Ecological Restoration as a Means of Managing Inland Flood Hazards

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Many streams and rivers experience major floods. Historically, human societies have responded to such floods by moving away from them or by abating them, the latter with large negative impacts on stream and river ecology. Societies are currently implementing a strategy of "living with floods," which may involve ecological restoration. It further involves flood mapping, forecasting, and warning systems. We evaluate 14 different stream- and river-restoration measures, which differ in their capacity to modify water retention and runoff. We discuss these restoration measures in the light of predicted changes in climate and flooding and discuss future restoration needs. We focus on the Nordic countries, where substantial changes in the water cycle are foreseen. We conclude that sustainable solutions require researchers to monitor the effect of flood management and study the relative importance of individual restoration measures, as well as the side effects of flood attenuation.

Keywords: climate change, restoration/remediation, river ecology, ecosystem engineering, hydrology

Streams and rivers provide substantial ecosystem services associated with hydraulic complexity, including fisheries, fertile floodplain soils, the retention of water, the provision of habitat, biodiversity, and the cycling of organic and inorganic matter (Tockner and Stanford 2002). Many of these services have attracted people to live close to streams and rivers (Douben 2006). Free-flowing rivers have floods that vary with climate and geomorphic catchment settings, such as valley slope and degree of confinement (Arnell and Gosling 2013). Although floods are necessary for the maintenance of dynamic stream and river ecosystems, they can sometimes become exceptionally large and hazardous. Resh and colleagues (1988) defined such extreme floods as those floods "in which water depth or discharge exceeds two standard deviations of the mean, based on a flow record that spans at least several decades." Others define extreme floods by their return interval—that is, as floods that are likely to occur on average only once in a certain period, such as 100 years (Kidson and Richards 2005). History includes many examples of such floods, and human alterations of landscapes may be involved in enhancing flood magnitudes (Douben 2006, Barredo 2007, Hauer and Habersack 2009). Scientists also expect an increase in the frequency of extreme floods following climate change (Kvočka et al. 2016). In this article, we provide examples on how humans have affected the risks of extreme floods, and discuss whether ecological restoration can serve as a sustainable means to alleviate such (and future) floods.

The types of human impacts on landscapes that have increased the frequency and severity of floods include deforestation, channel-bed reconfiguration, floodplain development, drainage, agricultural intensification, and urbanization (Wheater and Evans 2009). For example, floodplain exploitation typically requires fast removal of water to the stream or river by drainage and ditches (Guillemette et al. 2005, Ballard et al. 2012, Buchanan et al. 2013, Arnalds et al. 2016), and channelization or removal of in-stream vegetation increases the conveyance efficiency of the stream or river channel (Nagasaki and Nakamura 1999). Such alterations tend to redistribute flood risks in the catchment from upstream to downstream areas (Shankman and Pugh 1992).

Historically, the human response to extreme floods has been to settle at safe distances from streams and rivers. Following later technical development, people have attempted to abate extreme floods by building defense structures and regulating flows by dams (Cheetham et al. 2015). Over time, an overconfidence in technical solutions caused a lax view of flood risks (Krause 2012), but recently, awareness has risen that "combatting floods" has technical limits and that "living with floods" may be a more sustainable solution (Kundzewicz 1999). Instead of channel reconfiguration aiming for fast discharge of floodwater, land managers started to invest in flood mapping, flood forecasting, warning systems, and the adjustment of human settlements (de Moel et al. 2009) but also in redesigning channels to accommodate large discharges (van Herk et al. 2015). In addition, managers restore ecosystems in catchments to increase recharge and storage in wet meadows, marshes, channel banks, and groundwater, thereby increasing the detention and retention residence times of water and reducing flood magnitudes farther downstream.

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Worldwide, there are examples of restoration projects resulting in increased water retention, but flood mitigation is seldom the articulated, primary objective of restoration. Instead, most of those restoration projects aim for increased biodiversity or improved habitat or water quality (Palmer et al. 2014). In most cases in which restoration supports flood-related ecosystem processes, the objective is to increase local flooding (Rood et al. 2005), which attenuates flooding downstream as a side effect. After such restoration, flood periods downstream may last longer but be of a lower, less hazardous magnitude.

We focused our synthesis of ecological restoration to lessen extreme floods on the five Nordic countries: Denmark, Finland, Iceland, Norway, and Sweden. Hydrologists foresee rapid changes in the water cycle in this region due to climate change (Beldring et al. 2006). Besides, the region also has a several decades long history of stream and river restoration. Given the large climatic gradient in the Nordic countries and, at many places, the considerable population density and development of infrastructure, an overview of their stream and river restoration will provide valuable examples of more generally applicable solutions of flood mitigation.

Our key questions for the Nordic countries are the following: (a) What are the stream and river types that are most susceptible to hazardous floods? (b) What are the currently used ecological restoration practices that can affect flooding, and how can they increase ecosystem resilience against hazardous floods? (c) What are the predicted future changes in variables such as mean annual discharge and the frequency, timing, and magnitude of floods? (d) Is there a need for tailored restoration and land-use practices with the projected changes in climate and flooding regimes? The Nordic rivers serve as examples beyond the Nordic countries and to other climatic regions because processes are universal and transferable, and on the basis of our review and synthesis, we propose some challenges for river-restoration designers.

Methods

The five Nordic countries are located on the northern European mainland and in the North Atlantic between 54°N and 71°N and 24°W and 30°E, ranging from the temperate to the Arctic zones. They cover a range of ecological and hydrological conditions, and catchments in all countries have undergone various degrees of ecosystem degradation, including deforestation, wetland drainage, stream and river channelization, overgrazing, urbanization, flow regulation, and construction works (Halldórsson et al. 2012).

As a basis for responding to the four questions, we used our expert knowledge and results from literature studies. We focused the literature search on English, peer-reviewed articles published in international journals available through the Web of Science and searched for them by using multiple combinations of keywords. First, we made a broad search using the search strings *restor* AND (stream* OR river*) AND flood** and received more than 3000 hits. Second, we selected the cases from the Nordic countries by adding truncated versions of their respective names (nouns and adjectives) to the same search string, receiving 1–36 hits per country. Third, we extended our search with many other keywords and included some gray literature and literature outside of the Nordic countries.

Stream and river reaches prone to hazardous floods

In natural, unaffected stream and river systems, there is a strong link between upstream and downstream hydromorphological processes, and the stream power associated with high-magnitude flow events and the amount and size of the sediment are strong determinants of river planform (Gurnell et al. 2009, Ziliani and Surian 2012). High discharges cause geomorphic changes, such as sediment redistribution and the lateral migration of stream and river channels, and they strengthen the physical and biological interactions between the channel bed, riparian areas, and floodplains. Such natural hydromorphological processes can attenuate flooding (Palmer et al. 2008). In channelized streams and rivers, however, the channel usually contains few roughness elements and has a high water velocity. The faster discharge will build up higher flood peaks downstream. We identified five different stream and river types in the Nordic countries where extreme flooding has hazardous consequences and ranked them from most to least hazardous: urban streams and rivers, lowland agricultural streams and rivers, boreal forest channelized streams and rivers, impounded streams and rivers, and diked streams and rivers (table 1). We are aware of that some streams and sections of rivers can fall within two or more categories, such as an impounded stream or river can run through a city, but we focused on typical examples. We excluded Icelandic glacial meltwater streams and rivers where volcanic eruptions cause flooding, because there are no realistic ways to mitigate such floods using ecological restoration. For each of the stream and river types, we will discuss the specific modifications that interact with the streamflow, as well as the services that make those stream and river types prone to hazardous floods.

Urban streams and rivers. Artificial structures such as quays and bridge piers heavily affect the flow in these streams and rivers, as does dredging to support shipping. Catchments of urban streams and rivers have a high cover of impervious surfaces, which decreases infiltration and increases the precipitation runoff rate and eventually the intensity and rate of change of streamflow in the stream or river channel (Paul and Meyer 2001). In many regions, the largest cities are in deltas of streams and rivers, which exposes them to stream and river flooding but also sea-generated floods. The hazardous impact of floods in urban areas is high throughout most of the year and the costs associated with the damages are relatively high because of intensive anthropogenic use (e.g., housing and infrastructure) and can even cause loss of human lives. For example, the costs for the flood caused by an intense rain event (cloudburst) in Copenhagen on 2 July 2011 amounted to 1 billion euros (Leonardsen 2012).

Table 1. Stream and river types in Nordic countries where floods act as hazards to human activities.

Stream and river type based on human activities	Modifications affecting flows	Type of primary hazard	Flood timing when economical costs will be highest
Urban streams and rivers	Constrained channels, often lacking riparian zones	Damage to homes, businesses, all structures, loss of human lives	All year
Lowland agricultural streams and rivers	Channelization, incision, culverting	Damage to crop production, pollution of seas	Summer
Boreal forest channelized streams and rivers (former timber floatways)	Channelization, channel simplification by straightening, closing of side channels, removal of obstacles	Damage to downstream floodplain structures	All year (depending on floodplain use)
Impounded streams and rivers (hydropower, transportation, water supply, flood control)	Damming and fragmentation, flow regulation	Dam failure due to high precipitation and discharge, especially when reservoirs are full	Late summer and fall
Diked streams and rivers	Dikes on banks	Damage to dikes resulting in damage to floodplain structures and cropland	All year

Lowland agricultural streams and rivers. Humans have generally strongly modified the courses of these streams and rivers, and crop production has heavily altered their floodplain land use. During the past 150 years, farmers have started to grow crops very close to the main channel, facilitated by intensive drainage of floodplains, including stream and river channelization and channel incision (Kronvang et al. 2005). In many areas, the drainage of old floodplains has increased the decomposition of soil organic matter, and the resulting decreased sediment cohesion may cause severe soil subsidence (Verhoeven and Setter 2010). The physical modifications and soil processes have increased flood risks, and managers commonly battle the resulting damage of crop production in the floodplain with more drainage. The hazardous impact of floods is therefore highest in summer, when crops are maturing prior to the harvest season.

Boreal forest channelized streams and rivers. Forestry companies severely decreased channel roughness in these streams and rivers to optimize timber transport during the nineteenth and twentieth centuries. Modification typically included the removal of obstacles (e.g., boulders, riffles, and wood), damming, channelization, and the closing of side channels (Nilsson et al. 2005). These modifications decreased shear stress and water retention times and substantially increased water velocities. In the Vindel River in northern Sweden, for example, channel modification reduced the time it took to float the logs from the inland area to the sea from 3–5 years to one summer season (Sörlin 1981). Consequently, water transport is also much faster and a heavy rainfall in upstream parts of the catchment may cause a short massive flash flood rather than a longer, less peaked flood. Flash floods increase hazard risks, including damage to crops, infrastructure, and housing, and the economic costs depend on the use of the floodplain. The hazardous impact of floods in boreal streams and rivers is equally high throughout the ice-free season and most likely in downstream areas, which are the most densely populated areas within the boreal zone.

Impounded streams and rivers. These streams and rivers have reservoirs and dams in areas that were formerly rapids. They serve hydropower, transport, water supply, irrigation, or flood control. This means that in many places, there is nothing left of the original channel-bed morphology and hydrology. Floodwater storage in large reservoirs in upstream reaches evens out downstream discharge over the year, motivated by the need for energy rather than natural patterns of runoff. The main hazards to flooding in these systems are dam failure during times of increased precipitation and runoff. The risks are highest in late summer and fall, when reservoirs are full and streams and rivers lack the capacity to accommodate heavy rains (Bergström 1999). Such flooding can lead to substantial sediment displacement (Evans et al. 2000), and the costs associated with the damage this causes may be extremely high.

Diked streams and rivers. Diked streams and rivers have dikes on both banks to prevent bank overflow. Diked streams and rivers are in many cases associated with or closely linked to transport infrastructure (e.g., roads and railways) and agricultural cropland. The relative distance between the dikes and the stream or river will determine the degree of impact that a dike has on the course of a stream or river. A problem with diked streams and rivers is that continuous sediment deposition in the channels requires higher dikes or dredging (Roth and Warner 2007). Dike breaches due to high discharge and overtopping can occur during cloudbursts or prolonged rain and cause major damage to infrastructure behind the dikes (Schmocker and Hager 2009).

Restoration practices that can increase ecosystem resilience to hazardous floods

Many different methods of ecological restoration can contribute to mitigating flood hazards, but so far, this has rarely been the major aim of restoration. For example, 27.3% of the cases presented by the River Restoration Centre (RRC 2017) mention flood mitigation as one of the aims, but only 1.0%

has flood mitigation mentioned as the single aim. For the Nordic countries, numbers are even lower: Only 12.1% mention flood mitigation in their aims, and only one of the 66 Nordic case studies presented by RRC (2017) has flood mitigation as the single aim. Despite this other focus, projects with other objectives often have involved methods that may result in similar impacts on flood mitigation. For example, restoration initiatives targeting in-stream habitat complexity by adding boulders or large wood (Polvi et al. 2014) or nutrient retention through wetlands (Newcomer Johnson et al. 2016) are both likely to increase on-site water retention capacity and reduce flood magnitudes downstream.

The general way to attenuate floods by ecological restoration is to increase channel roughness and evapotranspiration upstream from the hazard area. Such improvements of upstream water retention capacity will result in a more even distribution of water in the catchment and decreased runoff volume (Williams 1990). A recent term for this type of flow manipulation at a catchment scale is Natural Flood Management (NFM; Lane 2017). Figure 1 summarizes 14 restoration measures that can serve in mitigating floods in the Nordic countries. The channel bed, the floodplain, and the surrounding upland are three areas in which restoration can achieve increased water retention capacity (figure 1; table 2). First, in-stream measures force the water to take longer and slower paths (Gardeström et al. 2013), leading to increased retention. Second, floodplain restoration can improve retention and detention capacity by increasing bed roughness and the sponge effect (De Steven and Gramling 2012). Third, restoration measures in upland areas can have similar effects. Here, restoration efforts may focus on retentive vegetation, retentive ground structures, and the removal of drainage systems or large proportions of impervious ground. Below, we describe how these measures can act as flood-mitigation measures. We note that some restoration measures can have negative effects on ecological quality and may in some situations counteract targets set by the European Union Water Framework Directive and may therefore not be desirable. However, in this article, we do not cover the ecological consequences of the different flood-mitigation measures.

In-stream restoration increasing water retention. Stream or river restoration involving remeandering, placing large wood or boulders in the main channel (figure 2), reopening side channels, replacing road culverts with bridges, removing physical structures, decreasing bank slope or introducing beaver, are likely to increase in-stream water-retention capacity (figure 1; table 2). Remeandering of the stream or river channel is a common practice in agricultural streams and rivers in many southern parts of the Nordic countries, because it also increases floodplain biodiversity and reduces nutrient export to downstream reaches (Kristensen et al. 2014). Removal of dams and other facilities that regulate flows, combined with enhancement of channel complexity and links between the in-stream and riparian habitats, may also serve this purpose, particularly in boreal streams and rivers (Van Dyke 2016). Reintroduction of large wood and boulders to streams and rivers (figure 2) is a common restoration practice as well as reopening of side channels, historically cut off to reduce water retention and facilitate runoff (Nilsson et al. 2015). Creating two-staged ditches in the channel profile or decreasing bank slopes could increase shear stress and may increase bed roughness further by stimulating aquatic vegetation due to better light conditions (Roley et al. 2014). A last restoration measure is the introduction of beavers (or other ecosystem engineers) as beaver dams have altered water retention patterns in many of the systems after their reintroduction during the past decades (Halley and Rosell 2002).

Restoration increasing water retention in floodplains. Establishment of new floodplains, riparian wetlands or dry buffer strips will enhance the hydrological connectivity between the stream or river and the riparian areas. This will increase floodplain water retention and buffer against downstream flash floods (figure 1; table 2), because there will be more space for the floodwater. It will also increase the sponge effect of the soil and reduce nutrient runoff (Kronvang et al. 2013), although buffer widths may be narrower and less efficient compared with most floodplains and wetlands. Reprofiling of channelized streams and rivers (*sensu* two-stage channel design; Powell et al. 2007) is a method for creation of two new floodplains, one close to the channel for low flows and another farther away, that provides storage capacity during larger floods. In agricultural streams and rivers, drainage water from adjacent crop fields can feed these new floodplains. Riparian wetlands can be located at different places in the floodplain where water from streams or rivers or from drainage of adjacent crop fields, grazing areas or forests is available. In agricultural areas, creation of riparian wetlands is possible by raising water levels in the channel or by letting drainage water run into the wetland. Agricultural areas in the southern parts of the Nordic countries show examples of dry buffer strips, established by ending crop production in a strip along the stream or river. Farther north, foresters create such strips by leaving trees when clear-felling adjacent forest areas while aiming for increasing biodiversity (Hylander et al. 2002, Kuglerová et al. 2014).

Restoration increasing water retention in upland areas. The precipitation within a catchment will evaporate, recharge groundwater and soil storage or flow downstream. Therefore, measures that increase soil permeability and evapotranspiration in uplands are effective flood-mitigation measures. Examples used in Nordic countries are wetland and forest establishment, especially in eroded and otherwise open areas (figure 1; table 2). Along urban streams and rivers, installation of green roofs or green ground areas aims to reduce the area of impervious surfaces (table 2) and thus increase retention capacity (Carter and Jackson 2007). In agricultural

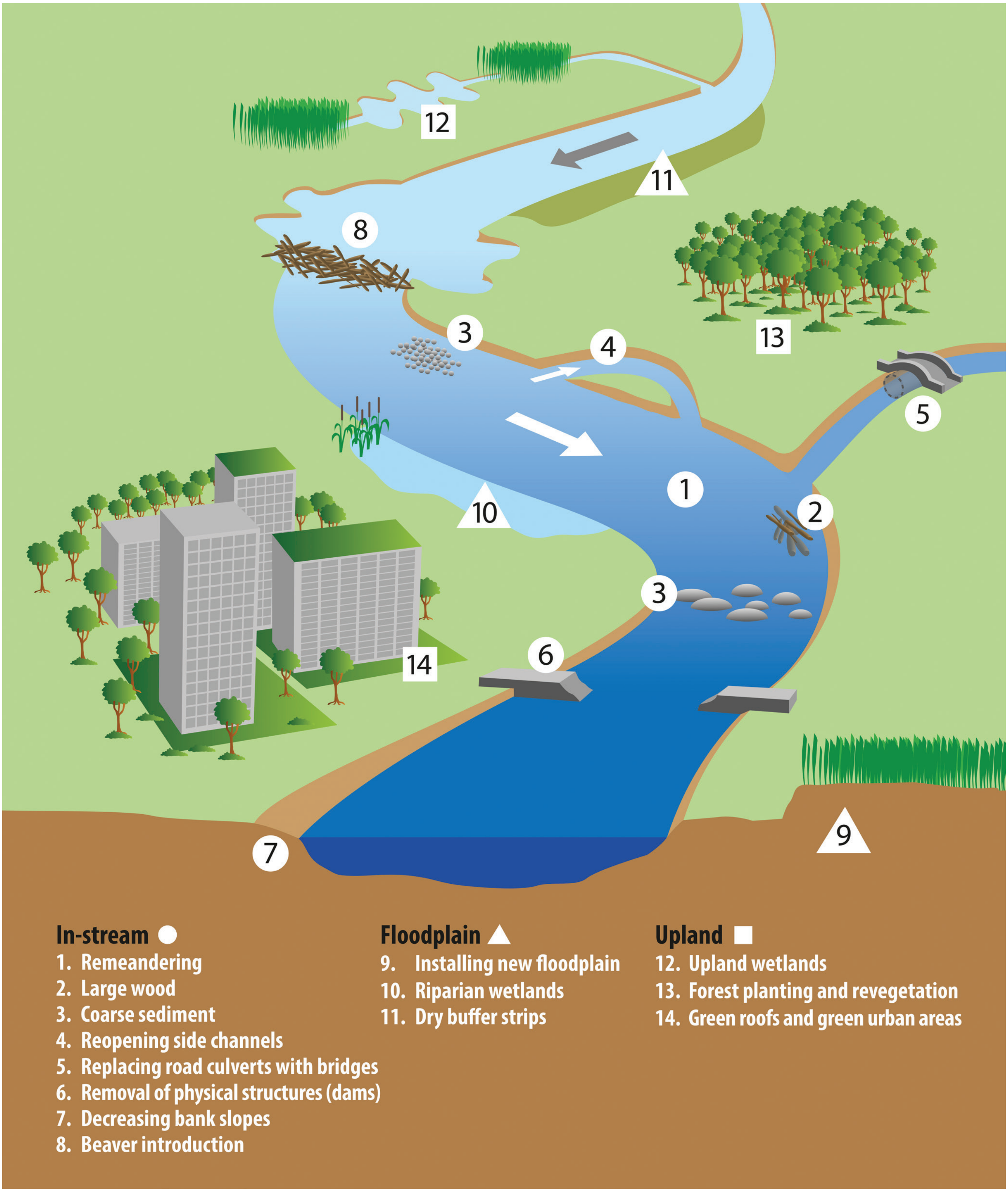

Figure 1. A visual overview of 14 different restoration methods that contribute to increasing on-site water retention capacity, thereby reducing flood peaks downstream. Note that a new floodplain is relatively wide, whereas a dry buffer strip is a narrow riparian zone (with terrestrial vegetation).

Table 2. Currently used ecological restoration practices in Nordic streams and rivers that can mitigate flooding downstream and thus increase the resilience to hazardous floods.

	Ecological restoration practices	Main restoration aims	Stream and river type and location	Potential change in hydrology	References
Action to increase water retention capacity in the channel upstream					
	Remeandering	Biodiversity	Streams and rivers in flat, fine sediment areas	Increased water retention capacity	Kristensen et al. 2014, Schmutz et al. 2016
	Addition of large wood	Biodiversity	Streams and rivers in forested areas	Increased water retention capacity, increased water volume	Engström et al. 2009
	Addition of coarse sediment	Biodiversity and recreational values/use	Streams and rivers in coarse sediment areas	Increased water retention capacity, increased water volume	Gardeström et al. 2013
	Reopening of side channels	Biodiversity	Multichanneled streams and rivers	Increased water volume	Gardeström et al. 2013
	Replacing road culverts with bridges	Fish passage	Any small and midsized streams	Increased water volume	Erkinaro et al. 2017
	Removal of physical structures (dams)	Dispersal and movement of organisms	Dammed streams and rivers	Restore natural flow regime	Lejon et al. 2009
	Decreasing bank slopes (friction, vegetation increase)	In-stream plant abundance	Any stream or river	Increased water retention capacity	Pedersen et al. 2007
	Beaver introduction	Biodiversity	Any stream or river	Increased water retention capacity, increased water volume in dammed areas	Halley and Rosell 2002
Action to increase water retention capacity in the floodplain upstream					
	Installing new floodplains	Nutrient retention and removal and biodiversity	Agricultural streams and rivers	Increased water retention capacity	Poulsen et al. 2014
	Riparian wetlands	Water retention, nutrient retention and removal	Any stream or river	Increased water retention capacity	Poulsen et al. 2014
	Dry buffer strips	Nutrient retention and removal	Any stream or river	Increased water retention capacity	Ulén 2003
Action to increase water retention capacity in the upstream and adjacent uplands					
	Upland wetlands	Nutrient retention and removal	Any stream or river	Increased water retention capacity	Windolf et al. 2016
	Forest planting and revegetation	Bank stabilization	Any stream or river	Increased water retention capacity	Hylander et al. 2002
	Green roofs, green areas, (underground) water storage in urban areas	Rain water retention	Urban streams and rivers	Increased water retention capacity	Berndtsson et al. 2009

Note: Based on experience of different restoration practices, we allocated the use of each restoration practice to increase resilience to hazards in each of the five identified stream and river types prone to hazardous floods.

lowland streams and rivers in Denmark, wetlands placed in uplands adjacent to crop fields have become a new mitigation measure against nutrient runoff to streams and rivers (Kjærgaard and Hoffmann 2010). In Sweden and Finland, plugging ditches in drained peatlands is another method to increase upland water retention (Mälson et al. 2008).

Restoration effects on flood risks. Modeling prior to actions is becoming increasingly common for addressing the effect of restoration on flood risks. However, we did not find any clear examples of Nordic restoration projects with thoroughly quantified and evaluated flood-related hydrological effects downstream from restored sites after restoration. However, in the agricultural Skjern Stream in Denmark, model calculations show that remeandering would increase local flooding duration from 0% to 10% of the year (Kristensen et al. 2014), but concomitant hydrological changes downstream were not isolated. Globally, we found a few more examples. However, most of these are anecdotal, lacking precision, based on simple models, or measured on insufficient temporal or spatial scales to be useful for more in-depth analysis. For example, Hammersmark and colleagues (2008) reported from restoration of drained wetland areas passed by channelized streams in northern California, United States. The methods used were plugging channels and allowing deeper flooding of the floodplains. This raised groundwater levels and increased water storage in the restored wetlands, resulting in a lower annual runoff downstream

Figure 2. Lidsbäcken, a tributary of the Vindel River in northern Sweden, before (above) and after (below) restoration. Practitioners restored the stream channel by returning coarse sediment that timber-floating companies had removed to facilitate timber floating. Photograph: Daniel Jonsson.

(Hammersmark et al. 2008). Liang and colleagues (2015) presented a similar case from northern China, where models suggested that retentive measures in catchments in China's Loess Plateau would lead to reduced discharge downstream.

Predicted future changes in flood regimes

Climate change scenarios predict substantial changes in stream and river flow regimes up to the end of the current century in the Nordic countries. For most of the area, precipitation and discharge will increase over the year (Milly et al. 2005). However, in southern Scandinavia, and possibly much of Finland, hydrologists foresee minor decreases in both precipitation and discharge (Madsen et al. 2014). The discharge will increase most strongly during winter because more precipitation will fall as rain instead of snow because of increased air temperatures. Because of this shift from snow to rain and increasing temperatures, the EEA (2014) predicts the spring flood to become lower in magnitude but also to occur earlier (EEA 2014). Such a change may also lead to less severe ice break-ups and ice jams, unless more frequent shifts between freezing and thawing will boost ice production. When climate change results in frequent zero crossings in temperature, this may trigger the formation of frazil ice, anchor ice and hanging ice dams, which especially in smaller streams may lead to winter floods that can be extensive (Lind and Nilsson 2015). However, further warming and less ice formation may decrease the occurrence of such ice-driven winter floods (Lind and Nilsson 2014).

By the end of the twenty-first century, most glaciers in Iceland, Norway and Sweden will have lost more than 50% of their volume (Jóhannesson et al. 2011), which will likely affect the base flow and flooding in rivers fed by glacial water. For instance, in Iceland, Björnsson and Pálsson (2008) expected river discharge to increase during the next 40–50 years and then decline. Also in Iceland, Jónsdóttir (2008) predicted a 25% higher runoff during the last three decades of this century compared with the period between 1961 and 1990, most of which would come from glaciers.

The magnitudes of the current 100-year floods may change in different directions for different parts of the Nordic countries. The expectations are a slight increase up to year 2050, especially in central Sweden and central-eastern Finland. During the latter half of this century, however, these areas will face a reduction of the magnitudes of the 100-year floods (Paprotny and Morales-Nápoles 2017). In contrast, northern and southern Sweden, western and southwestern Norway, and northern Denmark may get less prominent 100-year floods in the future (Paprotny and Morales-Nápoles 2017). Most of Sweden, Finland, Norway, and Iceland may experience a future reduction in the frequency of extreme floods, whereas most of Denmark and parts of south-central Sweden and southern Norway can anticipate an increased frequency of floods currently categorized as 100-year floods (Hirabayashi et al. 2013). Although seasonal variations in flow will likely decrease in the future, the highest daily precipitation events (cloudbursts) will probably increase both in magnitude and frequency in most parts of the study area and will be most pronounced in the south (Gregersen et al. 2015). Such cloudbursts can rapidly result in local torrential floods, especially when they hit impervious ground, full reservoirs, or heavily constrained stream or river channels that cause rapid runoff.

Future perspectives in the face of predicted climate change

Our survey of restoration methods and climate-change predictions shows that in some stream and river types, extreme floods will continue to pose a hazard to human societies in the Nordic countries. The projected flood risks, however, show both increases and decreases depending on how changes in temperature and precipitation interact. It also shows that ecological restoration has a potential to mitigate but not eliminate the impacts of hazardous floods.

Much of the contemporary restoration work, even if accomplished with other primary aims, may contribute to reducing hazardous floods, but more focused work has the potential to improve the outcomes. Today, the Nordic countries spend millions of euros per year on stream and river restoration. A typical aim has been to increase biodiversity, but recent initiatives also include climate-change adaptation. For example, in Denmark new projects aim at reducing peak discharge in streams and rivers running through towns by increasing upstream water retention in new wetlands (Danish Agency for Water and Nature Management 2017). A success criterion for stream and river restoration should be that stream or river systems can accommodate external perturbations without any significant investment in follow-up maintenance (Palmer et al. 2005). Restoration of geomorphic structures, paving the way for a more natural hydrology, will lead to such a situation. We will point to a few facts that are important in developing a framework for implementing flood mitigating restoration measures.

Overall, a catchment perspective is imperative in discussions of flood hazards and the location of restoration actions (Wissmar and Bechta 1998). These considerations involve a distribution aspect (i.e., where and when things will take place), an effect-size aspect (i.e., the impact of floods and different restoration methods), and a successional aspect (i.e., in which order to restore sites for restoration to be most efficient). For example, Dietrich and colleagues (2014) suggested that ecosystem recovery in stream and river catchments is most effective when restoration begins in headwater reaches and proceeds downstream, and this suggestion may have a bearing on flood-mitigation effects, too. For instance, cloudburst-caused floods have the highest impact in headwater regions where streams are smallest. Restoration measures in such places can help to attenuate flooding farther downstream in a cost-effective way, especially if flooding in downstream areas is hazardous.

Besides the main aims of restoration to mitigate floods, there might be negative side effects to consider before using a restoration approach primarily to mitigate flood hazards. First, restoration may include, at least temporarily, increased nutrient runoff, increased siltation, the enhanced dispersal of exotic species, reduced habitat quality, and reduced biodiversity. These are crucial effects, and a general decrease of ecological quality in streams and rivers may counteract the targets set by the European Union Water Framework Directive. Second, if restoration interferes with the timing of floods from different parts of a catchment, flooding may exacerbate if peak flows synchronize and arrive at a confluence at the same time instead of after each other. If the side effects of certain restoration measures turn out to be too serious, alternative actions require consideration.

The recovery of ecological processes has proven to be slow (Nilsson et al. 2015, Leps et al. 2016), and this makes financing evaluation programs difficult, which may be a reason for the limited evaluation of results observed in this survey. However, to increase knowledge transfer between old and new projects, more monitoring and evaluation of both the hydrological and ecological outcomes of accomplished restoration projects are necessary, especially when it comes to the areas downstream from restored sites. The assessment of hydrological effects, unlike ecological parameters, needs shorter time intervals, and monitoring is less labor intensive. It is reasonable to predict, however, that many of the current restoration measures have a retentive effect on water flow as channel-bed roughness and water storage capacity in the floodplain or upland increase (table 2). More detailed knowledge of downstream hydrology in all parts of a catchment will make it possible to model how different parts of a catchment interact in affecting the rate, timing, and magnitude of flooding. Such an understanding may also provide guidance on the use of different restoration practices in various settings of the catchment. To put things in perspective, evaluations of the hydrological effects of stream and river restoration will benefit from keeping the historical flood pulses in mind because these provide the framework according to which channels have developed.

Conclusions

We have shown that the Nordic countries include many stream and river types in urban, agricultural, and forested landscapes that are susceptible to hazardous floods. We have also given examples of ecological restoration practices that can attenuate flooding in these streams and rivers, basically by applying retentive actions in one or more of the areas catchment, riparian zone, or floodplain and in-stream channel, thereby reducing flooding downstream from restoration sites. Following further climate change, hydrologists predict that the mean annual discharge (base flow) will increase in many streams and rivers in the northern parts of the Nordic countries, although with a reduced range of water-level variations. An anticipated increase in the frequency of cloudbursts may, however, give rise to more large floods in the future, especially when the interception and storage capacity of rain are low, such as in smaller watercourses. Therefore, designers of future stream- and river-restoration schemes in the Nordic countries and elsewhere have imminent challenges to deal with.

The first challenge is finding out at which scales various restoration methods work and how different parts of a catchment interact. This involves an evaluation of the extent to which the NFM method works for larger catchments, as has been addressed by Lane (2017). As an essential variable for such an evaluation, we recommend the continuous monitoring of flow dynamics both upstream and downstream from major restoration sites, before as well as after restoration.

A second challenge is to determine the relative importance of individual restoration actions. Restoration managers usually combine different measures and often combine their restoration with changing other land-use practices. This makes it complicated to quantify the importance of a restoration action per se. However, modelers have taken the first steps and provided useful insight. For example, Dixon and colleagues (2016) modeled hydrological effects of separate restoration actions in the United Kingdom and found that riparian forest restoration at the subcatchment scale was the most promising restoration scenario in reducing flood peaks.

A third challenge is to find a balance between useful and harmful floods. Although very large floods can be destructive to ecosystems and infrastructure, too little flooding also has unwanted side effects. For example, exotic-species invasion may follow the reduction of peak flows (Catford et al. 2011, Scott et al. 2016). Again, scale and scope are important. Although increasing hydraulic complexity throughout a catchment can lead to flood attenuation and sustainable flows in the entire stream or river, similar actions along an individual reach may magnify local flooding to an extent that people in the area may consider harmful.

A fourth challenge, finally, is to adapt the new knowledge to the wide spectrum of new conditions predicted to hit the Nordic countries following climate change. In this context, the Nordic countries may serve as models for many other countries while also benefiting greatly from lessons learned in other parts of the world. In ecological restoration, however, there are no one-size-fits-all solutions. In arid and semiarid parts of the world, for example, water retention and detention and evaporative loss work in direct conflict with water delivery for municipalities, agriculture, and even environmental flow prescriptions, and ecological restoration measures will require other designs.

In summary, by outlining these four challenges, we have provided a framework for critically examining how ecological restoration can serve freshwater flood attenuation. Promoting the skills to piece these challenges together will be crucial for planners and managers seeking to design future stream- and river-restoration measures in the ecologically, economically, and socially most efficient ways.

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