Dunes:* plant species and morphology; topography and terrain morphology; wind speed/direction; wave forces/height/energy; natural recovery rates; vegetation cover extent in short- and long term. *Shoreline vegetation barriers and damping:* plant species habitat and tolerance, substrate limitations and suitability, wave height/energy/forces; storm duration/intensity/speed/track, water quality, root water uptake, transpiration rates, soil permeability and water retention characteristics, sedimentation rate/transport, currents/tides; spatial coverage and density of vegetation; wave dynamics and characteristics; wind characteristics; nutrient availability and distribution; organic material content; bed friction and vegetation drag. *Gabions:* topographic survey (shape, elevation) and landscape settings; wave forces/energy/height; sea levels/bathymetry; currents/tides; soil properties, gabion fill properties, wire mesh properties, currents/tides; bed friction; storm duration/intensity/speed/track; sedimentation rate/intensity/location. *Beach nourishment and scrapping:* shore length/topography, wave forces/energy/height; sea levels/bathymetry; currents/tides; soil properties, storm duration/intensity/speed/track; sedimentation rate/intensity/location/source; erosion rates; scale and timing of the intervention. *Cobble berms and dynamic revetments/breakwaters:* source and type of cobbles (fill material); permeability and gravity of fill material; shore length/topography, wave forces/energy/height; sea levels/bathymetry; currents/tides.
To determine a matrix of elements required to fill these gaps.	1) Design standards including specifications and bills of quantities; 2) Quantification of benefits of NBS over traditional 'hard' engineering solutions; 3) Centralised database(s) of (un)successful application of NBS against erosion and storm surge and 4) Data standards - sampling, monitoring, reporting, management, formatting;
To analyse both enabling factors and potential barriers towards the implementation of NBS in the 7 OALs and the identification of strategies to overcome such barriers;	1) *Enabling factors:* cheap, use of sustainable materials, eco-beneficial, advances biodiversity, carbon sequestration, less likely to require maintenance/replacement/replenishment. 2) *Potential barriers:* land take, data intensive design, no existing standards, siting restrictions, species restrictions, species salt tolerance, human intrusion; lack of expertise and/or qualified labour for installation and monitoring; 3) *Strategies to overcome barriers**:*** management programmes at local, national and international level; awareness raising; community engagement
To pave a strong foundation for project activities relating to the design and implementation of NBS, their evaluation and evidence to the users as well as establishing the basis for their market uptake and exploitation activities.	1) *Design and implementation:* co-design involving SMEs, academic partners, and communities should be undertaken to explore one/several of the viable options. Implementation should be based on the same concept (co-implementation). Where the costs/scale precludes full implementation, pilot studies should be undertaken and supported by numerical modelling. 2) *Evaluation and evidence to users:* (un)successful interventions to be recorded from inception to monitoring stage so double-loop learning can be achieved. 3) *The basis for market uptake and exploitation activities:* costs of design, implementation, and monitoring should be collated for all employed NBS and, to achieve comparability, should be presented both in a monetary and CO_2 footprint form.

5 Increased nutrients and sediment loading

Using the methodology given in Section 2, the focus of this Section is to: (i) map the NBS deployed in OPERANDUM OALs, in Europe and worldwide; (ii) map the knowledge of NBS efficiency in reducing the element loads; (iii) identify and prioritise gaps in the knowledge of NBS efficiency in terms of elements and spatial and temporal scales; and (iv) identify enabling factors and barriers for NBS deployment and solutions to overcome the barriers. Furthermore, by using SLR and interviewing experts in the OAL countries, the environmental, economic and social factors and planning tools enabling or making barriers for NBS deployment against nutrients and sediment loading as well as ways to overcome the barriers are identified. In addition to this, an expert evaluation in the OAL countries are carried out to identify and prioritise gaps in the knowledge of NBS efficiency against hydro-meteorological hazards. From Sections 5.1 to 5.4, we presented a background information that is relevant for triggering the excess nutrient and sediment loading. In Section 5.5 we outlined the NBS which are potential to deploy in OAL, Europe and worldwide. Section 5.6 gives knowledge of the efficiency of NBS in reducing the element and suspended solids loads. The identified factors and barriers which prevent deployment of NBS and ways to overcome the barriers are given in Section 5.7. The lists identified knowledge gaps related to the NBS are presented in Section 5.8.

5.1 Increase nutrients, sediment loading and NBS

Activities related to forestry results in increased nutrient (N and P) and sediment loads (we use term suspended solids onwards) to the recipient watercourses, and further deterioration of water quality. Effect maybe even stronger because of the high precipitation events, after long dry and warm periods and during snow melting period in spring. In the future, climate change may induce more changes in hydro-meteorological conditions, and therefore increase leaching of elements and suspended solids (e.g., Inkala et al., 1997, Nazara-Sharabian et al., 2018). The use of NBS in operated forest area may mitigate deterioration of water quality in recipient water bodies.

There are several potential NBS available to mitigate export of nutrients and suspended solids caused by harvesting, for example, riparian buffer zones, constructed wetlands, peak flow control structure, sedimentation ponds and pits, overland flow area, submerged dams, breaks in cleaning. In addition, it is possible to control suspended solids and nutrient load with forest management regimes, for example, using continuous cover forestry method (CCF) instead of clearcutting. CCF is a forest management regime without clear-felling. The term clearcutting/clear-felling is defined as a forestry/logging practise in which most or all trees in an area are cut down.

5.2 Forest practices effect on soil and water quality in recipient water bodies

In general nutrients and suspended solids loss from forested catchments are low (Kortelainen and Raikkonen, 1998; Mattsson et al., 2003) but after forest operations, such as harvesting, their exports usually increase depending on the:

- Site related factors
  - climate;
  - topography and
  - soil (mineral/organic).
- Treatment related factors

- the intensity of the harvesting;
- amount and composition of harvested biomass;
- the extent of the harvested area and
- proximity to watercourses.

For example, loads from peatland dominated (organic soil) catchments are higher than from mineral soils dominated. After harvesting more precipitation reach the forest floor because there is more uncovered soil. Infiltration of precipitation into the soil depends on surface roughness and porosity, which are strongly altered by harvesting and soil preparation. The logging residues are subject to mineralization and the organic matter that is already incorporated into the soil may be subject to increased mineralization as a result of changes in soil temperature and moisture conditions and nutrient cycling after harvesting (e.g. Smolander et al., 2019). The nutrients, which have been released from the soil may be taken up and cycled by microbes and plants, retained in the soil through cation exchange reactions or leached with dissolved organic carbon.

Leaching of elements to the recipient watercourses has long lasting effects on water bodies. It is also very likely that inputs of suspended solids and nutrients such as N and P to the aquatic systems will increase in the future as a result of climate change. Due to the climate change has been predicted more frequently occurring extreme hydro-meteorological events such as increased heavy rainfall (IPCC, 2014). The magnitude and timing of the extreme events affect also biogeochemical processes in water bodies. Because N and P are limiting nutrient resources for plant and microbial growth in most boreal waters, the excess N and P input into watercourses may lead to nutrient enrichment, eutrophication, which is a common environmental problem in Finnish inland waters and coastal areas of Baltic Sea. Eutrophication has substantial effects on ecosystem function and composition, including algae blooming (excessive growth of algae) and water quality deterioration, resulting in changes in the aquatic flora and fauna.

The Lake Puruvesi, the OAL-Finland (Figure 1), is known from its clear water and excellent ecological status. Nevertheless, eutrophication has increased around the large and shallow basins of Lake Puruvesi. This is especially alarming in Vehka-Kuonanjärvi sub-catchment, which is surrounded mainly with drained peatland forest. Conducted forest operations have increased nutrient and suspended solid loads to the lake; today the former sand bottom of the lakes has a thick sediment layer above with high phosphorus content, the colour of the water has changed from clear to turbidity and ecological status of the lakes of Vehka-Kuonanjärvi sub-catchment is only moderate (Tossavainen, 2019). In anoxic conditions, which may prevail in the bottom of the lake, phosphorus does not bind to the bottom sediments, on the contrary, it starts to release and cause eutrophication of the lake. Furthermore, phosphorus rich sediment moves easily forward, for example, during the strong winds, to the bigger lake basin and onwards to the other parts of the Lake Puruvesi which may cause eutrophication of large areas. Eutrophication of the lake has negative effects on recreation, fishing and biodiversity of the area.

5.3 Climate change

Climate change alters climate conditions, including temperature, rainfall and the frequency and magnitude of extreme weather events. Over the next 15 to 20 years the latter will have the most important impact on European regions (Figure 27). Droughts and peak summer temperatures will be an increasingly frequent event in the Mediterranean regions, while winter floods and summer droughts will become more common in continental Europe. Storms and heavy rainfalls, as well as mild winters, will change biophysical conditions in Western Europe, in north Europe winters will be milder and summers warmer, precipitation will increase especially during wintertime (EEA, 2017).

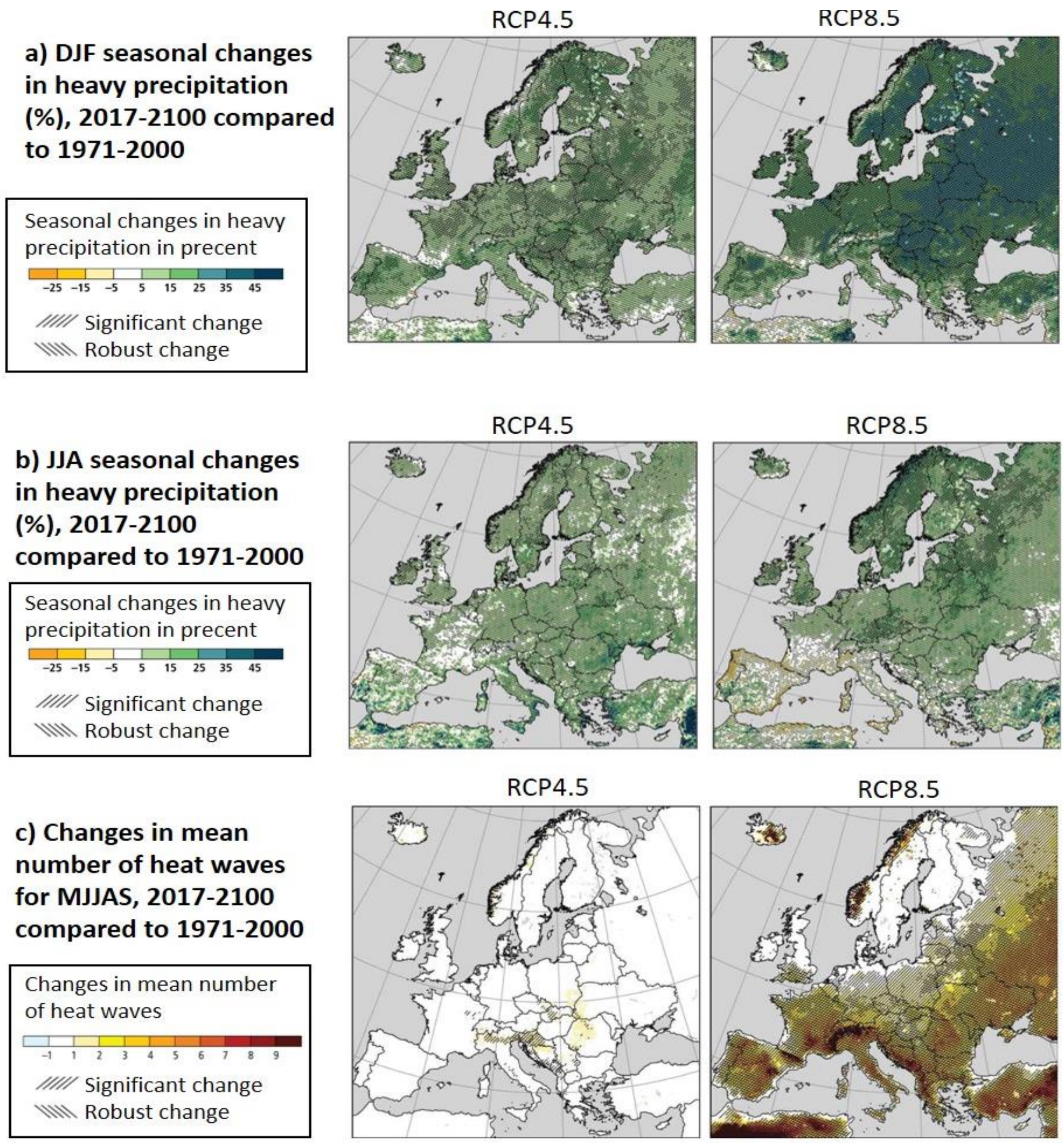


Figure 27: (a) and (b): Projected seasonal changes in heavy precipitation is defined as the 95th percentile of daily precipitation (only days with precipitation >1mm/day are considered) for the period 2071–2100 compared to 1971–2000 (in %) in the months of December to February (DJF) and June to August (JJA). (c) Projected changes in the mean number of heat waves occurring in the months May to September for the period 2071–2100 compared to 1971–2000 (Source: Kovats et al., 2014).

In Figure 27, heatwaves are defined as periods of more than 5 consecutive days with daily maximum temperature exceeding the mean maximum temperature of the May to September season of the control period (1971–2000) by at least 5°C. Hatched areas indicate regions with robust (at least 66% of the models agree in the sign of change) and/or statistically significant change (significant on a 95% confidence level using Mann–Whitney U test). Changes represent the mean over 8 (RCP4.5, left side) and 9 (RCP8.5, right side) regional model simulations compiled within the Coordinated Downscaling Experiment – European Domain (EURO-CORDEX) initiative (Jacob et al., 2014).

5.4 Forests

5.4.1 Global

Forests are found in all climate zones except the coldest and driest (Figure 28). There are three main forest zones that are separated according to their distance from the equator: the tropical, temperate and boreal forests. In addition, there are more specific forest types within these large areas, such as a subtropical forest. About 60% of the world's forests are primarily or partially used for the production of wood and non-wood products. Forest practices induce increased leaching of nutrients and suspended solids regardless of where the forest is located.

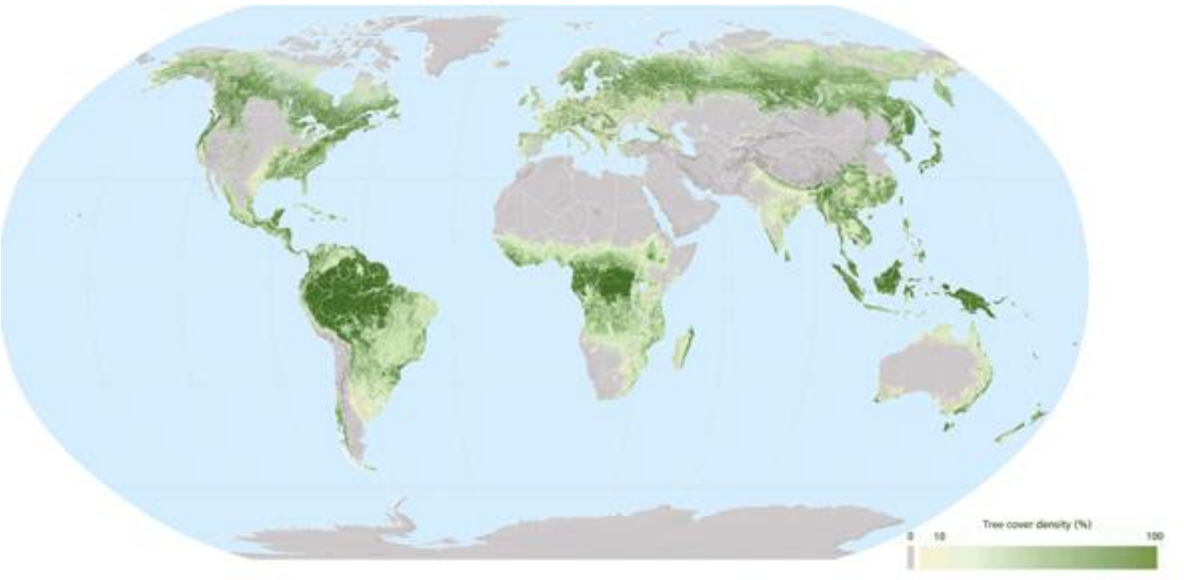


Figure 28: World's forest cover density in percentage (Source: FAO, 2010).

5.4.2 Europe

Forest Forest area in Europe varies greatly. In Finland, Sweden and Slovenia forest cover of the land area is greater than 60%, while for example in the Netherlands and the UK it is only 11%, and in the South part of Europe, it is less than 24%.

The subregion of Northern Europe includes countries of Finland, Norway, Sweden, Denmark, Iceland and Ireland as well as the Baltic countries of Estonia, Latvia and Lithuania. Representative vegetation zones include alpine, subalpine, boreal, boreal-nemoral and nemoral zones. The majority of the forests are coniferous (Figure 29a), predominantly Scots pine (*Pinus sylvestris)* and Norway spruce (*Picea abies*), which are often mixed with broad-leaved trees such as birch (*Betula sp*.) and quaking aspen (*Populus tremula*) (FAO, 1997). Southern parts of North Europe broad-leaved trees such as oak (*Quercus robur*), beech (*Fagus sylvatica*) and elm (*Ulmus sp.*) become more common. Historically, forestry has played a major role in the economies of Finland, Norway and Sweden.

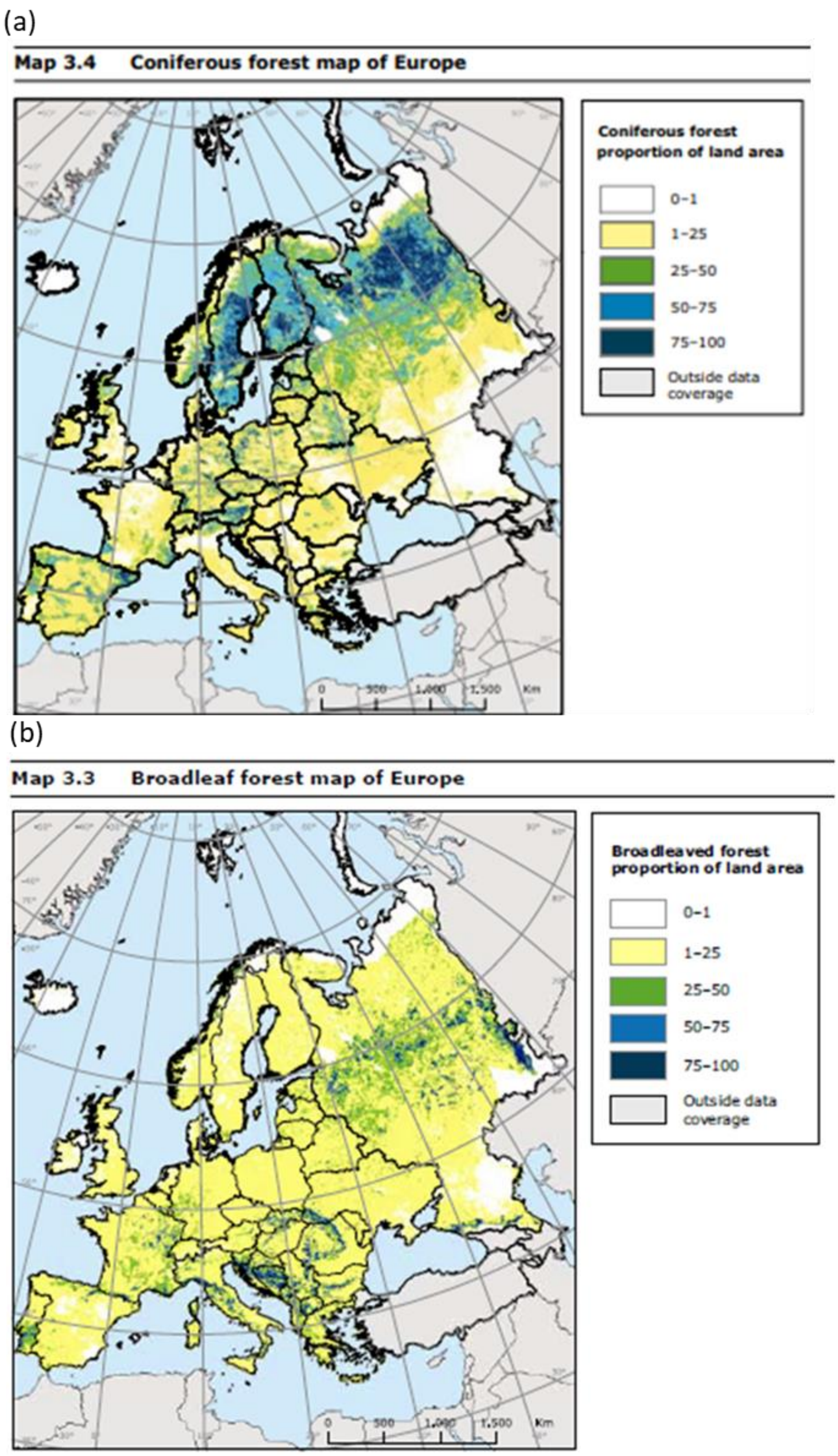


Figure 29: Coniferous (a)and broadleaved forests (b) in Europe (Source: EEA, 2006).

In central and south parts of Europe have more mixed forest than in north Europe, but especially in eastern part of Europe share of coniferous forest is still high (40%), while in western part of Europe share is less than 30%, broadleaved forest being more dominating, such trees as oak (*Quercus sp.*), maple (*Acer platanoides*), beech (*Fagus sylvatica*), elm (*Ulmus sp.*) and ash (*Fraxinus excelsior*) being common (Figure 29b). Broad-leaved tree species dominates also in the south-east part of Europe. Historically forest has been important in Central and South European economy, even so, that most forests was cut down for agriculture, building material, heating or other purposes before 1900 century, which after large areas have reforested. Today forest plays still an important role, especially in the economy of Germany, France and Poland.

5.5 NBS against nutrient and suspended solid loads in Europe and worldwide

The purpose of carrying out NBS (Tables 6 and 7) in a forested area is to mitigate nutrient and suspended solid export from the forest after forest management practices and furthermore be prepared possible extreme weather events, which in the future can in unexpected ways to increase exports of the suspended solids and nutrient load. The most efficient NBS have constructed wetlands (CW) and overland flow areas (OLF) (also known as wetland buffers). Their efficiency is based on that they can besides slowing down water flow and enabling sedimentation of soil particles and adhered nutrients, they can also retain dissolved nutrients through biological and physiological processes.

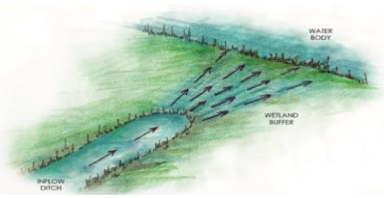
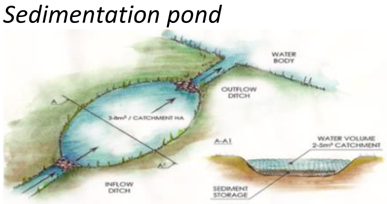
Constructed wetlands (CW) provide a low-cost and low maintenance alternative to traditional wastewater treatment. Although CWs are used around the world they are primarily used to treat municipal and domestic wastewaters, however, treatment of many types of industrial and agricultural wastewater, stormwater runoff and landfill leachate have become more frequent (Vymazal, 2008). In recent years in Finland use of constructed wetlands to retain leached nutrients and suspended solids caused by forest management, has become more common, however, use of CWs only for forest management purposes in other countries than Finland is rare. Overland flow areas are widely used around the world, but mainly for other purposes than forest management (http://www.nwrm.eu). Well-designed overland flow areas protect and maintain wetland functions by removing sediments and associated pollutants from surface water runoff. They also maintain habitat for aquatic, semi-aquatic and terrestrial wildlife. In the urban environment, they are built for management of stormwater, avoidance of hazards from flooding and protection of property from future hazards associated with extreme hydro-meteorological events (Planners guide, 2008). However, in connection of forestry overland flow areas are most commonly used in peatland forest in Finland. Related to the forest management they are best applicable in the cooler and wetter forest regions.

Efficiency of sedimentation ponds and pits breaks in cleaning, submerged dams and peak flow control structures is based on their ability to reduce flow velocity, which due these water protection structures are able to capture eroded suspended solids and particulate nutrients released from the active forest management area before they enter to the receiving water body (Finer et al., 2018). Sedimentation ponds are used around Europe in different environments (http://www.nwrm.eu). They are common, for example, at construction sites, where they are usually temporary structures, which will be filled after the construction period. More permanent structures are built on urban environments to protect the disturbance of storm waters (e.g. Melbourne water, 2013). But in addition, sedimentation ponds are used in forest management, where their use is best suited to peatland forest, where ditch network maintenance has been conducted (Finer et al., 2018). In connection of forest management, sedimentation ponds are generally used in Finland, but not in other parts of Europe. Peak flow control (PFL) structures have been used for water management in urban drained areas (e.g. Akan and Antoun, 1994) and also been tested for agricultural sites (e.g. Fiener et al., 2005), the basic idea is to retain storm runoff for a certain time and reduce peak discharge. This prevents erosion, increases sedimentation and improves water quality. In drained peatland areas, the peak flow control has been used at peat harvesting site (Kløve, 2000; Marttila and Kløve, 2009) and in temperate forests (Amatya et al., 2003) with good results. In Finland peak, the flow control system is used mainly in peatland forest management. Other NBS such as a submerged dam, breaks in cleaning and sedimentation pits are also used mainly in peatland forests management in Finland and there is not much information on their use in other parts of Europe. However, in Sweden, especially in North Sweden, where forest type is similar to Finland some attempts to use the aforementioned structures to prevent sediment and nutrient load have conducted (pers comm. Skogsvårdföreningen).

In addition to water protection structures, it is possible to control sediment and nutrient load with forest management regimes. By leaving adequate riparian buffer zones between water bodies and tree cutting area erosion and water load is reduced. In Finland, riparian buffer zones are commonly used in the forest (in mineral and peatland forest), because most of the forest is owned by private people and a major part of them have voluntarily certified their forest. The most common certification systems are Programme for the Endorsement of Forest Certification (PEFC) and Forest Stewardship Council (FSC). According to those, there has to be a riparian buffer zone between the logged area and water body, however, the width of the riparian zone varies depending on the certification system. In Sweden consequently, 66.7% of the forests have certified (https://www.swedishwood.com), similarly in Norway certification system (PEFC/FSC) is in use as well as in Estonia and Latvia (Ring et al., 2017). Furthermore, in most of the European countries, either the PEFC or FSC certification system is in use and partly outside of Europe (Asia, North and South America, parts of Africa). Therefore, we can assume that NBS riparian buffer zone between forest cutting areas and water bodies are used globally.

Over the past years continuous cover forestry (CCF), which involves the maintenance of a forest canopy at all the time, has received increased attention in European countries. The CCF is assumed to be flexible and sustainable alternative for forest cuttings, mainly because the forest will be saved of the drastic changes which clear-felling causes in the forest. Furthermore, if water bodies located nearby forest cuttings area, the leaching of sediment and nutrients is less to the recipient water bodies, because the forest is covered with vegetation all the time. However, in Nordic countries like Finland and Sweden, less than 5% of forest area is managed using CCF method, clearcutting is dominant tree harvesting method there (Axelsson and Angelstam, 2011), while in Germany, France, Switzerland and Slovenia CCF is currently a dominant forest management method (Gustafsson et al., 2019). It appears that in Europe the difference between uneven-aged management largely reflects differences between forest biomes with clearcutting being the typical form of harvesting in the boreal regions with conifer-dominated forests (Kuuluvainen, 2009) and CCF being more associated with temperate, broadleaved forests (Bauhaus et al., 2013).

Table 6: Description of NBS (water protection structures and forest management). Colour of the column (blue, brown, violet, yellow, white) indicates method which reduces suspended solids and element load (white colour indicates the method does not affect the NBS.

Method		flow velocity	suspended solids	nutrients in particles	dissolved nutrients
Water protection structures:		method reduce:			
Constructed wetland (CW)  Photo: Achim Dreps, Puruvesi (2019)	*Constructed wetland (CW)* is an artificial wetland structure to retain suspended solids and nutrients. CW structures consist of partially open water, with deep water and low water areas. Its cleaning efficiency is based on reduced water flow velocity, which enables deposition of suspended solids on the CW bottoms as well as nutrients, which have bound to the suspended solids. In addition, the vegetation growing on the CWs and micro-organisms in them play an important role in removing nutrients, for example, plants use phosphorus in a soluble form directly from the water and through the bottom sediment				
Overland flow area (OLF)  Figure: Ilze Pauline (2018)	*An overland flow area (OLF)* is a wetland buffer between managed areas and recipient water body, it can be constructed simple by routing runoff from forested area to natural wetlands. Besides slowing down water flow and enabling sedimentation of soil particles and adhered nutrients, OLF areas retain nutrients through biological accumulation in wetland vegetation and chemical adsorption in their soils.				
Sedimentation pond  Figure: Ilze Pauline (2018)	*The sedimentation pond or pits* are deepened and widened Section of a ditch, where water flows through a wider flow cross-Sectional area, thereby reducing the flow velocity and erosion and increasing deposition of suspended solids and particulate nutrients released from the active forest management area before they enter to the receiving water bodies.				
Peak flow control structures (PFC)  Photo: Seppo Ollikainen and Puruvesi, (2018)	*Peak flow control structures (PFC)* are designed to reduce flow velocities and erosive force of water. PFC structures with runoff regulating pipes have been shown to reduce efficiently the transport of sustainable solid matter, even finer particles, and particulate nutrients (N,P) and decrease the size of flood peaks. A sedimentation pond is also usually excavated above the PFC structure to retain the sediments which are released although there is the PFC structure.				

<u>*Submerged dam*</u>  Photo: Antti Leinonen (2018)	*A Submerged dam* is usually built of stones, wood or other suitable material set on the stream bed to reduce flow velocities. Submerged dams reduce eroding of soil and capture suspended solids.				
Breaks in cleaning  Photo: Erkki Oksanen and Viinamäki (2011)	The load from the individual ditch can be reduced using *breaks in cleaning*, which are built in an unditched part of the ditched area. They reduce suspended solids and nutrient load in individual ditches				
Forest management:					
Continuous cover forestry (CCF)  Photo: Erkki Oksanen (2015)	*Continuous-cover-forestry (CCF)* is a forest management regime without clearfelling. It involves the maintenance of a forest canopy at all times. After the felling of individual large trees, the remaining trees accelerate their growth, and new trees grow from the undergrowth reserve and more emerge through natural regeneration. It is assumed that less nutrient and sediment leaching occur using CCF regime, compared clearfellings, mainly due to that forest is covered with vegetation all the time and therefore leaching of sediment and nutrients is less.				
Riparian buffer zones:  Photo: Erkki Oksanen and Hangonniemi (2008)	Leaching of suspended solids and nutrients caused by the tree felling can be reduced by leaving adequate *riparian buffer zones* between water bodies and tree felling area. Avoiding disturbance of soil, saving the shrub layer and avoiding the use of pesticides in the buffer zone reduce erosion and water load. Buffer zones also play an important role in biodiversity and landscape.				

Table 7: NBS for water protection and their protection mechanism.

Types of NBS	Forest regime	Built structure	Cleaning		Efficiency is based on		
			Particles	Dissolved nutrients	Vegetation cover filter on land	Reduced flow velocity	Vegetation filter in water
Continuous cover forestry	x		x	x	X		
Riparian buffer zone	x		x	x	X		
Constructed wetlands		x	x	x	X	x	x
Overland flow area		x	x	x	X	x	x
Sedimentation pond		x	x			x	
Sedimentation pit		x	x			x	
Peak flow control structure		x	x			x	
Submerged dam		x	x			x	
Breaks in cleaning		x	x			x	

5.6 Map the knowledge of NBS efficiency in reducing element loads

As aforementioned, the efficiency of the most of NBS, which are used in forest ecosystems, are based on their ability to reduce flow velocity, which due these water protection structures are able to capture eroded suspended solids and particulate nutrients released from the active forest management area before they enter to the receiving water body. Such NBS are sedimentation ponds and pits, breaks in cleaning, submerged dams and peak flow control structures. Studies related to the efficiency of different NBS has collected to Table 8. Studies in Finland have indicated that for example, peak flow control structure can decrease the velocity of the flow by 91% and amount of suspended solids by 86% respectively (Marttila et al., 2010). However, the most efficient NBS have constructed wetlands (CW) and overland flow areas (OF) (known as wetland buffers, too) (Finer et al., 2018; Nieminen et al., 2017). For example, in a study carried out in Finland (Joensuu et al., 2013) showed that CW reduced a load of suspended solids nearly 70%, although reducing of nutrients was less efficient (Table 8, 9). To achieve best results with CWs in forestry it is important that the size of the catchment is at least 0.5% of the catchment area, CW has to be easy to maintain, and it should be established on the suitable area (Joensuu et al., 2013). Also, OLF studies have indicated that the key factor explaining the nutrient and suspended solids retention efficiency is the size of the buffer relative to the size of the whole upstream catchment area. Studies of Väänänen et al. (2008) and Vikman et al. (2010) showed that retention of nutrient was highest in large catchment areas compared to small ones (at least >1% of the catchment area) (Table 8), furthermore the length of the buffer zone seem to be important, which is probably due to the fact that the formation of continuous flow channels across buffer area is lower for long buffers than short buffers (Nieminen et al., 2014). Also, the dense vegetation has importance in nutrient retention, not only through nutrient accumulation in plant biomass but also because of dense vegetation cover forms a hydraulically rough surface and slows down the water flow velocity through the buffer area (Nieminen et al., 2014). In addition, soil type and the age of the buffer seem to affect retention efficiency. Light organic particles and fine textured mineral soil particles are retained less efficiently than heavy and high-density mineral. When the buffer is ageing, it can be saturated on nutrients and therefore the capacity for nutrient retention decrease. However, it is very unlikely in the forested catchment, because the nutrient loadings into wetland buffers in forested areas are lower than for example from agriculture or wastewater areas (Nieminen et al., 2014). The new wetland buffer area (overland flow area) can be also a source of nutrients, especially for phosphate. This is due to the fact that the redox-sensitive phosphate compounds in peat are released along with filling in or blocking ditches and consequently rewetting the buffer, when the water table is rising (Vasander et al., 2003; Nieminen et al., 2014).

As indicated earlier peak flow control structures (PFC) are proven to be an effective method for runoff and water quality management in peatland forestry in boreal conditions, reducing peak runoff rate and peak concentrations. Study of Marttila and Klove (2010) indicated that PFC structure trapped 86% of the incoming suspended solids, 67% of total phosphorus (Ptot) and 65% of total nitrogen (Ntot). Despite high retention of total P and N, PFC is not effective to retain dissolved nutrients, so its efficacy is not high in the sites where nutrient load occurs mainly in dissolved form, such as recently harvested areas. The effectiveness of peak flow structure mainly depends on: catchment topography (slope) and available detention volume, dimensioning and location of the structure and runoff rates.

In general sedimentation ponds capture efficiently particles with diameters greater than 0.05mm, but their efficiency depends also on their design (pond volume and water retention time). Well-functioning sediment ponds reduce sediment transport by 30-40% and they are particularly effective for the coarse-textured (grain size > 0.63mm) sediment (Finer et al., 2018). Very large ponds (> 400 m3) may retain > 50% of the suspended solids loading (Nieminen et al., 2018). Results from a study of Joensuu et al. (1999) in a recent ditch maintenance network area indicated that average decrease of suspended solids was only 18% in 37 ponds (Nieminen et al., 2018). However, some of the ponds were established in erosion sensitive areas and therefore the efficiency of them was poor, probably due to the collapse of the pond walls (internal load). When erosion sensitive ponds were excluded, a decrease of suspended solids was 28%. Therefore, it is important that sediment ponds are not established in erosion sensitive areas and also notice that efficiency of ponds can be poor because sediments do not settle down before they have formed bigger flocks or aggregates (Finer et al., 2018).

There is not much literature about the efficiency of submerged dams, however, they reduce the velocity of the flow, and therefore enabling particles to deposit at the bottom of the stream. The modelling study of the Haahti et al. (2017) indicated that erosion-insensitive dams, which effectively dam up the water above them, could significantly reduce suspended solids export (Nieminen et al., 2018). Breaks in cleaning (or non-ditch breaks) should effectively decrease suspended solids leaching. Haahti et al. (2017), indicated in the modelling study that well targeted breaks in cleaning have the potential to decrease suspended solids effectively in the ditch network. Instead study of Vuollekoski (unpublished) found no difference in suspended solids concentrations below or above a ditch break. In the UK non-ditched breaks have used successfully, their steep slopes enable long breaks without raising the water level and potentially impairing tree vitality and growth upstream of the break (Carling et al., 2001). Experiences from those sites indicate that non-ditched breaks can be highly effective in reducing suspended solids exports.

In addition to water protection structures, it is possible to control sediment and nutrient load with forest management regimes. By leaving adequate riparian buffer zones between water bodies and tree harvesting area, erosion and water load are reduced, or by using continuous-cover-forestry method (CCF), which due less nutrient and sediment leaching occur because the forest is covered with vegetation all the time.

Table 8: Efficiency of NBS in reducing nutrient and suspended solids loads.

NBS	Reducing element	Retention efficiency %	Reference
Continuous-cover-forestry	Less nutrient and sediment leaching occur using CCF regime, compared to clearcuttings	Forest is covered with vegetation all the time - leaching of sediment and nutrients is less	Nieminen et al. (2017)
Riparian buffer zone	Total P/dissolved P	52-89%	Kubin et al. (2000)
(effect depends on the width of the buffer zone)	Total N/dissolved inorganic N	Up to 90%	Kubin et al. (2000); Laurén et al. (2005), Jack and Norrström. (2004)
Sedimentation ponds	Suspended solids	94%	Kubin et al. (2000)
	Suspended solids	30-70 %	Joensuu et al. (2011)
	Suspended solids	76%	Joensuu et al. (2013)
	N	2%	Joensuu et al. (2013)
	P	9%	Joensuu et al. (2013)
Overland flow area	NO_3N	10-87%	Vikman et al. (2010)
	NH_4N	7.5-89%	Vikman et al. (2010)
	NO_3N	93-99.9%	Vikman et al. (2010)
	NH_4N	69-99.9%	Vikman et al. (2010)
	PO_4P	24-95%	Väänänen et al. (2008)
	PO_4P	94-100%	Väänänen et al. (2008)
Constructed wetlands	Suspended solids	Up to 76%	Piirainen et al. (2017)
	Dissolved P and N	±0 %	Piirainen et al. (2017)
	Suspended solids	16-68%	Joensuu et al. (2013)
	N	0-36%	Joensuu et al. (2013)
	P	6-62%	Joensuu et al. (2013)
Peak flow structure	Suspended solids	81-90%	Marttila and Kløve. (2010)
	N	65%	Marttila and Kløve. (2010)
	P	67%	Marttila and Kløve. (2010)
Riparian buffer zones	P	20%	Ahtiainen and Huttunen (1999)
	NO_3N	30%	Ahtiainen and Huttunen (1999)
	NH_4N	40%	Ahtiainen and Huttunen (1999)
	Suspended solids	43%	Ahtiainen and Huttunen (1999)
	Suspended solids	23%	Löfgren et al. (2009)
	P tot	12%	Löfgren et al. (2009)

The efficiency of forest riparian zone to reduce suspended solids and the nutrient load was studied in Finland and Sweden (Ahtiainen and Huttunen, 1999; Lofgren et al., 2009). In these studies, were estimated the efficiency of forest riparian zone to retain nitrogen, phosphorus and suspended solids that enter water bodies after tree harvesting at mineral soil sites. The width of the studied buffers varied from 5 to 30m, the soil type for mineral soil sites to peatlands, and the study duration ranged from two to three years. The efficiency of forest buffers to retain inorganic nitrogen varied from 30 to 40%, P total 12-20% and suspended solids 23-43%. Although the CCF method has had increasing attention, there are no results available to indicate how efficient the method is in regards to water protection.

Table 9: Input and output (kg/ha/year) from two constructed wetlands in forestry areas Kosteikot metsätaloudessa – selvitys, Constructed wetlands in forestry - report (in Finnish only); NE = not exist (Source: Joensuu et al., 2013).

Site	input/outpu	Suspended	Total-P	PO_4^{3}-P	Total-N
Pakopirtti, 700ha	input	24.5	0.210	0.082	3.04
	output	20.6	0.163	0.155	2.89
Torsajoki, 1600ha	input	162.0	0.250	0.090	7.2
	output	39.4	0.229	0.066	7.1
'no-treated area', mean (Finland)	NE	5.1	0.049	NE	1.3
treated area' range (Finland)	NE	0.92-47.5	0.017-0.146	NE	0.29-2.3

5.7 Identify enabling factors and barriers for NBS deployment and solutions to overcome the barriers

We interviewed ten forest professionals (designers of NBS, forest management advisors) in Finland to cover the barriers for NBS deployment as well as solutions to overcome them. We chose Finnish experts to this survey because in Finland NBS for water protection due to forest harvesting are generally in use. Especially important the use of them is in peatland forests, which we have in Finland 5 million ha. From the bare and broken organic peatland soil suspended solids and nutrients leach easily. Ten forest professionals participated in our survey. The experts located in different parts of Finland, excluding the northernmost part of Finland and they represented either a private company or state-owned institute/company. Table 10 presents their experience of different NBS and their information sources. Results showed that experts were familiar with most of the NBS, only from the continuous cover forestry (CCF) there was less experience. It is probably due to the fact that in Finland, prevailing forest cutting regime has been clear cutting for decades, only during the past few years interest of CCF management has raised but so far there is not much knowledge, for example, its superiority over clear cuttings in context of water protection. Experts have got information about different NBS from guidebooks, which, however, were found to be too general, therefore own experience and knowledge of local conditions were best guidelines. In addition, companies had own guidelines and in case of buffer zones, usually, FSC or PEFC certification rules were followed and furthermore Forest law of Finland was important as a general rule.

Table 10: Experience of forest professional on different NBS and information sources. Where 1* = Constructed wetlands, 2* = Sedimentation pond, 3*= Peak flow control structure, 4*= Overland flow area, 5*= Sedimentation pit, 6* = Breaks in cleaning, 7*= Submerged.

Expert	1*	2*	3*	4*	5*	6*	7*	8*	9*	Guidelines used			
										Guideline books	company own guidelines	Certification (PEFC, FSC)	own experience
1	x	x	x	x	x	x	x		x	x			x
2	x	x	x	x	x	x	x		x				x
3	x	x		x			x			x			
4	x	x	x	x	x	x			x	x	x	x	x
5			x		x				x	x			
6	x				x	x	x		x	x			x
7	x	x	x	x	x	x		x	x	x	x	x	x
8	x	x	x	x			x	x	x				x
9	x	x	x	x			x			x	x		
10	x		x	x						x			x
sum	9	7	8	8	6	5	6	2	7				

5.7.1 Functionality of NBS

The survey indicated that there is variation how different NBS have worked. Constructed wetlands and submerged dams were the ones, which, according to survey have performed well, but also the other NBS have mainly worked as expected, only one or two experts had a poor experience of those. Only two persons had little experience of CCF management but did not know about the efficiency of the method in a water protection, but it was mentioned that at least on some regions forest harvesting in peatland forest is usually conducted using 'management of natural forest', i.e. shelterwood cuttings were carried out, which remains CCF method. The most variation was perceived inefficiency of sedimentation pits, where positive and negative experiences were even; one expert, for example, told that sedimentation pits work well first three years, which after they are filled with sediment (which actually shows they have worked), one expert told sedimentation pits are useless and has stopped using them. Overall many of the experts said that water protection structures, which have made from natural material (like NBS should be) work better than structures where have used other materials, for example, plastic or metal. For instance, in the peak flow control structure, although it is one of our NBS, the plastic or metal pipe is used. The pipe is blocked easily if the diameter of it is too small causing flooding upstream of the catchment or by-pass flow over the structure. Usually, NBS has, however, worked as expected, although some repairing after building the structure has been needed. Only two of the experts estimated that different NBS work only on a satisfactory level but they did not have experience concerning all of the listed NBS. However, it is not usual, that there is water quality monitoring after building the NBS, only visual monitoring (not regular), therefore experts only assumed that structures have worked as they are presumed to work.

5.7.2 Challenges and barriers

There were plenty of challenges and barriers related to the NBS but also solutions, the most common challenges and solutions have collected to Table 11. The regional applicability is the greatest challenge. For example, on a flat region, some of the NBS cannot be used, because water needs to flow in some direction, and to do that there should be some slope on the land area. Standing water is not good in peatland forests, because the soil needs to dry. On the other hand, the steeper the slope of the area, more easily soil is eroded, and more sediment load will exist. Experts felt that guidelines are too general, therefore it is clear that to build certain NBS, the knowledge of the local conditions is needed. All sites have different characters, such as slope and soil type. For example, if there is an intention to build a sedimentation pond, the soil quality should be checked. If sand of the sedimentation pond is very fine, it erodes easily, and the pond is filled up with sediment origin from itself. There can be problems with private landowners, who are sometimes reluctant to build NBS in their area, especially if they have to pay the building cost and on the other hand if they lose income from the area, where NBS will be built. However, if the area is wasteland, not productive area, it is more acceptable to build the NBS (for example constructed wetland or overland flow area) from the point of view of landowners.

Table 11: Challenges and solutions related to the build NBS.

Barrier and challenge	Specific	Solutions
Regionality		The experts who design and build the NBS should know their region better.
Guidelines	Too general	Discuss with other experts, discuss with local people, trust own experience, participate in training.
	Outdated	Guidebooks should regularly update, new tools (GIS) and methods.
Attitude of landowners		Inform landowners benefits of NBS and disadvantages if NBS is not build.
Lack of funding		update the system how the financial support to build water protection structure is directed
Problems related planning of NBS	Lack of funding/time	More time and funding should be allocated to the plan and build of NBS.
	Regionality	Sometimes one solution does not solve the problem, there is need for combination of solutions (e.g. constructed wetland - submerged dam - peak flow control structure), often it would be better that all persons whose living forest harvesting/NBS effect plan together the NBS which will be carried out.
Climate change	Warmer winters, more raining	The future climate should be taken care when building the NBS.

The lack of funding often results in too short planning time, which due to the chosen NBS for example, is not the best one to the area or is wrongly sized.. Overall the sizing of the structure and right information related to the sizing is difficult sometimes to find. The single problem which was mentioned often related to the controlling of the velocity of the flow. Warmer winters are also a challenge in some regions, because usually soil is frozen during the spring floods, but because winters have been warmer lately, the soil has not frozen during winter, and when the snow melts, under is unfrozen soil. Spring floods remove easily loose matter (containing suspended solids and nutrients) from the unfrozen topsoil, which may leach to the recipient watercourses. This will be a real problem in the future, if the climate will change and warmer winters and rainy periods become more frequent, as has been predicted, it is also probable that other areas of boreal forest meet similar problems in the future.

5.7.3 Ways to overcome the barriers

Because forest harvesting usually results in increased nutrient and suspended solids leaching to the recipient watercourses, the water protection measures are important. It is very essential that designers and contractors know profoundly the region where they are going to conduct the NBS. Especially the experience and knowledge of used water protection method of the contractor were seen very important factor when building successful NBS. It was also mentioned that one solution does not solve everything, usually there is a need to conduct several solutions to solve the problem. Therefore in the beginning of the project, all people who will be influenced by the forest practices/NBS should participate in the designing, planning, deploying and monitoring of the process. It was also stated that functionality of the structures which are built using natural materials is better than those built using other than natural materials or which are the result of engineering design such as sedimentation ponds and peak flow structure. Structures built by natural material usually work better and have more resilience to unexpected phenomenon such as heavy rains; for example, retaining capacity of nutrients is greater. Overall guidelines should be updated regularly, advisor persons should update their knowledge regularly and new advanced methods and tools (e.g. GIS-tools) should be used in planning of NBS, for example, in the design of buffer zones and harvesting. General opinion was that NBS, which will be built, should not only 'treat the symptom' but they should also fix the situation (i.e. stop leaching of suspended solids and nutrients and deterioration of the recipient water body). The improved management of peat forests was seen as solution: e.g. continuous cover forestry, undergrowth utilization, ash fertilization, lighter soil preparation methods, i.e. focus should be moved more on forest management methods than building water protection structures. From the single problems, controlling of flow velocity got a lot of attention, because the flow effects on how suspended solids and nutrients move (deposit) in the water. Fresh idea was to set trees to the channel (ditch/stream) to slow down the flow. Future climate was a great concern, to be prepared for that NBS structures should be built in such a manner that they will work also in a changing climate. It was suggested, for example, that surface area of them should be bigger (constructed wetlands), riparian buffer zones should be wider (5 to 15 m is not enough), breaks in cleaning should be build enough far away from the water bodies.

5.8 Identified gaps in knowledge

Only a few gaps in knowledge where found, mostly related to effects on changing climate and continuous cover forestry management method. In addition, there was a need to have information about the new available tools and developed methods, which can be used in designing and building NBS. In this regard, Kabisch et al. (2016) identified four main knowledge gaps associated with the effectiveness of NBS; (1) lack of monitoring and sharing information about the NBS projects already implemented to tackle social challenges; (2) relationship between NBS and society (drawbacks linking to the recognition of a best method of transferring successful and unsuccessful outcomes of NBS; (3) design of NBS (i.e., the optimal design of different NBS can be unknown); and (4) implementation aspects such as lack of clarity in which types of NBS optimal, for example, to meet sustainable development goals.

6 Drought

Through the methodology outlined in Section 2, the interviews and stakeholder engagement activities summarized in Section 3.3.3 (i.e. since the stakeholders are concerned for both flood and drought hazards), the aims of this sub-task will be to concentrate on the existing information on water availability and usage (OAL-Greece in Sperheios valley, OAL-Italy in Po river), identify the critical parameters and develop strategies for best practice in order to overcome these challenges. An extensive SLR served as the starting point, involving the study of over 210 papers, conference presentations, maps, measurement results and studies, specifically for OAL Greece. All the documentation was classified and stored in the OAL Greece data cloud, which is readily available to the whole OPERANDUM team.

The strategy developed will focus on total hydrological management. We will also investigate the negative impact of the salt intrusion from the Adriatic Sea into the Po river mouth in OAL-IT. Following the negative consequence of droughts and salt intrusion the potential NBS will be identified via co-design and co-development in close collaboration with multidisciplinary stakeholders and local authorities. The following Sections outlines and reflect on these issues which includes the water availability of Spercheios River Basin (Section 6.2), saltwater intrusion (SWI) in the southern Po valley (Section 6.3), the factors that triggers SWI such as natural and anthropogenic forcing (Section 6.4), the SWI and their negative consequences in the southern Po valley (Section 6.5) and phytoremediation as potential NBS against SWI (Section 6.6).

6.1 Preface

The drainage basin of Spercheios River belongs to the water district of Eastern Central Greece, which is characterized as mountainous to semi-mountainous. The morphology of the basin is flat to hilly with intense local gradient changes and a longitudinal axis that coincides roughly with the riverbed of Spercheios River. The lowest altitude is sea level (0m) at the outlet of the basin and the highest (2,281m) at Oiti Mountain (Figure 30). The basin is characterized by intense multifarious terrain and dense hydrographic network, which in combination with the non-permeable geological background, promote the erosion and transfer of sediment. It is estimated that the total annual loss is 2,850,000 t/y, while the total annual quantity of sediment that arrives in Spercheios delta is of 1,140,080 m^3 (Gounaris, 2012). Intense rainfall events occur in the area, often resulting in floods.

Spercheios River has a length of 82km, an average annual runoff of 0.703km^3 and is the main feeder of Maliakos Gulf (Skoulikidis, 2009). It springs from the mountain Tymfristos (Velouchi) of Evritania (height of 2327m), enters Fthiotida Region and the OAL Greece area crossing the homonymous valley-between mountain Oiti and the western extension of Mount Othrys and ends in the Maliakos Gulf (Figure 30)

The average slope of the riverbed ranges from 0.5% in the delta area up to 24% in the mountainous part of the river basin. In the last third of the route, Spercheios changes in a lowland river and crosses low areas that are often flooded (Gounaris, 2012) (Figure 30).

The aquifers in the Deltaic area are: (a) a free aquifer with water level ranging from 8.5 to 12.1m and (b) two artesian aquifers with water levels ranging from 53 to 71m and from 280 up to 292m respectively. In the groundwater of the eastern and Deltaic part of Spercheios there are intense phenomena of salinization, due to both the intrusion of the sea, because of over pumping, and to the infiltrations and lateral transfusions of thermo metallic waters of the springs of Thermopyles and Phornerion (Gounaris, 2012) (Figure 30).

Maliakos is a semi-enclosed bay located in the eastern part of central Greece and connected to the Aegean Sea and the North Evoikos Gulf through two small channels (the canal of Oreon and Knimidos canal, respectively). In closed and semi-enclosed areas of this type, where the exchange of water with the open sea is limited, the accumulation of trace elements is reinforced (Okay et al., 1996; Karageorgis et al., 2002). In addition, the specific areas usually act as a repository of materials leaching, due to human activities in the catchment area. The climate of Spercheios basin is characterized as lowland continental, meaning that the main volume of rain falls at the end of autumn and during the winter.

Water shortages can arise either from an increase in water abstractions or by reducing the available water resources. Many interdependent parameters contribute to water shortages as human activities and climate change. To have a better understanding of water scarcity, it is necessary to map all the components and representative variables that can be used to characterize the phenomenon as depicted in Figure 31, embedded in the DPSIR platform.

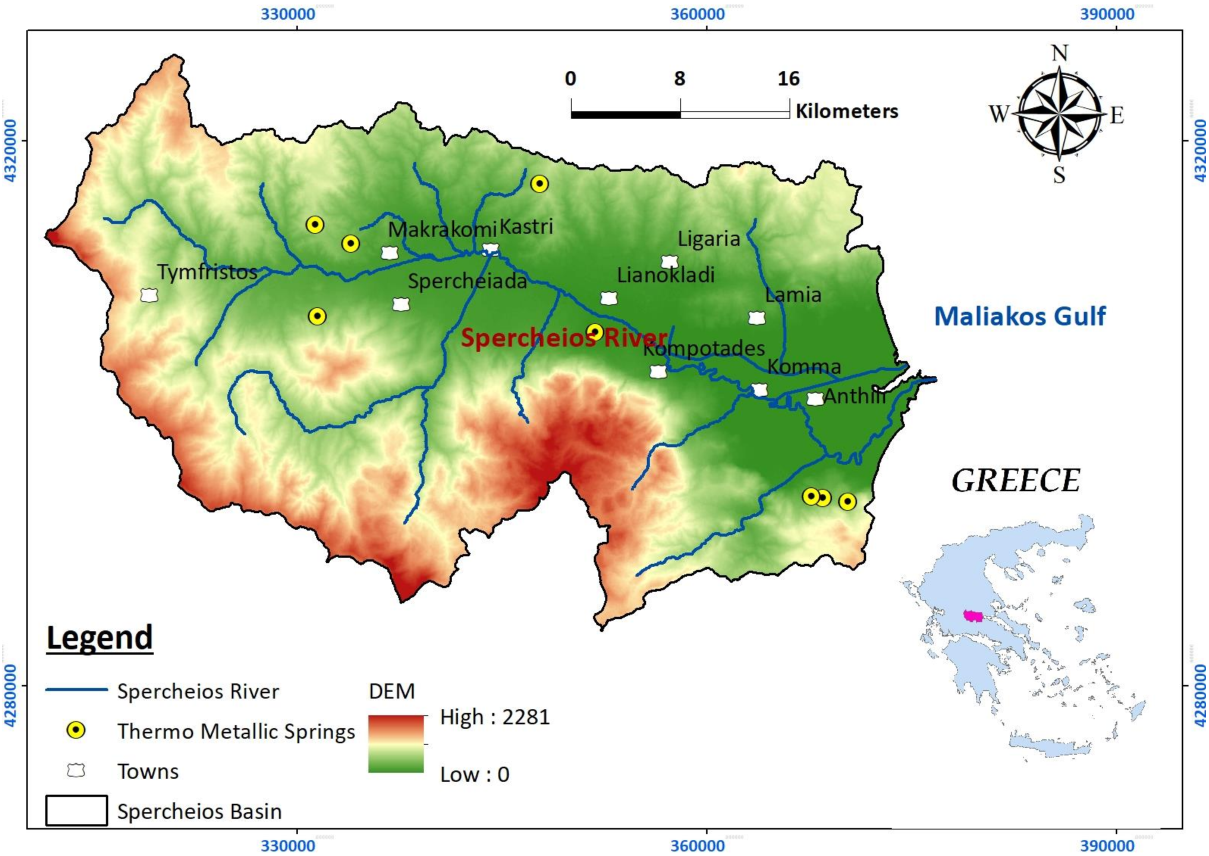


Figure 30: Geomorphological setting map of Spercheios River Basin.

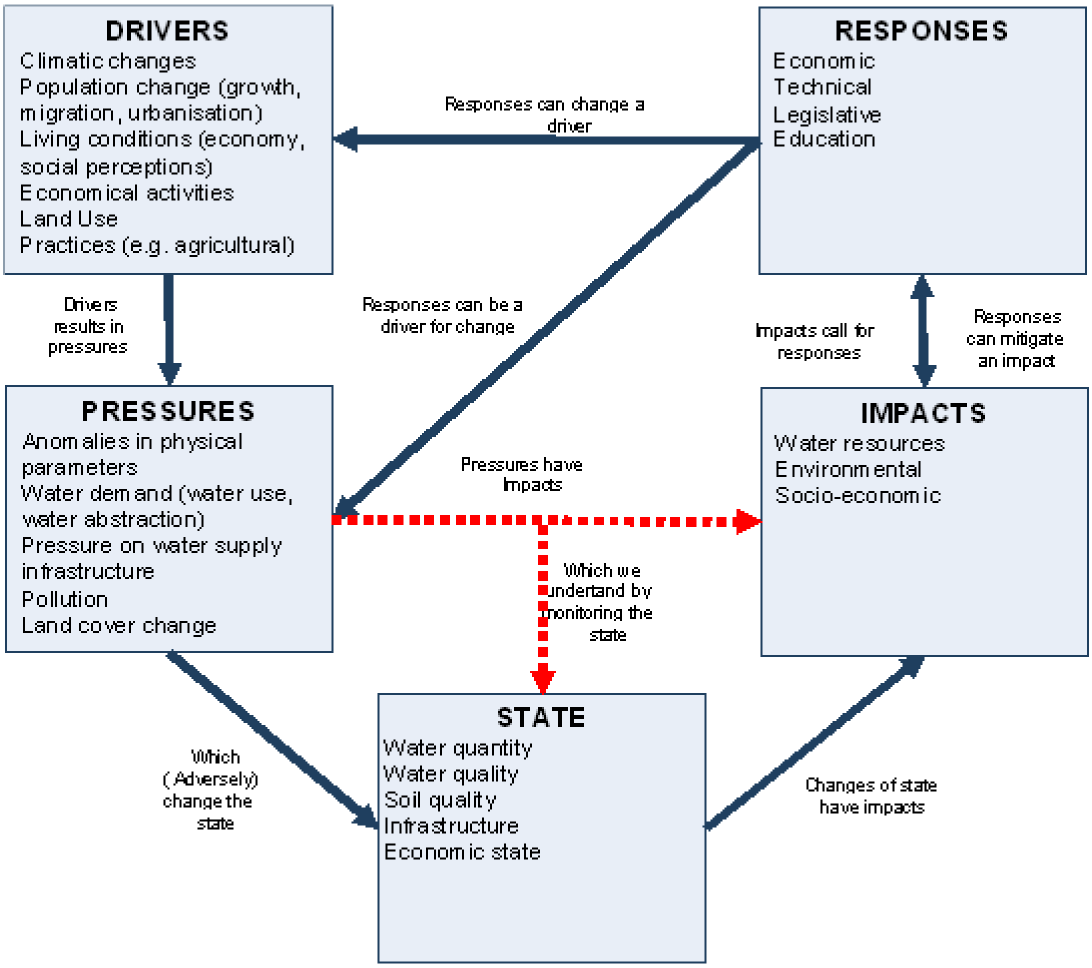


Figure 31: Representative variables that can be used to characterize the water shortage phenomena (Source: Kossida et al., 2009).

6.2 Water availability

In order to assess the water availability of Spercheios River Basin and particularly of the area where the OAL Greece is planned, we are presenting in the following Sections a set of related data.

Land cover/use: the plant cover of the research area shows seven categories of natural vegetation where combined with the rich fauna composes a rich and powerful ecosystem. Specifically, the flora of the Spercheios River basin is varied, with the presence of the following four characteristic zones:

- the zone of the EU Mediterranean vegetation with main species the *Quercus coccifera*, *Pistacia lentiscus*,
- the paramesogenic zone with dominant species the *Quercus coccifera* and *Quercus Frainetto*,
- the zone of fir and the paramesgeion conifer with dominant species the *Abies Borisii-Regis* and *Abies cephalonica*,
- the wetland azonic vegetation which with significant participation in the hydraulic state of the river occupies a significant part of the banks of the river, with main species the *Platanus orientalis* and *Salix alba*.

Therefore, the percentage of forests in the area is particularly high (49%), enabling a significant protective and hydrological impact in relation to extensive torrential phenomena. The land cover and use of the area is shown in Figure 32.

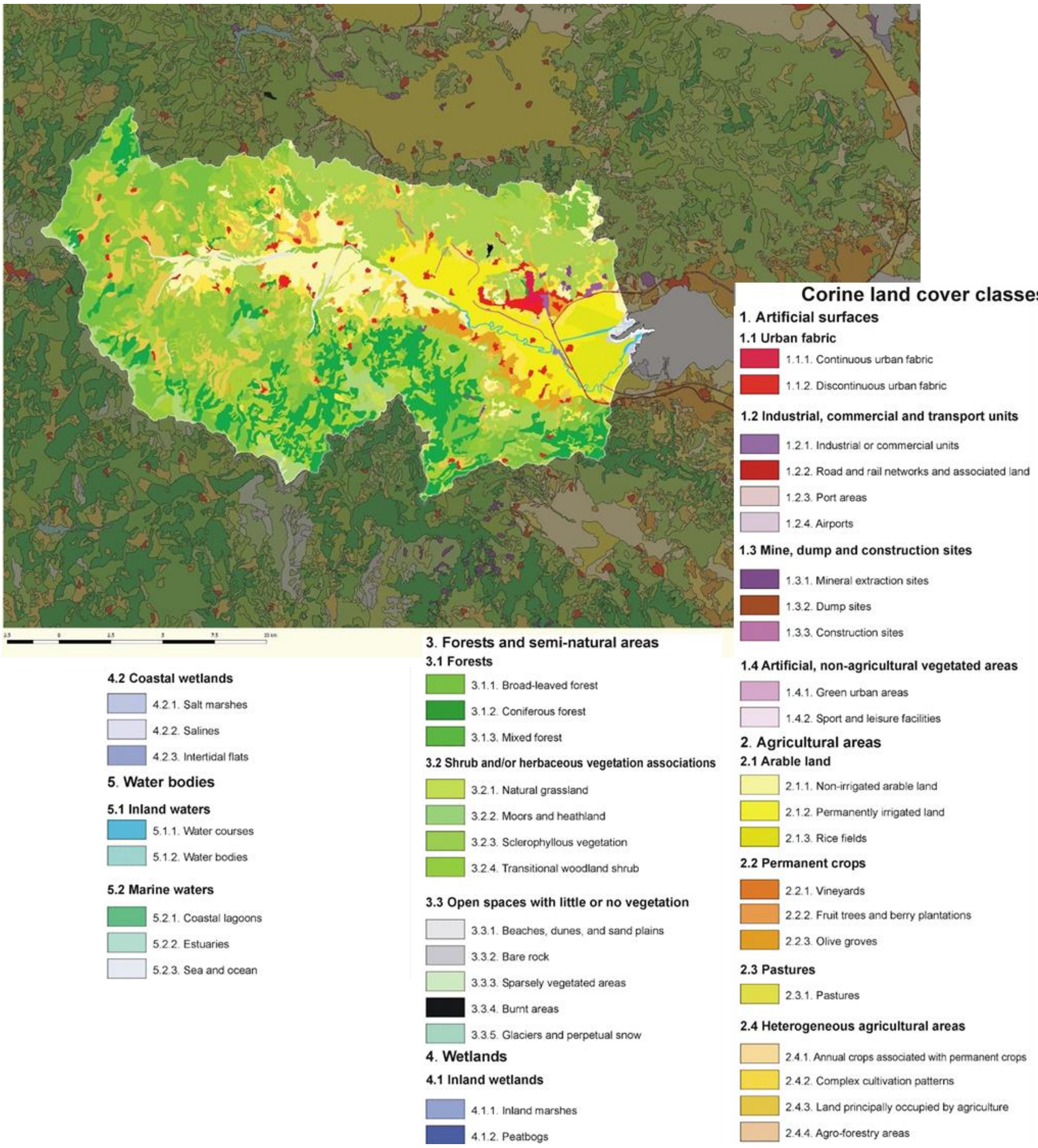


Figure 32: Land cover and use (authors own figure).

6.2.1 Hydrogeology

Spercheios basin is covered by impermeable, semi-permeable, alluvial and karst formations, in percentages of 62.6%, 0.2%, 20.5% and 16.7% respectively (Table 12). The hydro-lithological formations of Spercheios River Basin are shown in Figure 33. The two stations from which continuous rainfall data is available are Lamia and Ypati stations. The typical annual rainfall sizes for each rainfall station are shown in Table 13. Hydrological balances of Spercheios basin, as calculated by the Model MIKE BASIN (DHI, 2017), are presented in Table 14.

Table 12: Hydro Lithological formations.

Formations	Category	Description	The total formations
Porous (alluvial and semipermeable)	I1 I2 I3	Granular alluvial deposits, floating water permeability.	20.1%
		Granular deposits of moderate to very low water permeability.	0.1%
		Granular Molassian deposits, relatively small water permeability.	0.2%
Karst	C	Limestones and extended growth marbles, medium to high permeability.	15.1%
	C1	Limestone and limited growth marbles, floating permeability.	1.6%
	C1΄	Triadic Limestone latadice of the Ionian Zone, small to moderate permeability.	0.0%
Impermeable	A1	Flysch	48.1%
	A2	metamorphic rock	3.6%
	A3	Plutonic and volcanic rocks	11.0%

Table 13: Typical annual rainfall sizes of rainfall stations.

Station	Hydrological years (from – to)	Average annual rainfall (in mm)	Standard deviation (in mm)	Minimum annual rainfall (in mm)
Lamia	1980-1981, 2000-2001	561	152	283
Ypati	1980-1981, 2009-2010	802	293	342

Table 14: Hydrological balances (MIKE BASIN), where % is showing the percentage of water balance parameters on total precipitation (Source: YPEKA 2013).

Spercheios River Basin	urface km²	Precipitation MSHE (mm/yr)	Evapotranspiration MSHE (mm/yr)	%	Infiltration MBASIN (mm/yr)	%	Surface runoff MBASIN (mm/yr)	%	Supply from secondary streams MBASIN (mm/yr)
Upper Spercheios	237.5	1187.0	510.0	43.0	217.4	18.3	435.5	36.7	0.0
Spercheios Makrakomi	398.8	835.0	449.0	53.8	244.8	29.3	250.0	29.9	209.7
Vistrizas	287.1	1151.0	513.0	44.6	390.2	33.9	253.4	22.0	NA
Spercheios Ypati	242.4	781.0	474.0	60.7	172.2	22.0	141.0	18.1	449.3
Spercheios estuary	495.0	829.0	487.0	58.7	231.2	27.9	117.9	14.2	222.8

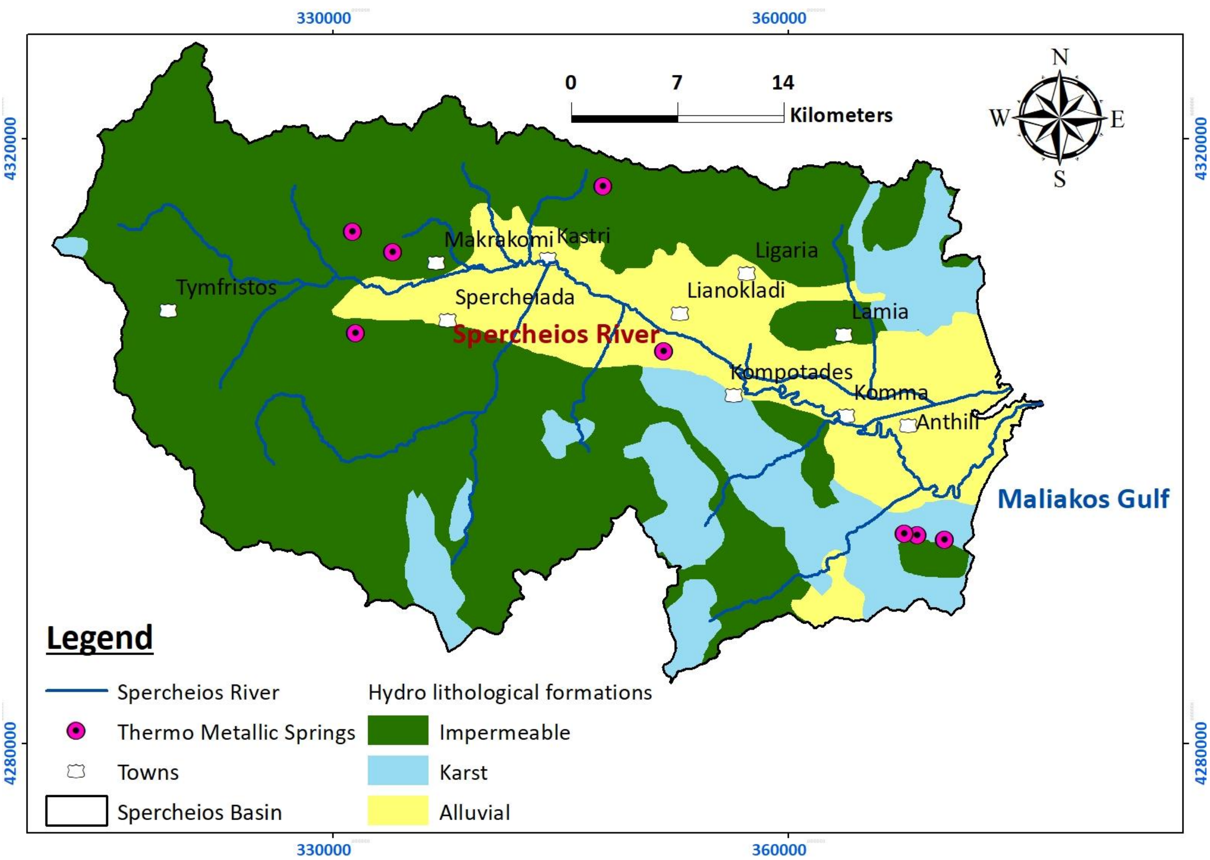


Figure 33: Hydro Lithological formations of Spercheios River Basin (Koutsoyiannis et al., 2003 with modifications).

6.2.2 Water Balance in the Central Part of Spercheios Basin

The area where OAL Greece is planned is the central part of the Spercheios basin (Figure 34). The geology in this area consist of: (a) alluvium, (b) carbon, (c) flysch, (d) neogenic, (e) ophiolite, (f) conglomerates and (g) slate deposits (Psomiadis, 2010). Based on the surface geology, the rainfall and evapotranspiration the water balance for this area follows Table 15.

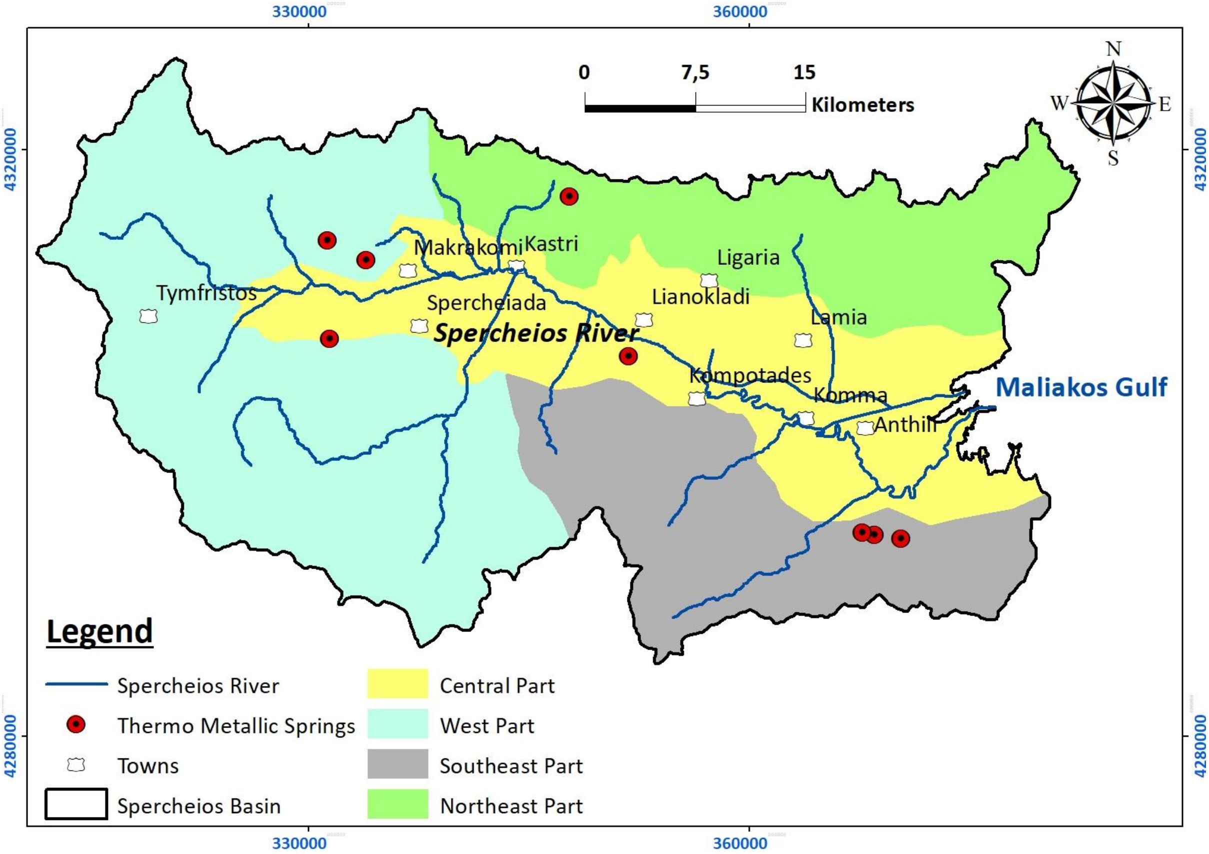


Figure 34: Parts of Spercheios basin with regard to water balance (Source: Psomiadis: 2010).

Table 15: Water Balance in the Central Part of Spercheios Basin (Source: Psomiadis, 2010).

Geology formation	Area (km²)	Percentage (%)	Rainfall volume distribution
Alluvium	345.92	74.27	Vp1 = F1 x P = 345.9 x 585.5 = 202363.2 x 103m³
Carbon	11.55	2.48	Vp2 = F2 x P = 11.6 x 585.5 = 6762.5 x 103m³
Flysch	25.55	5.49	Vp3 = F3 x P = 25.6 x 585.5 = 14988.8 x 103m³
Neogenic	3.52	0.76	Vp4 = F4 x P = 3.5 x 585.5 = 2049.3 x 103m³
Ophiolite	26.76	5.75	Vp5 = F5 x P = 26.8 x 585.5 = 15691.4 x 103m³
Conglomerates	48.62	10.44	Vp6 = F6 x P = 48.6 x 585.5 = 28455.3 x 103m³
Slate	3.85	0.83	Vp7 = F7 x P = 3.9 x 585.5 = 2283.5 x 103m³

The basin in this Section has the following characteristics (Psomiadis, 2010):

- Total Area (A) = 465.8km^2,
- Average rainfall (P) = 585.5mm,
- Average annual rainfall volume (Vp) = A x P = 465.8 x 585.5 = 272.7 x 106 m^3
- Average annual evapotranspiration (E)=483.9mm,
- Average annual evapotranspiration volume (VE) = A x E = 465.8 x 483.9 = 225.4 x 106m^3 (82.7%),
- Average annual total discharge volume: VA= 465.8 x 101.6 = 47.3 x 106m^3 (17.3%),
- Average annual surface discharge volume: VR= 39.2 x 106m^6 (82.9%) and
- Average annual groundwater discharge volume: VI= 8.1 x 106m^3 (17.1%).

6.2.3 Water Usage

The assessment of the available water potential is the energy strand of supply and demand balance. The water uses of economic importance in the area of study, are identified in the following Sectors: (1) use of water in the primary sector including agriculture, livestock farming and Mines, (2) water use in the secondary sector including industry and construction and (3) use of water in the tertiary sector including the provision of tourism services, other services (public and private) as well as households. In the determination of the exploitable water potential, the quality of water plays a decisive role. Consequently, the available potential water is determined by the suitability for the intended use. In the supply-demand balance, the volume of groundwater must also be added, in order to derive the total available water potential as a sum of the surface and groundwater potentials. The uses of water are distinguished in:

- Supply,
- Irrigation,
- Livestock and
- Industry.

Table 16: Draw-off from surface water bodies (Source: YPAN, 2008).

Water Body	Average Summer Supply (10^6 m^3/month)	Average Year drawn off (10^6 m^3)	Average Monthly drawn off during the summer period (10^6 m^3)
River Inahos	5.2	12.1	2.9
Spercheios (Roustianitis)	2.7	2	0.5
Spercheios (Alamana)	7.8	15.1	3.7
Spercheios (Alamana1)	17.6	25.9	6.8
Gorgopotamos	4.8	4.2	0.42

According to river basin management plan of the basin district of Eastern Central Greece (YPEKA, 2013), the most important demand corresponds to irrigation. The demands for water supply, industry and livestock are considerably smaller. The demand for irrigation water, is constantly increasing, due to the users desire to irrigate ever larger areas and for longer periods. This causes water shortages, especially during dry years. This phenomenon is due to the increase of the monthly temperatures and to the low level of irrigation efficiency. The irrigation inefficiency is caused by the old and poorly maintained transmission and distribution networks and the uncontrolled conditions of water application. The Water draw-off of the area of interest is presented in the tables below (Tables 16, 17, 18 and 19). All the water bodies mentioned are tributaries of the main Spercheios River.

Table 17: Draw-off from groundwater systems (Source: YPAN, 2008).

System's Name	Average Year Supply (10^6 m^3)	Average Year draw-off (10^6 m^3)
Lamia	35	6.7
Spercheios	85	92
Ipati	130	9.4

Table 18: Distribution of water supply needs (Source: YPAN, 2008).

Municipality	Average Year Needs (m^3)
Lamia/Gorgopotamos	338,555
Lamia/Lamia	5,447,671
Lamia/Lianokladi	250,831
Lamia/Ipati	471,556

Table 19: Distribution of irrigation needs (Source: YPAN, 2008).

Area	Average Year Needs (m^3)
Damasta	280,009
Frantzi	1,330,042
Amouri – Lianokladi – Zilefto	4,412,829
Sikas	1,326,365
Mexiates	5,483,656
Vistrizas	10,756,433
Fakitsas	1,202,818
Anthili	12,064,054

6.2.4 Identification of critical parameters

The problems of availability of water resources are deteriorating through the significant increase in consumption, pollution and persistence of extreme phenomena (droughts) (Souflias, 2008). The specific area of interest (Spercheios Basin) is particularly problematic in terms of natural enrichment, as it accepts small amounts of rain, unevenly distributed in time. It experiences catastrophic floods, especially in winter, and major droughts during summer. This inequality is expected to deteriorate with climate change, increasing the risk of flooding and at the same time the severity of droughts. Water resources management in the area is characterized by reckless use and uncontrolled waste. Huge quantities of water are lost, due to the poorly maintained irrigation systems and the unsustainable attitude of people in the agriculture sector. Furthermore, mitigation measures have been, up to now, fragmental and uncoordinated, thus being ineffective, or in several cases aggravating. In developing best practice strategies for hydrological management, the basic tools for the rational management of water demand are the following (Asimakopoulos, 2008):

- Enforcement (legislation, strict standards, standards),
- Encouragement (consumer support for the rational use of water),
- Technology and design (leakage management and loss minimisation, consumption measurement, pressure reduction, flow reducers),
- Financial instruments (financial incentives and pricing) and
- Training (access to data, information, and consumer awareness)
- (Asimakopoulos, 2008).

In the case of OAL-Greece, apart from the above general measures, the implementation of NBS such as FSR serving as Natural Water Retention Measures, in a coordinated and complementary manner will have positive impacts and co-benefits within a large range of disciplines. The general concept of the proposed interventions is shown schematically in Figure 35 and the actual typology and positioning of the NBS being implemented currently is shown in Figure 36.

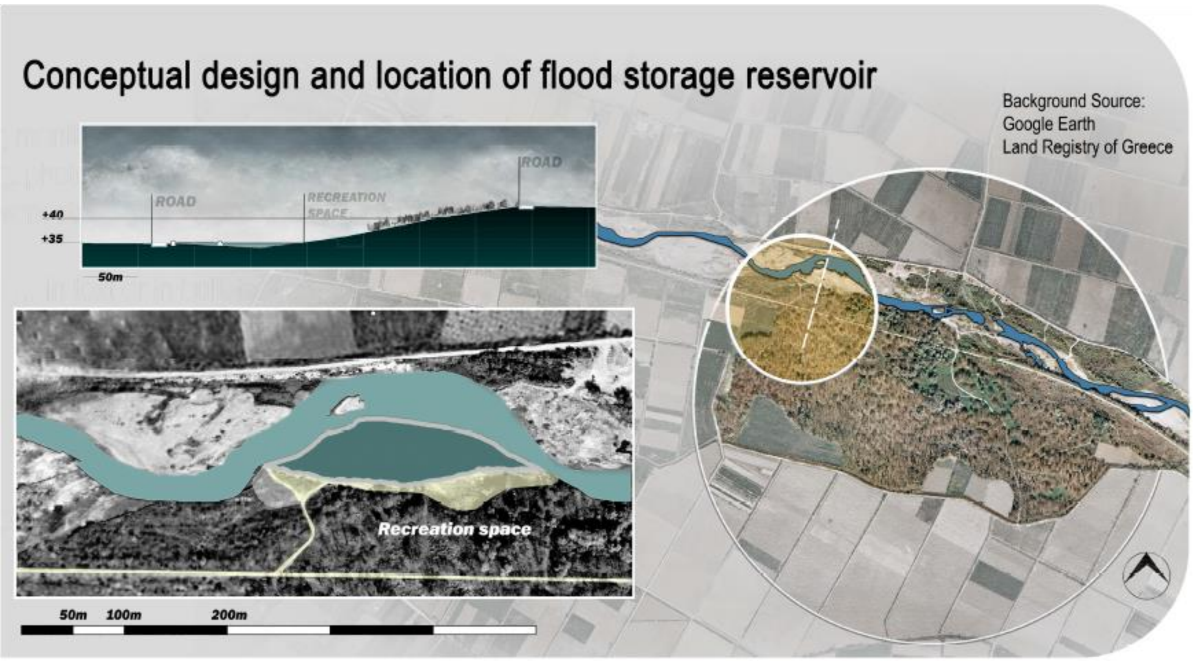


Figure 35: Proposed interventions of NBS in the case of OAL Greece (Source: KKT-ITC, 2019).

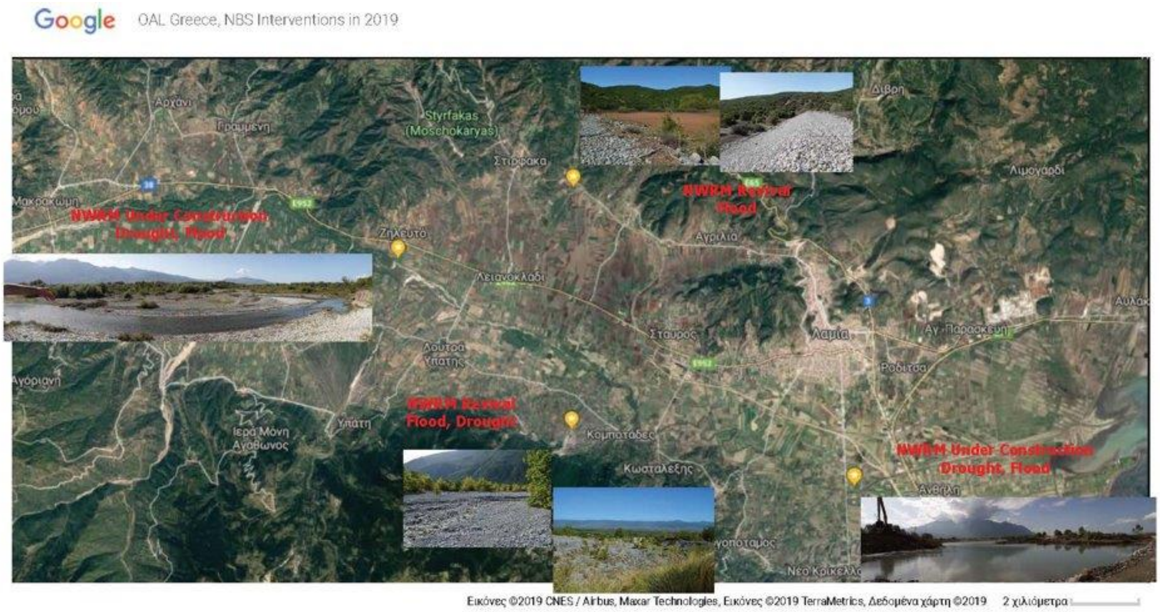


Figure 36: implementation of FSRs and other NWRMs in OAL Greece (Source: KKT-ITC, 2019).

6.2.5 Stakeholder discussions - OAL Greece

The stakeholders discussions in OAL Greece, included one Workshop with a Questionnaire distribution to 92 stakeholders, two FGD and Interviews with experts in several levels. The results were mapped according to the PESTEL methodology and they are described extensively in Section 3.3.3., as the whole process combined flood and drought. The reason to focus primarily in the hazard of flood derives from the results of the questionnaire shared with SHs, which was also confirmed through the first FGD held locally. The question asked was "Which, in your opinion, could be the biggest hydrological problem the Spercheios valley is facing?" The results are presented in Figure 37 below.

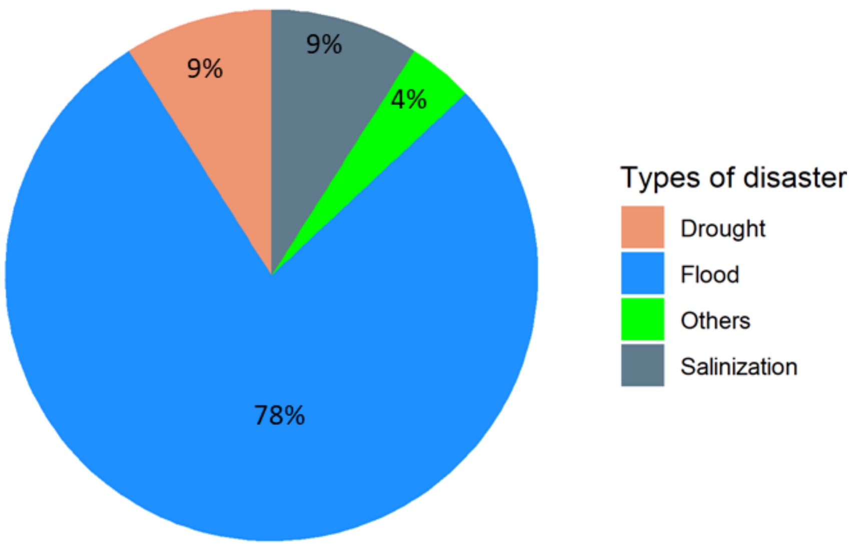


Figure 37: Stakeholders' perception of hazard in OAL Greece (Source: KKT-ITC, 2019).

6.3 Salt intrusion

6.3.1 Introduction to Saltwater Intrusion (SWI)

More than 60% of the world population lives in coastal areas, i.e. within 100km from shorelines. By 2050, this amount may increase up to 71% considering the forthcoming socio-economic and climate scenarios (Merkens et al., 2016). Hence, a huge demand for freshwater is expected, affecting dramatically the primary reservoirs and alternative sources around these regions naturally formed of coastal aquifers and estuaries. The overuse of these resources exposes coastal environments to an anomalous penetration of salt water into the freshwater, also known as SWI. Almost imperceptible at first, the detection of this phenomenon is usually late and, therefore, the economic costs for repair are heavily expensive for local communities. In some cases, SWI can reach unmanageable levels especially in regions highly affected by climate change (Paul et al. 2001, Le et al. 2008, Bhattchan et al. 2018, Pham et al. 2018).

Considered a density-driven current, SWI occurs when saline water either displaces or mixes with freshwater (Todd and Mays, 2005). It is identified in terms of salinity, a chemical parameter which counts the amount of salt dissolved in a water mass (primarily chlorine and bromine). According to U.S. Geological Survey (USGS, 2019), freshwater is characterized by salinity levels smaller than 1ppt (parts per thousand), whereas salt water by levels ranging from 20 to 50ppt. For intermediary values, the term brackish water is often used. For a complete discussion concerning the various salinity definitions, see Stewart (2008).

Along the coastal aquifers, the SWI starts when the salt water (heavier) displaces underneath the freshwater induced by the hydrostatic balance. According to the Ghyben-Herzberg principle, this equilibrium condition (not-mixed) is maintained while the salt water remains below the water table level. Otherwise, the seawater flows directly inland (Todd and Mays, 2005). Consequently, the quasi-stationary condition can be disturbed by sea level rises, land subsidence and freshwater depletion, reinforcing the SWI phenomenon (Antonellini et al., 2008; Abdoulhalik et al., 2017, Klassen et al., 2017; Siaka et al., 2017; Abd-Elhamid et al., 2018). Even estuaries are affected by SWI once the river discharge counter-balances the seawater inland flow. Then, the positioning of the transition zone between fresh and salt water becomes highly variable, both in location and extension. And it varies according to season, precipitation, sea level, tides and human activities (Grass et al., 2008; Chen et al., 2014; Ross et al., 2017; Xie et al., 2017; Haddout et al., 2019).

In the past decades several methods to control SWI have been identified and its assessment depends basically on the specific location characteristics. According to Todd and Mays (2005), some of the most common recognized solutions are:

a) Pumping pattern and planning: this method consists of the installation of several wells inland in order to control the freshwater pumping rate from the water table to the surface during dry seasons or severe SWI periods, allowing the natural recharge of freshwater;
b) Artificial recharge: when multiple water resources are available, the redistribution of freshwater into coastal aquifers and rivers helps the environment to regulate the salinity level during severe SWI periods;

c) Extraction barriers: similar to the previous method of pumping pattern and planning, this one also consists of the installation of wells. But, in this case, the wells must be positioned to pump out salt water from the affected aquifer to the sea;
d) Injection barriers: an alternative method for the extraction barriers, in situations whereas the affected aquifer by SWI reach the equilibrium with the seawater and the output flow vanishes. For these cases, the injection of freshwater through the wells can support a high-pressure system to maintain a counter-flow seaward; and
e) Subsurface barriers: the aim of this method is to prevent the inland flow of seawater placing impermeable subsurface barriers parallel to the shoreline.

Even considering the elevated cost and several successful worldwide applications, those solutions are certainly not entirely resolutive since SWI is a continuous phenomenon with a large variation of magnitude and distribution in time and space. Hence, only continuous monitoring allied to constantly adjusting on the method can produce an effective mechanism facing the SWI problems.

6.3.2 Monitoring SWI in rivers

By definition, SWI is identified by the amount of salt in the water, hence by its salinity concentration. And this parameter can be directly monitored at different locations, periods and depth. However, the measurement of salinity also presents low-frequency samples and external resource demanding as laboratory analysis. Therefore, SWI monitoring requires the use of other parameters which allows a more accurate description of the phenomenon, either salinity correlated or not. These parameters can be obtained through regression models based or parameterizations using other variables as water conductivity, precipitation, river discharge, sea level and land subsidence.

Considering that the salinity can be written as a function of the ratio between the conductivity of the water sample and the standard potassium chloride solution, three-dimensional distributions of salinity are possible through measurements of the water conductivity C (or its resistivity R=1/C) over several locations of a water body (Stewart, 2008). These distributions permit to detect the interface between fresh and saline water performing isohaline surfaces assessments. In the absence of permanent stations, dedicated campaigns collecting several samples along the river path at different depth levels helps to identify the magnitude of SWI.

As commented before, the greater density of sea water tends to displace the freshwater producing a depth dependent counter-flow. The intrusion of seawater in riverbeds persists even if the water table lies above the sea level. Thus, the freshwater transported and discharged by the river influences directly with the saline incursion. In addition, the amount of precipitations over the watershed also influences the river flux, which must be accurately monitored to obtain a reliable estimate of the salinity distribution by regression models (Saenger et al. 2008). River discharge can be measured by either permanent station or during dedicated campaigns, while precipitation values can be easily collected by nearby weather stations.

The sea level is another forcing of the SWI which varies due to meteorological conditions, tidal effects and climate change. According to Kim et al. (2007), land subsidence also contributes to sea level, within a long-term variation. Its estimative is crucial in assessing the SWI risk, since it influences the global sea level rise and shoreline retreat phenomenon (Nicholls and Cazenave, 2010). Sea level values are directly collected by oceanographic stations, whereas land subsidence data are obtained by GNSS devices (Devoti et al., 2017; Zerbini et al., 2017) and SAR interferometers (Carbognin et al., 2011; ARPAE, 2018).

6.3.3 SWI in the southern Po valley

The Po valley is an alluvial plain located in northern Italy and surrounded by the Alps (northward) and the Apennines (southward) ranges. The river which names this valley has headwater under the northwest face of Monviso (in the Cottian Alps) and flows eastward along 691km until reach the mouth, namely Delta di Po, at the northern Adriatic Sea. Nowadays, such delta covers an area regarding 400km² where the main river splits into five active tributaries: Po di Maistra, Po di Pila, Po di Tolle, Po di Gnocca and Po di Goro (Figure 38).

Figure 38: The principal tributaries of Po River at delta area: Po di Maistra (19.1km), Po di Pila (13.4km), Po di Tolle (11.2km), Po di Gnocca (21.7km) and, the largest, Po di Goro (49.3km).

Many factors contributed to shaping the Po Valley. The contour of the river and the natural damned sites suggest that this plain was completely covered by water during the Quaternary identified by the climatic transition of the last glacial age (18000 BC) and by the second human occupation during the Neolithic period (4500 BC) (Marchetti, 2002). Now human activity becomes the main force, even on geological scales. According to Simenoni and Corbeu (2004), several activities related to urban and agricultural developments drastically changed the landscape found in the Po river delta. And the main result is the increasing number of events of coastal erosion, water depletion, land subsidence, hydrogeological instability, and biodiversity loss.

6.4 Natural and anthropogenic forcing

The influence of SWI across the Po river delta area is well documented (Antonellini et al., 2008 and ARPAE, 2006b), where recent studies indicate an increase in the frequency and the dimension of events associated with multiple factors. As an alluvial plain, the Po river delta is subjected to natural land subsidence with an estimated magnitude of about 3-4mm/y. However, between the 40s and the 70s, this magnitude reached values around 20-40mm/y, mainly due to the groundwater and methane-water abstraction for several anthropogenic activities. After the 70s, the trend of land subsidence has been reduced and stabilised to the current values (Salvioni et al., 1957; Zerbini et al., 2017).

The sea level is another important SWI forcing with direct impacts along the Italian coast, in the northern Adriatic. According to Carbognin et al. (2011), only during the period between 1896 and 2006, the relative sea level increased from values of 2.4mm/y in Venezia, up to about 9mm/y in Ravenna. These rates result from the combination of absolute sea-level variations with land subsidence along the coast. Over the last century, in fact, the absolute sea level in the Northern Adriatic has increased at an average rate between 1.2-1.3mm/y (Zerbini et al., 2017). Over the same period, land subsidence has presented a strong non-linear behaviour even exceeding the cm/y level between the 40s and the 80s (Arca and Beretta, 1985; Zerbini et al., 2018). At present, subsidence values have considerably reduced, but the coast remains one of the areas with the largest subsidence rates of the Po Valley. The rise of sea-level in areas interested by relevant subsidence rates increases both the risk of occurrence and the severity of salt intrusion events.

Furthermore, the Po valley has often been exposed to very long periods of extremely dry conditions, which substantially alters the level of the Po river and its tributaries, and the pumping mechanisms already installed in the region. Just as a reference, during a severe drought of July 2006, the discharge into the Po river in Pontelagoscuro (Ferrara) reached 168m^3/s. This value represents only 16% of the expected for the period, which has an average of 1069m^3/s between 2000-2018 (ARPAE, 2018).

6.5 SWI and soil contamination

The SWI in the southern Po valley has been monitored at multiple points since June 2003. From there to now, every record of salinity above 1ppt is characterized as SWI event, and its concentration and distance from the river mouth also guide the diagnostic of the event. Figure 39 summarizes the SWI monitoring along the largest Po river tributary, Po di Goro, and shows the long journey of the salt intrusion across the shoreline, varying from tens of meters to several kilometres inland. Indeed, anomalous salt concentrations may be found more than 20km from the river mouth and, usually, such extreme events develop under conditions of severe drought when the river discharge reaches prominent minimal levels. As an example, during the event of July 1st, 2003, the SWI extension reached the remarkable value of 26.7km and the Po discharge at Pontelagoscuro (about 90km from Po di Goro river mouth) recorded less than 300m^3/s, about one-third of the climatology, pointing out the relevance of the river level to avoid SWI.

Assessing the impact of strategies against SWI depends on a large number of factors and physiographic properties of the affected site. Enabling its implementation without a very deep study can produce blind results which are nothing more than mere speculation. In fact, to perform artificial recharge or build artificial barriers near to river mouth can soften some SWI impacts in the absence of precipitation or reducing on tributaries discharge. But only the implementation is not enough. For this reason, any policy aiming to handle the SWI should head to mitigation and resilience. It is crucial to understand the SWI consequences to build a suitable estimative of how the implementation cost of the solution could impact on the local community (farmers, fishermen, researchers, authorities, inhabitants, tourists etc.) and the surrounding ecosystem. Thus, the primary interest must be to learn the stakeholder's needs and their interrelationships. Otherwise, any planning is intended to inexorably fail.

The main SWI effect is the freshwater contamination of aquifers and rivers. However, such consequence may be direct, when the seawater contaminates the water body, or indirect, when the seawater infiltrates the soil, producing the groundwater contamination, and hence the water body. Moreover, high salinity levels influence negatively germination, growth and fertility of plants, as well as many other phyto-physiological processes, potentially leading to plant death (Mahajan et al., 2005). In fact, soil contamination is considered an immediate SWI consequence, often preliminary to the aquifer contamination, which is considered to be irreparable. To prevent such a catastrophic event, it is then necessary to act since the first symptoms. Moreover, because of its extremely negative effects on crops, soil salinization immediately translates into economic damage (Sing, 2005). In the northern Emilia-Romagna, where farmlands cover more than 80% of the territory (ARPAE, 2006a), such a threat can easily lead to a real crisis of the whole agricultural sector.

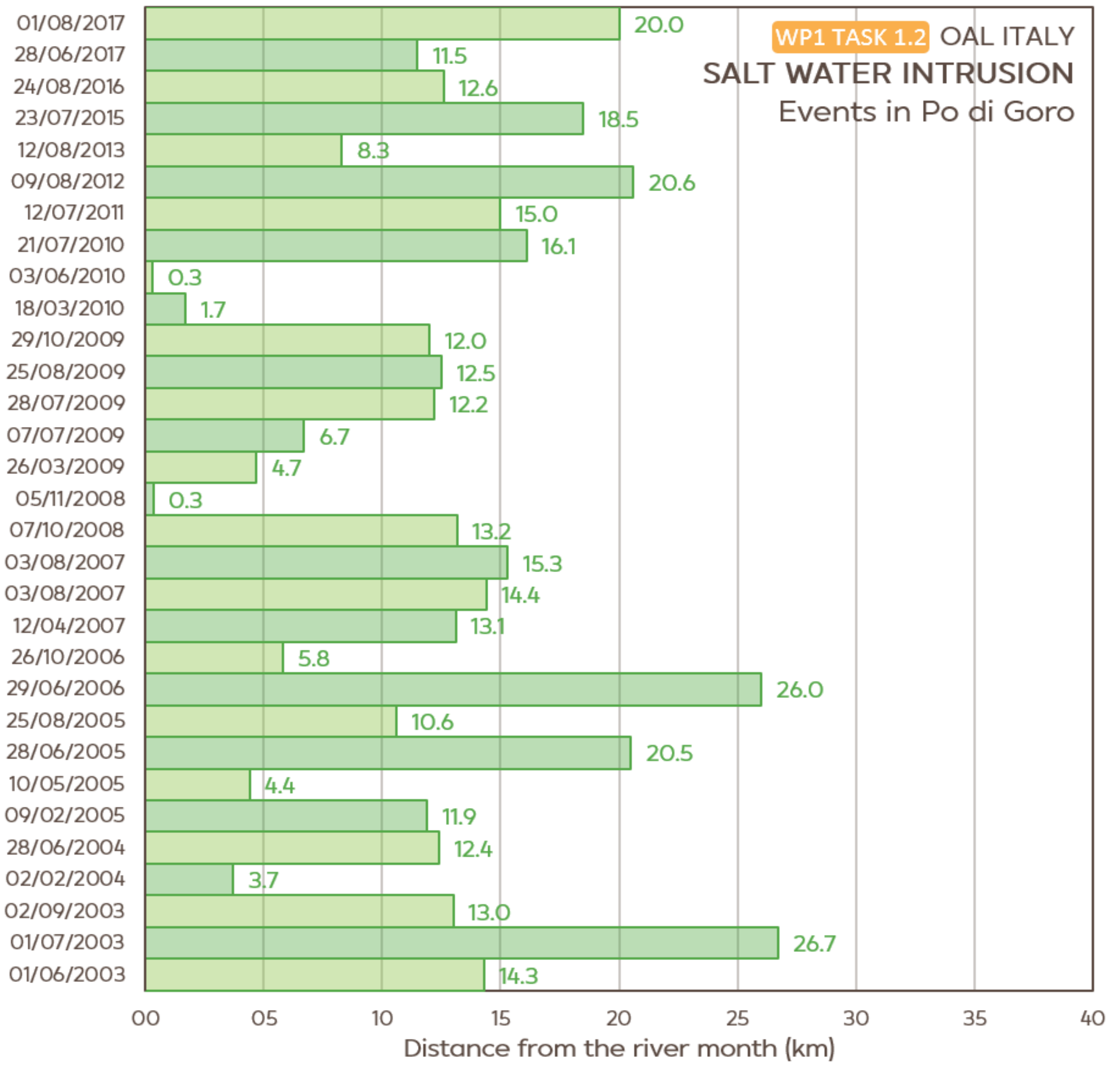


Figure 39: Salt water intrusion events in the Po di Goro in a period from 2003 to 2017 (Source: Adapted from ARPAE, 2006b).

6.6 Phytoremediation as NBS

The strategies cited before are internationally defined as the main solutions to contain SWI, but they cannot be categorized in the realm of NBS. Indeed, it is designed to heavily impact the whole ecosystem using man-made physical barriers to produce almost instantaneous effects against SWI and, in many cases, it only prevents other negative events without addressing the actual land remediation. Moreover, very few of these solutions can be adopted in estuaries, leaving only one possibility: reducing the water usage and waiting for the natural recharge. Such solution can be costly, both economically and ecologically, and presents a little impact on the SWI itself, due to several uncertainties such as the self-restoring river capacity.

On the other hand, according to Balian et al. (2014), NBS refers to “the use of nature in tackling challenges such as climate change, food security, water resources, or disaster risk management, encompassing a wider definition of how to conserve and use biodiversity in a sustainable manner”. Under this perspective, a solution with a big potential which both addresses the soil contamination and satisfies all these definitions is the phytoremediation (Salt et al., 1998). Several researchers have recently proposed it as an alternative solution based on cost-effectiveness and resilience, which consists in the environmental clean-up realized by salt-tolerant plants, halophytes (from ancient greek háls (salt) and phutón (plant)). It is important to note that this strategy is not definitive and should be implemented following other resilience policies.

Halophytes are classified into three categories: obligate, facultative and habitat-indifferent. According with its ecology: the first group naturally grow in salty habitats, the second is considered salt-tolerant but prefers low salt conditions, and finally the third group which is indifferent to the habitat. These plants can significantly reduce the soil salt concentration, in quantities varying accordingly with the above ground biomass (Hasanuzzaman et al., 2014).

Recently many studies assess the efficiency of phytoremediation by halophytes in soil reclamation (Ravindran et al., 2007). Qadir et al (2007), phytoremediation shows many pervasive advantages as:

a) No financial outlay to purchase chemical amendments;
b) Accrued financial or other benefits from crops grown during amelioration;
c) Promotion of soil-aggregate stability and creation of micropores that improve soil hydraulic properties and root proliferation;
d) greater plant-nutrient availability in soil after phytoremediation;
e) More uniform and greater zone of amelioration in terms of soil depth and
f) Environmental considerations in terms of carbon sequestration in the post-amelioration soil.

Phytoremediation meets the general requirements on which the concept of NBS is built up. However, to reach a degree of effectiveness, preliminary assessments are required in order to recruit the halophyte species with the best performances, ranked by efficiency, salt tolerance threshold, amount of absorbed salt, growing rate, specimen replacement frequency and many others (Hasanuzzaman et al., 2014).

Even considering this solution to be very prominent, there are several critical issues related to phytoremediation. The first one is related to a long time to observe a significant decrease in salt concentrations. Generally, a long growing season is needed to gain appreciable effects. Another issue is represented by the relatively short action range, since salt absorption occurs only at the ground surface layer (the rooting zone). Then, even if phytoremediation prevents aquifers contamination, it doesn't affect their recovery. However, the aquifer contamination is a serious issue, which should be prevented. A third criticality may be found in the applicability degree: heavily contaminated soils inhibit plant growth and germination, making difficult to achieve appreciable salt depletion (Hasanuzzaman et al., 2014). Despite these negative aspects, phytoremediation remains a powerful technique for soil bio-reclamation, especially for its differentiated impact on the whole ecosystem.

7 Landslides

NBS based mitigation strategies against landslides, including soil bioengineering measures preventing slope failure, adapted management of cultivated slopes and restoration of susceptible or already failed slopes, can provide an effective alternative to conventional technical engineering solutions (e.g. Stokes et al., 2013; Rey et al., 2019). However, suitable mitigation measures against landslides highly depend on the landslide type. A landslide is defined as 'the movement of a mass of rock, earth or debris down a slope' (Cruden, 1991), including different types of landslides classified by the involved material and movement type (Cruden and Varnes 1996; Hungr et al., 2014). In regard to these classifications, this Section specifically addresses landslides of the slide-type of movement (translational and rotational) of engineering soils, which are caused by gravity and triggered by rising pore water pressures in response to hydro-meteorological events. Following the classification of mitigation measures intended to reduce landslide risk presented in Section 1, examples are presented and described. Following SLR (Section 2), this Section focuses on the long-term performance, cost-effectiveness, and social perception of the following NBS against landslides. More specifically, this Section outlines: (i) topography and climate-driven afforestation (Section 7.1), (ii) implementation fascines and drainage systems (Section 7.2), (iii) adapting forest and cropland management (Section 7.3), and (iv) live retention walls (Section 7.4).

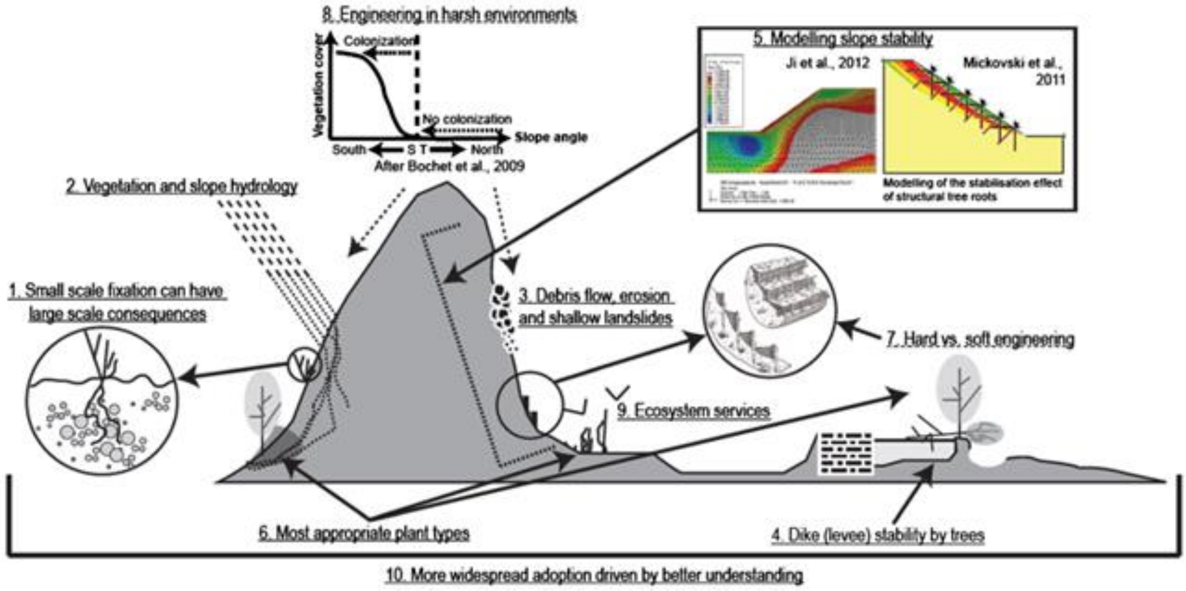


Figure 40: Key issues for slope stabilization and erosion control (Source: Stokes et al., 2014).

7.1 Topography- and climate-driven afforestation

Afforestation procedures belong to the so-called bioengineering measures, allowing to control or modify a physical system by means of organic and natural solutions. The main aim of these kinds of actions is to interfere with geomechanically and hydrological hillslope conditions crucial for slope stability including the enhancement of soil strength within the rooting zone and to act on the hydrological system in terms of interception and evapotranspiration (Sidle and Bogaard et al., 2016; Vergani et al., 2017). Geomechanical effects of forests include:

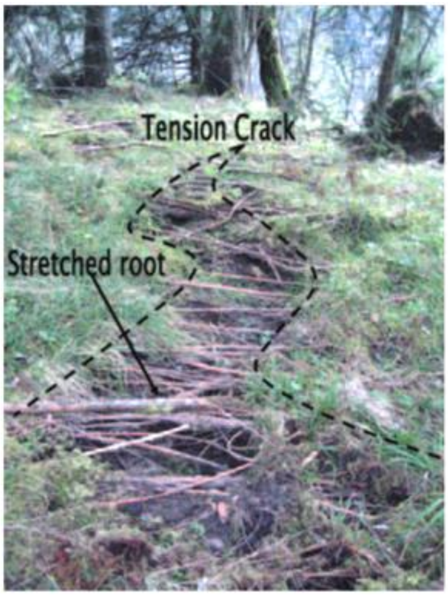
- Reinforcement of the soil material’s shear and tensile strength by roots,

- Arching and buttressing, counteracting downslope forces and
- Tree surcharge increasing the normal force.

Hydrological effects of forests include:

- Interception and evaporation reducing the amount of effective precipitation,
- Suction and transpiration reducing soil moisture in the vicinity of trees and
- Infiltration and subsurface flow which is affected by the effects of root dynamics (e.g. growth and decay) and the structure of the soil material.

Several studies have shown that erosion processes including the occurrence of shallow landslides can enhance after vegetation removal (Bathurst et al., 1996; Preston and Crozier, 1999; Imaizumi and Sidle, 2012; Vergani et al., 2017; Lehmann et al., 2019). With the roots starting to decay, their stabilizing effects vanish, and slopes may become increasingly susceptible to landsliding (Figure 41). On the contrary, in the course of afforestation measures a complex matrix of roots interlocks with the soil particles, directly enhancing slope stability. The root strength increases with tree growth. In case the roots directly penetrate the slip surface they anchor the unconsolidated material with the more stable regolith and bedrock beneath. Laterally oriented roots can increase the soil's tensile strength, depending on the displacement (e.g. formation of tension cracks). Tree surcharge has only minor effects on slope stability by increasing the normal force. Also loading effects by wind or intercepted snow do not lower a slope's stability distinctively (Stokes et al., 2008, Schwarz et al., 2012; Vergani et al., 2017).



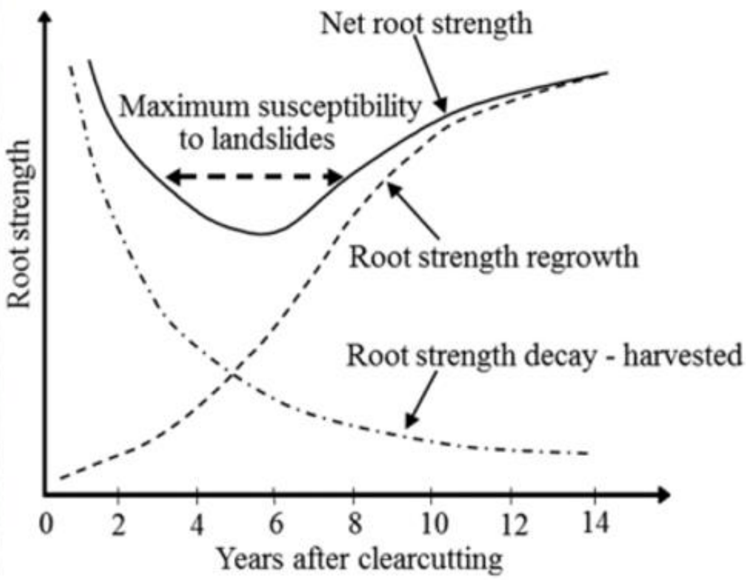


Figure 41: Example of lateral roots anchoring a failing slope (left; source: Schwarz et al., 2012) and temporal course of root strength following the logging of trees (right) (Source: Sidle and Bogaard, 2016).

The forest canopy intercepts part of the incoming precipitation and prevents it from reaching the ground. Minor rainfalls may be completely intercepted and even in the beginning of more intense rainfalls trees can hold up to 5mm of rainfall in the canopy (Keim and Skaugset, 2003). Also, low vegetation and plant litter prevents precipitation from infiltration. In regions characterized by a seasonal climate, coniferous trees have a higher interception capacity compared to deciduous species during their leaf-off period. However, during heavy, landslide-inducing rainfall events interception effects generally play a minor role (Dhakal and Sullivan, 2014; Sidle and Ziegler, 2016).

Trees reduce the soil moisture in their vicinity due to their water uptake and release parts of it via transpiration. Deep-rooting trees may therefore reduce the pore water pressure near the potential slip surface. However, the potential of transpiration strongly depends on the local climate and soil hydrological conditions and is typically limited in temperate regions during the cold season. In regions with a diurnal climate such as the tropics transpiration effects may have a higher impact since they can be observed year-round (Sidle and Bogaard et al., 2016).

The infiltration capacity and interflow velocities of vegetated soils are affected by the density and architecture of the root system. Root systems can enhance preferential flow in soils by establishing macro pores, enhancing both infiltration and interflow and therefore reduce the pore water pressure in susceptible slopes (Stokes et al., 2009; Uchida et al., 2001). However, preferential flow along root systems may also cause concentrated water flow increasing pore water pressure at certain spots (Ghestem et al., 2011). Particularly downslope tree trunks concentrated water flows may occur due to stemflow (Liang et al., 2007).

In common slope stability modelling approaches based on limit equilibrium concept, slope stability is defined as the resistance of an inclined surface to failure. Slope stability can be assessed by different techniques and with different aims (e.g. Duncan, 1996; Cheng et al., 2007; Paparo and Tinti, 2017), also considering the effect of vegetation (e.g. Greenwood, 2006; Schwarz et al., 2012; Lehmann et al., 2019). In this view, the stability of a slope can be assessed as the ratio of driving and resisting forces, resulting in a dimensionless factor of safety (FOS) as a function of depth *d* and time *t* (equation 2):

$$FOS_{(d,t)} = \frac{\tan\varphi'}{\tan\beta} + \frac{c' + c_r - \psi(d,t) * \gamma_w * \tan\varphi'}{(s_t + \gamma_s * d) * \sin\beta * \cos\beta} \quad (2)$$

where ϕ' [deg] is the angle of internal friction for effective stress, c^'[Pa] is the soil cohesion for effective stress, c_r [Pa] is the root cohesion, ψ(d,t) [Pa] is the pore water pressure with depth and time variated by the infiltrating effective rainfall, γ_w (9806.6 Nm-3) is the unit weight of water, β [deg] is the slope angle, s t [Pa] is the tree surcharge and γ_s [Pa] is the unit weight of soil (e.g. Zieher et al., 2017). The above-mentioned various effects of vegetation on a slope’s hydrological and Geomechanical condition can be considered and simulated.

Before the actual implementations of soil bioengineering structures their effectiveness must be proven with a proper stability analysis performed with sufficient accuracy. Since the efficiency of the NBS is commonly influenced not only by soil mechanics but also by hydro-geological factors, such a task can become quite complex due to the combined effects of the above-mentioned aspects and the required data. The performance and functionality of NBS should also be repeatedly assessed based on updated data. Therefore, the sites must be periodically inspected to assure the proper conservation of the NBS. To this goal, several studies about the long-term behaviour of technical and biological methods have been proposed (Pastorok et al., 1997; Anand and Desrochers, 2004). Appropriate modeling of NBS on long terms is still highly needed in the sense that long-term observations of such solutions are still lacking.

Clearly, the effectiveness of afforestation as a mitigation measure against landsliding strongly depends on the average depth at which it can be performed. The basic principles of reinforcements through bushes and trees have been widely studied (e.g. Gray and Leiser, 1982; Coppin and Richards, 1990; Schiechtl, 1996). Typically, the growth rate of roots is related to the volume of the cuttings and the choice and preparation of cuttings must be carefully selected. Intra-annual variations in root demography (Mao et al., 2013) and soil moisture (Pollen, 2007), resulting in periods of the year when slope stability is reduced, and these inter- and intra-annual windows of susceptibility should be better defined and quantified. Generally, the species should have a root system that penetrates to the required depth. In humid regions, bushes and trees with high transpiration would be more effective in decreasing soil moisture. Nevertheless, the choice of the appropriate vegetation should fall in the class of the local flora. In numerous soils, herbaceous vegetation is more effective than trees in improving collective stability due to the greater density of fine roots and associated fungal hyphae, both of which entangle soil particles (Gyssels et al., 2005; Fattet et al., 2011). Overall, the effects of different types of vegetation on slope stability and their spatial and temporal variability regarding hydrological and mechanical characteristics are still poorly understood. While it has been shown that vegetation can remove a substantial amount water from the soil, the detailed process that leads to a change in soil cohesion is not clear. If this procedure is related to seasonal effects, the soil type or depth is similarly unknown for many vegetation and climates classes. Studies suggest that soil moisture in the root zone can periodically reach saturation in more humid environments, decreasing the additional cohesion due to suction. All this considered, the long-term effect of these stabilization methods depends on the peculiar site characteristics and on the type of the bio-engineering structure practiced (Stokes et al., 2007).

7.2 Fascines and drainage systems

Drainage systems refer to both, engineering and soil-bioengineering interventions including tunnels, galleries, adits, wells, ditches and drainage trenches. Generally, draining a slope is often an effective remedial measure due to the important role of the groundwater level and the associated pore water pressure in reducing the soil material's shear strength, having a direct effect on slope stability. Particularly drainage trenches qualify as (green) NBS, as long as natural materials are used. Fascines offer a sustainable solution against streambed or riverbed erosion preventing the undercutting of embankments.

Drainage trenches have been proven to be an effective intervention for reducing the destabilizing effects of the otherwise infiltrating water for both, shallow landslides (Stanic, 1984; Conte and Troncone, 2018) and deep-seated landslides (Cotecchia et al., 2016). Compared to engineering solutions, they perform better in terms of cost-effectiveness. Nevertheless, on a long-term perspective maintenance costs must be considered since the drains must be controlled and maintained periodically. Particularly if the drains are built of geotextiles their long-term performance must be ensured (Veylon et al., 2016). Generally, the control of the groundwater level is achieved by deep drains implemented as trenches sunk into the ground to intersect the shear surface and extending below it. An example of a slope susceptible to landsliding with an implemented network of drainage trenches as shown in Figure 42.

The terrain characterization, by means of runoff and drainage properties, is crucial in determining the type, cause, and position of a potential slope failure. For instance, the type of seepage, drainage forms or surface precipitation can influence the choice of appropriate engineering techniques to drain a slope and re-establish vegetation. As we have remarked in the previous Section, knowledge on the long-term interactions between vegetation types, engineering structures, and slope hydrology are still lacking. This fact does not allow the understanding of long-term properties of NBS in form of drainage systems.

Figure 42: Diverted drainage in a case-study in Southeast British Columbia, Canada, caused by a landslide in February 2002 (left). In March 2003 (right), live pole drains systems (i.e. cylindrical bundles made of live fascines with desirable rooting properties, used as a collector drain in conjunction with lateral drain fascines installed in a chevron pattern) were installed to address underground seepage rising into the upper third of the slope. Vegetated lifts, brush layers, fascines and live staking (planting of live poles) were installed at the same period. Note that this example represents an application of a set of different NBS in the attempt to control a mass failure process. source: (Stokes et al., 2014).

7.3 Adaptation of forest and cropland management

While the aforementioned structural NBS may show immediate effects and short-term improvement considering the impacts of landslides, tackling their causes needs long-term action, including adapted land use planning. Current practices in agricultural or forestry management should be optimized to reduce their driving impact on the causes of landslides (e.g. Galve et al., 2015). As above-mentioned, the hydrological effects of forests can be modified by adapting the tree species composition and structure of forest stands. To reduce a slope of landslide susceptibility forest management should aim at optimizing the hydrological effects by enhancing transpiration and interception. In the same sense, suitable crop species, crop cultivation and adapted grazing cycles may have hydrological effects on a hillslope scale (Haddeland et al., 2007; Tuppad et al., 2010). On the contrary, landslides can lead to the abandonment of cropland (Deng et al., 2018).

Adapting present natural resource management practices specifically with regard to the hydrological causes of landslides can help mitigating landslide activity on the long-term perspective. This includes forest management, road construction, agricultural practices, and torrent, stream and river management (e.g. Dolidon et al., 2009). Nevertheless, these practices are strongly dependent on local community's needs. Clearly, a community in mountain areas often relies on the soil stability for their livelihoods, but this latter is as well influenced by the community itself. Thus, all the specific natural management procedures should be planned properly considering the local socio-economic aspects. This would require integrating natural hazard management into spatial planning. However, according to a recent study including 19 European countries and 5 regions only 4 of them (17%) already integrate geohazards in their urban and land use planning procedures (Mateos et al., 2017).

The ideal scale to identify the best procedures in a selected area and to organize spatially different land use is the watershed (or catchment area). It provides a framework for land use planning and permits addressing upstream-downstream linking issues. Nevertheless, planning actions exactly with the watershed boundaries is not always possible. Institutions face a big challenge in the actions of implementing watershed scaled policies, and the lack of knowledge regarding the scientific evidence of forest role in landslides phenomena is an additional obstacle. In order to estimate the long-term effectiveness of forest management on landslide activity, Dakhal and Sidle (2003) proposed a model capable of assessing the effect of different procedures on landslide initiation and volumes. The approach uses a physically based slope stability model and considers the effects of multiple harvesting entries on such a process. Thus, the cumulative impacts of afforestation and deforestation are considered. By embedding hydrological models to evaluate specific safety factors the study revealed that most of the simulated slides were clustered within 5 to 17 years after initial harvesting.

7.4 Live retention walls

Biotechnical slope-protection systems are commonly embedded into the landslide body itself. This class of NBS highlights the use of natural, locally available materials, such as soil, rock, timber, and vegetation, in contrast to artificial materials, such as steel and concrete. The conventional artificial structures have a strong impact on the local environment, while soil bioengineering makes use of native materials, such as plant stems or branches, rock, wood or soil. A classification scheme of the main stabilization methods is presented in Figure 40.

Broadly speaking, the NBS are soft engineering techniques, in the sense that their impact on the local environment is not so manifest. Nevertheless, the engineering community has some concerns about using this type of approach. Soil bioengineering is often viewed as a simple stabilization method acting just on the superficial layers, with low depth-effectiveness. While this is true regarding the effect of live vegetation (roots can reach limited depths), reinforcing effects deeper in the soil are possible by means of inert but natural material insertion in deeper layers (Gray and Sotir, 1996). In the previous Sections, we have remarked the lack of detailed studies on the long-term performance of NBS, but the theoretical durability of these class of structures is sometimes comparable to the artificial ones (Böll et al., 2009). The natural variability that occurs in soft engineering structures seems to hamper their efficiency in time. Nonetheless, this aspect is not damaging to the structure effectiveness itself. For instance, the durability of wooden structural elements is dependent on-air temperature, humidity and soil moisture variability (Lacasse and Vanier, 1999). Wood decay in soft engineering structures can be estimated through monitoring physical properties such as wood density (Rinn et al., 1996). In selected cases, it is been proved that wood decay is in the order of 10% in 10 years.

It seems clear that the hard engineering constructions like gabions, retention walls, anchors and check dams, offer an immediate solution for slope stability. Nevertheless, a suitable and immediate solution could be represented by a combination of soft and hard engineering designs to achieve short- and long-term sustainability as well as deep-seated and shallow stability. The purely soft engineering structures, such as brush layers or fascines, can be constructed with wood or live plant cuttings (Gray and Sotir, 1996), but take longer to fully stabilize soils. These soft structures are suitable where a study about the slope stability is previously performed and the live plant material is likely to have time to develop enough strength, perhaps within a period of several years. This delay in attaining adequate strength by the vegetation is an inherent weakness of soft engineering structures.

Monitoring programs help to establish the lifetime and efficiency of vegetation and engineering structures on slope stability and erosion control in different pedoclimatic environments. For instance, in Hong Kong, monitored data from soil bioengineered sites are catalogued in geo-referenced databases (http://hkss.cedd.gov.hk). Regarding the large-scale slope stability, the effectiveness of vegetation over time can be tracked using remote sensing coupled with ground truth measurements (Forzieri et al., 2009; Schwarz and Thormann, 2012). This method is particularly effective when assessing the damage on hillslopes following major storm events and can provide information on phenomena like the increase in excessive-rainfall-triggered landslides due to root decomposition after tree felling (Preti, 2013). Developing and maintaining monitoring programs and databases is a major challenge, but information obtained would help engineers design the correct structure for a given problem, depending on the immediate requirements and long-term specifications for the site.

The cost of non-structural remedial measures is considerably lower when compared with the cost of structural solutions. On the other hand, structural solutions such as retaining walls involve opening the slope during construction and often require steep temporary cuts. Both these operations increase the risk of failure during construction, due to over-steeping or increased infiltration from rainfall. In contrast, the use of soil nailing as a non-structural solution to strengthen the slope avoids the need to open or alter the slope from its current condition.

8 Summary and Conclusions

Through SLR (Sections 1-7), interviews and stakeholder involvement (Sections 3, 5 and 6), this deliverable critically analysed and documented Hydro-meterological hazards and good practice examples of NBS to manage the risks posed by flooding, droughts, salt intrusion, landslides, coastal erosion and storm surge, nutrients and sediment loading across OPERANDUM OALs. In summary, the reviewed documents showed that the hydro-meterological hazards have occured regularly with strong intensity and have caused significant loss of life and economic damage in the past. These hazards are projected to increase in severity and duration under future climate change scenarios. In response to this, we reviewed and presented recent findings on how NBS can play a significant role in buffering communities, environment, cultural heritage, assets and pivotal economy from hydro-meterological risks at different scales. The deliverable also summarised enabling factors and potential barriers for the implementation of NBS, and recommended strategies to overcome these barriers as summarised in Table 20.

Table 20: Summary of the identified gaps, potential barriers and possible ways to overcome these barriers for the implementation of NBS.

Gaps and potential barriers	Possible ways to overcome these barriers
Lack of funding	- Update the system how the financial support to build water protection structure is directed.
Uncertainties linked with the application, upscaling and replication of NBS.	- The experts who design and build the NBS should know their region better, - Lack of clarity in which types of NBS optimal against hydro-meteorological hazards and - More researches are needed to evaluate at what scale and under which situations different NBS are most effective than grey approaches.
Lack of evidence on social trade-offs - Attitude of landowners.	- Inform landowners benefits of NBS and disadvantages if NBS is not build and - During the planning and implementing NBS projects, potential trade-offs among social developments need to be considered to avoid gentrification developments resulting in spatial segregation and displacement as well as conflicts.
Lack of experience to implement NBS, e.g: - Lack of guidelines and standards to follow-up an implementation of NBS, - Lack of practical experience, - Complexity in the construction stage, - Lack of monitoring and sharing information about the NBS projects already implemented, - Relationship between NBS and society, - Lack of expertise and/or qualified labour for installation and monitoring and - Lack of multi-disciplinary/inclusive debates of NBS.	- Discuss with other experts, discuss with local people, trust own experience, participate in training, - Practical formation to the enterprises, - Organise short courses and training courses, - Developing a new and using the existed ne NBS information platform/databases such as Oppla, ThinkNature, Climate-ADAPT, etc, - Management programmes at local, national and international level; awareness raising; community engagement, - Bringing together resources, skills and knowledge, - Using the existing materials, more tools, manuals, guidelines and quality criteria. for practitioners need to be developed in collaboration with science and - Evidence and experience-based guidelines about climate change proofing NBS (e.g. species selection) should be developed to ensure that ecological functions and biodiversity gains are resilient to future changes.
Lack of integrating NBS with multidisciplinary stakeholders from the early stages of project planning, designing and implementation, e.g., - Highly dependent on grey approach and - Lack of time and consideration.	- Funding of NBS related projects, - Training courses to improve the labour, - Organising more meetings, conferences, congress and workshops to disseminate executed NBS projects, - Involvement of citizens and organizations throughout the life cycle of NBS projects (before and beyond the project implementation phases – planning, execution, monitoring and evaluation) to create trust, ownership and stewardship and - Foster participatory processes for co-design, co-development, co-deployment and co-management of NBS implementation.
Absence of strong evidence on NBS and their typology, e.g. - Lack analysis cost-benefits of NBS implementation Lack of case studies with documented implementation phase, - Species restrictions, - Lack of key performance indicators (KPI) of NBS against hydro-meteorological hazards and	- More public investment, - Share costs and risks between the private and the public sector, - Assess effectiveness of NBS at different scales, climatic and environmental conditions, - Data standards - sampling, monitoring, reporting, management, formatting, - Indicators of NBS efficiency should be selected at the beginning of the project and respective measurements undertaken, - Comprehensive monitoring and evaluation of NBS before and beyond the project implementation phase will help to identify benefits and potential trade-offs and

- Lack of clear steps for monitoring and evaluation of NBS.	- Integrating NBS and the benefit they provide with social network and policy analyses will bring more favour toward the implementation of NBS
Lack of studies that urban soil management as NBS.	- Increase awareness on how to consider the application and the benefits of unsealed soils and high organic soils as NBS, which helps for carbon sequestration and storage and mitigate climate change and hydro-meteorological hazards
Lack of studies on the comparison of hybrid approaches and their resistance against future climate change .	- During the implementation of NBS, responsible stakeholders need to consider the combination of blue and green approaches with grey approach, which have the potential to cope with future climate change.
Lack of holistic research approaches that focused on identifying social and environmental synergies and trade-offs of NBS.	- Holistic research approaches are needed that consider both potential synergies and trade-offs between environmental and social developments to assess impacts of, for example, potential gentrification, social displacement or spatial segregation effects. - Clear-cut research on NBS as implementation may bring negative health effects, e.g. through potentially enhanced allergies from transmission of pollen from allergenic plants or increased vector-borne diseases through, e.g. creation of favourable habitats for vectors is needed.
Lack of long-term stability in the planning process of NBS.	- NBS implementation based on the integration of different policy instruments such as regulation, financial incentives for public-private partnerships, investments as well as participatory community measures is recommended.
Climate change	- The future climate should be taken care when building the NBS.

NBS for considered Hydro-meterological hazards showed different barriers and gaps for their successful implementation. Across the three OPERANDUM OALs (Germany, Ireland and Greece), financing the NBS was an important implementation factor which is mainly solved through public funds (Table 20). The barriers associated with NBS awareness and application could be solved to a large extent with an early stakeholder engagement and an open public participation process or other measures such as land consolidation (see Table 20). In general, the attitude and commitment of the main stakeholders seems to be important for a successful implementation of NBS against HMRs. The stakeholder discussions in OAL Ireland, Greece and Germany showed that there was very little scope for discussions on NBS options and their various trade-offs because NBS were either already in place or dominated over by the use of traditional approach. Stakeholders might not be happy to discuss about different NBS options if there is only one available and its implementation has already happened. Nevertheless, there were some differences and more similarities between the OALs regarding barriers that hinders the wider uptake of NBS. In the OAL-Germany and OAL-Greece, stakeholder engagement poses a key barrier to the implementation. Even if an early stakeholder engagement has already happened in both OALs, the procedure is consistent with the identified barrier in the SLR (see Table 20). Additional barriers to the implementation of NBS, such as the threat of wolves to livestock, are area-specific and probably need a combination of different enabling factors such as early stakeholder engagement and local governance. A comprehensive summary is given in Table 20 that includes the potential barriers and ways to overcome them which are applicable for the entire OPERANDUM OALs.

A range of NBS against coastal erosion and storm surge reviewed here showed that the majority of data gaps lie in the full environmental and technical characterisation of the events, materials and species involved in the design and construction of the NBS. The spatio-temporal scale of the NBS, the lack of monitoring data and a standardised way of quantification of the NBS benefits have been identified as major barriers for implementation. Strategies for overcoming these barriers may involve co-design and co-implementation on a local or pilot-scale as well as standardisation of materials and procedures involved in the design and implementation of NBS against erosion and storm surge. In terms of implementation of the reviewed NBS and in view of the gaps identified, it is considered that the NBS implementation efforts in this project should be focussed on the stabilisation of the landward side of the coastal zone and/or numerical modelling of the seaward side of the coastal zone.

Survey of the different NBS feasibility to prevent suspended solids and nutrient load to the recipient water courses (caused by forest practices) indicated that one of the main knowledge gap and barrier for the NBS implementation is linked to the uncertainty on how the NBS will work in changed climate conditions. In addition, the effect of NBS was often too small; flat landscape was challenging and lack of funding and limited time to plan NBS caused problems. To overcome these barriers, it was suggested to do a comprehensive planning for the focused area and not to build only one NBS structure, but to build several of them to have the maximum effect. It is also important to reserve enough time and funding to implement NBS. In addition, the models which will be developed in this project (NutSpathy, Vemala, Rusle) will help to predict how the chosen NBS will work in different climate scenarios.

The area of Spercheios suffers from recurrent and severe flash flood events which are becoming even more frequent. Available climate change data predict the continuation of these phenomena and caused deterioration. Key elements for reducing drought risk are proper management of existing water resources and exploiting flood water to the maximum possible extent through Flood Storage Reservoirs and other Natural Water Retention Measures. Evidently, these types of NBS could serve multiple purposes, such as mitigating flood risks, creating opportunities in enriching aquifers, preventing SWI and augmenting water availability during the dry season.

The growth of trees and therefore their effects on a hillslope's hydrology and stability depends on site-specific factors and the suitability of particular tree species to prosper. Hence, the tree species must be adopted to these factors, and their stand composition and structure should be adapted in the light of expected changes due to climate change. Conventional engineering solutions are accepted as a viable and reliable measures for preventing slope failures or their consequences. However, the efficiency of these solutions must be evaluated in the light of expected changes due to climate change. In many cases, a nature-based alternative may be a more sustainable and cost-effective solution. Nevertheless, if public safety is at risk, the most effective mitigation measure must be taken. In this regard, NBS for landslide mitigation still have to prove their feasibility.

Overall, the basic concepts and the main technical elements of past studies, projects and case-studies reviewed and presented here feeds into recommendations for developing synergies within current policy process, scientific plans and practical deployment of NBS for HMRs reduction in Europe. However, the links between science and practitioners such as policy/decision-makers is often hampered by a lack of communication and collaboration, thereby creates a barrier to the successful implementation of NBS against HMRs (Table 20). We suggested that multidisciplinary stakeholders from different sectors, such as policy areas, social and natural sciences can overcome the barriers and foster the uptake of NBS against Hydro-meterological hazards than traditional approach. This can also build and promote synergies between different parts of community by linking together resources, skills and knowledge (see Table 20). Furthermore, in practice NBS has not yet been proven to provide complete or an acceptable efficiency of defence against Hydro-meterological hazards, therefore there is still a long way to go. For instance, more studies are needed to develop a global network of countries which can develop the NBS concept for building a better understanding of its performance against a range of multiple risks and further develop co-creation processes and stakeholder engagement to support sustainable NBS in OPERANDUM OALs. There is also a need to standardise the remote sensing/data monitoring and its accessible storage for future use in activities, such as modeling of future climate, NBS and its efficiency. For more recommendations to overcome the barriers, improve planning processes and strengthen the funding for NBS project implementations and continuity, see Table 20.

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ANNEX 1 – Flowchart illustrating the co-design and co-deployment process followed by OAL-UK

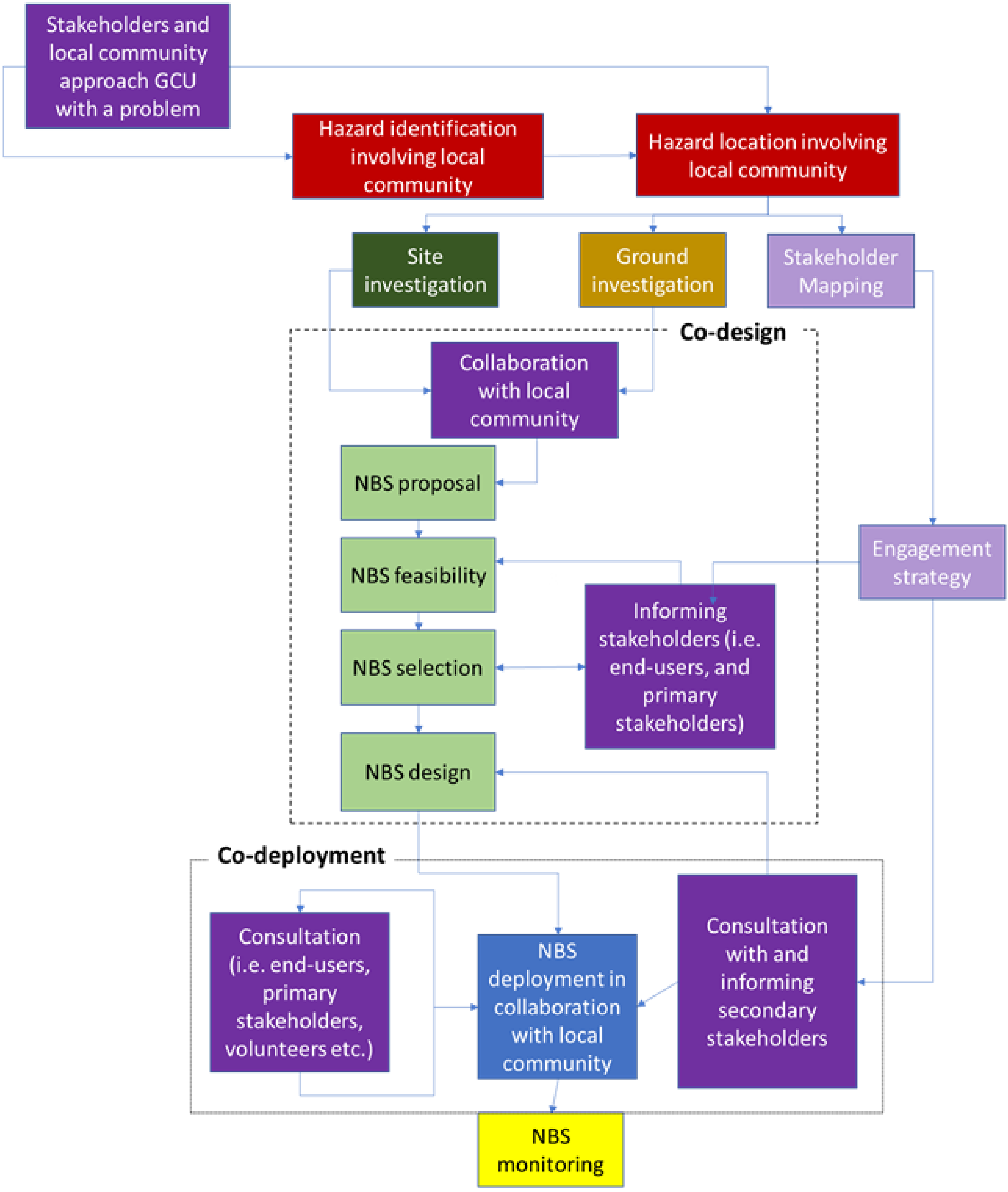

Figure 43 (Annex 1): Flowchart illustrating the co-design and co-deployment process followed by OAL-UK to select, design and deploy NBS against landslides, storm surge and coastal erosion.

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