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REVIEW **Open Access**

The potential use of nature-based solutions as natural hazard mitigation measure for linear infrastructure in the Nordic Countries

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Abstract

Background Reliable infrastructure is vital for Nordic societies, but they face escalating climate risks. Climate change is increasing magnitude and frequency of floods, storms, and landslides, making adaptive solutions crucial.

Methods This review explores Nature-Based Solutions (NbS) for mitigating natural hazards along Nordic linear infrastructure. The motivation of the review comes as result of a preliminary survey conducted among to the main infrastructure managers in the Fennoscandian peninsula. The objective was to pinpoint the natural hazards that pose greatest concern under future climate scenarios, as well as to understand which specific information is needed to adopt NbS

Results Floods, erosion, landslides and rockfalls emerged as primary hazards of concern for the infrastructure owners, hence the review process was focused only on NbS aimed at mitigating the effects of these specific hazards. A total of 78 documents were identified from the review process and were integrated with examples and case studies from other relevant on-going and past projects. Despite only a few of the NbS identified in these documents were directly implemented for linear infrastructure such as roads and railways, and none dealing with electric grids, several NbS were identified to have a potential for implementation for Nordic linear infrastructure. A list of NbS options, not all implemented along linear infrastructure but with potential for it, is provided. This list is meant to serve as "vade mecum" for a quick and easy access to NbS as mitigation options for linear infrastructure managers in the Nordic Countries. The NbS are classified in green, blue, green/blue and hybrid approaches, and supported by examples of case studies both in the Nordic Countries as well as countries having similar climates.

Conclusions This review underlines the challenges and opportunities of adopting NbS. Challenges such as the lack of expertise, space and climate constraints, and path dependency on adoption of traditional infrastructure must be addressed to mainstream NbS. The review highlights the importance of standardization, European guidelines, and technical manuals in promoting NbS adoption among infrastructure managers, as well as the necessity of accounting for the wider co-benefits of NbS, including carbon sequestration, biodiversity and ecosystem services. This paper contributes to the understanding of NbS as potential natural hazards mitigation options for Nordic infrastructure networks in the face of evolving climate risks, providing valuable insights for infrastructure managers and policymakers alike.

Keywords Climate change adaptation, Disaster risk reduction, Review, Hazard mitigation, Barriers

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Introduction

Resilient and reliable infrastructure networks for transportation, communication and energy supply (e.g. roads, railways and power lines) are fundamental for the societal wellbeing in all societies. In the Nordic region (consisting of Denmark, Norway, Sweden, Finland, Iceland, and the Faroe Islands, Greenland, and Åland), essential infrastructure networks pass through large rural areas with geotechnically sensitive terrain and high-relief landscapes exposed to natural hazards. Climate change is increasing frequency and intensity of extreme precipitation events, and floods, storm surges and landslides are expected to increase all over Europe (Debele et al. 2019). The combination of climate change, demography, and land use change has led to an ever-evolving risk landscape when it comes to natural hazards and extreme weather. Thus, it is crucial to develop monitoring, management and mitigation systems that are adaptable to maintain daily life and the economy at a high level of quality.

A recent study on projected future changes in heatwaves, droughts, and flood impacts for 571 European cities found that whilst cities in southern Europe will suffer intensified drought conditions and increasing trend of days with extreme heatwaves, northern European cities will experience intensified river flooding (Guerreiro et al. 2018), given a warmer, wetter, and more erratic climate concerning freeze–thaw and wetting–drying cycles (Hanssen-Bauer et al. 2017). As for floods, the risk will further increase because of ongoing population and global changes (Alfieri et al. 2016; Vormoor et al. 2016). At large scales, higher temperatures, milder winters, and changes in the rainfall patterns, will modify the hydrological cycle, having direct consequences on flood regimes (Vormoor et al. 2016; Sorteberg et al. 2018), permafrost melting leading to quicker soil saturation, and frequency, magnitude, and location of landslides (Bärring et al. 2006; Jaedicke et al. 2008; Scaringi and Loche 2022).

Flooding, storm surges, erosion of embankments, debris flows, rockfalls, snow avalanches, frost heave, and subsidence are all threats posed by climate change to road infrastructure in Europe identified by the ROADAPT project from the CEDR—Transnational Road Research Programme (ROADAPT D4 2015). In Nordic regions, the stability of road embankments may also be affected by changes in freezing–thawing cycles caused by rising temperatures (Shin et al. 2020). Moreover, changes in winter snowfall will further impact avalanche regimes.

A recent EU research project, Safeway, studied the effect of sudden extreme natural hazard events due to climate change on road and railway infrastructure in Europe. The study identified a range of hazards affecting different regions: in Portugal, forest fires and floods have emerged as significant challenges; while in Spain, infrastructure is particularly vulnerable to flooding, landslides, earthquakes, heavy rainfall, and temperature fluctuations. Similarly, the UK faces notable impacts from wind, flooding, and snow-related events on its infrastructure (Eidsvig et al. 2019). Although the project did not directly investigate Nordic regions, the findings from the UK case study offer valuable insights that may be relevant to Nordic infrastructure.

Nordic infrastructure networks traverse geotechnically challenging terrain and are exposed to many of these hazards, especially landslides, snow avalanches, and floods. Ice storms, variations in precipitation, snow loading, strong winds, and other forms of extreme weather have the potential to devastate infrastructure networks at larger spatial scales.

Natural hazards in the Nordic countries, except Iceland, were summarized in a report produced within the framework of the European Spatial Planning Observation Network—ESPON 2000–2006 programme (Schmidt-Thomé et al. 2006), and an overview of geo-hazards in the region was published by Nadim et al. (2008). The major hazards for the whole region are floods, landslides, storms and cyclones, and snow avalanches. In addition, overviews of specific hazards in individual countries have partly been published, such as Sólnes et al. (2013), which gives an overview of volcanic activities and earthquakes in Iceland.

These hazards vary among the countries due to geographical and geological differences (Schmidt-Thomé et al. 2006). Iceland is the only country where volcanic and seismic hazards are of significance (Nadim et al. 2008). The coastal areas are primarily threatened by storm surges/winter storms and floods; the alpine areas are threatened by avalanches/landslides and floods; river valleys are threatened by river floods and landslides; and areas that are located above tectonic active zones are threatened by volcanic eruptions and earthquakes, tsunamis and landslides.

While Nordic electric grids are expected to be affected by extreme windstorms (Jasiūnas et al. 2023a, 2023b), Tang et al. (2018) indicates that for transport infrastructure slopes in the Nordic climatic region of Europe, both shallow landslides and debris flows triggered by rainfall events are expected to increase, especially in the winter season. In Norway, nearly 90% of the landslides mapped in the national database are located within 100 m of a road. An instance is from the severe storm event "Hans" occurred in August 2023, which caused the triggering of 120 landslides, with 30% of them located within 500 m of a road (Rüther et al. 2024).

The effects of climate change may be even worsened by anthropogenic factors, such as slope modifications, levelling, change of hydrological regime through drainage, and water supply to the slopes. Recent studies investigated the relationship between mountain roads, snowmelt and rainfall runoff in landslide activation, suggesting the key role of road's position in altering snowmelt runoff directions, as well as its contribution in the foreseen likely activation of a shallow landslide (Mauri et al. 2022). Therefore, relying only on the analysis of weather-related factors may not be enough to get a complete picture of the actual risk (Papathoma-Koehle and Glade 2013; Winter et al. 2010).

The ability of infrastructure to ensure continued provision and service despite the increasing extreme weather events requires an urgent adoption of climate change adaptation measures, as clearly stated by the United Nations Economic Commission for Europe Group of Experts on Climate Change Impacts and Adaptation for Transport Networks and Nodes for railway systems (UNECE 2018). In this sense, new concepts which include sustainability and biodiversity must be explored further, since, according to the European Green Deal (EGD) conventional approaches will not be sufficient to manage the increased risk from climate change (EC 2019).

Nature Based Solutions (NbS) provide a toolset from which to develop sustainable and cost-effective mitigation measures with reduced environmental and ecological impacts (Cohen-Shacham et al. 2019), while simultaneously enhancing biodiversity. NbS are solutions that use nature or mimic its processes for climate change adaptation. In the last decade many definitions and relative terminologies have been introduced to describe the NbS concept, from the International Union for Conservation of Nature—IUCN (Cohen-Shacham et al. 2016) and the European Union (EC 2021).

NbS for mitigating natural hazards along Nordic linear infrastructure is still at its embryonal phase, as almost no literature is available on the current evidence base regarding their adoption.

This article aims to provide an overview of NbS regarding Nordic regions and comparable climates. These solutions offer sustainable approaches for mitigating the natural hazards that pose significant concerns for involved in linear infrastructure stakeholders.

The review builds on a preliminary survey conducted among the main infrastructure managers in the Fennoscandian peninsula, aimed at identifying the natural hazards of most concern for the rail, road authorities and power lines for future climate, and what is their current knowledge on NbS. The results of the survey are used as selection criteria for the review process.

The outcomes of the review were then supplemented with examples of test plots on NbS in Nordic Countries form on-going and past research projects where the authors were/are involved, not necessarily dealing with linear infrastructure, but with potential to be adopted also in this specific context.

The results of the review process are grouped in three main sections, discussing respectively (1) the type of studies conducted, hazards and multi-hazards addressed and countries of NbS implementation, (2) the type of NbS practices that can be adopted for each of the natural hazard of concern, and (3) supplementary information on test plots and case studies in the Nordic, with potential for adoption for linear infrastructure. In conclusion, NbS approaches and strategies, limitations, and opportunities for mainstreaming NbS for natural hazard mitigation within Nordic infrastructure are discussed, and future research directions are proposed.

Motivation of the review

The primary objective of this paper was to collect information on how linear infrastructure owners in the Nordic Countries, with a focus on the Fennoscandian peninsula (Sweden, Norway and Finland), deal with natural hazards, and what are alternative solutions that can be employed in this specific context. An initial survey sent to pertinent stakeholders formed the foundation of the review, as the findings directly informed and shaped the subsequent review process. Key information included identifying prevalent natural hazards of concern to linear infrastructure owners for current and future climate. The survey was part of the NordicLink project, financed by the Nordic Council of Ministers through NordForsk—which aimed to increase the security and resilience of transnational Nordic linear infrastructure networks, here represented by roads, railways and power lines, regarding extreme weather and natural hazards, to ensure the high-quality continuation of daily life and the economy. The research consortium consisted of the Finnish Meteorological Institute (FMI), Chalmers University of Technology in Sweden, and the Norwegian Geotechnical Institute (NGI), joined by 5 stakeholders involved in infrastructure management and development, all representing the three countries located and interconnected at the Fennoscandian peninsula. The stakeholders are responsible for safety, as well as building, operating and maintaining roads, rails and electricity networks and contribute to identify research needs to be addressed within the duration of the project.

The main findings of the survey formed the backbone of the ad-hoc review process on NbS.

Recently Sandin et al. (2022) conducted a thorough review of the situation of NbS implementation in the Nordic Countries and identified 64 publications that covered research related to Nordic NbS. Most of these studies assessed the NbS functions concerning biophysical qualities, such as water retention capacity, flood risk reduction, health benefits, biodiversity contribution, as well as potential economic benefits. Although most of the articles focused on empirical and modelling studies, some consisted of review studies. They identified and collected examples of projects implementing NbS in different ecosystem types (urban, forest, agriculture, freshwater, peatlands and coastal-marine) and in three main categories: conservation, restoration and sustainable use. However, disaster risk reduction was not the main aim of their research.

The present review has a large focus on NbS for protection of linear infrastructure from natural hazards, despite the currently sparse literature available on the topic. Relevant cases from Sandin et al. (2022) were also included, as well as additional relevant literature with a focus on Soil and Water Bioengineering (SWB) for slope stabilization (Preti et al. 2022) and results from past and on-going research projects for climate resilience of road infrastructure, such as ROADAPT (Bles et al. 2016) and ICARUS, both funded by the CEDR – Conference of European Directors of Roads.

NbS and mitigation measures in this work are not to be confused with climate change mitigation, which aims at the reduction of climate change via for example minimizing greenhouse gas emissions.

Survey of Natural Hazards along linear infrastructure in the Nordic Countries

An initial survey of "Natural Hazards along linear infrastructure in the Nordic Countries" was conducted to collect information on the natural hazards that pose greatest concern to infrastructure stakeholders under both present and future climate scenarios, and to collect information on their level of knowledge on NbS.

A total of 7 stakeholders, out of the 12 reached, responded to the survey (Fig. 1).

The skew in participants between the three countries partly reflects the distribution of stakeholders in the project, partly relates to how the main public authorities for roads and railways are organized (split in several organizations in Norway), and partly reflects the fact that NGI—a Norwegian organization—conducted the survey and received more feedback from more familiar contacts. The authors are aware that low reply number does not allow statistical inference, as the survey was aimed to set the directions of the review process.

Results of the survey and inputs to the review process

Natural hazards currently most frequent

As a first question, a list of different natural hazards, selected by the research partners, was provided and participants were asked to give a score from 1 (low) to 5 (high) to the natural hazards that the stakeholders are currently facing most frequently along their infrastructure. In cases where the hazard was not experienced at all by user partners, the user partner was requested to skip this and avoid scoring.

The results of the survey have been grouped by infrastructure type revealing several resemblances in terms of natural hazards faced across countries. Roads and railways operators in Sweden and Norway have indicated river-, coastal- or stormwater flooding, and strong winds among the most frequent natural hazards (Fig. 2). Landslides have also been reported to be a frequent natural hazard, as also confirmed by Rüther et al. (2024).

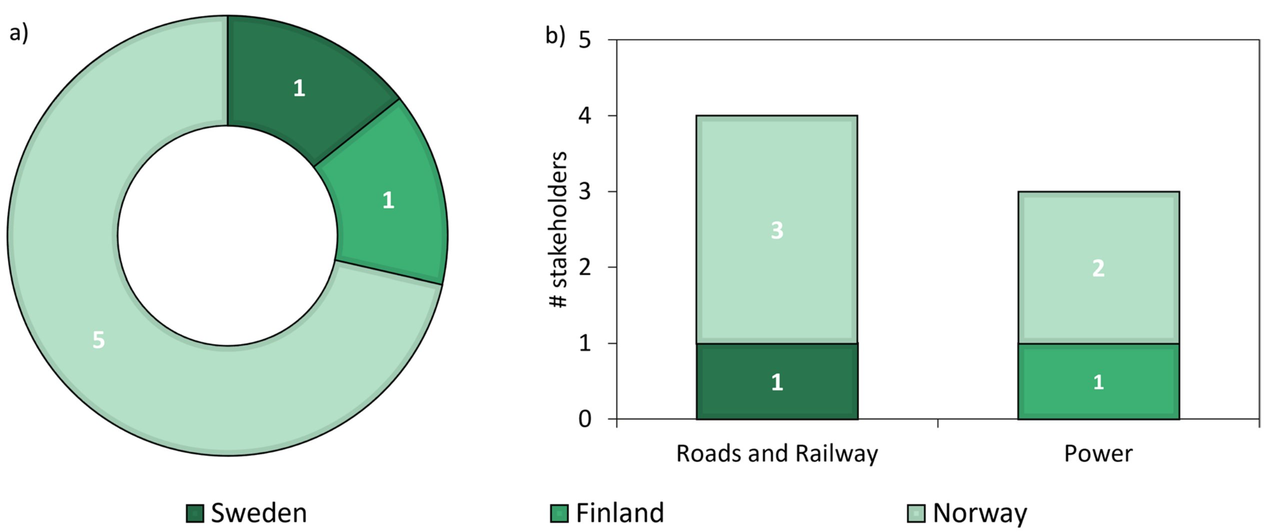

Fig. 1 Country of affiliation of the stakeholders and type and distribution of infrastructure owners

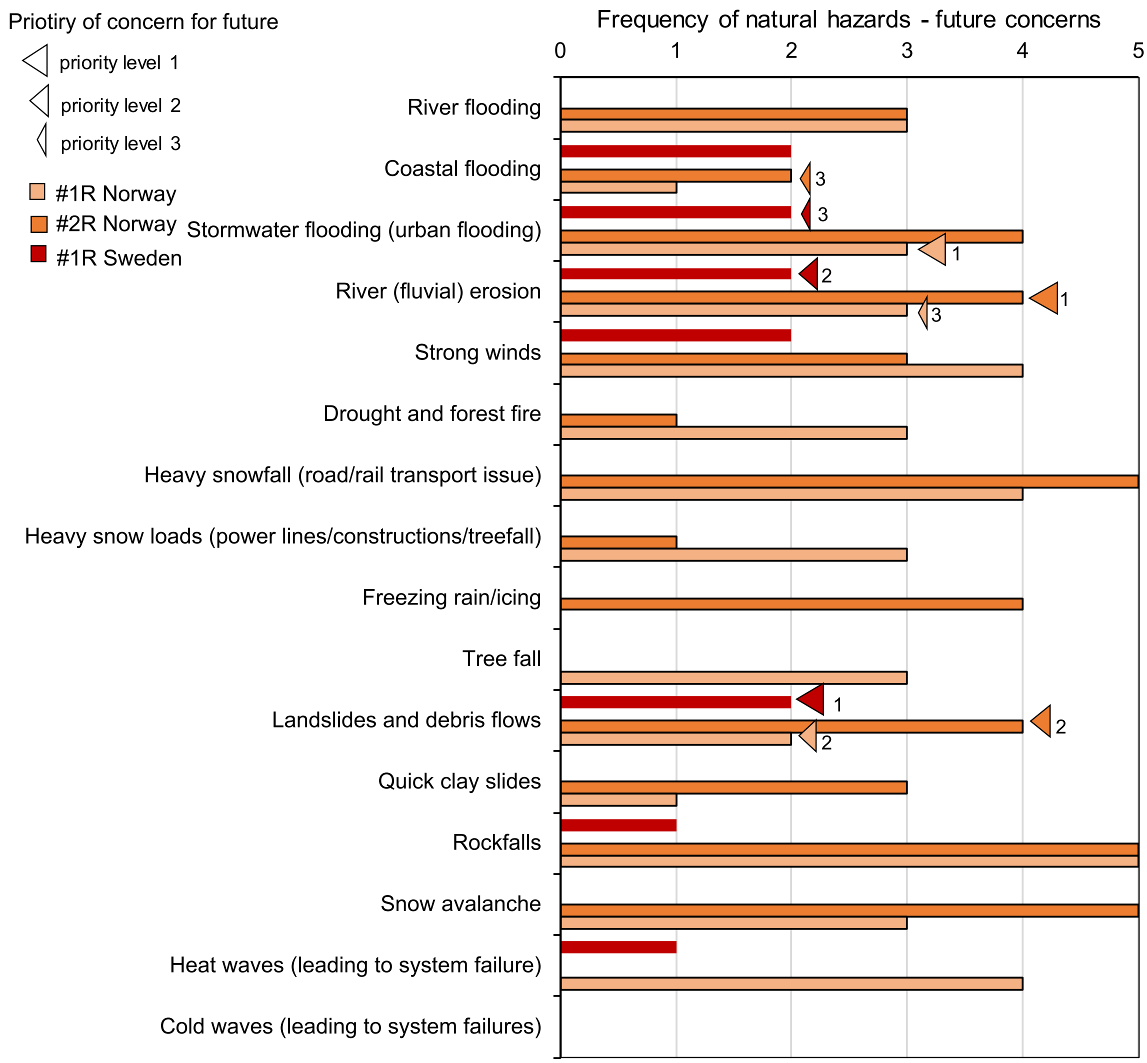

Fig. 2 Main hazards of concern for Norwegian (#1R and #2R Norway) and Swedish (#1R Sweden) roads and railways authorities (#R stands for road and railway infrastructure). On the x-axis the frequency of natural hazards is represented on a scale from 1 (low) to 5 (high) score. The bars indicate the hazards of current concern for power line infrastructure owners. The arrows indicate the hazards that stakeholders consider could represent a relevant concern in future climate conditions. The thickness of the arrows indicates the degree of concern or the priority level (thin—low; medium—medium; thick—high)

However, while rockfalls and snow avalanches are significant hazards for Norwegian railways and roads, these hazards are not a main concern for Swedish transportation infrastructure.

Quick clay slides do not represent a major concern for Norwegian and Swedish road and railway infrastructure operators. In Norway the risk from quick clay slides is relatively low for roads, because both time and efforts are spent in risk management to make sure that these events do not occur. In Sweden, sensitive clays are mainly present in the southwestern areas of the country, so this does not represent a big challenge at the national level. However, as recently as September 2023 a quick clay event on the E6 road connecting Oslo (Norway) and Gothenburg (Sweden), caused the closure of the road for months, putting again the focus on quick clay landslide risk. Snow avalanches, heavy snow falls and rockfalls are also a concern mainly for Norwegian road and railway infrastructure.

For electricity transmission, most of the hazards are linked to treefalls as a consequence of strong winds, heavy snow loads, and freezing rain or icing, without substantial differences in terms of frequency between Finland and Norway (Fig. 3). This is supported also by recent studies conducted for Finnish electric grids (Jasiūnas et al. 2023a, b). Additionally, stakeholders pointed out that thunderstorms and lightning can damage and destroy the components of smart grids (electricity, telecom). Strong winds are the main cause of treefalls, which cause problems both for overhead lines and traffic (repairing the line faults). This situation is shared by infrastructure owners in all countries, who also experienced outages because of treefalls due to heavy snow with the same frequency. Finally, electricity stakeholders operating in Norway are also affected by landslides, debris flows, quick clay slides and snow avalanches in steep terrain. Such hazards have not been reported as a problem in Finland due to the topographical differences between the two countries.

Natural hazards in the future climate

The stakeholders were asked to select and rank the top three hazards that pose the greatest concern in future climate conditions. In this case, the hazard that represents the largest concern to all stakeholders are landslides (high and medium priority in Fig. 2, low priority in Fig. 3). River fluvial erosion (priority high, medium and low in Fig. 2) and flooding also represent a major concern for the future (priority high in Fig. 3). Heat waves have been listed as a threat for road and railway operators in Sweden, while freezing/icing, heavy snow fall and rockfalls appear to be still the main concern for Norway.

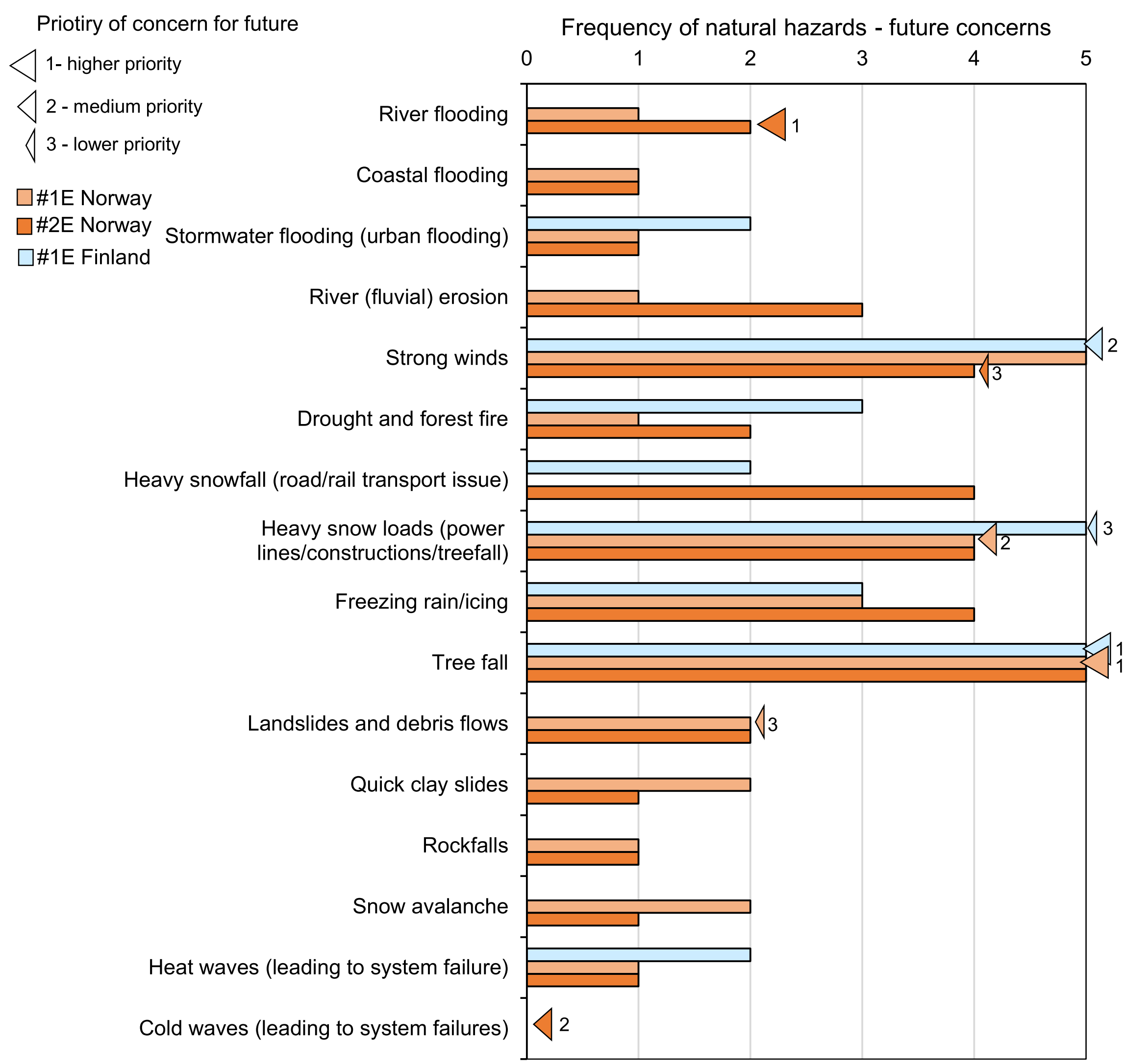

Fig. 3 Main hazards type of concern for Norwegian (#1E and #2E Norway) and Finnish (#1E Finland) power infrastructure owners (#E stands for electric infrastructure). On the x-axis the frequency of natural hazards is represented on a scale from 1 (low) to 5 (high) score. The bars indicate the hazards of current concern for power line infrastructure owners. The arrows indicate the hazards that stakeholders consider could represent a relevant concern in future climate conditions. The thickness of the arrows indicates the degree of concern or the priority level (thin—low; medium—medium; thick—high)

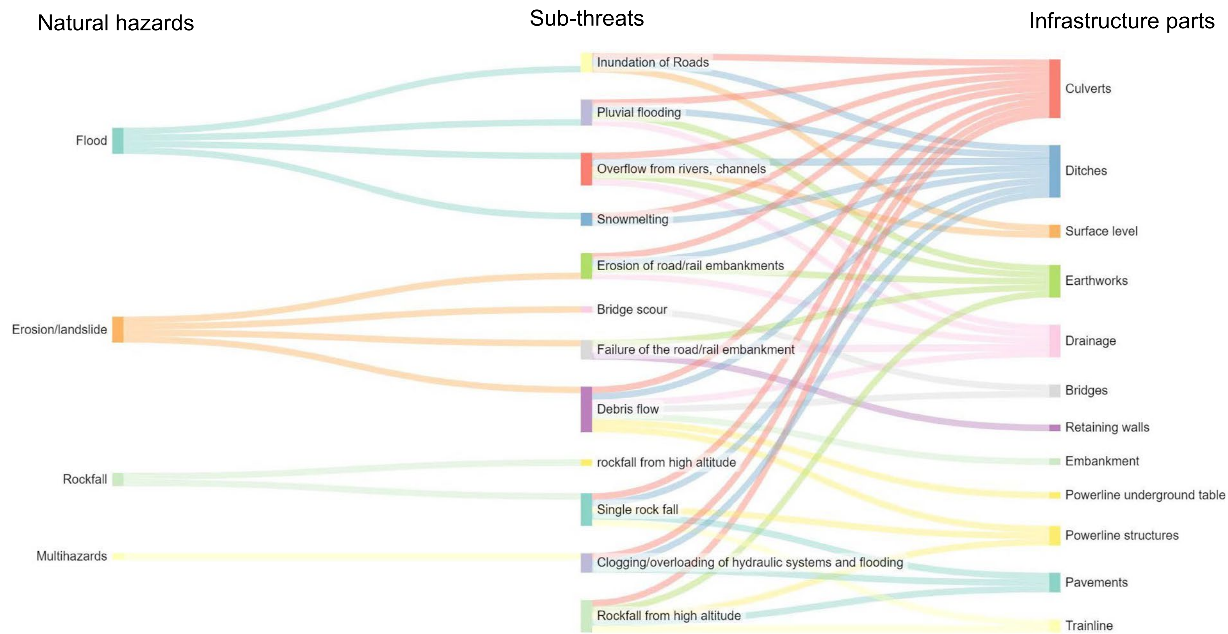

Fig. 4 Casual chain of main hazards of concern, the sub-threats, and the target vulnerable infrastructure parts

With regards to power line infrastructure, all the stakeholders agreed that both strong winds and treefalls will remain a major challenge, but some of the stakeholders have also expressed concerns for river flooding, landslides and cold spells, especially for the underground electricity cables (Fig. 3).

These results are consistent with what identified in the ROADPT project, where flooding of road surface, erosion of road embankments, landslides and avalanches were listed as main climate change threats for road infrastructure in Europe (ROADAPT D4 2015).

A casual chain was produced to identify the main vulnerable parts of infrastructure that can be impacted by the three main hazards of concern to the stakeholders. In addition, the category multi-hazard was added, which will be described below. From the main hazards, the sub-threats, namely the threats that can directly impact the infrastructure as well as the vulnerable parts of infrastructure, were adapted from ROADAPT project, including also power lines and railways (Fig. 4). Culverts and ditches represent the vulnerable points that can be mostly impacted, followed by earthworks and drainage systems, as well as road pavements.

Nature-based solutions: level of knowledge

The last question was related to which type of information the stakeholders would like to receive from NordicLink about NbS, applications and examples. All the surveyed stakeholders were interested in receiving information about solutions, with focus on NbS, used in Nordic countries. Others were more specific mentioning that information on NbS implementation related to technical standards could be useful for new projects as well as for infrastructure maintenance. Many also requested examples of solutions and experience in terms of efficiency, maintenance, economic implications, and co-benefits such as improving biodiversity. Additionally, some stakeholders suggested including a cost–benefit analysis approach to consider NbS in the selection process of mitigation measures, considering the environmental impact.

In light of the responses to this final question, we have opted to narrow the scope of this review to the identification of Nature-based Solutions (NbS) that are either currently employed or have the potential for implementation as part of the mitigation strategies for the specific hazards associated with linear infrastructure in Nordic Countries. This will serve as “vade mecum” (from Latin language: “go with me”) for a quick and easy access to NbS options for infrastructure managers, with examples of applications and considerations regarding approaches, strategies, barriers and opportunities for their adoption.

Materials and methodology of the review process

Search strategy

The main aim of the literature review was to provide an overview of NbS for the mitigation of hydro-meteorological hazards in the Nordic Countries, with a focus on linear infrastructure. To have a full overview of the

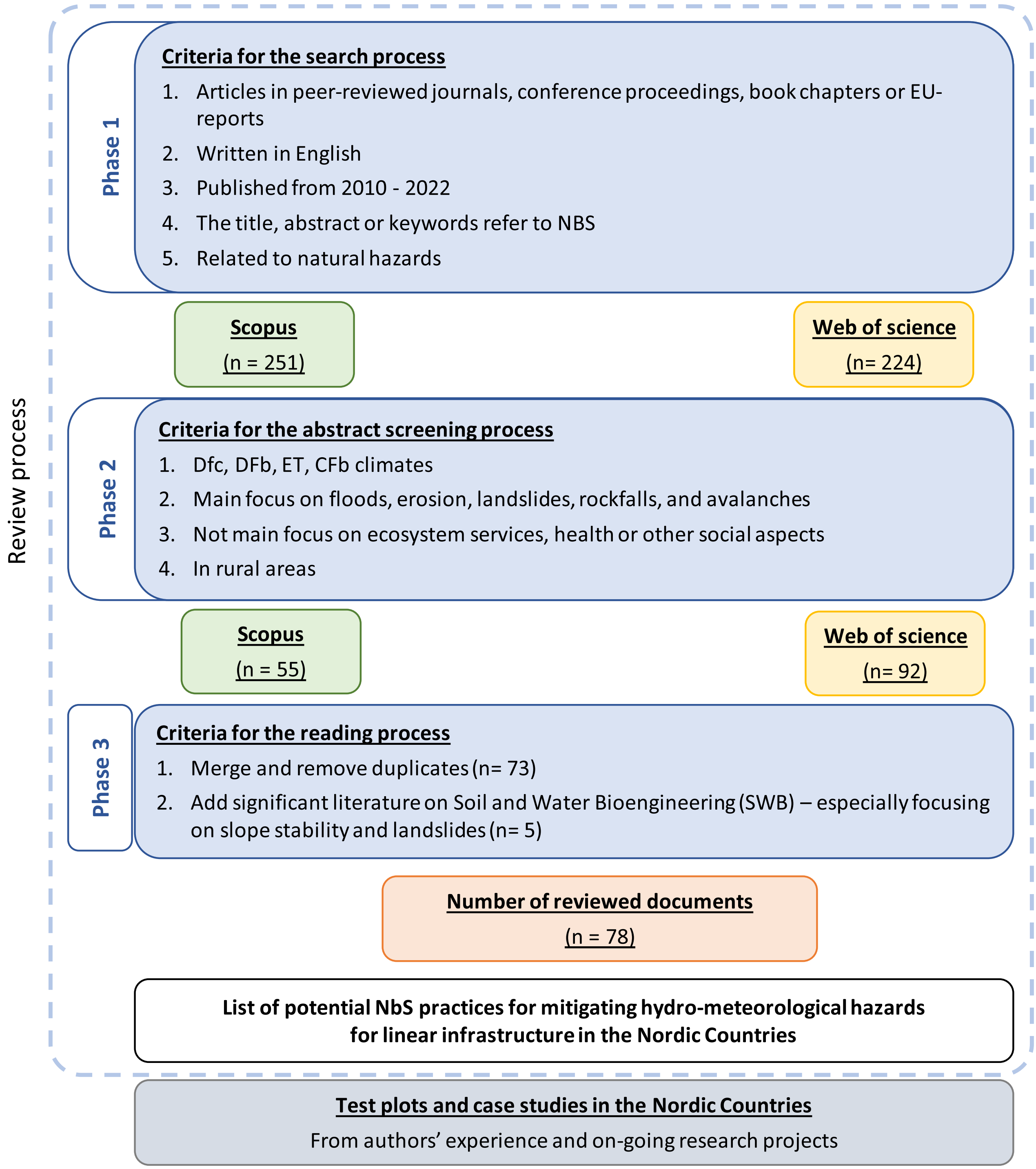

Fig. 5 Flow diagram of the selection process for the NbS review, contained in the dashed box. The final number of reviewed papers is 78. Dfc, Dfb, ET, and CFb refer to subarctic climate, humid continental climate, tundra climate and oceanic climate, respectively, according to the Köppen climate classification system. Additional test plots and case studies were provided at the end of the review from author's past and ongoing research projects

potentialities of NbS in these regions, relevant literature from countries that share similar climates and environmental conditions was also included in the review process. To do so, we have created a workflow to systematically select the most relevant research items from Scopus and Web of Science databases, later supplemented with relevant grey literature (i.e. reports, working papers, government documents among others). The result was a list of potential NbS for mitigating hydro-meteorological hazards for linear infrastructure in the Nordic Countries. At the end of the review process, case studies provided by the authors from on-going and past research projects were integrated into the data gathered. The latter case studies are aimed to provide practical examples based on personal experience of the authors.

The review process workflow is divided into three phases (Fig. 5).

Phase 1 consists of the search process, *Phase 2* consists of the abstract screening, and *Phase 3* consists of the reading of the final selection of literature.

In *Phase 1*, the first searching was only focused on whether the words "NbS" OR "Nature-based solutions" OR "Nature based solutions" OR "nature based solutions" were present in the title, abstract or keywords. Although the authors are aware that the NbS concept may be expressed with different names and terminologies, they intentionally used only NbS in the review process, since this is now identified as umbrella concept, and theoretically it includes all the terminologies that have been used in the past. In addition, the aim of the study was to identify the most recent sustainable mitigation measures, in light of the European and national legislation, which are now expressly embracing the NbS concept for climate change adaptation. The systematic review of the literature published between January 2010 and June 2022 based on the internationally recognized databases Web of Science and Scopus was conducted. We found a total of 475 research items for review after applying the filters, 251 from the Scopus database, and 224 from Web of Science (Fig. 5).

In *Phase 2*, a more restrictive criterion has been adapted to focus on the identified stakeholders' concerns (see "Results of the survey and inputs to the review process" section), accounting for the fact that linear infrastructure in the Nordic Region commonly goes through vast rural areas and include only NbS examples from sites with vegetation and climate similar to what is found in the Nordic Region. Thus, only articles focusing on NbS for mitigating floods, erosion, landslides, rockfalls, and snow avalanches in rural areas and with climates belonging to the same climate zones of those of the Nordic region have been selected. In the search strategy, the authors deliberated omitted any terms related to "infrastructure", to encompass the full spectrum of NbS potentially be applicable to infrastructure. NbS examples in areas with subarctic climate (Dfc), humid continental climate (Dfb), tundra climate (ET), and temperate oceanic climate (Cfb) according to Köppen climate classification (Beck et al. 2018) have been chosen.

After applying the *Phase 2* filter, the number of articles to review has been narrowed down to 55 items from Scopus and 92 items from Web of Science (Fig. 5).

In *Phase 3*, after merging the two databases and removing the duplicates, the total number of articles to review was 73. Although one of the main interests of the review is NbS for slope stability and mitigation of landslides and rockfalls, only a small group of the research items deal with this topic. However, the use of vegetation to enhance slope stability and reduce landslide hazard has been widely addressed by the SWB community. Due to the similarities between NbS and SWB, a manual selection of significant literature regarding the use of SWB for slope stability and landslide mitigation has been included (Capobianco et al. 2021; de Jesús Arce-Mojica et al. 2019; Gonzalez-Ollauri et al. 2021; Kalsnes and Capobianco 2022; Mickovski et al. 2021). Finally, 78 articles have been considered for the final review.

The main outcome of the review process is a list of potential NbS for mitigating hydro-meteorological hazards for linear infrastructure in the Nordic Countries. In addition to the list obtained from the review process, test plot applications with examples of design and implementation from author's on-going and past research projects are presented and discussed (see "Test plots and case studies in the Nordic Countries" section).

Results of the review

Study types and hazards addressed

During the abstract screening process (*Phase 2*), the documents were categorized based on the document type and their main focus (Fig. 6a). Most of the screened literature consists of research articles (85%), while the remaining are conference papers (6%) books or book chapters (6% and 3%).

Given the multidisciplinary nature of NbS, many searched documents did not deal only with one specific topic. Thus, assigning only one category to each contribution would therefore be limiting (Fig. 6b). In such cases, the documents have been assigned to multiple categories. For example, several documents implemented frameworks for case studies, hence were assigned to both categories "case studies" and "model/method/framework".

Most of the screened literature is linked to a case study, and in 33 documents models, methods or frameworks are described. Socio-economic aspects related

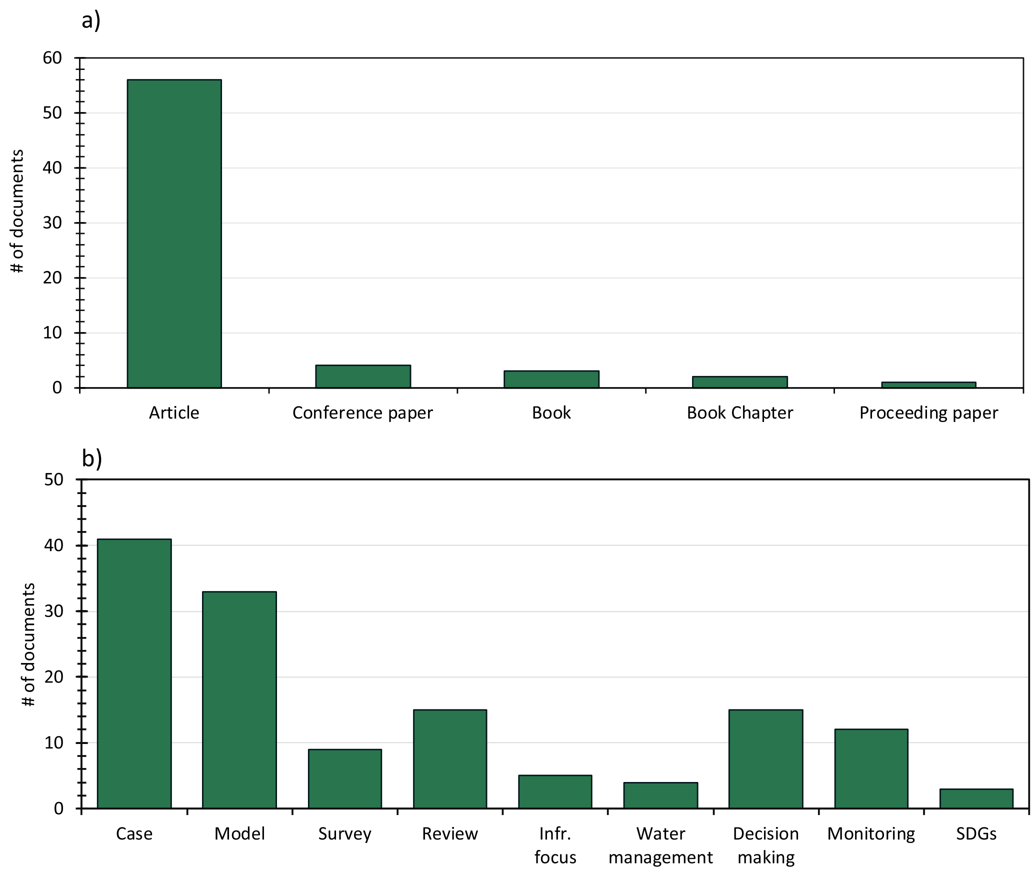

Fig. 6 a Number of documents by document type and **b** topic type

to NbS are treated in several documents. Nine items include surveys to stakeholders or population, fifteen documents address governance and decision-making topics, water management strategies and sustainable development goals are mentioned in four and three of the abstracts respectively. Fifteen items consist of review papers. Since review papers give a good overview of the state-of-the-art on NbS, most of them were also kept in *Phase 3* of the selection process. Only 5 papers deal directly with infrastructure. Among these five papers, none specifically addresses power line infrastructure. However, it is worth noting that certain NbS identified within these studies might still hold potential for adaptation within the context of power line corridors.

Hydrometeorological hazards addressed

The types of hazards addressed in the papers reflect the first initial filtering applied in *Phase 2*.

Figure 7 shows the percentage of papers dealing with the different hazard types selected for our review. In addition, a new category called "multi-hazards" has been introduced, which encompasses research that tackles more than one hazard type instead of a singular one. Heatwaves and droughts have also been mentioned in some of the reviewed items and have been kept in the review process. Flooding appears to be the most frequently addressed hazard (56%) (Fig. 7a). This is consistent with Debele et al. (2019), who concluded that across Europe NbS have been extensively adopted for flood risk mitigation. A similar conclusion was shared by (Ruangpan et al. 2020), who found that 82% of the published papers from 2007 to 2020 dealt with NbS for urban flooding mitigation. Despite the focus of our review was on rural areas, the category "flood" includes both river flooding and urban flooding. The second most addressed hazards are multiple hazards (13%), followed by landslides (12%), erosion (10%), droughts (3%), rockfalls (1%) and heatwaves (1%). These findings align with the results of the survey sent to railway managers in UK and Australia by Blackwood et al. (2023), who found that most of the NbS adopted in rail infrastructure address high precipitation, which can cause both floods and landslides. Finally, around 3% of the review articles did not mention any specific type of hazard. These were mostly documents that did not have hazard mitigation as the focus, but

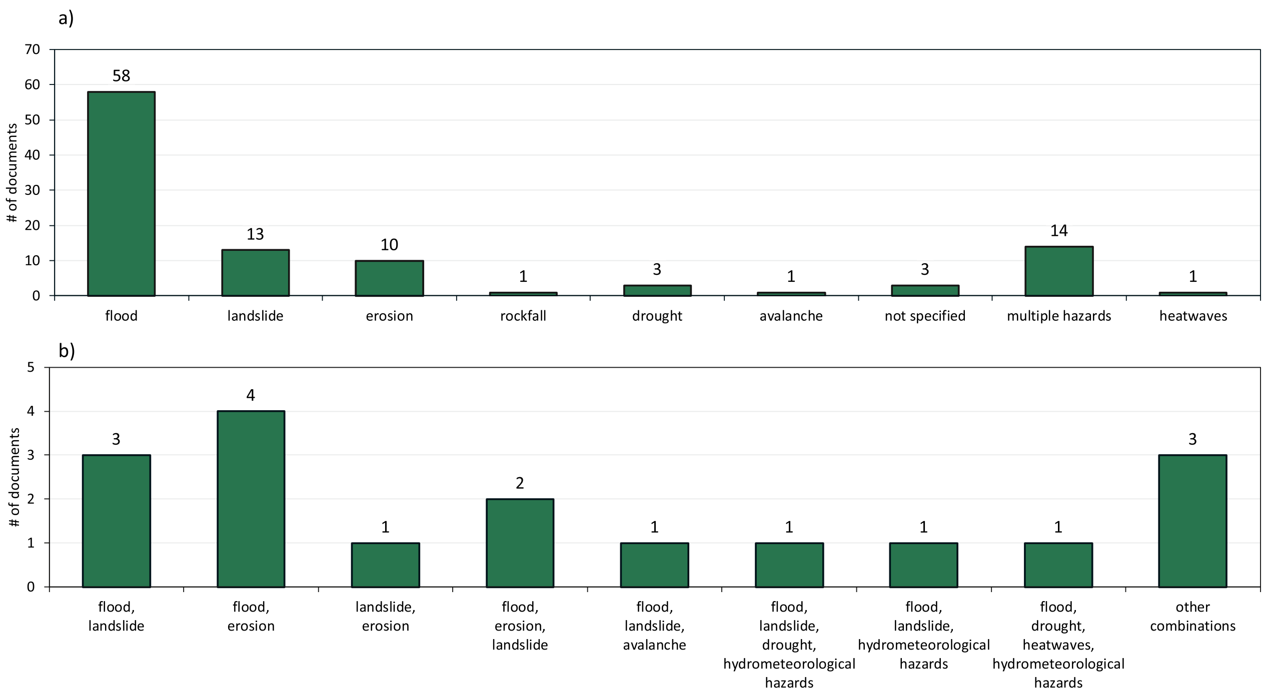

Fig. 7 Number of papers dealing with NbS for **a** single hazards and **b** multiple hazards

rather ecosystem restoration. Among the research items that focused on multiple hazards, floods and erosion were the hazard combinations most frequently addressed together (23%). This fact is reasonable because floods, especially in rural areas, are mostly caused by river overflows, which can be caused by a reduction of the river capacity due to sediment deposition as consequence of bank erosion. Streambank erosion and failure could also be a consequence of a flooding event. Erosion of road embankments can cause the clogging of culverts in a road network, increasing the probability of flooding over the road surface (Roadapt D4 2016). Floods and erosion are interconnected hazards that need to be addressed parallelly in risk mitigation strategies, often because triggered by the same climate event, namely rainfall. Following, 17% of the documents dealing with multi-hazards, focused on floods and landslides. Also in this case, securing the stability of the riverbanks is a way to reduce the risk of flooding due to an obstruction of the water course. Floods, erosion, and landslides are also addressed together in some studies, as well as floods in combination with droughts and heatwaves. Landslides and erosion are also hazards addressed together in many papers. It is worth noting that floods are the most addressed hazard also among the documents considering multiple hazards. All the multi-hazard combinations found, except for "landslides and erosion", include floods as one of the hazards. This confirms again that much focus has been put on NbS for flood risk mitigation, given that flooding stands as the most recurrent natural hazard in Europe, despite these solutions are not taken for granted yet. However, this does not necessarily imply that NbS are not a valid solution for other hazards. It simply indicates that in the Nordic region and regions with similar climates, NbS tailored for these hazards have yet to see widespread adoption. This is most likely due to a lack of evidence about NbS effectiveness to mitigate the effects of such hazards when compared to grey infrastructure (Solheim et al. 2021). This confirms the wider adoption of hybrid solutions compared to NbS, as further explained in the following sections.

Countries where NbS are implemented

For the documents categorised as "case studies" (Fig. 6b), the largest number of NbS was found to be implemented in the United Kingdom (n. of papers = 5), followed by examples in Italy, Spain and France (n. of papers = 4). It is worth mentioning that the United Kingdom has been a pioneer country in the adoption of NbS especially for railway infrastructure, and recent studies by Blackwood et al. (2022, 2023), highlight that a collection of NbS case studies is recommended as means to gather robust evidence to inform the adoption and development of these measures.

The NbS found may be most likely implemented only in parts of the countries identified that fit into one of the climates outlined in *Phase 2* of the Review process in Sect. 3.1. Thus, only examples from Alpine regions in northern Italy, France and Spain are included.

No examples were found from Canada, Australia and New Zealand, which partly share the same climate as the Nordics. Additionally, no examples were found from Greenland. Most of the literature comprises cases from central and southern Europe.

NbS types

An overview of the NbS practices used for mitigating the hazards of interest to this study is provided in Table 1. The measures were taken from literature selected in *Phase 3* of the review (Fig. 5). The measures are arranged in descending order of frequency as encountered in literature, and categorized based on the type of hazard they address. The NbS are classified into (i) Green approaches, (ii) Blue approaches and (iii) Hybrid approaches, based on the classification used in other review articles for different climates (Debele et al. 2019; Enu et al. 2022). An additional NbS type was considered in this work, which is the Green/blue approach.

A more detailed description of the approaches with practical examples of NbS is provided in the following paragraphs. For each practice, the potential scale of implementation and the strategies needed to mitigate the hazard, based on the policy matrix for adapting road and rail infrastructure to climate changes threats proposed by Bles et al. (2016), are also indicated. The scales considered space between the single object-stretch, to the national network, including object-stretch-network and regional network in the middle. In this specific case, the strategy “prevention” is aimed to relocate or eliminate vulnerability, the “pro-active attitude” aims at reducing the hazards. Pro-active strategies may also imply the re-location of an infrastructure from a more hazardous to a less hazardous area, or in an area where there is space to implement NbS to reduce hazard. “Upgrade/retrofitting/new construction” is a strategy meant to improve the capacity of infrastructure to withstand extreme events, via resilient construction. The strategy aimed at “preventing maintenance and replacement” refers to acting beforehand via adoption of NbS that will replace existing measure or maintain in a better way the functionality of an infrastructure. These strategies are in line with flood risk mitigation strategies proposed by Hegger et al. (2016), who identify prevention, defence, mitigation, preparation and recovery as main generic categories.

In addition, a tentative classification of the effects of the NbS on linear infrastructure was proposed, where (D) is Direct and (I) is Indirect effect. This additional information was considered important, since NbS are not always directly implemented on roads or railways (D), but rather in areas in their vicinity (I), such as constructed wetlands to reduce flood hazard, or protection forests to reduce the landslide hazard, which will consequently affect the risk posed on the infrastructure traversing these areas.

Green approach

The use of vegetation, forests and urban forestry as NbS for addressing climate change impacts represents the means of the so called "Green approaches". SWB for slope stability and erosion protection, protection forests for snow avalanches and landslide mitigation and rain gardens, green roofs or drainage systems, belong to this category. Debele et al. (2019) found that green approaches, such as urban or protection forests, are indicated as potential solutions for landslides and heatwaves in various parts of Europe.

Green roofs are particularly applicable in urban environments, where there is not enough space to implement larger drainage systems. However, they represent a sustainable solution in some specific elements of the transport network such as rail stations, terminals, logistic centres and so on, and in general extensive infrastructures which large areas of roofs that could be exploited as massive drainage elements. The main drawback of green roofs is related to the notable increase in the budget of the construction, particularly in the structural design, in infrastructures with this type of drainage elements (Morales Gámiz et al. 2019). Moreover, the maintenance costs are higher than for traditional systems, since design and typology must be carefully chosen.

Soil and water bioengineering (SWB)

SWB is a discipline that combines technology and biology in which native plants and plant communities are used as living building materials to solve erosion and conservation problems. SWB mainly aims to protect infrastructure and land uses in conflict situations between opposite needs: the land use requirements of large areas for its activities and infrastructures, and the natural systems need for development space (Fernandes and Guiomar 2018). In the Basque Country (Spain), due to orographic, edaphic and climatological conditions, landslides occur frequently. In the last fifteen years, the Department of Road Infrastructure requested a series of technical projects along road embankments, where SWB was preferred to traditional engineering solutions. Live structures like live crib walls (Fig. 8) or surficial drainage using living drains are some of the SWB techniques proposed for slope stability and erosion protection, in addition to restoration actions to the slope morphology and its natural gradient and vegetation (Sangalli and Tardío, 2023). Multiple SWB works have also been implemented in the UK within the Open-Air Laboratory

Table 1 List of NbS types and practices used for mitigating hydro-meteorological hazards, description, the frequency they were encountered in literature (column "Fr.") the sources (column "Reference"), potential scale of application and management strategy for their adoption, (Green NbS are vegetation-based; blue NbS are water-based; green/blue combine blue and green NbS; hybrid NbS combine green and blue NbS with constructed/grey structures)

Hazard addressed	NbS practice	NbS type	Description/function	Fr	References*	Potential Scale of implementation	Potential Strategy
Flood	Planting of vegetation and trees (D)	Green	Increase infiltration, slowing down runoff and reduce discharge	11	[1–10; 37]	Regional network	Prevention
	Sedimentation ponds, retention ponds (D)	Blue	Temporary catchment of eroded and disturbed sediments during rain/flooding	10	[3, 11–19]	Object-stretch-network	Pro-active attitude
	Peatlands, Wetlands and Constructed wetlands (I)	Blue	Floodwater storage, water retention. Reduce runoff and discharge	9	[3–4, 11–13,16, 18, 20–21]	Regional network	Pro-active attitude
	Ditches, swales, two-stage ditches, detention basins and dry ponds (D)	Green/Blue	Temporary storage/reservoirs for runoff/storm waters	8	[3, 9–12, 14, 16, 19]	Object-stretch	Upgrade / retrofitting / new construction
	Floodplain protection, woodland restoration (I)	Green/ Blue	Maintaining the function of floodplains, increase infiltration, reducing runoff and discharge in floodplain	7	[5, 7, 13, 16, 18, 21–22]	Regional network, national network	Pro-active attitude
	Swales and rain gardens (D)	Green/Blue	Permaculture installation working as temporary water storage/reservoir for runoff/storm waters	6	[3, 13, 18, 19, 23, 24]	Object—stretch	Upgrade / retrofitting / new construction
	River renaturation, re-meandering and restauration (I)	Blue	Restoring natural river pathways	5	[12, 13, 18, 20, 22]	Object—stretch—network	Pro-active attitude
	Leaky barriers (D)	Green	Slowing down streamflow, increasing soil conductivity most effective for mitigating smaller floods	4	[5, 10, 15, 22]	Object—stretch	Upgrade / retrofitting / new construction
	Excavation of floodplains (I)	Blue	Increasing floodplain area to reduce streamflow and runoff	4	[9, 13, 20, 22]	Regional network	Prevention
	Dike and dike relocation (D)	Green	Flood defence structures, physical barrier between land and water	4	[2, 7, 9, 10]	National network	Pro-active attitude
	Green roofs (I)	Green	Increase drainage capacity on top of roofs; reduce runoff in urban areas	4	[11, 18, 19, 23]	Regional network-national network	Pro-active attitude
	Porous pavements and surfaces (D)	Hybrid	Increasing drainage capacity in urban areas; reduce runoff	4	[12, 17, 19, 23]	Object -stretch -network	Upgrade /retrofitting / newconstruction

Table 1 (continued)

Hazard addressed	NbS practice	NbS type	Description/function	Fr	References*	Potential Scale of implementation	Potential Strategy
	Large Woody debris (LWD) and Engineered log jams (ELJs) (I)	Green	Flood regulation and increased hydraulic roughness of the channel. Reduce downstream discharge	3	[3, 9, 13]	Object – stretch-network	Pro-active attitude
	Floodplain restoration and reconnection (I)	Hybrid	Restoring natural extent of floodplain, increasing the discharge capacity	3	[4, 5, 14]	Regional network	Prevention
	Dams and vegetated dams (D)	Blue	Flood water storage/reservoir	3	[32, 16, 25]	Object -stretch -network	Upgrade /retrofitting / newconstruction
	River and river-bed widening (I)	Blue	Increase streamflow capacity, reduce flooding; past river channel	3	[10, 14, 18]	Object -stretch -network	Prevention
	"Room for the river"(I)	Blue	A Dutch initiative to lower floodplains, creating water buffers and, increasing depth of side channels and relocate levees increase the river discharge capacity	2	[11, 12]	Regional network	Prevention
	Rewilding and vegetation restauration (I)	Green	Increase infiltration, slowing down runoff	2	[11, 17]	Object -stretch -network	Pro-active attitude
	Stone/soil bunds(I)	Green	Restricting upstream flow, reducing downstream discharge	2	[11, 13]	Object -stretch -network	Pro-active attitude
	Natural water-retention and retention landscapes (I)	Blue	Retaining water upstream, reducing downstream discharge	2	[10, 11]	Regional network	Prevention
	Offline storage areas, buffer areas to retain water(I)	Blue	Water retention upstream, reduce discharge	2	[22, 33]	Object -stretch -network	Pro-active attitude
	Geotextiles and mulches(D)	Hybrid	Increase capillarity, absorbs water and increase drainage	2	[11, 33]	Object-Stretch	Prevention
	Barrier removal, clear blockages and remove recent accumulation of debris (D)	Green	Remove obsolete dams, restoring the watershed system. Natural watershed systems reduce floods more than undersized or wrongly placed barriers and dams	2	[20, 33]	Object-Stretch	Prevention
	Chipped branches (D)	Green	Increase water absorption	1	[11]	Object-Stretch	Prevention

Table 1 (continued)

Hazard addressed	NbS practice	NbS type	Description/function	Fr	References*	Potential Scale of implementation	Potential Strategy
	Grassed waterways(I)	Green	Stable waterways with reduced erosion, stable discharge point. Only medium runoff threshold, roaded catchment are recommended if water is to be collected and stored in dams	1	[11]	Regional network	Pro-active attitude
	Water harvesting (D)	Blue	Collection of rain to retain water, reducing total runoff	1	[12]	Object -stretch -network	Preventivemaintenance and replacement
	Disconnected roof drains(D)	Hybrid	Leading drained waters to area with high absorption and infiltration capacity. Reduce runoff and discharge	1	[12]	Object -stretch -network	Pro-active attitude
	Catchment woodlands (I)	Green	Total area of woodland within a catchment or more specific: cross-slope, riparian or floodplain woodland. All increase infiltration and reduce streamflow velocity	1	[22]	Object -stretch -network	Pro-active attitude
	Soil and land management(I)	Green	A type of runoff management. Physical barriers and infiltration	1	[22]	Object -stretch -network	Pro-active attitude
	Cyclic floodplain rejuvenation (I)	Blue	Restoring diverse floodplain vegetation. Increase infiltration capacity, reduce streamflow velocity	1	[25]	Object -stretch -network	Preventive maintenance and replacement
	Continuous cover forestry (I)	Green	Increase infiltration capacity and reduce streamflow velocity	1	[16]	Regional network-national network	Pro-active attitude
	Overland flow areas (I)	Green	Semi-permeable dam, retaining water	1	[16]	Object -stretch -network	Pro-active attitude
	Preservation of upstream forests (I)	Green	Increasing infiltration, reduce runoff and downstream discharge	1	[21]	Regional network-national network	Prevention
	Watershed renaturation (I)	Blue	Reestablishing the infiltration capacity and water retention in the natural watershed	1	[20]	Regional network	Pro-active attitude
Erosion/Landslide	Live cribwalls and facines (D)	Green	Low wall of living material to protect toe and grading of the soil. Stabilizing steep slopes and protecting banks of streams against erosion	5	[16, 26, 27, 34, 36]	Object -stretch -network	Upgrade /retrofitting / newconstruction

Table 1 (continued)

Hazard addressed	NbS practice	NbS type	Description/function	Fr	References*	Potential Scale of implementation	Potential Strategy
	Soil bioengineering structures, hydroseeding (D)	Green	Introducing vegetation to steep slopes, e.g., Hydroseeding: a slurry of seeds, sediments, nutrition, water that is sprayed onto a slope in order to have roots and vegetation stabilizing the sediments	5	[25, 32, 35, 18, 26, 37]	Object -stretch -network	Upgrade /retrofitting / new construction
	Biodegradable road embankment, geotextiles (D)	Green	Biodegradable liners used to cover man-made road embankment for erosion protection due to heavy runoff	3	[26, 33, 34]	Object -stretch	Upgrade /retrofitting / new construction
	Cover crops(I)	Green	Add lower growing vegetation in between higher growing crops to increase infiltration and root systems stabilizing and strengthening the soil	3	[3, 11, 28]	Object -stretch -network	Pro-active attitude
	Live pole drains (D)	Green	Bundles of tree branches to form tubular structures to improve surface water drainage along a slope	2	[22, 36]	Object -stretch	Upgrade / retrofitting / new construction
	Permanent grassing (D)	Green	Grassing very effective for soil conservation	1	[29]	Object -stretch -network	Prevention
	Vegetative barriers and grass filters (D)	Green	Narrow strips of stiff and densely growing vegetation planted perpendicular to the slope, stabilize soil and slope, reduce runoff	1	[30]	Object—stretch -network	Prevention
Rockfall	Afforestation/reforestation, forest maintenance (I)	Green	Forests dampen velocity and impact pressure of rock fall	3	[26, 31, 35]	Regional network-national network	Prevention
	Natural protection measures (D)	Hybrid	Protective structures made of logs placed on instable rocks to prevent from release	1	[35]	Object -stretch	Upgrade / retrofitting / new construction
Multi-hazard	Buffer strips, riparian forest buffers (I)	Green	A vegetative buffer on the edge of a stream/river bank, intercepting, slowing down runoff and stabilizing the eroding banks,	7	[3, 4, 11, 16, 29, 32, 35]	Object -stretch	Pro-active attitude
	Terraces (D)	Green	Water retention upstream, reduce water discharge along a slope	3	[11, 26,35]	Object -stretch—network	Upgrade /retrofitting / new construction

Table 1 (continued)

Hazard addressed	NbS practice	NbS type	Description/function	Fr	References*	Potential Scale of implementation	Potential Strategy
	Debris deflectors (D)	Green	Embankments or natural fences aimed at changing the debris flow path	2	[9, 26]	Object -stretch—network	Upgrade /retrofitting / newconstruction
	Grazing management (I)	Green	Managing the grazing areas to maintain higher vegetation than short cut grass, better infiltration and reduced runoff, improves slope stabilization	1	[17,32]	Object -stretch—network	Pro-active attitude
	Sustainable forest management (D)	Green	Conservation and sustainable management of forests in steep terrain, plantation of new forests	1	[18]	Regional network	Prevention

The category multi-hazard here refers to flood- erosion/landslide

* List of references: [1] Moreau et al. (2022); [2] Niazi et al. (2021); [3] Adams et al. (2018); [4] Albert et al. (2019); [5] Hankin et al. (2021); [6] Murphy et al. (2021); [7] Wübbelmann et al. (2021); [8] Page et al. (2020); [9] Carnelli et al. (2020); [10] Bokhove et al. (2019); [11] Keesstra et al. (2018); [12] Chiu et al. (2022); [13] Norbury et al. (2021); [14] Mubeen et al. (2021); [15] Leakey et al. (2020); [16] Gallotti et al. (2021); [17] Gao et al. (2018); [18] Kalsnes and Capobianco (2019); [19] Morales Gámiz et al. (2019); [20] Pagano et al. (2019); [21] Guerrero et al. (2018); [22] Cooper et al. (2021); [23] Qui et al. (2021); [24] Pathirana et al. (2021); [25] Janssen et al. (2020); [26] Capobianco et al. (2022); [27] Sangalli and Tardío (2023); [28] López-Vicente et al. (2020); [29] Stanchi et al. (2021); [30] Frankl et al. (2021); [31] Scheidl et al. (2020); [32] Zaimes et al. (2021); [33] Bles et al. (2016); [34] Mickovski (2021); [35] Solheim et al. (2021); [36] Preti et al. (2022); [37] Blackwood et al. (2023)

Fig. 8 Example of live crib walls along a mountain road in Leizaran, Spain **a** during construction and **b** after plants establishment. The wood structure is almost all covered by vegetation. (Pictures courtesy of P. Sangalli, European Federation of Soil and Water Bioengineering https://efib.org/)

of the Horizon2020 project OPERANDUM, to mitigate and manage shallow landslides and erosion. Examples of these NbS are live crib walls and high-density plantations of woody vegetation (Gallotti et al. 2021), which resulted effective in controlling landslides. The authors also highlighted that in cases where the main structure is expected to degrade with time, the vegetation can have a crucial effect on the long-term stabilization. Mickovski (2021) mapped more than 20 case studies of civil engineering projects addressing climate change challenges around Europe, such as erosion, shallow landslides, and flooding, concluding that many of them help meeting the Sustainable Development Goals (SDGs).

Live fascines, different from Sustainable Drainage Systems (SuDS), represent a valid alternative to traditional surficial drainage systems for road embankments, and an example of this SWB technique adopted for a railway embankment is presented in the next paragraphs.

Use of vegetation and protection forests

Moos et al. (2017) assessed the performance and efficacy of protection forests in decreasing damages of hydro-meteorological hazards in mountainous areas, finding that forests are highly efficient and effective to mitigate hydro-meteorological risk by reducing their onset probability, propagation probability and intensity. Forested areas are also beneficial at valleys, as natural flood management measures in floodplains or riparian areas. They influence the hydrological cycle and thus the flood response.

Hydroseeding or permanent grassing are commonly employed NbS in man-made slopes such as road embankments or in agricultural areas, to diminish water runoff, erosion and soil loss (Mickovski 2021; Capobianco et al. 2022; Stanchi et al. 2021). In the proximity of agricultural areas where a riverbank or streambank is present, buffer vegetation and forest buffer are applied to avoid runoff of pesticides or polluted water from the agricultural fields, while providing root reinforcement along the steepest part of the banks. Such measures act like barriers for the sediment that otherwise would reach the water, both providing an increased nonpoint source of pollutants in aquatic ecosystems, and clogged riverbeds that could lead to flooding. This approach has been implemented in a heavily farmed area near Lake Massaciuccoli in Tuscany, Italy, where runoff from the fields into irrigation canals, and from there to the highly polluted lake, has been a problem for years. Through a H2020 project Phusicos, a system of vegetated buffer strips along the channels which lead to a vegetated purification- and sedimentation basin before the lake, has recently been implemented. These measures have been combined with modifications of the canal cross sections to prevent sediment deposition. The modifications aim at making the NbS more effective as flood prevention measures, as previously eroded sediments from the banks often clogged the canals (Pignalosa et al. 2022). A long monitoring time series on 30 streams in Iowa state (USA), showed a high variability of streambank erosion with the seasons and pointed spring as the season where most erosion occurs. It was observed that the presence of riparian forest buffers and green filters significantly mitigated the bank erosion, while grazing and traditional agricultural practices had accelerated the process (Zaimes et al. 2021). Spring represents a critical season also in Norway, with snow melting that increases the amount of water infiltrating into the soil and reaching the rivers. Indeed, many major flood and landslide events have been recorded during this season, with catastrophic damages to infrastructure.

Cooper et al. (2021) reviewed natural flood management strategies applied in woodlands of the United Kingdom. The authors found that forests, in addition to directly influencing the hydrological flux, indirectly affect runoff and flood flows by changing the physical properties of the soil, changing the soil hydraulic roughness of the flooded area and reducing erosion and downstream situation. They concluded that natural flood management in different parts of the catchment can influence the flood response by (i) delaying the flood peaks both temporarily and spatially, (ii) increasing the flood height in the floodplains and (iii) increasing infiltration rate and evapotranspiration. However, both large spatial scales and long timescales are needed to notice considerable effects on flood risk mitigation.

A benchmark study in Norway of how to take into account vegetation for riverbank stability is provided by Capobianco et al. (2021). They proposed a methodology for assessing the role of riparian/buffer vegetation into slope stability and concluded that the higher effect of vegetation on slope stability is given by the hydrological reinforcement, especially in spring/summer period, while a combination of species (trees, shrubs and grass) is preferable to both improve the stability and the biodiversity.

De Jesús Arce-Mojica et al. (2019) conducted a systematic literature review on shallow landslide processes and mitigation techniques to assess the extent to which vegetation is identified as a NbS for shallow landslide risk reduction. Most of the research articles focus on use of vegetation for controlling the slope stability through the root system, or protective functions of ecosystems for shallow landslides, such as restoration, recovery, succession, and revegetation. Geographically, many case studies were in China, followed by Europe, USA and Canada, and South America. None of them is local and specifically dealing with a linear infrastructure, but rather are management practices such as Ecosystem-based Disaster risk reduction (Eco- DRR) or ecosystem-based adaptation (EbA).

The effect of protection forests against shallow landslides has been widely studied in Switzerland. For transport infrastructure, an example is the report provided by Schwarz (2019), where a quantitative study on risk reduction on railway systems and railway operations due to protection forests has been carried out for the Swiss Federal Railways (SBB AG).

Despite the sustainable management of protection forests is not directly addressing infrastructure authorities, some natural hazards, like landslides and debris flows that are triggered in high elevations, can still reach and damage infrastructure in the valley. Thus, an inclusive approach, involving dialogue between infrastructure owners and other stakeholders like forest owners and farm owners, can be advantageous when considering green approaches as mitigation options.

Blue approach

Blue NbS contain full components of water bodies which help with flood mitigation (Debele et al. 2019). Some of the approaches imply modifying/re-shaping/reconnecting water bodies, such as riverbed widening, river renaturation, re-meandering and restauration, with the main aim to make "room for the river" (Keesstra et al. 2018; Chiu et al. 2021; Table 1). Peatlands, wetlands and floodplains, both constructed and restored or re-connected, represent also a natural way to reduce peak flows and help with flood risk mitigation.

All these measures require space to be implemented and to be effective, thus are mostly applicable in rural areas.

Natural and artificial wetlands are large shallow water surfaces with abundant vegetation and water bodies such as lakes and swamps. Usually, the water is collected by a natural drainage system, but sometimes for artificial wetlands the runoff water needs to be conveyed, thus a whole drainage around the wetland must be designed.

In urban and industrial areas, including all the related infrastructures, nature reintroduction can be achieved in a large measure, through both constructing new areas and recovering or reintroducing near-to-natural hydrological structures that help reducing the risk of flooding. For example, deculverting/ daylighting buried watercourses can be beneficial to increase the capacity of streams and creeks near to roads and buildings (Fernandes and Guiomar 2018).

Nature-based sedimentation ponds and infiltration solutions have been implemented for many years in the road transport sector as climate adaptation measures for the treatment of runoff from roads (Myrabø and Roseth 1998). They are mostly referred as blue or blue-green infrastructure, especially in the urban context. Retention ponds consist of shallow surface reservoirs with permanent level of water and additional volume for lamination of peak flows. They can contain aquatic vegetation, which helps with sediment deposition and nutrient absorption.

A water retention pond was implemented in Greece within the OAL (Open Air Laboratory) of the Horizon2020 project Operandum. Despite the climate is not comparable to the climates of interest to this specific study, this solution can still represent an example of blue infrastructure to address flooding in a specific area. In this case, the NbS was aimed to reduce the overflow of the river that can cause damages to infrastructures such as roads and railroad networks (Gallotti et al. 2021). The downside of retention ponds is that in dry periods they can create anaerobic conditions. A good management of these water bodies also during summer and dry period is needed. River restoration as a NbS in urban and rural environment can mitigate high groundwater levels and prevent groundwater flooding. This was demonstrated for an urban river restoration case for Copenhagen by Jørgensen et al. (2023).

Increasing the capacity of retention ponds, floodplain management and restoration, river widening, opening and meandering, represent other actions that can be taken at different scales to mitigate flood risk. Land management to create landscape connectivity and reduce flood risk represents the way to go in the framework of NbS for flood risk mitigation, as they also enhance ecosystem services (Keesstra et al. 2018), however, these solutions require space and this can cause problems related to property issues, which is therefore one of the experienced barriers against implementing NbS (Solheim et al. 2021; Sarabi et al. 2020).

Monitoring and modelling groundwater level in (near) real time to support climate adaptation, water management and spatial planning has recently been developed as part of the Hydrological Information and Prognosis system. The system includes the option to act as early warning for drought and especially (groundwater) flooding, that can cause serious damage to transportation infrastructure and affect water supply infrastructure and thereby water and food security (Henriksen et al. 2020). And a web-based framework for flood-risk to protect infrastructure has been reviewed for Nordic countries (Henriksen et al. 2018).

Green/blue approach

Green/blue infrastructure integrate both green and blue approaches together as strategy for flood risk reduction. The creation of green/blue infrastructure is key to ensure the water retention and storm water control, simultaneously leading to the creation of leisure zones and diversified habitats (for example thematic parks).

Examples of green/blue NbS for road and rail network are ditches, swales or detention basins. Swales are shallow and relative wide ditches covered by vegetation (normally grass) that provide temporary storage for storm and reduced peak flow, while protecting from surface erosion. They are usually placed along road and residential streets to treat the runoff from non-permeable areas (Morales Gámiz et al. 2019).

Detention basins are surface depressions used to store large volume of water reducing risk of flooding by laminating the water flow. Surface detention basins can be considered as storm tanks or controlled flood-prone areas. They can be implemented at critical depression points of the road network.

Together with ponds and wetlands, swales, ditches and detention basins can form the so-called sustainable urban drainage systems (SuDS).

Adams et al. (2018) modelled and quantified the effects of adding a storage such as swales, ditches or sedimentation ponds in small catchments and concluded that this can reduce the overall flood peaks as well as decrease the concentration of suspended sediments and total phosphorous up to a total of 10%.

Hybrid approach

Hybrid approaches imply the use of NbS or natural materials in combination with engineered structures or inert materials, such as stones, geotextiles and porous pavements (Capobianco et al. 2022).

Debele et al. (2019) found that including NbS in hybrid solutions is the most common way of managing flood problems. In their review, hybrid approach is the most used measure to manage flooding (23%) followed by fully green approaches (20%), e.g. green roofs.

Overall, the proportion of case studies analysed shows that green approaches (49%) are contributing a significant role in buffering communities from hydro-meteorological risks at different locations in Europe followed by hybrid (37%) and blue approaches (14%).

An example of a hybrid approach for rockfall risk mitigation along a transport infrastructure in Artouste, the French Pyrenees, is provided by Solheim et al. (2021). The proposed NbS consisted of different structures made by wood and/or local stones. The solutions rely on active measures (manual stabilization and/or timber structures) to stabilize the source areas, and passive measures (mixed wood and/or stone structures) to slow down and/or divert rocks in their trajectories enhancing the protective role of the forest (Fig. 9). To reduce the environmental footprint, all materials were lifted in with helicopter flights and all construction work done by hand.

Another example provided by Solheim et al. (2021) is along the same road as Artouste, but on the Spanish side, in Santa Elena. The hazard is caused by erosion in a glacial moraine ridge, resulting in debris as well as larger boulders entering the road. The measures implemented at Santa Elena consist of terraces formed by a 5 m high dry masonry wall at the base followed by 10 terraces constructed using wooden logs (Fig. 10). The log constructions are in the form of timber gabions or Krainer cribwalls (Fig. 10C, D) and are filled with local sediment. Finally, a 10 cm layer of organic soil is placed on top for planting of bush vegetation on the terraces. In addition, ca. 1 m deep holes are filled with organic soil at 3 m intervals along the terraces for the planting of larger trees.

Fig. 9 Examples of implemented protective structures in the slope at Artouste (Photo: S. Fábregas)

Each log terrace step is roughly 2 m high. The width of the construction is 32 m at the base and narrows off to ca. 20 m at the upper, 10th terrace. In line with the idea behind this type of crib wall terraces, the selected vegetation, with deep root systems, will take over the stabilization of the steep slope when the wooden constructions decay, after probably 20–30 years.

Recently the measures implemented at Artouste and Santa Elena are being planned for three other locations along roads in the same region, inspired by these measures implemented during the H2020-Phusicos project.

Test plots and case studies in the Nordic Countries

This chapter is aimed to offer deeper insights into pilot cases gathered from past and ongoing research projects in the Nordic Countries where the authors are involved, providing practical information to practitioners about design and implementation of the measures, with potential for exploitation for transport infrastructure managers.

Case studies in Norway

Pilot cases in research projects represent a valid way to assess the effectiveness of NbS to withstand different hazards.

A successful story of NbS implementation in Norway is provided by the municipality of Øyer, where a development project for new family housing was halted due to potential flood hazard from a nearby creek. As part of the H2020 project Phusicos, a series of measures were implemented. A length of approximately 200 m where the creek was buried in pipes was re-opened. This was combined with re-meandering of the creek, a small sedimentation basin, and revegetating the stream banks. The lower part of the creek was also turned into a green park area and playground, which will serve as a floodplain in extreme situations (Solheim et al. 2021). The originally planned road, adjacent to the family housing, was moved further away, in order to allow a larger floodable area between the creek and the built area. The new road will be on the other side of the floodable area of the re-opened creek (Fig. 11).

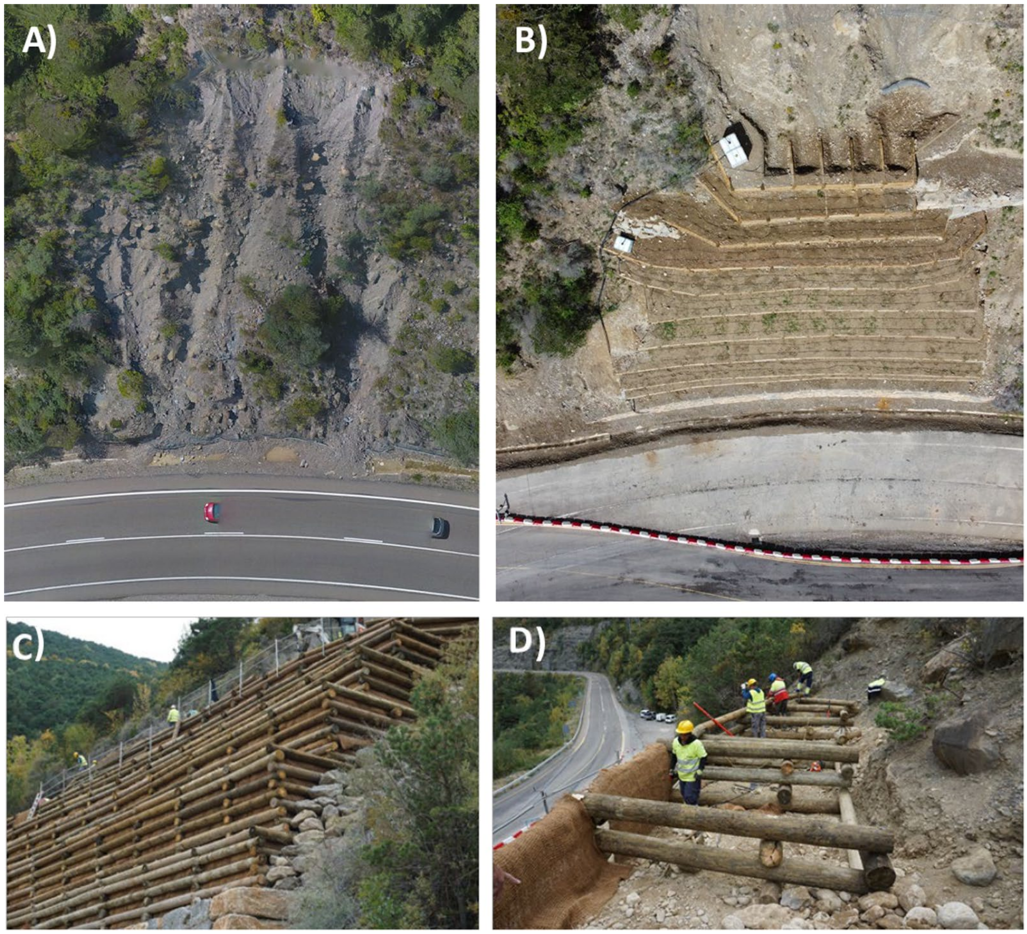

Fig. 10 Drone photo of the slope **A** before the intervention and **B** during the construction (October 2022). The road has been temporarily moved. **C** Close-up of the wooden terraces. **D** Construction of the wooden gabions supporting the terraces. Notice the use of coconut mats on the outer parts of the gabions that prevent spillover of sediment. Pictures kindly provided by Phusicos project

A plan to monitor the performance as well as the co-benefits that the NbS will bring to the area has been proposed and will continue after the official end of the Phusicos project.

Case studies in Sweden

The Swedish Geotechnical Institute (SGI) has recently implemented SWB techniques (NbS) along a stretch of the Göta river, located few kilometres north from the city of Gothenburg and few meters away from the European road E6, connecting Norway to Sweden. Three types of NbS for riverbank erosion were adopted along hotspot areas of the river experiencing shore erosion due to wave impact caused by shipping. Local materials including stones, timbers, and coir logs, were used as building materials for these NbS. The first mitigation measure consisted of a barrier of Christmas trees in between two lines of wooden piles located few meters away from the shore and parallel to the shoreline. The barrier was filled with 600 used Christmas trees that are usually collected at recycling sites in a municipality in Sweden at the beginning of the new year. The bundle of Christmas trees serves as a wave breaker and new Christmas trees are added every year (Fig. 12a). The wave barriers will create a calm environment behind, and vegetation will naturally re-establish itself. The barrier protects the shoreline until vegetation has re-established properly. Vegetation growth and wild fauna are being monitored through biotopes statistics, and sample counting.

The other measure, placed directly north of the barrier of Christmas trees, consisted of a submerged sill or small wave breaker. The barrier is also located few meters away from the shore and is made of two sills of natural stones (Fig. 12b). Also in this case, vegetation will naturally re-establish itself in the calm area behind the sill, and the idea was to compare the effectiveness of the barrier and

Fig. 11 Drone photos of the Trodalen site in Øyer municipality, Norway, after completion of the interventions, but before planting along the streambanks is fully completed (Solheim et al., 2023)

the sill of natural stone in protecting the shoreline. This will be done through comparing the vegetation growth in the two different sites.

The third NbS consisted of a palisade made of coir logs placed as protection along a stretch of the riverbank where clay rich soil have been eroding and causing a steep slope (Fig. 12c). The coir logs are fixed along the riverbank with wooden piles firmly nailed into the riverbed. This allows a direct protection of the bank surface from wave erosion. From 14c it is possible to observe the erosion and the layer of clay exposed to ship waves.

The Swedish Transport Administration tested out vegetation as mean for erosion and shallow slide protection in steep road embankments in two regions in Sweden (TR Geo 13 2016; Lundström 2017). The experimental campaign was conducted in the period 2004–2006 from a team of experts from the Swedish Civil Contingencies Agency, SGI, the Swedish Transport Administration and the Swedish University of Agricultural Science. This has been one of the first attempts to use vegetation in Scandinavia for slope stabilization purposes.

The slopes tested were silty slopes that are often found in unsaturated conditions in the shallow layers. However, when rainfall occurs for a prolonged period, the soil gets saturated and the shear strength is reduced, leading to solifluction. This latter is the gradual movement of wet soil or other material down a slope and occurs especially where frozen subsoil acts as a barrier to the percolation of water. Hence, this phenomenon occurs especially in cold regions. The aim of using vegetation was to help with the de-saturation of the soil via plant transpiration and avoid the occurrence of solifluction via root reinforcement. Several SWB techniques have been adopted in different test areas. The main hazards were erosion and solifluction due to frost heaving and rainfall-thawing. One measure tested was a brush layering using cuttings of local species of shrubs. Brush layering consists of live cut branches and rooted plants placed in layers into excavated terraces and filled with compacted soil material. Since brush layers are linear structures, they are usually completed with plantation or seeding (Stangl 2007). The advantage of this technique is that it provides immediate protection from the first vegetative year (López Gunn et al. 2023) and it is particularly suitable for slopes up to 40% steepness. The main issues experienced when adopting this technique in Sweden were related to the extreme cold weather in winter period, which sometimes can hinder the vegetation establishment and thus compromise the entire effectiveness of the measure (e.g. cuttings that do not develop deep rooting, or poor sprouting of the grass). To overcome this problem some preventive measures should be adopted. It is good practice to consider a diversity of live cuttings from different species, possibly found locally. Thick cuttings are to be preferred to thin

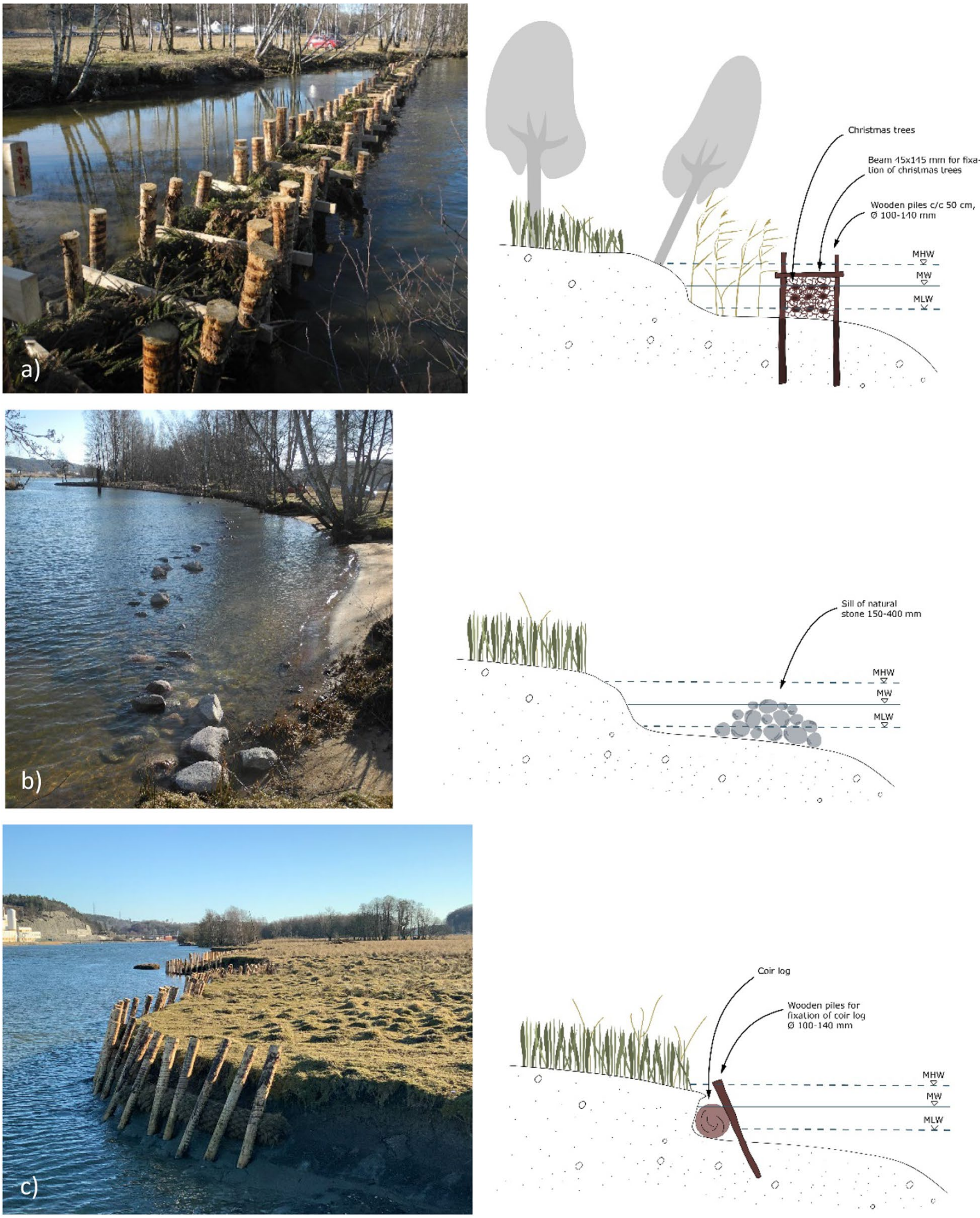

Fig. 12 Three testing areas along the Göta river (Sweden) where different NbS for riverbank erosion due to ship waves are implemented: **a** wooden pier filled with Christmas trees; **b** submerged stone barrier; **c** coir logs fixed with wooden piles. (Illustrations P. Danielsson, SGI)

cuttings, which find it more difficult to survive to the first vegetative year in these soil and climate conditions. A good geotextile made of natural fibers, such as coconut, should be placed on top of the soil surfaces, after the positioning of the cuttings and the seeding, in order to prevent soil erosion in the first year as well as protect the seeds and foster the sprouting.

Another success story from using vegetation against erosion and shallow instabilities (1–2 m deep) is provided by a very steep road embankment (almost 45° inclined) on the panoramic road 975, in Näsåker. Here the road, since its construction in 1918, experienced several landslides due to the marginal stability of the slope, worsened by high groundwater levels in some periods of the year, frost heaving and runoff erosion. After several attempts of improving the slope stability via a series of gabion walls, drainage measures and soil nailing techniques, in 2005–2006 the authorities decided to adopt a hybrid solution, with reinforcement via vegetation and soil nailing. The reinforcement consisted in alternating hydraulically pounded angel-iron bars with 2.5–3 m long salix-cuttings. Steel net and plates were used to nail the pounding directly from the road. On top of that, grass seeding covered with coconut fiber mat was carried out. The stabilization measures were adopted only on the top part of the slope, adjacent to the road, while a control zone was left as it was in the lower part of the slope, also due to the low accessibility via heavy machinery. The measure proved to be effective until now as it remained intact and withstood also a landslide event in 2013, where only the lower part of the slope experienced a slide.

Case studies in Denmark: natural assurance schemes as NbS

The concept of Natural Assurance Schemes was developed as a nature-based way to mitigate the impact of water related risks, avoided costs and damages, and additional co-benefits (López Gunn et al. 2023). Nature-based solutions were developed in response to flood and drought risk, demonstrated at nine European cases at spatial scales from (local) urban to regional. Natural Assurance Schemes (NAS) are considered Ecosystem-based risk reduction to reduce the risk of damage to assets in monetary terms, increasing water and climate security while harvesting the advantages of co-benefits, such as increased biodiversity and its related effects in the form of e.g. more attractive living environment, connected physical and mental public health, decreased air pollution. Barriers for actual implementation were addressed through assessing technological-, institutional and investment readiness (López Gunn et al. 2023; Van Cauwenbergh et al. 2023). Although protection of critical infrastructure was not directly addressed, NbS as a measure to mitigate effects of flooding and drought can be attributed to infrastucture, as demonstrated for a number of regions and areas in Europe, e.g. in the case of flood mitigation for the Lower Danube, Thames Basin, Brague Basin, City of Copenhagen and Rotterdam at the catchment, peri-urban and urban scale respectively. The city of Copenhagen experienced inundation of road infrastructure in parts of the city in 2011, which prompted the city to adopt a climate adaptation plan to implement green and blue solutions to protect the city from future cloudburst events. In (Jørgensen et al. 2023), an urban river restoration scenario was simulated using a hydrological model to evaluate the effect on high urban groundwater levels that hamper the drainage network to function properly and cause large damage to road and public transportation infrastructure. Economic assessments of NbS for water related risks were conducted by Le Coent et al. (2023). Integrated cost–benefit analyses were done for NbS strategies for reducing water risks in four case studies and confirmed the cost-effectiveness of NbS as compared to grey solutions for the same level of water risk management where co-benefits represented the largest share of value generated by NbS.

Discussion

NbS approaches and strategies

The findings of the review underscore a considerable scarcity of literature showcasing widespread adoption of Nature-based Solutions (NbS) within Nordic linear infrastructure and countries with similar climates. Among the 78 articles identified during the search process, only 5 addressed infrastructure in a general context, revealing a limited representation of NbS application within this domain. In addition, among these studies, not all provide a concrete example of NbS implementation. For instance, Asadabadi et al. (2017) focuses on stochastic modelling of future climate impact predictions for optimal investment planning and sustainable mitigation of transportation infrastructure, while Fernandes and Guiomar (2018) provide a good overview of potentialities and limits of NbS, with some examples applicable for transport infrastructure. They highlight that the main aim of NbS is protection of infrastructure and land uses in situations of conflict between opposite needs: the land use need for larger areas for its activities and infrastructures, and the natural systems intrinsic need for development space. Qui et al. (2021) provide some guidelines for the decision-making on planning of NbS for flood risk management with a focus on urban areas, concluding that concentrating NbS, such as porous pavements implemented along secondary roads and parking lots, downstream of a catchment, can be more cost-effective than spreading the solutions throughout the catchment area.

Although the lack of studies specifically investigating NbS for transport infrastructure and power lines, the compilation of NbS identified in Table 1 following the review process can serve as a valuable reference for infrastructure managers. These insights offer a vade mecum, meant to help managers in the decision-making process of selecting mitigation measures for the natural hazards of greatest concern to infrastructure in the Nordic Countries. The majority of NbS identified are for flood risk mitigation, with a total of 34 NbS practices, followed by NbS for Erosion/Landslides (NbS practices = 7), multi-hazards (NbS practices = 5) and rockfalls (NbS practices = 2). These findings confirm a pronounced emphasis on NbS for mitigating flood risks, reflecting the prevalence of flooding as the most recurrent natural hazard across Europe. Moreover, with climate change anticipated to increase the occurrence of floods, storm surges and landslides all over Europe (Debele et al. 2019), the prioritization of NbS in flood risk management initiatives is further validated.

Figure 13a clearly shows how the green approach emerges as a suitable NbS strategy for addressing various hazard types, appearing to be the sole feasible NbS approach, with some exception for hybrid approaches, for landslides, rockfall and multi-hazard mitigation. Blue approaches appear instead to serve as a viable alternative for flood risk mitigation. Indeed, among the identified NbS for flood risk mitigation, a nearly equal proportion falls within both the blue and green approach categories, while the remaining are classified as Green/blue approaches and Hybrid approaches.

Irrespective of the chosen NbS approach, a proactive strategy emerges as the predominant strategy for implementation. This entails considering NbS for hazard reduction or potentially relocating infrastructure from high-risk to lower-risk zones, or to areas where there is space availability to for NbS implementation.

Following the proactive approach, prevention, upgrade/retrofitting, and new construction emerge as the second and third priorities, respectively. This highlights the opportunity to implement NbS directly at vulnerable infrastructure points or along critical stretches.

An interesting finding emerges when distinguishing between NbS that directly influence infrastructure (D in Table 1) and those that do so indirectly (I in Table 1). Results show that that NbS that can be directly implemented along linear infrastructure are 23, while the remaining 25 are only indirectly impacting the infrastructure. For instance, afforestation, including protection forests, recognized as a green approach for mitigating rockfalls and landslides, involves implementing NbS not directly on infrastructure but rather along adjacent mountains or slopes. Despite not being directly applied

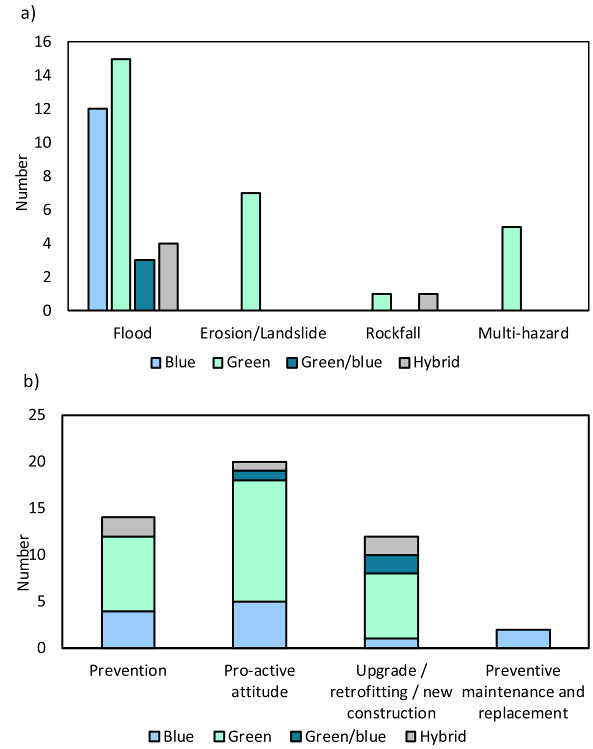

Fig. 13 **a** The count of NbS practices categorized under various approaches—Blue, Green, Green/Blue, and Hybrid—determined for the different natural hazards examined in the study and **b** the count of NbS practices categorized under the adoption strategies—prevention, pro-active, upgrade/retrofitting/new construction, preventive maintenance and replacement

to infrastructure, these measures effectively mitigate risks by addressing hazards in the areas around them. This highlights the importance of an inclusive approach which prioritize dialogue between infrastructure owners, other public authorities, as well as private actors, like forest and farm owners, for a successful adoption of NbS.

Limitations, barriers and opportunities for NbS implementation for Nordic linear infrastructure

Many of the main findings highlighted by Blackwood et al. (2023), regarding barriers in implementing NbS for road infrastructure, find confirmation by other studies dealing more in general with NbS for urban areas (Ershad Sarabi et al. 2019) or rural areas (Solheim et al. 2021).

Table 2 summarises the factors that, based on the key findings from this review as well as the dialogue established with the stakeholders of the NordicLink project, hinder the implementation of NbS for natural hazards mitigation along linear infrastructure in the Nordic Countries. In this section we discuss the barriers and identify opportunities that arise to overcome them.

Table 2 Barriers for implementing NBS in the Nordic infrastructure sector, and opportunities to overcome them

	Education	Success stories	Long term thinking	Sharing experiences	Promotion of NbS in industry	EU Policy and standards	European guidelines	Client specification	Innovative research pilot tests	Monitoring	Data sharing	Data collection, databases	Hybrid solutions	Long term planning	Funding, incentives	Payments for ecosystem services	Landowner partnerships	Climate-adaptive design	Benefits
Lack of NbS infrastructure awareness	■	■	■	■	■							■	■						
Resistance to change					■	■		■											
Path dependency		■			■	■			■	■									■
Safety concerns													■					■	
Cost									■		■								
Lack of financial incentives						■										■	■		
Time to grow													■	■				■	
Uncertainty in functionality in harsh climate		■		■					■	■	■	■	■						
Climate change uncertainty	■		■	■										■				■	
Limited land - space constraints															■	■	■		
Maintenance						■	■			■	■		■	■					
Lack of Cost Benefit Analysis	■						■	■	■										■
Lack of regulation/standards						■													

According to Solheim et al. (2021), Ershad Sarabi et al. (2019) and later supported by Aanderaa et al. (2020) and Blackwood et al. (2023), the lack of knowledge about the ability of NbS to deliver a series of co-benefits and their anticipated (monetary and non-monetary) value for society (Le Coent et al. 2023), in addition to their risk-reducing effects, represents one of the main barriers to mainstreaming NbS. This is particularly valid for linear infrastructure owners, given their significant safety concerns. Uncertainties regarding the effectiveness of NbS and their associated co-benefits may become visible many years after the implementation, thus in this case the adoption of hybrid solutions may be the way forward.

In addition to the lack of knowledge about effectiveness, a certain mindset which fosters resistance to change and a strong dependence on conventional 'grey' infrastructure may perpetuates a state of path dependency, posing a significant initial barrier for NbS implementation. This is highlighted in a recent study that assessed and compared a series of barriers for both 'green' and 'grey' measures (Linnerooth-Bayer et al. 2023).

The idea of NbS is often abandoned in the design phase for several reasons, not the least due to initial costs for implementation, which can be relatively high compared to consolidated concrete structures (Van Zanten et al. 2023). In urban areas, notably for NbS in climate adaptation plans in Copenhagen, costs of NbS implementation in the city centre were lower than the high sunk costs of establishing larger dimension drainage channels due to very disruptive construction in busy city neighbourhoods and flexibility together with large co-benefits (City of Copenhagen 2015). Limitations include that NbS are always implemented in conjunction with grey solutions (hybrid solutions) as an additional measure whereas barriers include the financing of NbS as part of yearly budget negotiations and subject to prioritization.

The uncertainty in functionality as well as maintenance of NbS in harsh climates represents one of the main factors that hinder a large adoption of NbS along linear infrastructure in the Fennoscandian peninsula, as most roads and railway lines traverse challenging landscapes. This is confirmed by a lack of examples specifically from Nordic regions for natural hazards mitigation along linear infrastructure.

Another barrier that may be encountered in Nordic infrastructure is related to the space constraints for implementing NbS. Hazards along linear infrastructure are usually treated considering a single problematic point and implementing local mitigation measures. NbS sometimes require more space than conventional measures, and it may be easier to plan, design and build NbS features into new infrastructure under construction rather than retrofit measures into existing infrastructure, especially in urban areas (Ershad Sarabi et al. 2019).

Finally, regulations and guidelines on cost–benefit analysis, design, implementation and monitoring are now lacking but are very needed to help "breaking" the path dependency of adopting traditional 'grey' infrastructure and foster the adoption of NbS.

Opportunities and suggestions to overcome these barriers can include sharing success stories to showcase not only the risk reduction capabilities of NbS, but also their capacity to deliver multiple co-benefits. Additionally, prioritizing education and adopting a long-term thinking are also key requirements for the selection and design of mitigation measures as well as addressing maintenance issues.

To overcome the lack of knowledge about potential alternatives to 'grey' mitigation measures and their effectiveness, databases about NbS options and their functions need to be shared. The possibility to select a gamut of environmentally friendly landslide risk mitigation measures was recently introduced in the webtool LaRiMiT (Landslide Risk Mitigation Toolbox). More than 20 NbS for erosion protection were updated in the database of mitigation measures, and scores for each of them were provided by surveyed experts in the field of soil and water bioengineering and ecological engineering (Capobianco et al. 2022). This tool can be very useful to decision-makers and practitioners in the preliminary phase of a project, when selection is often based on "what has been done in the past". At the same time, alternative and more sustainable solutions may be more suitable but end up not being chosen because of lack of knowledge.

Sharing experiences from countries with similar climates may be extremely important for Nordic regions, as it happened with the Swedish Road Authorities that adopted SWB techniques that can be found in LaRiMiT, but experienced some issues for the vegetation establishment due to harsh conditions in Nordic Regions (see Sect. 4.3). Guidelines regarding technical limitations associated with the technical and biological limits of vegetation and other living organisms (Fernandes and Guiomar (2018), should be provided. In addition, such finding highlights the importance to set up research pilot tests, for example over a short road stretch, to assess the durability (under certain climate conditions), scalability and replicability of potential NbS, before mainstreaming them for linear infrastructure in the Nordics.

In other cases, the measure's effectiveness can be proven only several years after their implementation. Thus companies, site owners or authorities need to take responsibility for following up after the research project's end, thus again adopt a long-term thinking.

For the NbS to be implemented in Bodø (Norway), where live fascines were designed as nature-based drainages for a steep slope along the railway, one of the challenges to overcome was finding a local NbS entrepreneur willing to take care of the implementation phase (including vegetation provisioning, pruning, and placement of the live cuttings in the trenches). A long-term planning is also necessary when new solutions are tested and a follow-up programme needs to be considered to assess the effectiveness over the years.

Moreau et al. (2022) surveyed 17 practitioners in the Rhone Alps basin (France) to explore to what extent NbS require a shift in management paradigm to be adopted for riverbank protection. This study is relevant also for infrastructure, since they traverse rivers in the Nordic Countries. They concluded that adopting soil bioengineering techniques requires a shift, from the "predict and control" paradigm, to " adaptive management".

A combination of monitoring, NbS and early warning, may be adopted as an indicator of slope failure in hotspot areas along linear infrastructure and can require relatively low costs for implementation and monitoring. Coppola et al. (2022) highlighted the importance of monitoring soil-based and hydraulic variables in addition to rainfall data to improve the accuracy and performance of Landslide Early warning systems, especially when slope pre-failure deformations and variation in soil suction can be considered as precursors of landslide initiation.

Piciullo et al. (2022) proposed a framework for a IoT-based local landslide early warning system (Lo-LEWS). The main aim was to collect real-time monitored data, including soil suction and volumetric water content, which can directly feed machine learning algorithms to forecast a possible instability and to warn the infrastructure owner. A preliminary application was performed on a monitored unsaturated slope located adjacent to a railway track in Eastern Norway, which has been extensively monitored since 2016. The presence of existing local vegetation was included in the modelling for the assessment of the Factor of Safety (FoS). They found that when vegetation is present, it is necessary to include it in the model to better portray the hydraulic behaviour of the slope. One of the main conclusions is that by simply preserving the existing vegetation, the soil volumetric water content is already reduced by the roots uptake, and this in turn results in a hydrological improvement of the slope stability. Shin et al. (2020) intentionally cut the vegetation cover from a monitored road embankment in Øysand, Northern Norway, to induce a failure and studying the effects of freeze–thaw cycles on the slope stability. The slope failed after one year of monitoring. In contrast, the adjacent slope, with the same topographical, water and soil conditions, did not experience any failure because it was left covered by trees. Removing trees from slopes adjacent to linear infrastructure would be detrimental to their stability. This highlights that policies and guidelines that recommend preserving existing vegetation along slopes as much as possible are essential, especially for road and railway authorities.

Testing out innovative systems involving nature and digitalization can enhance preparedness, reduce the carbon footprint and, in the meantime, ensure the provisioning of ecosystem services. More pilot sites that can be used for research purposes should be made available to test the effectiveness of innovative mitigation measures, including NbS.

To overcome the space related constraints, a holistic approach to risk mitigation may be more effective for infrastructure owners that want to adopt these solutions. This will allow to move the focus from the single slope to longer infrastructure sections, including a direct dialogue with other public entities, farmers and landowners. Financial incentives may be triggered for allowing landowners for expropriation of part of their lands to implement NbS.

Ecosystem-based preventing actions are also a viable solution contemplated by the concept NBS. A strategic build-up of ecosystem resilience could serve well as a measure to reduce disaster risk in the Nordic countries. This new thinking towards ecosystem prevention for natural hazard mitigation was one of the aims of the ERMOND project, which aimed to facilitate new solutions in preventing damage and loss of lives due to natural hazards in the Nordic countries, primarily by moving the focus from disaster management toward ecosystem-based preventive actions (Halldórsson et al. 2017).

Finally, the development of guidelines aimed at assisting infrastructure managers in the design, implementation, and maintenance of these solutions can significantly promote their widespread adoption.

Sangalli and Tardío (2023) anticipated that the Provincial Council of Biscay, northern Spain, has commissioned two local companies to form a working group for the definition and development of a technical manual of SWB works applied to linear infrastructures. The manual is under preparation and will contain all the latest advances in SWB discipline, including a description of constructive details of the techniques, root reinforcement models, work design methodologies in the short- and long-term, deterioration models of the used materials etc. The complete manual is expected to be finished and published in 2023. This manual can form the basis for developing a European technical manual on SWB and NbS for linear infrastructure.

Conclusions

In this work we present the results of a systematic review on the status of NbS for mitigating the risk from natural hazards along linear infrastructure in the Nordic Countries and Countries with similar climates. The main outcomes from a survey conducted among stakeholders in the field indicated the directions of the review process adopted.

The aim of this review was to provide an overview of potential NbS approaches for mitigating the natural hazards of greatest concern for Nordic linear infrastructure with future climate scenarios. A list of NbS options, not necessarily implemented along linear infrastructure but with potential for it, was provided. This list is meant to serve as “vade mecum” for a quick and easy access to NbS as mitigation options for linear infrastructure managers in the Nordic Countries. In addition to the results from the review process, case studies provided by the authors from on-going and past research projects were also integrated into the data gathered. The latter case studies are aimed to provide practical examples based on personal experience of the authors.

The NbS approaches and strategies identified, as well as the current limitations for mainstreaming NbS are discussed. In conclusion, new opportunities and research directions that arise to overcome these barriers are proposed and discussed.

Below are summarized the key conclusions that can be drawn from this study.

- Floods, erosion, landslides, rockfalls and multiple hazards (typically combination of floods and landslides) pose significant threats to Nordic linear infrastructure. While these hazards affect mostly culverts and ditches, followed by earthworks, drainage systems and road pavements for transport infrastructure, Nordic electric grids are expected to be affected by extreme windstorms. These concerns will persist and probably aggravate under climate change for affected stakeholders in the future.
- Nature-based Solutions are not currently a prioritized mitigation option for linear infrastructure managers in the Nordic Countries. However, there is a growing interest in the topic, as highlighted by the results of the survey, still hindered by a lack of knowledge necessary for widespread adoption.
- The current available literature on NbS for mitigating of these hazards for infrastructure in Nordic regions and similar climates is very scarce and consists of documentation on primarily case studies. Most of the literature comprises cases from Europe, like Italy, Spain and France, as well as the United Kingdom, which is currently exploring the state-of-the-art of NbS for transport infrastructure (Blackwood et al. 2023).
- Although Nature-Based Solutions are widely implemented in urban areas, their adoption in rural or semi-rural areas, which are of particular interest to Nordic infrastructure, remains limited. The majority of identified NbS practices are aimed at mitigating flood risks, reflecting the prevalence of flooding as a recurrent natural hazard in Europe. A small fraction of these documents however is specifically addressing infrastructure in the Nordic regions, with very few concrete examples of NbS implementation.
- A list of 34 NbS options, not necessarily implemented along linear infrastructure but with potential for it, is provided. The NbS are classified in green, blue, green/blue and hybrid approaches, and supported by examples of case studies both in the Nordic Countries as well as countries having similar climates. A collection of additional case studies from past and on-going research projects of NbS in the Nordic Countries, provides practical information to practitioners about design and implementation of the measures, with potential for exploitation for transport infrastructure managers.
- A proactive attitude towards implementation, including hazard reduction and potential infrastructure relocation to lower-risk zones, emerges as a predominant strategy. This approach highlights the importance of considering NbS early in infrastructure planning and decision-making processes, including space and climate constraints that may hinder the implementation, especially in Nordic countries.
- The main barriers identified for implementing NbS in Nordic linear infrastructure aligns with those found in studies focusing on NbS in urban and rural areas. These include lack of knowledge and awareness of their risk reduction effectiveness, concerns about cost of implementation, and lack of regulations and guidelines on cost–benefit analysis, design, implementation, and monitoring. Specific barriers in Nordic countries are linked to uncertainties regarding the functionality of NbS in harsh climates and constraints related to land or space availability.
- Sharing experiences and lessons learned, especially from countries with similar climates, may be extremely important for Nordic regions. Prioritizing education, and adopting a long-term thinking and planning are key strategies for overcoming the barriers for implementation. Additionally, databases and tools that provide information on NbS options and their effectiveness can support decision-making in the preliminary phase. Research pilot tests should be implemented, such as on a short stretch of road, to evaluate the durability (under specific climate conditions), scalability, and replicability of potential NbS along linear infrastructure in the Nordic region.
- A good amount of NbS identified are indirectly impacting linear infrastructure. This means that they are not directly implemented on them, but they concur to the reduction of risk. For instance NbS for landslides and debris flows, such as afforestation, are not directly implemented on the interested road, but in nearby slopes or mountains. When these large-scale NbS need to be adopted, an inclusive approach, involving dialogue between infrastructure owners and other stakeholders like forest and farm owners, can be the winning strategy. Since NbS usually require space, financial incentives may be triggered for allowing landowners to "give up" some of their lands to implement NbS. In addition, NbS may not be always effective for a specific case. This suggests the importance of tailoring NbS approaches to specific hazards and infrastructure types, and, in some cases adopt hybrid solutions (a combination of green or blue approaches and conventional constructed/grey structures)
- The development of guidelines aimed at assisting infrastructure managers in the design, implementation, and maintenance of these solutions can significantly promote their widespread adoption. The adoption of NbS can be improved by promoting co-design, cost–benefit and decision support tools in industries, and by encouraging universities or other actors to perform capacity building, e.g. train skilled experts, as well as challenging local entrepreneurs

to accept innovative jobs for forthcoming business opportunity in the field of nature-based solutions.

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Author contributions
V.C., conceptualization of the survey and manuscript, review process, figures, writing, review; R.P. conceptualization of the survey, review process, figures, writing, review,; A.S. conceptualization of the survey, writing, final review; K.G. final review; G.G. conceptualization of the survey, final review; P.D. figures, writing, final review; P.vdK. writing, final review. The authors declare that there are no competing interests.

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Availability of data and materials
No datasets were generated or analysed during the current study.

Declarations

Competing interest
The authors declare no competing interests.

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