Nature-Based Solutions 5 (2024) 100127

Contents lists available at ScienceDirect

Nature-Based Solutions

journal homepage: www.elsevier.com/locate/nbsj

Modelled effectiveness of NbS in reducing disaster risk: Evidence from the OPERANDUM project

Paul Bowyer [a,*], Silvia Maria Alfieri [b], Bidroha Basu [c], Emilie Cremin [d], Sisay Debele [e], Prashant Kumar [e,f,g], Veronika Lechner [h], Michael Loupis [i,j], Massimo Menenti [b,k], Slobodan Mickovski [l], Alejandro Gonzalez-Ollauri [l], Jan Pfeiffer [m], Francesco Pilla [n], Beatrice Pulvirenti [o], Paolo Ruggieri [p], Arunima Sarkar Basu [q], Christos Spyrou [j,r], Silvia Unguendoli [s], Thomas Zieher [h], Silvana di Sabatino [p]

[a] *Climate Service Center Germany (GERICS), Helmholtz-Zentrum Hereon, Fischertwiete 1, 20095 Hamburg, Germany*
[b] *Faculty of Civil Engineering and Geosciences, Delft University of Technology, Stevinweg 1, 2825 CN Delft, the Netherlands*
[c] *Department of Civil, Structural and Environmental Engineering, Munster Technological University Cork, Ireland*
[d] *University of Glasgow - School of Social & Environmental Sustainability, Glasgow, UK*
[e] *Global Centre for Clean Air Research (GCARE), School of Sustainability, Civil and Environmental Engineering, Faculty of Engineering and Physical Sciences, University of Surrey, Guildford GU2 7XH, United Kingdom*
[f] *Institute for Sustainability, University of Surrey, Guildford GU2 7XH, Surrey, United Kingdom*
[g] *School of Architecture, Southeast University, 2 Sipailou, Nanjing 210096, China*
[h] *Department for Natural Hazards, Austrian Research Centre for Forests (BFW), Innsbruck, Austria*
[i] *General Department, National and Kapodistrian University of Athens, 157 72 Psachna, Greece*
[j] *Innovative Technologies Centre S.A. (ITC), 116 33 Athens, Greece*
[k] *State Key Laboratory of Remote Sensing Sciences, Aerospace Information Research Institute, Chinese Academy of Sciences, Beijing 100101, China*
[l] *Built Environment Asset Management Centre, Glasgow Caledonian University, Cowcaddens Road, Glasgow G4 0BA, Scotland, UK*
[m] *Institute for Interdisciplinary Mountain Research, Austrian Academy of Sciences, Innsbruck, Austria*
[n] *School of Architecture, Planning and Environmental Policy, University College Dublin, Ireland*
[o] *Department of Industrial Engineering, University of Bologna, Bologna, Italy*
[p] *Department of Physics and Astronomy "Augusto Righi", University of Bologna, Bologna, Italy*
[q] *Department of Civil, Structural and Environmental Engineering, Trinity College Dublin, Ireland*
[r] *Academy of Athens, Research Centre for Atmospheric Physics and Climatology, Athens 10679, Greece*
[s] *Hydro-Meteo-Climate Structure of the Agency for Prevention, Environment and Energy of Emilia-Romagna, Arpae-SIMC, Bologna 40122, Italy*

ARTICLE INFO

Keywords:
Nature-based solutions
Climate change
Landslides
River flooding
Surface flooding
Stakeholder engagement

ABSTRACT

The use of nature-based solutions (NbS) to address the risks posed by hydro-meteorological hazards have not yet become part of the mainstream policy response, and one of the main reasons cited for this, is the lack of evidence that they can effectively reduce disaster risk. This paper addresses this issue, by providing model-based evidence from five European case studies which demonstrate the effectiveness of five different NbS in reducing the magnitude of the hazard and thus risk, in present-day and possible future climates. In OAL-Austria, the hazard is a deep-seated landslide, and the NbS analysed is afforestation. Modelling results show that in today's climate and a landcover scenario of mature forest, a reduction in landslide velocity of 27.6 % could be achieved. In OAL-Germany, the hazard is river flooding and the NbS analysed is managed grazing with removal of woody vegetation. Modelling results show that the NbS could potentially reduce maximum flood water depth in the near-future (2031–2060) and far-future (2070–2099), by 0.036 m and 0.155 m, respectively. In OAL-Greece, the hazard is river flooding, and the NbS is upscaled natural storage reservoirs. Modelling results show that in a possible future climate the upscaled NbS show most potential in reducing the total flooded area by up to 1.26 km^2. In OAL-Ireland, the hazard is surface and river flooding, and the NbS is green roofs. Results from a modelled upscaling analysis under two different climate scenarios show that both maximum flood water depth, and total flooded area were able to be reduced. In OAL-UK, the hazard is shallow landslides, and the NbS is high-density planting of two different tree species. Modelling results under two different climate scenarios show that both tree

* Corresponding author.
E-mail address: paul.bowyer@hereon.de (P. Bowyer).

https://doi.org/10.1016/j.nbsj.2024.100127
Received 29 September 2023; Received in revised form 28 March 2024; Accepted 5 May 2024
Available online 8 May 2024

species were able to improve slope stability, and that this increased over time as the NbS matured. The significance of these results is discussed within the context of the performance of the NbS over time, to different magnitude events, impact with stakeholders in engendering wider support for the adoption of the NbS in the OALs, and the uncertainty in the modelling analyses.

1. Introduction

As the world continues to warm, natural hazards such as flooding, landslides, wildfires, and other weather and climate-related hazards, are increasing in frequency and magnitude around the world [1]. Traditionally, the response to the management of such natural hazards has emphasised grey (hard) engineering solutions. In recent years, however, there has been growing interest in the use of nature-based solutions (NbS) to try and reduce the risk posed by such hazards [2–9]. In relation to climate change more generally, NbS have been proposed both in a climate mitigation [10–15] as well as an adaptation context [16–18]. For example, NbS (or nature-based climate solutions) are essential in order to be able to achieve the goals of the Paris Accord [19], but also need to play a major role in attaining carbon neutrality at the city level [20,21].

NbS have been variously defined [22,23] but essentially constitute '*actions that involve people working with nature, as part of nature, to address societal challenges, providing benefits for both human well-being and biodiversity*' [24]. This multifaceted quality of NbS in providing co-benefits, in contrast to hard engineering solutions, is one aspect that makes NbS particularly attractive, given that there are many different factors (and actors) at play in generating any risk. The response can address multiple factors, and ideally not exacerbate other factors thus providing scope for more intelligent and sustainable solutions to climate-related hazards [25,26].

There is a growing body of evidence which demonstrates that NbS can indeed be effective in reducing the risks posed by various hazards [27–33], yet despite this, and their promotion and support at high policy levels, NbS have still not entered the mainstream. Indeed, a number of recent papers have cited the relative lack of evidence of their effectiveness in general, and vis-à-vis traditional grey solutions in particular, as being one of the main barriers to their wider uptake and implementation [34–39]. In addition to barriers related to their acceptance [40,41].

Another aspect which is of importance when considering the relative performance of NbS and traditional grey engineering solutions, is the cost-effectiveness and associated level of protection they may offer e.g. for a given return period event [42–45]. There are studies which have demonstrated that NbS can be more cost-effective than grey solutions, but this can depend on the time period over which the economic costs and benefits are considered [46], as well as the inclusion of co-benefits [47,48].

Moreover, there is a general dearth of evidence for the effectiveness of NbS in reducing risk over longer periods of time (at least a decade), and particularly in the context of climate change. Arkema et al. [49] were able to show that intact coral reefs and coastal vegetation on the US coast, would be able to reduce the risks associated with coastal flooding under five different future sea-level rise scenarios. Walters & Babbar-Sebens [50] used climate projection data to analyse the effectiveness of additional wetland areas in reducing peak flows and flooding in the Eagle Creek watershed in Indiana, USA, for both the present-day and a future climate period. They were able to show that the introduction of new wetland areas within the watershed might be able to reduce peak flows in both time periods, by 17.6 % in the present-day, and by 18.8 % in the future time period. Spyrou et al. [51] also use climate projection data to analyse the effectiveness of a natural water retention NbS over the 21st century and were able to show that the NbS was able to reduce maximum water depth, and reduce the area of land flooded. This lack of evidence is important because investment decisions in relation to NbS should also consider their sustainability which includes the design lifetime of a particular intervention, in comparison to any grey solutions. This is particularly important within the context of economic development and the opportunity cost that bad investments represent [52]. Moreover, if we seek to establish the use of NbS more widely and for them to realise their potential in reducing risk, then this is a challenge which needs responding to.

In this paper, we aim to address this research gap by presenting model-based evidence from five case studies carried out in the EU Horizon 2020 funded project OPERANDUM, where the effectiveness of five different NbS in reducing risk posed by river flooding, and deep- and shallow-seated landslides, have been tested in both the present-day, and possible future climates.

2. The OPERANDUM project

'OPEn-air laboRAtories for Nature baseD solUtions to Manage hydro-meteo risks' (OPERANDUM), was an innovation action project funded by the European Commission's Horizon 2020 Environment and Resources programme. The overall aim of OPERANDUM was to provide evidence of the effectiveness of a wide range of NbS to reduce hydro-meteorological risks at catchment level. Working in seven European open-air laboratories (OALs), in Austria, Finland, Germany, Greece, Ireland, Italy, and the UK, a wide range of NbS were developed, implemented, and tested in-situ, to investigate their effectiveness in reducing risks associated with flooding, drought, water quality, deep and shallow landslides, and coastal erosion. All the results from the OPERANDUM project are available on the project information and knowledge portal the Geo-IKP (https://geoikp.operandum-project.eu/). A major innovation in OPERANDUM was the combination of monitoring the in-situ NbS with modelling studies, where the effectiveness of the NbS in reducing hydro-meteorological risk, both in the present-day and possible future climates could be tested. As such, the modelling studies in OPERANDUM address a significant gap in the literature, and the evaluation of the performance of the NbS in reducing risk, is the focus of the work presented here. Of the five case studies, OAL-Greece and OAL-Ireland represent examples of upscaled NbS and the potential this may bring to reducing the hazards.

3. Case study open-air laboratories

Five different NbS were investigated in five different open-air laboratories across Europe, and these are summarised in Table 1, while the location of the OALs is shown in Fig. 1. Background information on the hazards and NbS in the OALs is now described in turn.

Table 1
Summary of the hazard addressed and type of NbS investigated in each of the case study OALs.

	OAL-Austria	OAL-Germany	OAL-Greece	OAL-Ireland	OAL-UK
Hazard	Continuously moving deep-seated landslide	River flooding	River flooding	River flooding	Shallow landslides
NbS	Afforestation	Managed grazing	Flood storage reservoirs	Smart green roofs	High-density plantation of live branch cuttings

3.1. OAL-Austria

OAL-Austria (OAL-AT) comprises a continuously moving deep-seated landslide and its hydrological sub-catchment of about 5 km^2, ranging from 750 to 2200 m a.s.l. It is located on an east-facing slope at the entrance of the Watten valley in Tyrol, Austria (Fig. S1). The currently active landslide covers an area of 0.25 km^2 in the lower part of the slope and its shear plane is located at a depth of around 48 m below the surface. The landslide moves with an average velocity of about 4 cm/yr and shows phases of acceleration caused by enhanced groundwater recharge after prolonged rainfall and snow melt in the upslope catchment area [53,54]. In OAL-AT, these movements - and in particular differential surface deformation - cause severe damage to the buildings and infrastructure on top of the landslide, which may finally lead to abandonment [55,56]. In this light, the effectiveness of NbS for mitigating the risks of this continuously moving deep-seated landslide were investigated.

However, due to the enormous depth of the Vögelsberg landslide (around 48 m), NbS aiming at direct soil reinforcement (e.g. slope stabilisation with deep-rooting plants, live-anchors or related NbS, see OAL-UK in section 4.5) are not fitting the purpose in case of OAL-AT. Instead, measures reducing the hydrological driver of the landslide must be chosen. Technical mitigation measures aiming at reducing the pore water pressure in the sliding mass have proven successful for reducing the activity of deep-seated landslides [57,58]. Such typically grey measures (e.g. drainage trenches, tunnel- or borehole-aided deep-drainages) can be cost-intensive, energy-demanding, limited in life-time and require continuous maintenance. NbS aiming at reducing groundwater recharge on the other hand could provide a sustainable and long-term alternative. In particular, the hydrological effects of well-managed forests (enhanced interception, root water uptake and transpiration) on the activity of deep-seated landslides is still an underexplored component bearing a high mitigation potential, and this is what we investigate in this case study with a number of different landcover management scenarios, which are described in the supplementary material.

3.2. OAL-Germany

OAL-Germany is located in the Biosphere Reserve Lower Saxony Elbe Valley and is characterised as being a near-natural and species-rich landscape with floodplains with flood channels and old water lakes. Climate change is resulting in an increased occurrence of extreme precipitation across various regions, leading to a rise in both the frequency and severity of floods [59]. Riparian areas in Europe, such as the region of the OAL-Germany, are at an increased risk of flooding. OAL-Germany has experienced major flooding events in recent years, with significant flooding events in 2002, 2011, and 2013. In order to try and reduce the impact of such flooding events, a programme of cooperative floodplain management has been implemented by the local authorities, and as part of that there is a desire for existing floodplains to perform more effectively. Over time, vegetation along the riverbank grows, accumulates locally, and together this serves to slow down the rate at which water can exit the main channel. A NbS was implemented in winter 2014/2015, which saw the mechanical removal, cut-back, and clearing of woody vegetation along the riverbank in selected areas. This was combined with the use of various grazing animals, whose function was to prevent the regrowth of woody vegetation by consuming any regrowth, thus helping to maintain a more rapid flow onto the floodplain during times of flooding. In this case study we investigate the use of this NbS to try and reduce the hazard both for the present day climate, and for different possible future climates, which is described in more detail in the supplementary material.

3.3. OAL-Greece

The Spercheios river morphology, in combination with local heavy rainfall and riverbank overflow due to flood water from upstream, as

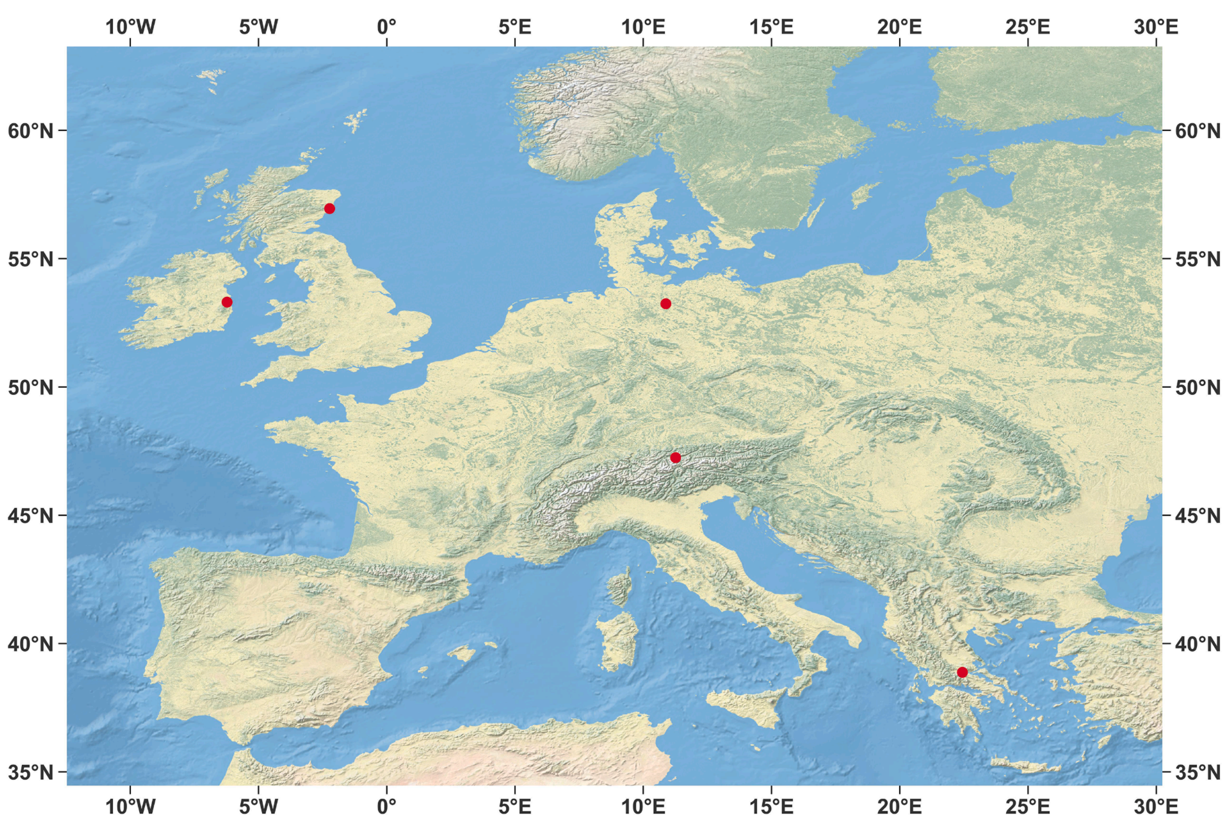

Fig. 1. Location of the five open-air laboratories (OALs), where the modelling case studies have been carried out: Austria, Germany, Greece, Ireland, and the UK.

well as the snowmelt in the upstream mountain areas, leads to flooding events mainly from October to May (Fig. S3). Such flooding events pose risk to human life, loss of crops and livestock, cause damages to properties and infrastructure, as well as difficulties in transportation, which under a changing climate are projected to increase [60]. In order to try and reduce these risks, a flood storage reservoir NbS has been implemented, leading to a reduction in flooded area, and water depth (Fig. S3, [51,61]). These modelling and monitoring results have demonstrated the effectiveness of the NbS in helping to reduce the risk of flooding and has stimulated interest in upscaling this NbS in order to try and achieve an even greater reduction in flooded area and water depth downstream. The construction of the reservoirs is achieved by restoring and stabilising the river banks, cleaning the bed material load, and widening the river bed. The first NbS at Komma has a storage capacity of approximately 600,000 m^3, and the second new one at Zilefto has a storage capacity of approximately 30,000 m^3 (Fig. S3). As such, the upscaling consists of increasing the number and not the size of the NbS. This approach is adapted to the conditions in the catchment, because there simply isn't room for larger NbS, given the proximity of the river to assets. In this case study we describe results from a modelling case study which investigates the additional benefit that adding a second NbS at Zilefto may bring in reducing flooded area and water depth, under the current and a future possible climate, which is described in more detail in the supplementary material.

3.4. OAL-Ireland

Extreme rainfall events, exacerbated by climate change and urbanization lead to the generation of excess surface runoff resulting in more frequent occurrence of flood events [62]. Fragmented land cover caused by urban development have resulted in alterations to the hydrological cycle [63]. The rate of surface runoff is dependent on various factors such as topography, morphology, river network [64], and the rainfall–runoff relationship [65]. Karamage et al. [66] reported that rapid urban expansion and agricultural intensification have resulted in an increase in the volume of rainfall-runoff.

The city of Dublin has experienced significant urban growth and development since the 1990s, with several major technology firms having offices in the city [66]. The River Dodder is one of the most important rivers in the Dublin area which originates in the Wicklow mountains and meets the River Liffey in the city centre of Dublin (Fig. S4). The River Dodder has a history of flooding and is known as a river which responds quickly to a rainstorm event [67,68]. Over 300 properties surrounding the Dodder catchment were affected by severe flooding when hurricane Charlie hit Dublin in 1986. Buyers behaviour in the housing market was also affected by past flooding events in Dublin [68].

Nature-based solutions (NbS) can potentially regulate the imbalances in water caused mainly by climate change [69]. Implementation of NbS in the form of parks, street trees, and urban green areas helps in regulating flood events [70]. This case study uses a Soil Water Assessment Tool (SWAT) to investigate the use of green roofs as a NbS to try and reduce the impact of such flooding events in the city of Dublin, both for the present day climate, and for different possible future climates, which is described in more detail in the supplementary material.

3.5. OAL-UK

Following recent prolonged rainfall events, the braes (hillsides) in Catterline Bay (Fig. S12) have recently experienced severe shallow landslides. This is important because the local hamlet of Catterline sits atop the braes, and as such there is a risk to property and life. In addition, past landslides blocked the only access road to the local beach and pier, which had an impact on local economic activities such as fishing, surfing schools, and tourism in general, but also prevented the local community from accessing their main recreational asset, thus impacting negatively on people's wellbeing and mental health. Under a changing climate, the frequency and magnitude of such prolonged rainfall events is expected to increase. As such, this represents a growing problem for the local community. Conventional civil engineering and other soil bioengineering techniques are not feasible to protect Catterline's braes, as these are very steep, hard to access, and lack workable earth materials. As such, nature-based solutions are needed in order to reduce the risk posed by the landslides. To date, there has been relatively little research undertaken on the hydrological and mechanical effect of vegetation on stabilising slopes, and it is common to see vegetated slopes fail following heavy rainfall, creating a negative perception around the use of vegetation for this purpose. In this case study we investigate the effectiveness of two woody plant species planted in high density from live branch cuttings, in stabilising the slope over time, under two different climate change scenarios, which is described in more detail in the supplementary material.

4. Materials and methods

4.1. A common methodological workflow in the OALs

A common modelling workflow for the evaluation of NbS performance in the different OALs was developed in OPERANDUM (Fig. 2a), building on recommendations provided in the OECD Handbook on constructing composite indicators [71]. The evaluation is based on modelling case studies and resulting bio-geophysical variables, which represent the effects of the identified NbS for mitigating the risks of the targeted natural hazards. The developed workflow consists of seven different steps which are summarised in Fig. 2a and described below.

The NbS operate on the bio-geophysical processes behind the natural hazards and either modify their impact directly e.g. flood reservoirs for lowering the water level, bio-engineering techniques for enhancing the stability of shallow soils, or indirectly e.g. green roofs for retaining rainfall and delaying runoff in flood-prone urban areas, or afforestation for reducing groundwater recharge of continuously moving deep-seated landslides. In order to include both principles in one workflow, the bio-geophysical variables representing the interaction of the NbS on the natural hazard process, were categorised into 'actionable variables' and 'impact variables'. Actionable variables were defined as bio-geophysical properties and processes at the landscape scale which are modified by the NbS e.g. infiltration capacity and hydraulic conductivity of green roofs, or evapotranspiration of forests. Impact variables were defined as bio-geophysical properties and processes which may change in response to the modification of bio-geophysical properties by deployed NbS and which may mitigate risks e.g. the probability distribution of flood water levels or landslide velocities. NbS designed to mitigate hydro-meteorological risks focus on reducing the impacts of the related natural hazards, and therefore modify the actionable variables in order to achieve a given impact.

The identification of actionable and impact variables for each NbS in the first step of the workflow requires a process level understanding which is typically based on previous monitoring campaigns [72,53] and/or process-based modelling case studies [51,54]. Based on this process level understanding, one or more suitable numerical experiments can be designed in the second step, which must represent the NbS effects on how natural hazards determine risks and include both actionable and impact variables. In a third step, the required model input (data and parameter values) are collected. After model application, the resulting time series must be checked for plausibility and validated in a fourth step. Based on the modelling results, one or more suitable indicators for assessing NbS performance must be defined in the fifth step. These indicators can be based on the previously defined impact variables or model results which can act as proxies for them. Furthermore, the indicators should meet several quality criteria [73,74] and must be chosen with care. Ideally, they are developed together with experts and stakeholders to make sure that the indicators are suitable for

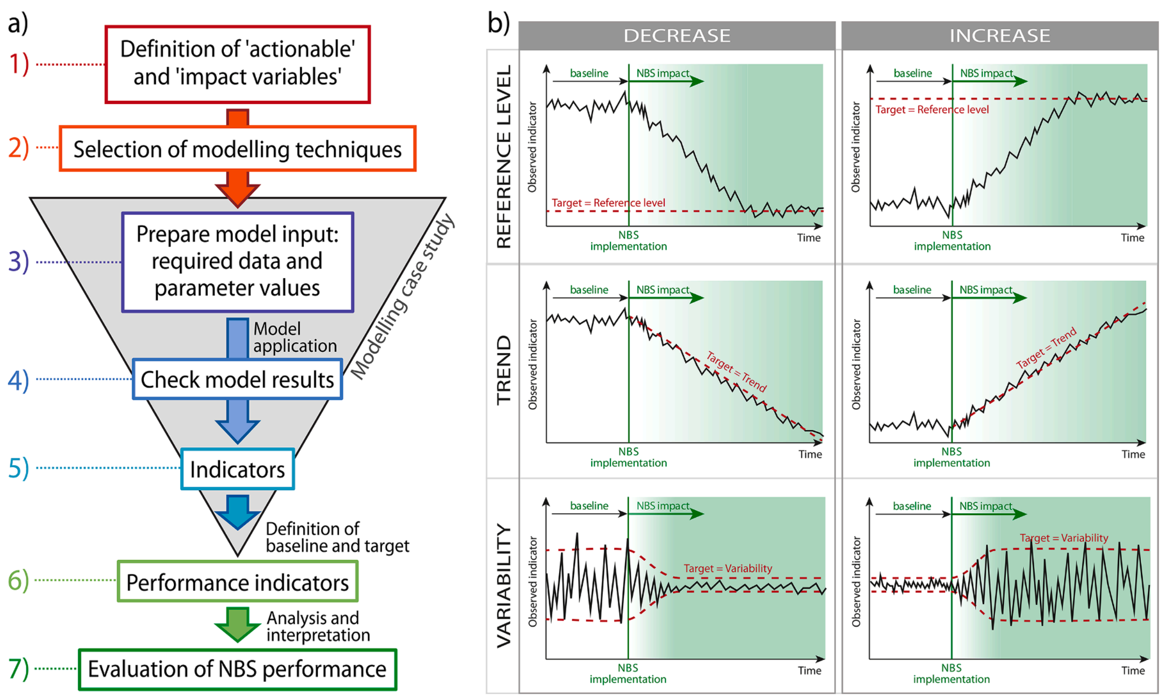

Fig. 2. (a) Seven-step workflow for evaluating the performance of NbS against HMHs based on modelling case studies and (b) examples for targets defined in order to assess NbS performance based on a selected indicator against a baseline scenario.

the intended purpose and accepted by decision makers. In a sixth step the defined indicators representing a baseline scenario are evaluated against defined targets, transforming them into performance indicators. In the presented case studies the baseline scenario refers to modelling results without the NbS. A range of different targets can be defined, depending on the selected indicator and its effects on a given land surface process. They can be defined as certain reference levels which should be reached, an increasing or decreasing trend, or an increase or decrease in the variability of an indicator (Fig. 2b).

Finally, in the seventh step, comparing the simulated changes of an indicator against the baseline scenario (without NbS), while considering the defined target allows one to draw conclusions about the performance of the NbS. The performance indicators need to capture first whether the NbS implementation leads to the desired change or not, i.e. 'does the NbS work as designed?'. Then other performance indicators should capture whether the NbS may trigger the intended impacts towards risk mitigation. Related results should be presented visually in a clear and accurate manner while communicating the most relevant information to the target audience. This is an important step since it influences the interpretability of the results by the target audience such as decision-makers, policy makers and other end-users.

Table 2 provides summary detail on the steps of the workflow for the different case studies. The work presented in the five case studies focuses on the evaluation of the impact variables. Considerable effort was also dedicated to the design of experiments which would also allow assessment of the actionable variables, and this formed the basis for a lot of monitoring activities within the OALs. Further information on the modelling techniques applied in the OALs can be found in the supplementary material.

4.2. *Testing NbS effectiveness under present-day and different future climates*

In order to provide a suitable test of the effectiveness of the different NbS under present-day and different possible future climates, a number of different climate data sets were used, both observations and climate model projections. For the observed data sets, different groups used different data, which consisted of station data, E-OBS [80], or ERA5 [81], and specific detail is provided in the supplementary material. To simulate the effectiveness of the NbS under different possible future climates, climate projection data (EUR-11) from the EURO—CORDEX project were used [82]. Ideally, the effectiveness of the NbS would be tested by running model simulations with climate data from hundreds of different possible future climates. However, given the resource constraints common in research projects a core ensemble of climate projections was selected from a much larger ensemble, in such a way that it sampled as much of the uncertainty in the full ensemble as possible. Details of the core ensemble members are given in Table 3.

These climate data were used by the different modelling groups to simulate the effectiveness of the NbS, under two different emission scenarios RCP4.5, and RCP8.5, whereby the RCP8.5 scenario was core, and RCP4.5 was optional for the modelling groups. More detailed information on the approach that the different modelling groups took is provided in the supplementary material.

5. Results

The effectiveness of the various NbS in reducing the hazards are described for each OAL below.

5.1. *OAL-Austria*

Time series of simulated and cumulated subsurface runoff per modelled land cover scenario and landslide velocity are shown in Fig. 3. Comparing the time series shows overall good correlations between the 30-day running sum of subsurface runoff and landslide velocity. However, the amount of subsurface runoff varies between the scenarios. On average and under present-day climate conditions the mean subsurface runoff is estimated at 60.7 l/s. In a scenario of mature forest covering all over the landslide catchment, the mean subsurface runoff is estimated at 34.8 l/s and therefore infers a potential reduction of the impact variable by 42.5 %. The scenario considering pole timber covering open land, which is currently not used for settlement or agricultural purpose, estimates a mean discharge of 54.7 l/s maintaining a reduction of the

Table 2
Summary detail of the unified methodological workflow outlined schematically in Fig. 2, for each OAL. The numbers in parentheses in column one indicate the step of the seven-step workflow to which it relates.

	OAL-Austria	OAL-Germany	OAL-Greece	OAL-Ireland	OAL-UK
Actionable variable (1)	Land cover type, LAI, fractional vegetation cover	Vegetation cover (preventing regrowth of woody vegetation)	Capacity of reservoir (retaining runoff during flood events)	Roof water storage capacity (interception, evapotranspiration, soil water storage)	Soil cohesion and matric suction changes due to presence of roots
Impact variables (1)	Water balance components (interception, evapotranspiration, subsurface runoff, groundwater recharge) Pore water pressure, landslide velocity	Flood water depth	Flooded area, flood water depth	Runoff, flooded area, flood water depth	Slope stability
Modelling technique (2)	Process-oriented SVAT model (LWF-Brook90) [75]	Hydrodynamic river model/ flood inundation model (HEC-RAS [76]	Hydraulic modelling system [77]	Soil Water Assessment Tool [78]	Process-based eco-hydrological model [79]
Model input (3)	Meteorological time series, parameterization of soil and vegetation characteristics for mapped HRUs	Meteorological time series, digital terrain model, parameterization of land cover (Manning's coefficient)	Precipitation time series, hydrographs, digital terrain model, soil characteristics	Time series of precipitation, temperature, relative humidity, sunshine hours and wind speed	Slope geometry, crib wall geometry, soil characteristics, plant attributes, timber attributes, meteorological time series, empirical plant-rainfall interactions, empirical allometric relationships (aboveground-belowground biomass).
Model results (4)	Time series of water balance components	Time series of flood inundation	20 % and 10 % annual exceedance probability (AEP) of events	Time series of water balance components	Daily time series of soil moisture, matric suction, suction stress, soil-root reinforcement and slope stability
Indicators (5)	Groundwater recharge, subsurface runoff, landslide velocity	Flood water depth	Flooded area, flood water depth	Runoff from the roof and soil moisture content in the green roof's soil strata; total flooded area, maximum water depth	Factor of safety
Baseline performance indicators (6,7)	Current land cover conditions and landslide activity	Flooded area/inundation depth and flood discharge without NbS (pre 2016)	Flooded area without flood storage reservoirs	Runoff from the roof without the deployment of green roof	Slope stability with and without NbS (i.e. fallow soil conditions)
Targets (6,7)	Reduction of subsurface runoff and groundwater recharge (negative trend), reduced landslide velocity down to <1 cm/yr (reference level)	Decrease in flood parameters: flood depth, duration, inundation extent, and flood peak with NbS deployment (post 2016)	Decrease in flooded area with NbS deployment for current and future climate conditions	Runoff reduction from the roof due to deployment of the green roof	Enhanced slope stability, reduced soil wetness, increased soil-root reinforcement

Table 3
The core ensemble of EUR-11 regional climate projection data used in the OPERANDUM modelling studies, made up of a global climate model and regional climate model pair, taken from the EURO-CORDEX project.

Global climate model	Regional climate model
MOHC-HadGEM2-ES	SMHI-RCA4_v1
ICHEC-EC-EARTH	CLMcom-CCLM4-8-17_v1
ICHEC-EC-EARTH	KNMI-RACMO22E_v1
MPI-ESM-LR	SMHI-RCA4
NorESM1-M	DMI-HIRHAM5

impact variable by 9.6 %. In case of a complete loss of currently prevailing forested areas, the mean discharge could increase up to 86.6 l/s (+38.3 %).

On the other hand, the determined change of the impact variable (i.e. landslide velocity) is less pronounced. The magnitude of potential velocity reduction by afforestation towards a mature forest is calculated to be in the order of −27.6 % (± 5.7 % 1σ) compared to velocities prevailing during a phase of accelerated landslide movement (Fig. 4). In terms of the likely scenario of pole timber deployed on open land the estimated velocity reduction accounts for −4.7 % (± 3.2 % 1σ). Whereas in the case that the land cover in the landslide's catchment would transform into open land, the landslide could accelerate by 18.9 % (± 4.7 % 1σ).

A reduction in velocity of 27.6 % would still mean that the landslide could accelerate up to 4.5 cm/yr. Therefore, also in the most optimistic scenario (complete cover by mature forests) the effect wouldn't be sufficient to reduce the landslide's velocity to an acceptable level at which buildings are not permanently damaged (e.g., <1 cm/yr). This means that the landslide risks are reduced, but not fully mitigated. Further measures including grey solutions should be bundled to further reduce groundwater recharge to a sufficient level for stabilizing the slope. One critical aspect remains the duration until the NbS effects are fully developed. In case of afforestation this may take more than 50 years until trees have reached maturity, particularly at high altitudes. The apparent damages at buildings however mean there is a demand for solutions in the short term. In addition, before implementing any drainage measures - NbS and/or grey solutions - it must be first ensured that the residents' freshwater supply remains secure. Furthermore, an updated cost-benefit analysis must be conducted if multiple solutions are selected.

5.2. OAL-Germany

The differences between post-NbS and pre-NbS scenarios were analysed and are presented in Fig. 5. The simulation outcomes highlighted the positive outcomes of NbS implementation, notably evidenced by a reduction in flood depths. With NbS measures implemented, flood depths decreased, especially under projected future climate scenarios. The simulation indicated that NbS measures led to a reduction in floodwater depth of approximately 0.036 m and 0.155 m during the near and far-future periods, respectively, in comparison to historical/control period (where the reduction was 0.023 m), as shown in Fig. 6a–f.

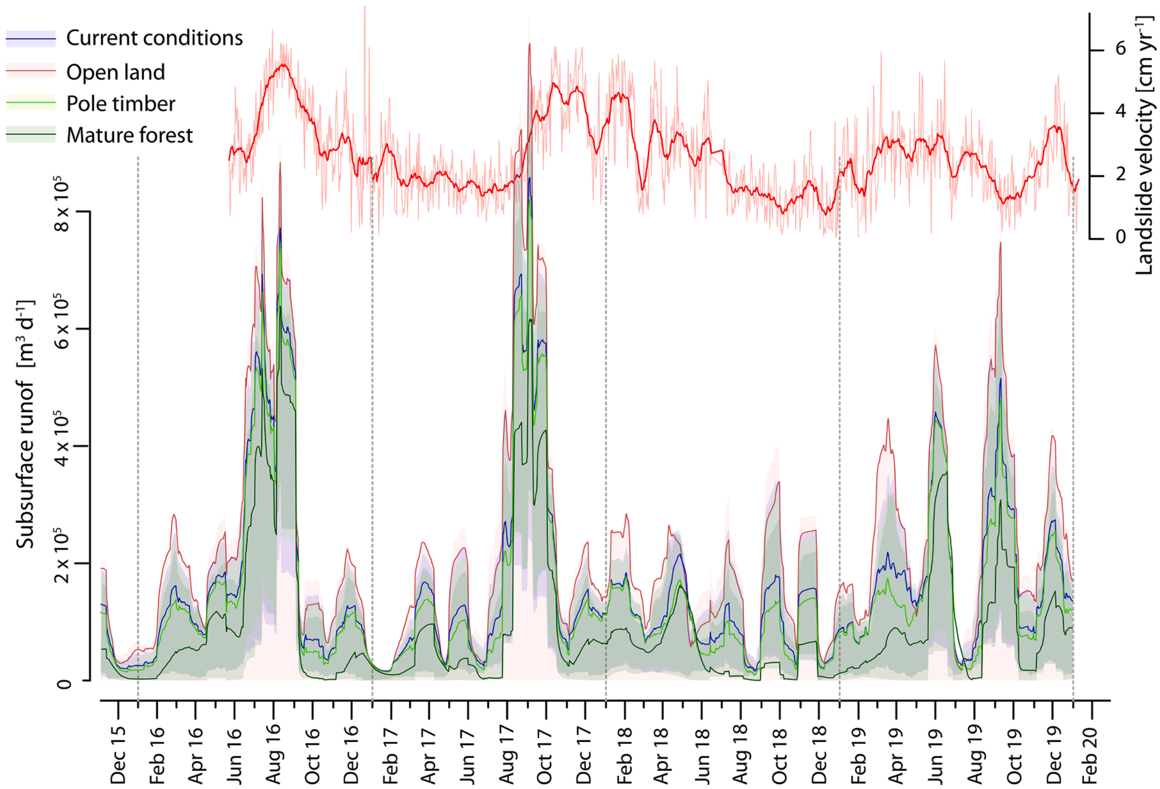

Fig. 3. Time series of simulated cumulated (30-day running sum) water surplus for different vegetation scenarios (pole timber, mature forest, current conditions and open land) in the catchment of OAL-AT and time series of landslide velocity (light red colour refer to daily measurements and the vibrant red to a 20-day moving average).

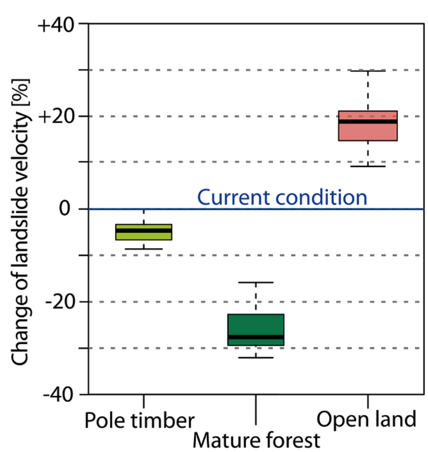

Fig. 4. Boxplots indicating expected changes in landslide velocity regarding different forest cover scenarios.

We assessed the NbS impacts on flood risk through modelling, comparing pre- and post-NbS conditions, revealing clear benefits in flood risk reduction. The adoption of NbS for flood risk reduction in OAL-Germany shows promising results. Our findings underscore riparian vegetation as a valuable NbS approach in flood depth reduction, especially under future climate conditions, and, as such, highlights the potential of this NbS to reduce flood risk. However, NbS should also complement broader flood management strategies, integrating with infrastructure measures and policies. Continuous monitoring and adaptation are vital for long-term NbS effectiveness as the climate changes.

Future research could delve deeper into the specific mechanisms through which NbS reduce flood depths, considering the interactions between vegetation, soil, and hydrological processes. Additionally, exploring the long-term sustainability and maintenance requirements of NbS will be crucial to ensure their continued effectiveness over time. Incorporating socio-economic factors into the analysis could also enhance the understanding of the overall benefits of NbS implementation, helping policymakers make informed decisions about flood risk management in riparian areas.

5.3. OAL-Greece

The results show that under the present-day climate without the NbS the maximum water depth is 12.18 m and with the upscaled NbS maximum water depth is slightly lower at 12.17 m, while the flooded area is 43.08 km^2 without the NbS, and 43.01 km^2 with the NbS. The 10 % AEP event results show good agreement with flood maps produced by previous studies [51,61], indicating that the modelling closely corresponds with the real world, thus providing confidence in the results.

For the future climate simulations, the results show that under all five simulations there is a reduction in maximum water depth and flooded area when the upscaled NbS are in place (Table 4). The most significant influence that the NbS have is in reducing the total flooded area with a reduction of up to 1.26 km^2 (38.85–37.59 km^2, Table 4).

While these changes in maximum water depth and total flooded area may on their own be considered to be rather modest, this is to be expected since the size of the NbS are also relatively modest, by design and of necessity. The criteria for selection of sites suitable for the NbS were the geomorphology of the area, land availability and accessibility, minimal disruption to other uses, concerns related to sustainability, and it was important that the NbS wouldn't pose any risk to the local communities. The final location was decided after thorough discussions with local experts and local community members. These modelling results combined with ongoing monitoring activities within the OAL, have demonstrated the value of the NbS in being able to reduce the magnitude

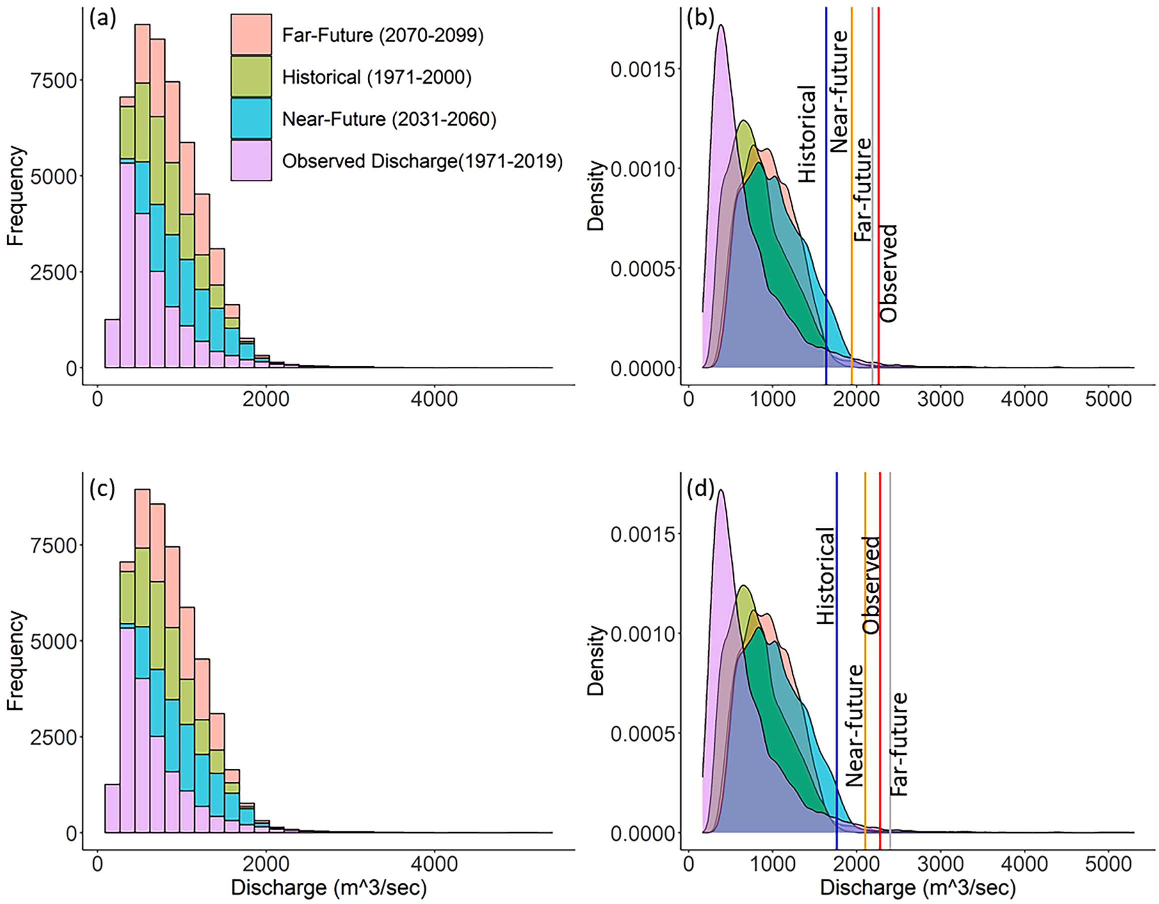

Fig. 5. Distribution of discharges (a and b) Wittenberg (upstream) and (c and d) Neu-Darchau (midstream) of Elbe River basin. The vertical solid lines are showing a 99 % percentile threshold used to extract extreme flood events from the whole time series of discharge and used as a boundary condition in the 1D and 2D hydraulic models.

of the hazard, and the implementation of additional NbS are already being planned, which will continue into the future.

5.4. OAL-Ireland

The results of the annual maximum flow obtained from the GEV with and without green roofs are shown in Fig. 7.

The total flooded area (TFA) and maximum flood water depth (MFD) for the historical and future periods corresponding to the three return period events are summarised in Tables 5 and 6, respectively. The results show that the use of green roofs can reduce TFA in the historical period by 21.4 %, 11.9 % and 11.4 % for the 10, 100, and 1000 year return period events, respectively. Under the RCP4.5 emissions scenario, the results show that for the future time period TFA can be reduced by 18.8–31.0 %, 11.2–15.3 %, and 11.2–12.8 %, for the 10, 100, and 1000 year return period events, respectively. For RCP8.5, the TFA is shown to be reduced by 18.3–23.6 %, 11.2–16.7 %, 11.4–13.4 % for the 10, 100, and 1000 year return period events, respectively.

The MFD for the historical period is reduced by 0.102 m, 0.106 m and 0.116 m for the 10, 100, and 1000 year return period events, respectively. For the RCP4.5 scenario, the MFD is shown to be reduced by 0.100–0.102 m, 0.102–0.108 m, and 0.109–0.138 m, for the 10, 100, and 1000 year return period events, respectively. While, under RCP8.5, the future time period MFD is shown to be reduced by 0.100–0.103 m, 0.102–0.109 m, and 0.104–0.138 m, for the 10, 100, and 1000 year return period events, respectively.

Overall, the simulation study of smart green roofs based on SWAT-LID showed clear potential for the green roofs to reduce flooding in the urban area and development of flood mitigation strategies for future climate change scenarios at the river catchment/city scale. The city-scale model needs to be validated based on real-world deployment of multiple green roofs and collating data. This model-based evidence supported a more extended deployment of monitored green-roofs across Dublin City Council. The data from these green roofs will provide more evidence to validate the projected flood maps.

5.5. OAL-UK

High-density planting had a positive effect in increasing the factor of safety (which is the ratio of driving to resting forces on the slope, denoting stability when FoS is above 1.3 and landslide when FoS is below 1.3), and thus slope stability when compared to fallow soil, and this is true for both species, and under both climate scenarios (Figs. 8, 9 (RCP8.5), and Fig. S13, S14 (RCP4.5) in the supplementary material). The improvement in slope stability increased over time as the vegetation developed, and was most pronounced during the growing season, and during the dry periods (Fig. 9, Fig. S13). The FoS was shown to increase substantially under both species to a maximum soil depth of 0.8 m below ground level (Fig. 9), but with the largest effect being observed in the uppermost 100–200 mm. The slope reinforcement effect generally increased with plant biomass, with Maple providing greater stability than Willow (Figs. 8, 9). Accordingly, the soil-root reinforcement effect also increased over time as vegetation grew on the slope. However, soil-root reinforcement mostly occurred within the top-most soil horizon (i.e., 0–0.5 m b.g.l) due to shallow vertical root distribution limited by the pedo-climatic features of the site [83]. Moreover, when individuals reached maturity after 50 years of growth, excessive plant surcharge led to slope instability issues in steep slope zones (i.e., slope gradient > 35°).

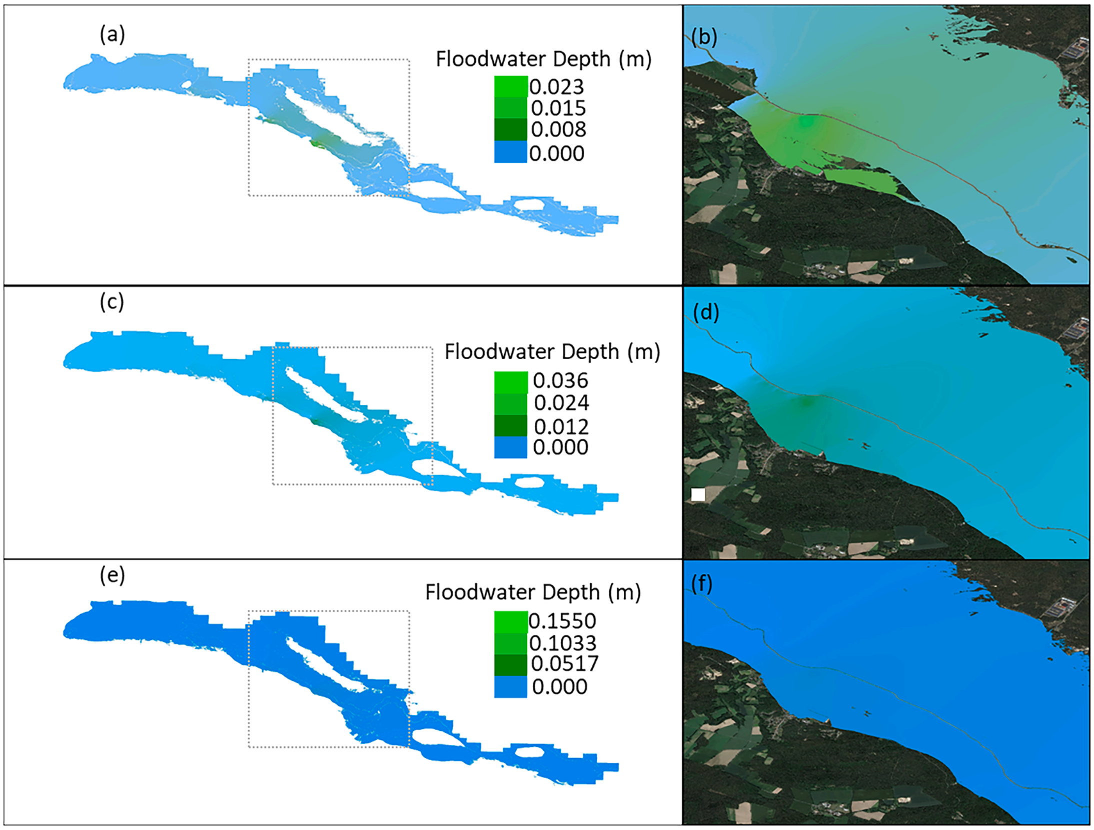

Fig. 6. Flood inundation/depth extents results for the historical (a and b), near-future (c and d), and far-future (e and f) under RCP 8.5. The results are showing the maximum flood depths reduced by the presence of NbS at midstream (b, d, f).

Table 4
River Spercheios maximum water depth and total flooded area (km^2), for the future climate simulations under RCP8.5, with and without the upscaled NbS. The values given are from the five different global and regional climate model pairs (GCM/RCM pairs).

Impact Variable and GCM/RCM pair	Without NbS	With upscaled NbS
Maximum water depth (m)		
ICHEC-EC-EARTH/ KNMI-RACMO22E_v1	11.89	11.86
ICHEC-EC-EARTH/CLMcom-CCLM4-8-17_v1	11.38	11.32
MOHC-HadGEM2-ES/SMHI-RCA4_v1	12.18	12.17
MPI-ESM-LR/SMHI-RCA4	11.98	11.94
NorESM1-M/DMI-HIRHAM5	11.61	11.56
Total flooded area (km^2)		
ICHEC-EC-EARTH/ KNMI-RACMO22E_v1	40.48	40.15
ICHEC-EC-EARTH/CLMcom-CCLM4-8-17_v1	38.85	37.59
MOHC-HadGEM2-ES/SMHI-RCA4_v1	42.97	42.87
MPI-ESM-LR/SMHI-RCA4	41.05	40.49
NorESM1-M/DMI-HIRHAM5	39.75	38.99

This observation suggests that woody vegetation can effectively protect shallow slopes against landslides, but additional interventions should be considered when slope-forming materials are deeper than 0.8 m and when deeper-seated landslides are likely. Furthermore, it also suggests that species selection in combination with plant cover management is crucial to ensure long-term slope stability. Lower woody biomass species, such as willow, are more suitable for the steepest slope zones. Thinning, coppicing, and clearcutting practices could also be considered when the plant cover reaches maturity to maintain slope stability. Management of vegetation's aerial architecture can also be beneficial for regulating the water cycle aboveground, which also has slope stability implications [84,85].

Overall, these results provide indicative evidence that high-density planting of woody vegetation is an effective NbS against shallow landslides, as compared to fallow ground. While substantial work is still needed to better understand how woody vegetation can be an effective NbS against shallow landslides, these results are thus in keeping with other analyses which have also shown this [86–89]. Importantly, from a practical implementation point of view, both studied plant species can be propagated from branch cuttings using locally available plant stock, making the implementation of this NbS feasible in remote slopes and under resource-limited situations.

6. Discussion and conclusions

All five model-based case studies have shown that the investigated NbS are able to reduce the magnitude of the hazard in their respective OAL. In the OALs studied, it is only OAL-Austria that has a specifically defined target level for hazard reduction, where, if the velocity of the landslide could be reduced to <1 cm/yr, there would be no risk of permanent damage to buildings. The results show that in the best case scenario of mature forest, the velocity could potentially be slowed to 4.5 cm/yr. As such, to really address this risk in OAL-Austria hybrid solutions would have to be considered where NbS and more traditional engineering solutions would need to be used [e.g. 58]. In the other OALs the model-based evidence shows that the NbS are able to reduce hazards, however, the question as to whether or not the effectiveness of the NbS has been demonstrated sufficiently enough to increase their wider adoption is something that has been discussed with stakeholders in the OALs. For example, in OAL-Ireland, the modelling results supported the deployment of more monitored green roofs by Dublin City Council at the city scale; while in OAL-Greece, the modelling demonstrated the effectiveness of upscaling the NbS, and additional NbS are already being planned to be implemented in the Spercheios catchment. These two examples demonstrate the importance of stakeholder dialogue and the role that the model-based evidence can play in the process of aiding the

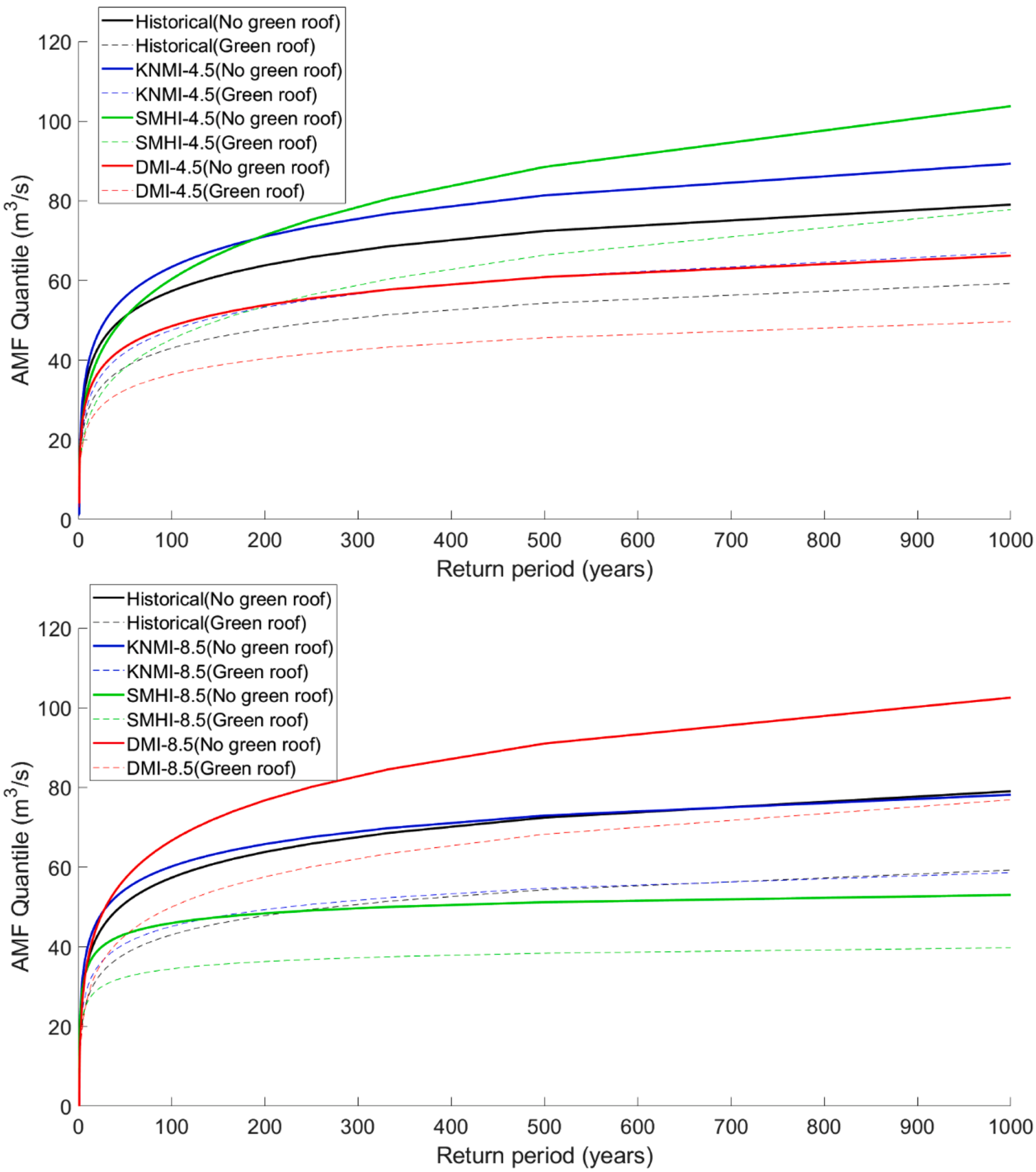

Fig. 7. Quantile plot of annual maximum flows using GEV distribution for the historical and future climate change scenarios (RCP4.5 top, and RCP8.5 bottom), with and without the 160 hypothetical green roofs.

wider adoption and uptake of NbS.

Another important factor related to the effectiveness of the NbS, is how well they may perform over time, and this is particularly important in the context of climate change. It is interesting to note that in OAL-Germany and OAL-UK, the NbS are shown to become more effective over time. In the case of OAL-UK this is because the trees grow over time and become more effective in stabilising the slopes. This is important, as in addition to the effectiveness in reducing the magnitude of the hazard, the time-period over which the NbS may be effective is an important consideration when assessing their cost-effectiveness [46]. Related to this, is the effectiveness of the NbS in reducing hazards associated with different magnitude events. For example, in OAL-Ireland the results show that the green roofs were able to reduce the hazard associated with longer return period event flooding when the impact variable considered was maximum flood depth, but this pattern was reversed when the impact variable considered was total flooded area (cf. Tables 5 and 6). This is important given that any investment decision will be made according to design criteria to provide a certain level of risk reduction, and in particular when viewed in comparison to their cost-effectiveness with grey infrastructure [43,90].

These modelling studies have been carried out within the context of the OPERANDUM project, where most of the NbS have actually also been implemented in the real world, and been subject to ongoing monitoring campaigns (only the NbS in OAL-Austria hasn't been implemented in the real world). As such, the model-based evidence is actively being considered within a real world setting, where the results are being used to inform the decision making process with stakeholders as to which NbS may be effective. An important question to consider when using model-based evidence in such a process is how closely do the modelling results correspond to their actual operation in the real world. There are two aspects to consider here: one, the assumptions made in the structure and function of the NbS in the models i.e. how they grow, develop, and operate; the other is, given the limitations that the modelling assumptions may impose, how closely do the model outputs validate against the real world.

In the cases presented here, the NbS as modelled in OAL-Greece and

Table 5
Comparison of total flooded area obtained from the flood inundation maps developed for the historical and future time period under two different emissions scenarios (RCP4.5 and RCP8.5) for different GCM/RCM pairs, with and without green roofs, and for different return periods.

Time period		Expected floods corresponding to 10 years return period			Expected floods corresponding to 100 years return period			Expected floods corresponding to 1000 years return period		
		Flooded Area (sq. km.)	Flooded Area with Green Roofs (sq. km.)	Reduction in flooded area due to Green Roofs (%)	Flooded Area (sq. km.)	Flooded Area with Green Roofs (sq. km.)	Reduction in flooded area due to Green Roofs (%)	Flooded Area (sq. km.)	Flooded Area with Green Roofs (sq. km.)	Reduction in flooded area due to Green Roofs (%)
Historical		0.63	0.50	21.4	0.81	0.71	11.9	0.92	0.82	11.4
Future period	KNMI4.5	0.66	0.54	18.8	0.84	0.75	11.2	0.97	0.86	11.9
	KNMI8.5	0.68	0.55	18.3	0.82	0.73	11.3	0.92	0.81	11.4
	SMHI4.5	0.59	0.43	27.7	0.82	0.73	11.2	1.05	0.92	12.8
	SMHI8.5	0.62	0.47	23.6	0.74	0.61	16.7	0.78	0.67	13.4
	DMI4.5	0.57	0.39	31.0	0.75	0.64	15.3	0.85	0.76	11.2
	DMI8.5	0.64	0.50	20.7	0.86	0.76	11.2	1.05	0.91	13.0

Table 6
Comparison of maximum water depths obtained from the flood inundation maps developed for the historical and future time period under two different emissions scenarios, with and without green roofs corresponding to different return periods.

Time period		Expected floods corresponding to 10 years return period			Expected floods corresponding to 100 years return period			Expected floods corresponding to 1000 years return period		
		Maximum Flood Depth (m)	Maximum Flood Depth with Green Roofs (m)	Reduction in Flood depth due to Green Roofs (m)	Maximum Flood Depth (m)	Maximum Flood Depth with Green Roofs (m)	Reduction in Flood depth due to Green Roofs (m)	Maximum Flood Depth (m)	Maximum Flood Depth with Green Roofs (m)	Reduction in Flood depth due to Green Roofs (m)
Historical		3.763	3.661	0.102	4.073	3.967	0.106	4.337	4.221	0.116
Future period	KNMI4.5	3.801	3.701	0.100	4.151	4.044	0.108	4.453	4.329	0.124
	KNMI8.5	3.823	3.723	0.100	4.111	4.004	0.107	4.328	4.212	0.116
	SMHI4.5	3.707	3.605	0.102	4.112	4.006	0.106	4.606	4.468	0.138
	SMHI8.5	3.743	3.641	0.103	3.914	3.812	0.102	4.015	3.911	0.104
	DMI4.5	3.679	3.577	0.101	3.950	3.848	0.102	4.186	4.077	0.109
	DMI8.5	3.769	3.668	0.102	4.191	4.082	0.109	4.594	4.456	0.138

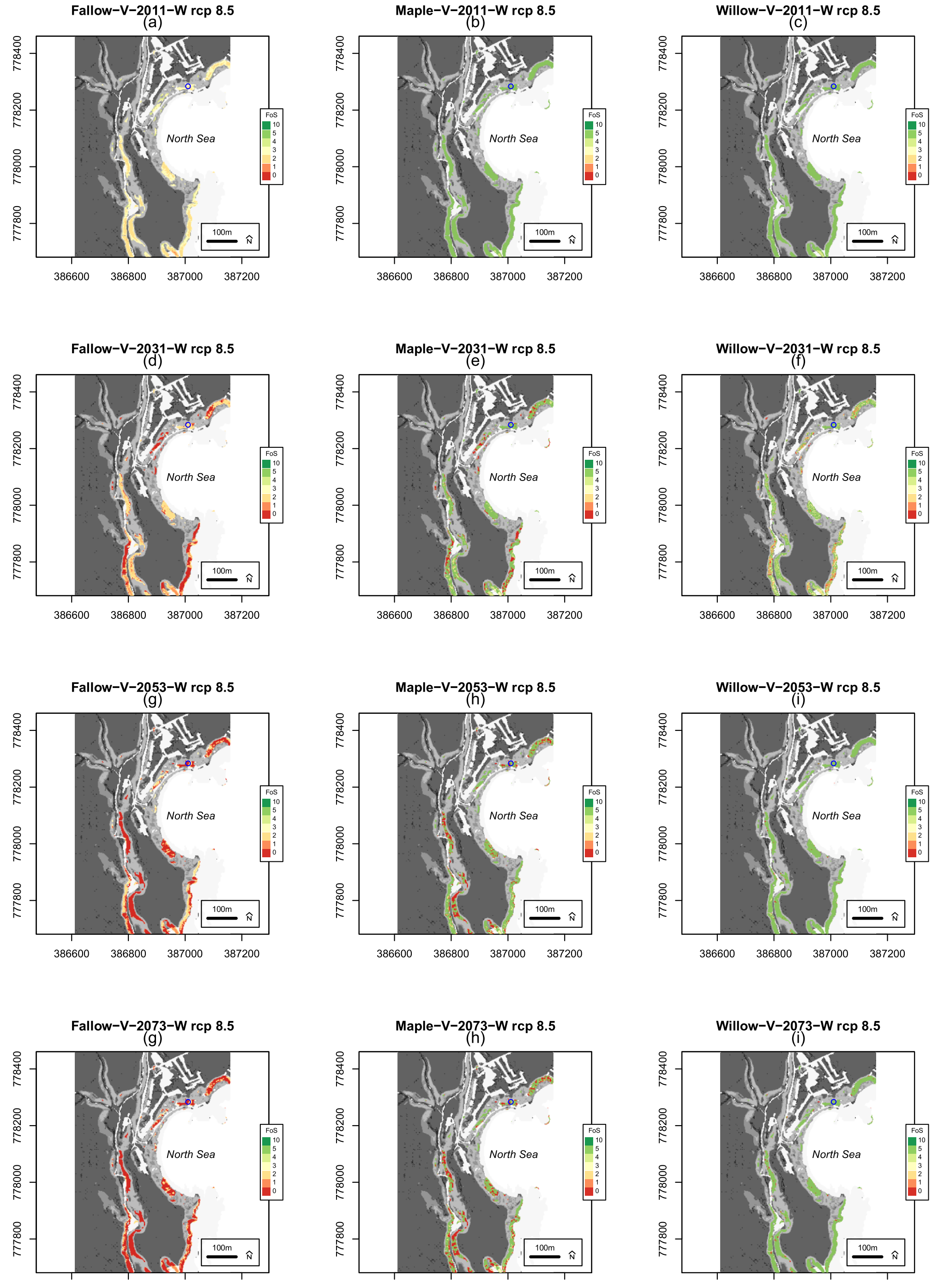

Fig. 8. Model outputs for the Factor of Safety (FoS) at 100–200 mm below ground level (b.g.l) for fallow, maple and willow groundcovers during the growing season and under *wetting cycles* for selected rainfall events predicted under the climate change scenario RCP8.5 for the years 2011, 2031, 2053 and 2073 (Table S1). Pixels in red denote landslides, whilst green pixels indicate that the slope is stable. Grey zones are zones where the model was not evaluated as they are not prone to landslides. The FoS profiles for the data point marked in blue are shown in Fig. 10.

OAL-Germany are identical in size and location to their counterparts in the real-world. In OAL-UK the modelling also closely relates to tests of NbS that have been made in the real-world albeit at a smaller scale than the modelling results [84]. In OAL-Greece, Germany, Ireland, and the UK, the temporal development of the NbS is modelled as it would occur in the real world. For example, the model used in the UK simulates plant growth following planting of the NbS, and doesn't assume that the plants are able to perform optimally from day one. This is indeed demonstrated in the modelling in the UK, where the effectiveness increases over time as the plants mature. The modelling in OAL-Austria doesn't provide information on the temporal evolution and effectiveness of the NbS as it matures however, since the modelling is carried out under the assumption that the forest is already at maturity, and thus able to provide optimal effectiveness. Clearly, any afforestation NbS would not reach full maturity (and thus effectiveness) until several decades after implementation. This is important because the time it may take for a given NbS to reach maturity and provide optimal effectiveness, is again an essential consideration when making investment decisions related to NbS [46].

Moreover, experience in OPERANDUM has demonstrated that the

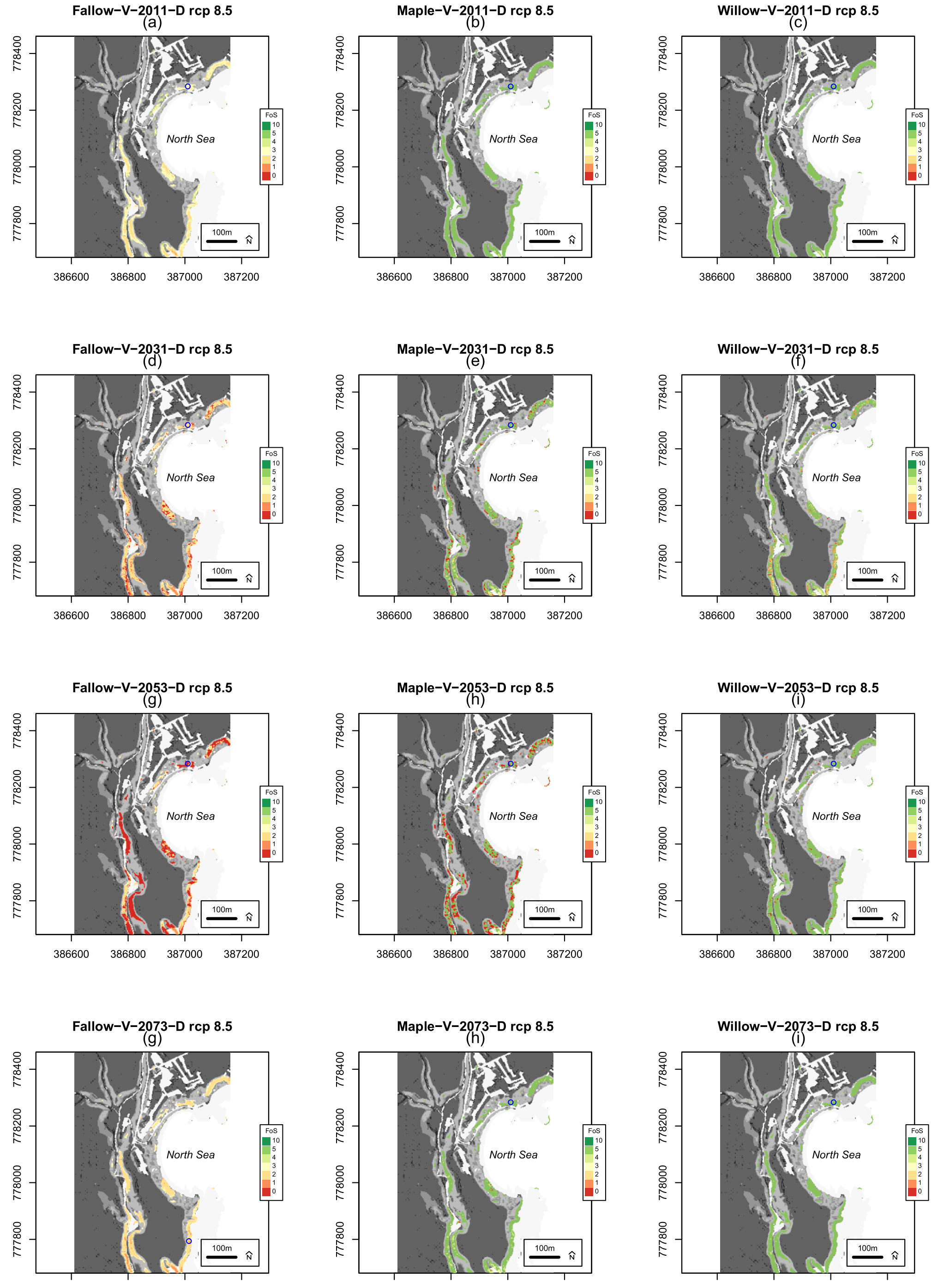

Fig. 9. Model outputs for the Factor of Safety (FoS) at 100–200 mm below ground level (b.g.l) for fallow, maple and willow groundcovers during the growing season and under *drying cycles* for selected rainfall events predicted under the climate change scenario RCP8.5 for the years 2011, 2031, 2053 and 2073 (Table S1). Pixels in red denote landslides, whilst green pixels indicate that the slope is stable. Grey zones are zones where the model was not evaluated as they are not prone to landslides. The FoS profiles for the data point marked in blue are shown in Fig. 10.

implementation of NbS is not a straightforward process, and they themselves are vulnerable to the kinds of natural hazards they are designed to protect against. An artificial dune NbS in OAL-Italy was destroyed during a winter storm before it could reach maturity, and the NbS had to be redeployed. This serves to highlight that while model-based evidence can help inform and promote the wider adoption of NbS, the road to implementation of NbS and actual effectiveness is not a straightforward one, and this may represent an almost irreducible uncertainty in comparison to grey solutions i.e. will the NbS actually ever reach maturity so that they can deliver on their potential in a given real-world situation? This is an issue worthy of further consideration, and possibly new modelling studies could be used to guide the design and development of NbS. One way might be to carry out simulations testing the intended NbS against observed extremes, and also under observed extreme plus additional climate warming in so-called storyline analyses [91], where the models are used to test under what kind of conditions might the NbS be destroyed, and/or not be able to provide a desired level of risk reduction. This also relates back to their effectiveness under different magnitude events, which may in turn help to inform the dimensioning of new NbS for a given level of risk reduction.

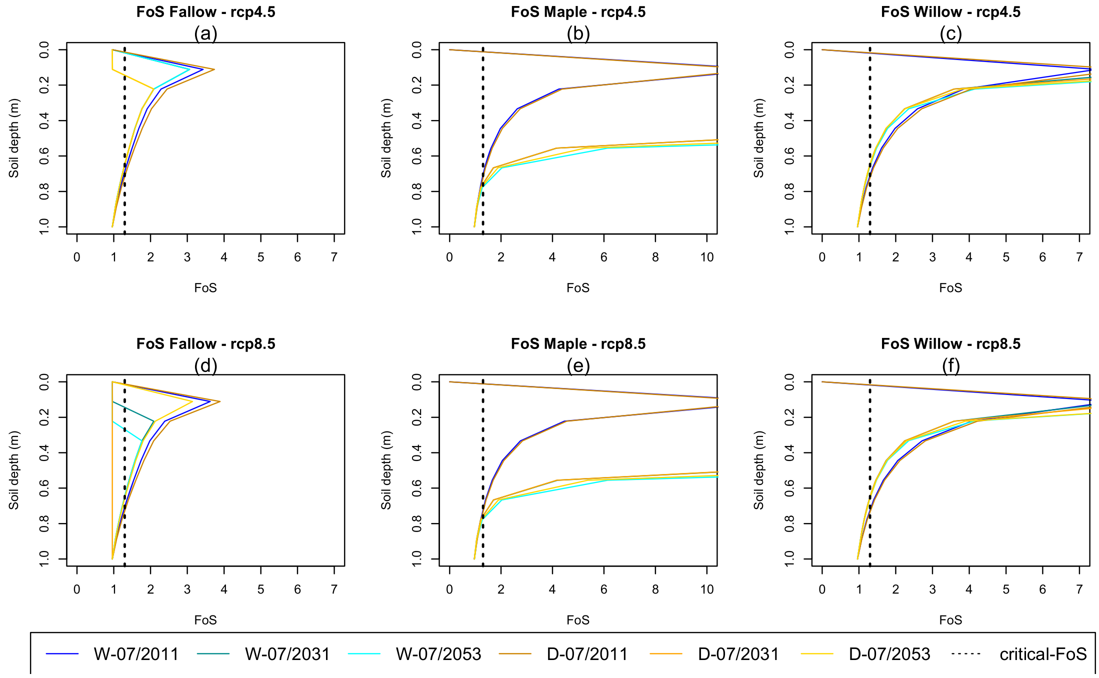

Fig. 10. Factor of Safety (FoS) profiles over the uppermost 1 m, deep soil profile retrieved from the data point shown in Fig. 11 following wetting (W) and drying (D) cycles during the vegetative season predicted with the climate change scenarios RCP4.5 and RCP8.5 for the years 2011, 2031 and 2053 (see Table S1). Slope stability was assessed using the factor of safety (FoS), which is the ratio of driving to resting forces on the slope, denoting stability when FoS is above 1.3 and landslide when FoS is below 1.3.

The different models that have been used to simulate the effectiveness of the NbS in the different OALs have all been tested and well validated in similar kinds of environments. While the NbS themselves may be modelled realistically, the number of model simulations is actually very small, and a relatively small amount of the uncertainty in the models and the climate projection ensemble data has been explored and quantified. In particular, the core climate ensemble data that was used to simulate the effectiveness of the NbS under possible future climates had a maximum of five members, and only OAL-Greece actually used all five. As such, while the NbS have been shown to be effective, in order to have more confidence in the results, many more simulations should be carried out, where the parameters of the impact models are also varied within plausible ranges, so that there is a better quantification of the uncertainty in the models. In addition, while OAL-Ireland and OAL-UK carried out modelling with two emissions scenarios (RCP4.5, and RCP8.5), in OAL-Greece and OAL-Germany, only RCP8.5 was used, which, while it may represent a potential worst-case experiment, depending on the design lifetime of a given NbS, it would be advisable to run simulations with additional emissions scenarios.

Overall, the uncertainties and limitations notwithstanding, the model-based evidence presented here shows that the NbS considered have potential to reduce the magnitude of the associated hazards both in present-day and future possible climates, and thus help to reduce the risks posed in the OALs. Discussions with stakeholders have already demonstrated the impact that such model-based evidence may have in stimulating awareness and understanding of their potential effectiveness which has led to the development of plans to implement the NbS more widely in a number of the OALs. Further modelling analyses which build on some of the issues highlighted here will lead to a strengthening of the evidence base for the effectiveness of NbS in reducing disaster risk, particularly in the context of climate change, and serve to promote their wider adoption and implementation.

NbS impacts and implications

- *Environmental*: in a warming world the challenges presented by natural hazards are only going to increase and thus the need for NbS is only going to grow in importance. The results presented in this paper provide clear evidence that NbS are able to reduce disaster risk.
- *Economic*: investment decisions made in response to the risks posed by natural hazards is a political decision based on an assessment of a range of different socio-economic factors. The results presented in this paper provide evidence to support complementary analysis on the costs and benefits of the NbS presented.
- *Social*: model-based evidence for the effectiveness of a given NbS provides a basis on which to engage with stakeholders and decision-makers to explore the potential for the wider adoption of NbS. The results in the paper highlight examples of where this has happened, and the changes it has helped bring about.

CRediT authorship contribution statement

Paul Bowyer: Conceptualization, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Silvia Maria Alfieri:** Conceptualization, Data curation, Writing – review & editing. **Bidroha Basu:** Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Emilie Cremin:** Writing – original draft, Writing – review & editing. **Sisay Debele:** Conceptualization, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Prashant Kumar:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing. **Veronika Lechner:** Data curation, Formal analysis, Visualization. **Michael Loupis:** Conceptualization, Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Massimo Menenti:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Slobodan Mickovski:** Supervision, Writing – original draft, Writing – review & editing. **Alejandro Gonzalez-Ollauri:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Jan Pfeiffer:** Data curation, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Francesco Pilla:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Beatrice Pulvirenti:** Writing – original draft, Writing – review & editing. **Paolo Ruggieri:** Writing – original draft, Writing – review & editing. **Arunima Sarkar Basu:** Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Christos Spyrou:** Conceptualization, Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Silvia Unguendoli:** Writing – original draft, Writing – review & editing. **Thomas Zieher:** Conceptualization, Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Silvana di Sabatino:** Project administration, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Some of the data from the OALs may be available upon request.

Acknowledgments

This work was supported by the European Union's (EU) Horizon 2020 research and innovation programme. It was funded by and carried out within the framework of OPERANDUM (OPEn-air laboRAtories for Nature baseD solUtions to Manage hydro-meteo risks) project (Grant no. 776848).

The discharge data used in the OAL-Germany case study were kindly provided by The Global Runoff Data Centre, 56068 Koblenz, Germany.

We acknowledge the E-OBS dataset from the EU-FP6 project UERRA (http://www.uerra.eu) and the Copernicus Climate Change Service, and the data providers in the ECA&D project (https://www.ecad.eu)

Pieter voor de Poorte and the Catterline Braes Action Group in OAL-UK for collection and access to meteorological data and coordination of co-design/co-deployment.

Fig. 1 was made with Natural Earth data.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.nbsj.2024.100127.

References

[1] IPCC[Core Writing Team K. Calvin, D. Dasgupta, G. Krinner, A. Mukherji, P. W. Thorne, C. Trisos, J. Romero, P. Aldunce, K. Barrett, G. Blanco, W.W.L. Cheung, S. Connors, F. Denton, A. Diongue-Niang, D. Dodman, M. Garschagen, O. Geden, B. Hayward, C. Jones, F. Jotzo, T. Krug, R. Lasco, Y.-Y. Lee, V. Masson-Delmotte, M. Meinshausen, K. Mintenbeck, A. Mokssit, F.E.L. Otto, M. Pathak, A. Pirani, E. Poloczanska, H.-O. Pörtner, A. Revi, D.C. Roberts, J. Roy, A.C. Ruane, J. Skea, P. R. Shukla, R. Slade, A. Slangen, Y. Sokona, A.A. Sörensson, M. Tignor, D. Van Vuuren, Y.-M. Wei, H. Winkler, P. Zhai, Z. Zommers, J.-C. Hourcade, F.X. Johnson, S. Pachauri, N.P. Simpson, C. Singh, A. Thomas, E. Totin, P. Arias, M. Bustamante, I. Elgizouli, G. Flato, M. Howden, C. Méndez-Vallejo, J.J. Pereira, R. Pichs-Madruga, S.K. Rose, Y. Saheb, R. Sánchez Rodríguez, D. Ürge-Vorsatz, C. Xiao, N. Yassaa, A. Alegría, K. Armour, B. Bednar-Friedl, K. Blok, G. Cissé, F. Dentener, S. Eriksen, E. Fischer, G. Garner, C. Guivarch, M. Haasnoot, G. Hansen, M. Hauser, E. Hawkins, T. Hermans, R. Kopp, N. Leprince-Ringuet, J. Lewis, D. Ley, C. Ludden, L. Niamir, Z. Nicholls, S. Some, S. Szopa, B. Trewin, K.-I. Van Der Wijst, G. Winter, M. Witting, A. Birt, M. Ha, J. Romero, J. Kim, E.F. Haites, Y. Jung, R. Stavins, A. Birt, M. Ha, D.J.A. Orendain, L. Ignon, S. Park, Y. Park, A. Reisinger, D. Cammaramo, A. Fischlin, J.S. Fuglestvedt, G. Hansen, C. Ludden, V. Masson-Delmotte, J.B.R. Matthews, K. Mintenbeck, A. Pirani, E. Poloczanska, N. Leprince-Ringuet, C. Péan, 2023: climate Change 2023: synthesis Report, in: H. Lee, J. Romero (Eds.), Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel On Climate Change, Intergovernmental Panel on Climate Change (IPCC), Geneva, Switzerland, 2023, https://doi.org/10.59327/IPCC/AR6-9789291691647 [Core Writing Team]IPCC.

[2] A. Bisaro, K. Meyer, Integrating Nature-based Solutions Into Policies for Climate Change Adaptation and Disaster Risk Reduction, IUCN, Gland, Switzerland, 2022.

[3] C. Davies, W.Y. Chen, G. Sanesi, R. Lafortezza, The European Union roadmap for implementing nature-based solutions: a review, Environ. Sci. Policy 121 (2021) 49–67, https://doi.org/10.1016/j.envsci.2021.03.018.

[4] S.E. Debele, P. Kumar, J. Sahani, B. Marti-Cardona, S.B. Mickovski, L.S. Leo, F. Porcù, F. Bertini, D. Montesi, Z. Vojinovic, S. Di Sabatino, Nature-based solutions for hydro-meteorological hazards: revised concepts, classification schemes and databases, Environ. Res. 179 (2019) 108799, https://doi.org/10.1016/j.envres.2019.108799.

[5] Nature-based solutions in Europe: policy, knowledge and practice for climate change adaptation and disaster risk reduction, https://doi.org/10.1163/9789004322714_cclc_2021-0190-608.

[6] S.E. Hobbie, N.B. Grimm, Nature-based approaches to managing climate change impacts in cities, Phil. Trans. R. Soc. B 375 (2020) 20190124, https://doi.org/10.1098/rstb.2019.0124.

[7] B.A. Johnson, P. Kumar, N. Okano, R. Dasgupta, B.R. Shivakoti, Nature-based solutions for climate change adaptation: a systematic review of systematic reviews, Nat. Solut. 2 (2022) 100042, https://doi.org/10.1016/j.nbsj.2022.100042.

[8] C. Nesshöver, T. Assmuth, K.N. Irvine, G.M. Rusch, K.A. Waylen, B. Delbaere, D. Haase, L. Jones-Walters, H. Keune, E. Kovacs, K. Krauze, M. Külvik, F. Rey, J. Van Dijk, O.I. Vistad, M.E. Wilkinson, H. Wittmer, The science, policy and practice of nature-based solutions: an interdisciplinary perspective, Sci. Total Environ. 579 (2017) 1215–1227, https://doi.org/10.1016/j.scitotenv.2016.11.106.

[9] K. Sudmeier-Rieux, T. Arce-Mojica, H.J. Boehmer, N. Doswald, L. Emerton, D. A. Friess, S. Galvin, M. Hagenlocher, H. James, P. Laban, C. Lacambra, W. Lange, B. G. McAdoo, C. Moos, J. Mysiak, L. Narvaez, U. Nehren, P. Peduzzi, F.G. Renaud, S. Sandholz, L. Schreyers, Z. Sebesvari, T. Tom, A. Triyanti, P. Van Eijk, M. Van Staveren, M. Vicarelli, Y. Walz, Scientific evidence for ecosystem-based disaster risk reduction, Nat. Sustain. 4 (2021) 803–810, https://doi.org/10.1038/s41893-021-00732-4.

[10] S.C. Cook-Patton, C.R. Drever, B.W. Griscom, K. Hamrick, H. Hardman, T. Kroeger, P. Pacheco, S. Raghav, M. Stevenson, C. Webb, S. Yeo, P.W. Ellis, Protect, manage and then restore lands for climate mitigation, Nat. Clim. Change 11 (2021) 1027–1034, https://doi.org/10.1038/s41558-021-01198-0.

[11] S. Deng, X. Deng, B. Griscom, T. Li, W. Yuan, Z. Qin, Can nature help limit warming below 1.5°C? Glob. Change Biol. 29 (2023) 289–291, https://doi.org/10.1111/gcb.16479.

[12] B.W. Griscom, J. Adams, P.W. Ellis, R.A. Houghton, G. Lomax, D.A. Miteva, W. H. Schlesinger, D. Shoch, J.V. Siikamäki, P. Smith, P. Woodbury, C. Zganjar, A. Blackman, J. Campari, R.T. Conant, C. Delgado, P. Elias, T. Gopalakrishna, M. R. Hamsik, M. Herrero, J. Kiesecker, E. Landis, L. Laestadius, S.M. Leavitt, S. Minnemeyer, S. Polasky, P. Potapov, F.E. Putz, J. Sanderman, M. Silvius, E. Wollenberg, J. Fargione, Natural climate solutions, Proc. Natl. Acad. Sci. U.S.A. 114 (2017) 11645–11650, https://doi.org/10.1073/pnas.1710465114.

[13] B.W. Griscom, J. Busch, S.C. Cook-Patton, P.W. Ellis, J. Funk, S.M. Leavitt, G. Lomax, W.R. Turner, M. Chapman, J. Engelmann, N.P. Gurwick, E. Landis, D. Lawrence, Y. Malhi, L. Schindler Murray, D. Navarrete, S. Roe, S. Scull, P. Smith, C. Streck, W.S. Walker, T. Worthington, National mitigation potential from natural climate solutions in the tropics, Phil. Trans. R. Soc. B 375 (2020) 20190126, https://doi.org/10.1098/rstb.2019.0126.

[14] C.J. Nolan, C.B. Field, K.J. Mach, Constraints and enablers for increasing carbon storage in the terrestrial biosphere, Nat. Rev. Earth Environ. 2 (2021) 436–446, https://doi.org/10.1038/s43017-021-00166-8.

[15] N. Seddon, E. Daniels, R. Davis, A. Chausson, R. Harris, X. Hou-Jones, S. Huq, V. Kapos, G.M. Mace, A.R. Rizvi, H. Reid, D. Roe, B. Turner, S. Wicander, Global recognition of the importance of nature-based solutions to the impacts of climate change, Glob. Sustain. 3 (2020) e15, https://doi.org/10.1017/sus.2020.8.

[16] S. Goodwin, M. Olazabal, A.J. Castro, U. Pascual, Global mapping of urban nature-based solutions for climate change adaptation, Nat. Sustain. 6 (2023) 458–469, https://doi.org/10.1038/s41893-022-01036-x.

[17] Mysiak, J., Castellari, S., Kurnik, B., Swart, R., Pringle, P., Schwarze, R., Wolters, H., Jeuken, A., Van Der Linden, P., 2018. Brief communication: strengthening coherence between climate change adaptation and disaster risk reduction through policies,methods and practices in Europe. Risk Assessment, Mitigation and Adaptation Strategies, Socioeconomic and Management Aspects. https://doi.org/10.5194/nhess-2018-80.

[18] M.A.R. Shah, J. Xu, F. Carisi, F. De Paola, S. Di Sabatino, A. Domeneghetti, C. Gerundo, A. Gonzalez-Ollauri, F. Nadim, N. Petruccelli, A. Polderman, F. Pugliese, B. Pulvirenti, P. Ruggieri, G. Speranza, E. Toth, T. Zieher, F.G. Renaud, Quantifying the effects of nature-based solutions in reducing risks from hydrometeorological hazards: examples from Europe, Int. J. Disaster Risk Reduct. 93 (2023) 103771, https://doi.org/10.1016/j.ijdrr.2023.103771.

[19] B. Buma, D.R. Gordon, K.M. Kleisner, A. Bartuska, A. Bidlack, R. DeFries, P. Ellis, P. Friedlingstein, S. Metzger, G. Morgan, K. Novick, J.N. Sanchirico, J.R. Collins, A. J. Eagle, R. Fujita, E. Holst, J.M. Lavallee, R.N. Lubowski, C. Melikov, L.A. Moore, E.E. Oldfield, J. Paltseva, A.M. Raffeld, N.A. Randazzo, C. Schneider, N. Uludere Aragon, S.P. Hamburg, Expert review of the science underlying nature-based

climate solutions, Nat. Clim. Change (2024) 1758–6798, https://doi.org/10.1038/s41558-024-01960-0.
[20] H. Pan, J. Page, R. Shi, C. Cong, Z. Cai, S. Barthel, P. Thollander, J. Colding, Z. Kalantari, Contribution of prioritized urban nature-based solutions allocation to carbon neutrality, Nat. Clim. Change (2023) 1758–6798, https://doi.org/10.1038/s41558-023-01737-x.
[21] C. Cong, H. Pan, J. Page, et al., Modeling place-based nature-based solutions to promote urban carbon neutrality, Ambio 52 (2023) 1297–1313, https://doi.org/10.1007/s13280-023-01872-x (2023).
[22] E. Cohen-Shacham, G. Walters, C. Janzen, S. Maginnis, Nature-based Solutions to Address Global Societal Challenges, IUCN International Union for Conservation of Nature, 2016, https://doi.org/10.2305/IUCN.CH.2016.13.en.
[23] European Commission. Directorate general for research and innovation., 2021. Evaluating the Impact of Nature-Based solutions: a Handbook for Practitioners. Publications Office, LU. http://doi.org/10.2777/244577.
[24] N. Seddon, Harnessing the potential of nature-based solutions for mitigating and adapting to climate change, Science 376 (2022) 1410–1416, https://doi.org/10.1126/science.abn9668.
[25] E. Gómez Martín, M. Máñez Costa, S. Egerer, U.A. Schneider, Assessing the long-term effectiveness of nature-based solutions under different climate change scenarios, Sci. Total Environ. 794 (2021) 148515, https://doi.org/10.1016/j.scitotenv.2021.148515.
[26] A. Pagano, I. Pluchinotta, P. Pengal, B. Cokan, R. Giordano, Engaging stakeholders in the assessment of NBS effectiveness in flood risk reduction: a participatory system dynamics model for benefits and co-benefits evaluation, Sci. Total Environ. 690 (2019) 543–555, https://doi.org/10.1016/j.scitotenv.2019.07.059.
[27] A. Chausson, B. Turner, D. Seddon, N. Chabaneix, C.A.J. Girardin, V. Kapos, I. Key, D. Roe, A. Smith, S. Woroniecki, N. Seddon, Mapping the effectiveness of nature-based solutions for climate change adaptation, Glob. Change Biol. 26 (2020) 6134–6155, https://doi.org/10.1111/gcb.15310.
[28] C. Cortinovis, P. Olsson, N. Boke-Olén, K. Hedlund, Scaling up nature-based solutions for climate-change adaptation: potential and benefits in three European cities, Urban For. Urban Green. 67 (2022) 127450, https://doi.org/10.1016/j.ufug.2021.127450.
[29] S.E. Debele, L.S. Leo, P. Kumar, J. Sahani, J. Ommer, E. Bucchignani, S. Vranić, M. Kalas, Z. Amirzada, I. Pavlova, M.A.R. Shah, A. Gonzalez-Ollauri, S. Di Sabatino, Nature-based solutions can help reduce the impact of natural hazards: a global analysis of NBS case studies, Sci. Total Environ. 902 (2023) 165824, https://doi.org/10.1016/j.scitotenv.2023.165824.
[30] C.A.J. Girardin, S. Jenkins, N. Seddon, M. Allen, S.L. Lewis, C.E. Wheeler, B. W. Griscom, Y. Malhi, Nature-based solutions can help cool the planet — If we act now, Nature 593 (2021) 191–194, https://doi.org/10.1038/d41586-021-01241-2.
[31] M.D. Morecroft, S. Duffield, M. Harley, J.W. Pearce-Higgins, N. Stevens, O. Watts, J. Whitaker, Measuring the success of climate change adaptation and mitigation in terrestrial ecosystems, Science 366 (2019) eaaw9256, https://doi.org/10.1126/science.aaw9256.
[32] L. Ruangpan, Z. Vojinovic, S. Di Sabatino, L.S. Leo, V. Capobianco, A.M.P. Oen, M. E. McClain, E. Lopez-Gunn, Nature-based solutions for hydro-meteorological risk reduction: a state-of-the-art review of the research area, Nat. Hazards Earth Syst. Sci. 20 (2020) 243–270, https://doi.org/10.5194/nhess-20-243-2020.
[33] S. Unguendoli, L.G. Biolchi, M. Aguzzi, U.P.A. Pillai, J. Alessandri, A. Valentini, A modeling application of integrated nature based solutions (NBS) for coastal erosion and flooding mitigation in the Emilia-Romagna coastline (Northeast Italy), Sci. Total Environ. 867 (2023) 161357, https://doi.org/10.1016/j.scitotenv.2022.161357.
[34] C. Albert, M. Brillinger, P. Guerrero, S. Gottwald, J. Henze, S. Schmidt, E. Ott, B. Schröter, Planning nature-based solutions: principles, steps, and insights, Ambio 50 (2021) 1446–1461, https://doi.org/10.1007/s13280-020-01365-1.
[35] E. Calliari, S. Castellari, M. Davis, J. Linnerooth-Bayer, J. Martin, J. Mysiak, T. Pastor, E. Ramieri, A. Scolobig, M. Sterk, C. Veerkamp, L. Wendling, M. Zandersen, Building climate resilience through nature-based solutions in Europe: a review of enabling knowledge, finance and governance frameworks, Clim. Risk Manag. 37 (2022) 100450, https://doi.org/10.1016/j.crm.2022.100450.
[36] N. Kabisch, N. Frantzeskaki, S. Pauleit, S. Naumann, M. Davis, M. Artmann, D. Haase, S. Knapp, H. Korn, J. Stadler, K. Zaunberger, A. Bonn, Nature-based solutions to climate change mitigation and adaptation in urban areas: perspectives on indicators, knowledge gaps, barriers, and opportunities for action, E&S 21 (2016) art39, https://doi.org/10.5751/ES-08373-210239.
[37] A.B. Paxton, T.N. Riley, C.L. Steenrod, C.S. Smith, Y.S. Zhang, R.K. Gittman, B. R. Silliman, C.A. Buckel, T.S. Viehman, B.J. Puckett, J. Davis, What evidence exists on the performance of nature-based solutions interventions for coastal protection in biogenic, shallow ecosystems? A systematic map protocol, Environ. Evid. 12 (2023) 11, https://doi.org/10.1186/s13750-023-00303-4.
[38] C.M. Raymond, N. Frantzeskaki, N. Kabisch, P. Berry, M. Breil, M.R. Nita, D. Geneletti, C. Calfapietra, A framework for assessing and implementing the co-benefits of nature-based solutions in urban areas, Environ. Sci. Policy 77 (2017) 15–24, https://doi.org/10.1016/j.envsci.2017.07.008.
[39] S. Sarabi, Q. Han, A.G.L. Romme, B. De Vries, R. Valkenburg, E. Den Ouden, Uptake and implementation of nature-based solutions: an analysis of barriers using interpretive structural modeling, J. Environ. Manag. 270 (2020) 110749, https://doi.org/10.1016/j.jenvman.2020.110749.
[40] C.C. Anderson, F.G. Renaud, S. Hanscomb, K.E. Munro, A. Gonzalez-Ollauri, C. S. Thomson, E. Pouta, K. Soini, M. Loupis, D. Panga, M. Stefanopoulou, Public acceptance of nature-based solutions for natural hazard risk reduction: survey findings from three study sites in Europe, Front. Environ. Sci. 9 (2021) 678938, https://doi.org/10.3389/fenvs.2021.678938.
[41] C.C. Anderson, F.G. Renaud, S. Hanscomb, A. Gonzalez-Ollauri, Green, hybrid, or grey disaster risk reduction measures: what shapes public preferences for nature-based solutions? J. Environ. Manag. 310 (2022) 114727 https://doi.org/10.1016/j.jenvman.2022.114727.
[42] J. Fennell, C. Soulsby, M.E. Wilkinson, R. Daalmans, J. Geris, Time variable effectiveness and cost-benefits of different nature-based solution types and design for drought and flood management, Nat. Solut. 3 (2023) 100050, https://doi.org/10.1016/j.nbsj.2023.100050.
[43] S. Hynes, R. Burger, J. Tudella, D. Norton, W. Chen, Estimating the costs and benefits of protecting a coastal amenity from climate change-related hazards: nature based solutions via oyster reef restoration versus grey infrastructure, Ecol. Econ. 194 (2022) 107349, https://doi.org/10.1016/j.ecolecon.2022.107349.
[44] H. Mahmoud, Barriers to gauging built environment climate vulnerability, Nat. Clim. Change 10 (2020) 482–485, https://doi.org/10.1038/s41558-020-0742-z.
[45] S. Narayan, M.W. Beck, B.G. Reguero, I.J. Losada, B. Van Wesenbeeck, N. Pontee, J.N. Sanchirico, J.C. Ingram, G.-M. Lange, K.A. Burks-Copes, The effectiveness, costs and coastal protection benefits of natural and nature-based defences, PLoS ONE 11 (2016) e0154735, https://doi.org/10.1371/journal.pone.0154735.
[46] L.G. Vogelsang, H.-P. Weikard, J.M. Van Loon-Steensma, B. Bednar-Friedl, Assessing the cost-effectiveness of Nature-based Solutions under climate change uncertainty and learning, Water Resourc. Econ. 43 (2023) 100224, https://doi.org/10.1016/j.wre.2023.100224.
[47] P. Le Coent, N. Graveline, M.A. Altamirano, N. Arfaoui, C. Benitez-Avila, T. Biffin, J. Calatrava, K. Dartee, A. Douai, A. Gnonlonfin, C. Hérivaux, R. Marchal, D. Moncoulon, G. Piton, Is-it worth investing in NBS aiming at reducing water risks? Insights from the economic assessment of three European case studies, Nat. Solut. 1 (2021) 100002, https://doi.org/10.1016/j.nbsj.2021.100002.
[48] C. Short, L. Clarke, F. Carnelli, C. Uttley, B. Smith, Capturing the multiple benefits associated with nature-based solutions: lessons from a natural flood management project in the Cotswolds, UK, Land Degrad. Dev. 30 (2019) 241–252, https://doi.org/10.1002/ldr.3205.
[49] K.K. Arkema, G. Guannel, G. Verutes, S.A. Wood, A. Guerry, M. Ruckelshaus, P. Kareiva, M. Lacayo, J.M. Silver, Coastal habitats shield people and property from sea-level rise and storms, Nat. Clim. Change 3 (2013) 913–918, https://doi.org/10.1038/nclimate1944.
[50] K.M. Walters, M. Babbar-Sebens, Using climate change scenarios to evaluate future effectiveness of potential wetlands in mitigating high flows in a Midwestern U.S. watershed, Ecol. Eng. 89 (2016) 80–102, https://doi.org/10.1016/j.ecoleng.2016.01.014.
[51] C. Spyrou, M. Loupis, N. Charizopoulos, I. Apostolidou, A. Mentzafou, G. Varlas, A. Papadopoulos, E. Dimitriou, D. Panga, L. Gkeka, P. Bowyer, S. Pfeifer, S. E. Debele, P. Kumar, Evaluating nature-based solution for flood reduction in spercheios river basin under current and future climate conditions, Sustainability 13 (2021) 3885, https://doi.org/10.3390/su13073885.
[52] A.I. Stefanakis, C.S.C. Calheiros, I. Nikolaou, Nature-based solutions as a tool in the new circular economic model for climate change adaptation, Circ. Econ. Sustain. 1 (2021) 303–318, https://doi.org/10.1007/s43615-021-00022-3.
[53] J. Pfeiffer, T. Zieher, J. Schmieder, T. Bogaard, M. Rutzinger, C. Spötl, Spatial assessment of probable recharge areas – investigating the hydrogeological controls of an active deep-seated gravitational slope deformation, Nat. Hazards Earth Syst. Sci. 22 (2022) 2219–2237, https://doi.org/10.5194/nhess-22-2219-2022.
[54] J. Pfeiffer, T. Zieher, J. Schmieder, M. Rutzinger, U. Strasser, Spatio-temporal assessment of the hydrological drivers of an active deep-seated gravitational slope deformation: the Vögelsberg landslide in Tyrol (Austria), Earth Surf. Process. Landf. 46 (2021) 1865–1881, https://doi.org/10.1002/esp.5129.
[55] J. Pfeiffer, T. Zieher, B. Schneider-Muntau, Slope stability evolution of a deep-seated landslide considering a constantly deforming topography, Earth Surf. Process. Landf. 48 (2023) 923–939, https://doi.org/10.1002/esp.5527.
[56] L. Tanzer, R. Außerlechner, Hangbewegungen und deren Auswirkungen auf Wohn- und Wirtschaftsgebäude im Alpenraum am Beispiel Vögelsberg, in: Proceedings of the Geoforum Umhausen 2021, 14-15 October 2021, Umhausen (Tyrol, Austria), 2021. https://atnastablobgeoforumarc01.blob.core.windows.net/geoforumarchive001/Tagungsband%2023%20Geoforum%20Umhausen%202021.pdf.
[57] E. Eberhardt, L. Bonzanigo, S. Loew, Long-term investigation of a deep-seated creeping landslide in crystalline rock. Part II. Mitigation measures and numerical modelling of deep drainage at Campo Vallemaggia, Can. Geotech. J. 44 (2007) 1181–1199, https://doi.org/10.1139/T07-044.
[58] R. Hofmann, J.T. Sausgruber, Creep behaviour and remediation concept for a deep-seated landslide, Navistal, Tyrol, Austria, Geomech. Tunnel. 10 (2017) 59–73, https://doi.org/10.1002/geot.201600066.
[59] H. Tabari, Climate change impact on flood and extreme precipitation increases with water availability, Sci. Rep. 10 (2020) 13768, https://doi.org/10.1038/s41598-020-70816-2.
[60] M.A. Caretta, A. Mukherji, M. Arfanuzzaman, R.A. Betts, A. Gelfan, Y. Hirabayashi, T.K. Lissner, J. Liu, E. Lopez Gunn, R. Morgan, S. Mwanga, S. Supratid, et al., Water, in: H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, et al. (Eds.), Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel On Climate Change, Cambridge University Press, Cambridge, UKNew York, NY, USA, 2022, pp. 551–712, https://doi.org/10.1017/9781009325844.006, and.
[61] C. Spyrou, M. Loupis, N. Charizopoulos, P. Arvanitis, A. Mentzafou, E. Dimitriou, S. E. Debele, J. Sahani, P. Kumar, Evaluating nature-based solution for flood

reduction in spercheios river basin part 2: early experimental evidence, Sustainability 14 (2022) 10345, https://doi.org/10.3390/su141610345.
[62] S.H. Mahmoud, T.Y. Gan, Urbanization and climate change implications in flood risk management: developing an efficient decision support system for flood susceptibility mapping, Sci. Total Environ. 636 (2018) 152–167, https://doi.org/10.1016/j.scitotenv.2018.04.282.
[63] J.D. Miller, M. Hutchins, The impacts of urbanisation and climate change on urban flooding and urban water quality: a review of the evidence concerning the United Kingdom, J. Hydrol.: Reg. Stud. 12 (2017) 345–362, https://doi.org/10.1016/j.ejrh.2017.06.006.
[64] F. Rodriguez, H. Andrieu, J.-D. Creutin, Surface runoff in urban catchments: morphological identification of unit hydrographs from urban databanks, J. Hydrol. (Amst) 283 (2003) 146–168, https://doi.org/10.1016/S0022-1694(03)00246-4.
[65] S. Cheng, R. Wang, An approach for evaluating the hydrological effects of urbanization and its application, Hydrol. Process. 16 (2002) 1403–1418, https://doi.org/10.1002/hyp.350.
[66] F. Karamage, C. Zhang, X. Fang, T. Liu, F. Ndayisaba, L. Nahayo, A. Kayiranga, J. B. Nsengiyumva, Modeling rainfall-runoff response to land use and land cover change in Rwanda (1990–2016), Water (Basel) 9 (2017) 147, https://doi.org/10.3390/w9020147.
[67] A. Sarkar Basu, F. Pilla, S. Sannigrahi, R. Gengembre, A. Guilland, B. Basu, Theoretical framework to assess green roof performance in mitigating urban flooding as a potential nature-based solution, Sustainability 13 (2021) 13231, https://doi.org/10.3390/su132313231.
[68] F. Pilla, S.S. Gharbia, R. Lyons, How do households perceive flood-risk? The impact of flooding on the cost of accommodation in Dublin, Ireland, Sci. Total Environ. 650 (2019) 144–154, https://doi.org/10.1016/j.scitotenv.2018.08.439.
[69] Depietri, Y., McPhearson, T., 2017. Integrating the grey, green, and blue in cities: nature-based solutions for climate change adaptation and risk reduction, in: Kabisch, N., Korn, H., Stadler, J., Bonn, A. (Eds.), Nature-Based Solutions to Climate Change Adaptation in Urban Areas: Linkages between Science, Policy and Practice, Theory and Practice of Urban Sustainability Transitions. Springer International Publishing, Cham, pp. 91–109. https://doi.org/10.1007/978-3-319-56091-5_6.
[70] N. Kabisch, H. Korn, J. Stadler, A. Bonn, Nature-Based Solutions to Climate Change Adaptation in Urban Areas: Linkages between Science, Policy and Practice, Theory and Practice of Urban Sustainability Transitions, Springer International Publishing, Cham, 2017, https://doi.org/10.1007/978-3-319-56091-5.
[71] OECD, European Union, Joint Research Centre - European Commission. Handbook On Constructing Composite Indicators: Methodology and User Guide, OECD, 2008, https://doi.org/10.1787/9789264043466-en.
[72] P. Kumar, S.E. Debele, J. Sahani, N. Rawat, B. Marti-Cardona, S.M. Alfieri, B. Basu, A.S. Basu, P. Bowyer, N. Charizopoulos, J. Jaakko, M. Loupis, M. Menenti, S. B. Mickovski, J. Pfeiffer, F. Pilla, J. Pröll, B. Pulvirenti, M. Rutzinger, S. Sannigrahi, C. Spyrou, H. Tuomenvirta, Z. Vojinovic, T. Zieher, An overview of monitoring methods for assessing the performance of nature-based solutions against natural hazards, Earth-Sci. Rev. 217 (2021) 103603, https://doi.org/10.1016/j.earscirev.2021.103603.
[73] D.W. Cash, W.C. Clark, F. Alcock, N.M. Dickson, N. Eckley, D.H. Guston, J. Jäger, R.B. Mitchell, Knowledge systems for sustainable development, Proc. Natl. Acad. Sci. U.S.A. 100 (2003) 8086–8091, https://doi.org/10.1073/pnas.1231332100.
[74] A.P.E. van Oudenhoven, M. Schröter, E.G. Drakou, I.R. Geijzendorffer, S. Jacobs, P. M. van Bodegom, L. Chazee, B. Czúcz, K. Grunewald, A.I. Lillebø, L. Mononen, A.J. A. Nogueira, M. Pacheco-Romero, C. Perennou, R.P. Remme, S. Rova, R.-U. Syrbe, J.A. Tratalos, M. Vallejos, C. Albert, Key criteria for developing ecosystem service indicators to inform decision making, Ecol Indic. 95 (2018) 417–426, https://doi.org/10.1016/j.ecolind.2018.06.020.
[75] Schmidt-Walter, P., Trotsiuk, V., Meusburger, K., Zacios, M., Meesenburg, H., 2020. Advancing simulations of water fluxes, soil moisture and drought stress by using the LWF-Brook90 hydrological model in R. Agricultural and Forest Meteorology 291, 108023. https://doi.org/10.1016/j.agrformet.2020.108023.
[76] HEC-RAS River Analysis System. Hydraulic Reference Manual. Version 1.0., https://apps.dtic.mil/sti/citations/ADA311952 last accessed 28 September 2023.
[77] TUFLOW, 2018, User Manual—Build 2018-03-AC. https://downloads.tuflow.com/_archive/TUFLOW/Releases/2018-03/TUFLOW%20Manual.2018-03.pdf last accessed on 9 October 2019.
[78] A.S. Basu, F. Pilla, S. Sannigrahi, R. Gengembre, A. Guilland, B. Basu, Theoretical framework to assess green roof performance in mitigating urban flooding as a potential nature-based solution, Sustainability 13 (2021) 13231, https://doi.org/10.3390/su132313231.
[79] A. Gonzalez-Ollauri, S.B. Mickovski, Plant-Best: a novel plant selection tool for slope protection, Ecol. Eng. 106 (2017) 154–173, https://doi.org/10.1016/j.ecoleng.2017.04.066.
[80] R. Cornes, G. van der Schrier, E.J.M. van den Besselaar, P.D. Jones, An ensemble version of the E-OBS temperature and precipitation datasets, J. Geophys. Res. Atmos. 123 (2018), https://doi.org/10.1029/2017JD028200.
[81] H. Hersbach, B. Bell, P. Berrisford, S. Hirahara, A. Horányi, J. Muñoz-Sabater, J. Nicolas, C. Peubey, R. Radu, D. Schepers, A. Simmons, C. Soci, S. Abdalla, X. Abellan, G. Balsamo, P. Bechtold, G. Biavati, J. Bidlot, M. Bonavita, G. De Chiara, P. Dahlgren, D. Dee, M. Diamantakis, R. Dragani, J. Flemming, R. Forbes, M. Fuentes, A. Geer, L. Haimberger, S. Healy, R.J. Hogan, E. Hólm, M. Janisková, S. Keeley, P. Laloyaux, P. Lopez, C. Lupu, G. Radnoti, P. De Rosnay, I. Rozum, F. Vamborg, S. Villaume, J. Thépaut, The ERA5 global reanalysis, Q. J. R. Meteoro Soc. 146 (2020) 1999–2049, https://doi.org/10.1002/qj.3803.
[82] D. Jacob, J. Petersen, B. Eggert, A. Alias, O.B. Christensen, L.M. Bouwer, A. Braun, A. Colette, M. Déqué, G. Georgievski, E. Georgopoulou, A. Gobiet, L. Menut, G. Nikulin, A. Haensler, N. Hempelmann, C. Jones, K. Keuler, S. Kovats, N. Kröner, S. Kotlarski, A. Kriegsmann, E. Martin, E. van Meijgaard, C. Moseley, S. Pfeifer, S. Preuschmann, C. Radermacher, K. Radtke, D. Rechid, M. Rounsevell, P. Samuelsson, S. Somot, J.-F. Soussana, C. Teichmann, R. Valentini, R. Vautard, B. Weber, P. Yiou, EURO-CORDEX: new high-resolution climate change projections for European impact research, Reg. Environ. Change 14 (2014) 563–578, https://doi.org/10.1007/s10113-013-0499-2.
[83] A. Gonzalez-Ollauri, C. Hudek, S.B. Mickovski, D. Viglietti, N. Ceretto, M. Freppaz, Describing the vertical root distribution of alpine plants with simple climate, soil, and plant attributes, CATENA 203 (2021) 105305, https://doi.org/10.1016/j.catena.2021.105305.
[84] A. Gonzalez-Ollauri, S.B. Mickovski, Hydrological effect of vegetation against rainfall-induced landslides, J. Hydrol. (Amst) 549 (2017) 374–387, https://doi.org/10.1016/j.jhydrol.2017.04.014.
[85] A. Gonzalez-Ollauri, A. Stokes, S.B. Mickovski, A novel framework to study the effect of tree architectural traits on stemflow yield and its consequences for soil-water dynamics, J. Hydrol. (Amst) 582 (2020) 124448, https://doi.org/10.1016/j.jhydrol.2019.124448.
[86] N. Pollen, Temporal and spatial variability in root reinforcement of streambanks: accounting for soil shear strength and moisture, Catena 69 (2007) 197–205.
[87] F. Preti, A. Dani, F. Laio, Root profile assessment by means of hydrological, pedological and above-ground vegetation information for bio-engineering purposes, Ecol. Eng., Special Issue: Veg. Slope Stab. 36 (2010) 305–316, https://doi.org/10.1016/j.ecoleng.2009.07.010.
[88] A. Stokes, G.B. Douglas, T. Fourcaud, F. Giadrossich, C. Gillies, T. Hubble, J. H. Kim, K.W. Loades, Z. Mao, I.R. McIvor, S.B. Mickovski, S. Mitchell, N. Osman, C. Phillips, J. Poesen, D. Polster, F. Preti, P. Raymond, F. Rey, M. Schwarz, L. R. Walker, Ecological mitigation of hillslope instability: ten key issues facing researchers and practitioners, Plant Soil 377 (2014) 1–23, https://doi.org/10.1007/s11104-014-2044-6.
[89] A. Gonzalez-Ollauri, S.B. Mickovski, Plant-soil reinforcement response under different soil hydrological regimes, Geoderma 285 (2017) 141–150, https://doi.org/10.1016/j.geoderma.2016.10.002.
[90] Z. Vojinovic, A. Alves, J.P. Gómez, S. Weesakul, W. Keerakamolchai, V. Meesuk, A. Sanchez, Effectiveness of small- and large-scale nature-based solutions for flood mitigation: the case of Ayutthaya, Thailand, Sci. Total Environ. 789 (2021) 147725, https://doi.org/10.1016/j.scitotenv.2021.147725.
[91] T.G. Shepherd, Storyline approach to the construction of regional climate change information, Proc. R. Soc. A: Math., Phys. Eng. Sci. 475 (2019) 20190013, https://doi.org/10.1098/rspa.2019.0013.