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Natural flood protection: streamlining the planning of flood detention in natural landscapes for the reduction of urban flooding

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ABSTRACT

A number of cost-effective and environmentally friendly flood reduction measures can provide detention of runoff from natural landscapes upstream of urban areas, with multiple added benefits. This study presents a methodology for assessing the needs for and feasibility of natural flood detention facilities. The candidate catchments for natural flood detention facilities were identified by GIS analysis and further assessed using data from maps and field inspections. Results for two case catchments show that a suitable topography and nature and biodiversity are key feasibility criteria for natural flood detention facilities. The study concluded that it is possible to streamline the process of selecting the location and type of natural flood detention facilities. Map analyses, field inspections and interdisciplinary collaboration are all important when planning natural flood detention facilities. As a result of the study, the City of Oslo will construct several natural flood detention facilities upstream of the city to gain practical experience with such facilities. While it is not expected that natural flood detention will solve all flooding problems in urban areas, it is expected that natural flood detention can positively contribute to future resilient stormwater management and the implementation of the EU Strategy on Adaptation to Climate Change.

Key words: flood management, integrated stormwater management, interdisciplinary collaboration, natural flood detention facilities, natural landscapes

HIGHLIGHTS

- By including small-scale natural flood detention facilities (NFDFs) in an integrated stormwater management system, the total investment in flood prevention measures can be reduced.
- It is possible to streamline the process of selecting the location and design of NFDFs.

ACRONYMS AND ABBREVIATIONS

CPH	Extreme rainfall in Copenhagen 2.7.2011
CSS	Combined sewer system
F	Field inspections
M	Map data
NFDF	Natural Flood Detention Facility
NL	Natural landscapes
RAF	Runoff Attenuation Feature
S3SS	Stormwater three-step strategy
UA	Urban area

INTRODUCTION

The increasing need for investment in stormwater management

Even under today's climate, urban areas face a number of stormwater-related challenges. Overflows from combined sewer systems, as well as surface and basement flooding during storms, can damage the built and natural environment which in turn creates costs to society (Finance Norway 2020; European Commission 2021). Climate change is expected to further increase stormwater damage in urban areas (IPCC 2021). Harmful floods continue to be experienced in many places around the world (Floodlist 2021). Risk analyses of urban floods show that extensive damage can also occur in urban areas that have not experienced extreme rainfall previously (Kvitsjøen *et al.* 2021a). Comprehensive measures are needed to lower the risk of urban flooding, which in turn will require significant investments.

Integrated stormwater management

A more holistic approach to flood management is emerging (Dadson *et al.* 2017). There is a positive trend towards the implementation of Catchment Based Flood Management with a focus on modifying land management from a catchment perspective to reduce flood risk. The European Union (EU) Strategy on Adaptation to Climate Change encourages the implementation of multipurpose nature-based solutions on a larger scale to increase climate resilience (European Commission 2021). Natural Flood Management is a part of Catchment Based Flood Management that aims to reduce flood damages and potentially provides significant co-benefits, such as enhanced ecosystem services (Dadson *et al.* 2017). An increased use of Natural Flood Management in urban areas can also contribute to the more efficient rehabilitation of combined sewer systems, as shown in a recent Norwegian study (Kvitsjøen *et al.* 2021b). Management actions to increase natural water storage by natural flood management range from small-scale detention features to large-scale flood detention reservoirs (Dadson *et al.* 2017). Small stores may fill quickly during rainfall and have no further effect in a major storm, while larger storage facilities can maximise the benefits of detention in major storms.

Small-scale natural flood detention facilities

There are claims that almost all landscapes inhabited by humans need to be revitalised because deforestation, agriculture and urban development have reduced vegetative interception and infiltration of rainfall and slowing of runoff through vegetated landscapes (Kravčík *et al.* 2012). Human activity has exacerbated floods, droughts, and the destruction of ecosystems. Kravčík *et al.* (2012) believe that this can be counteracted by building large numbers of small-scale detention facilities in the landscape (see Figure 1).

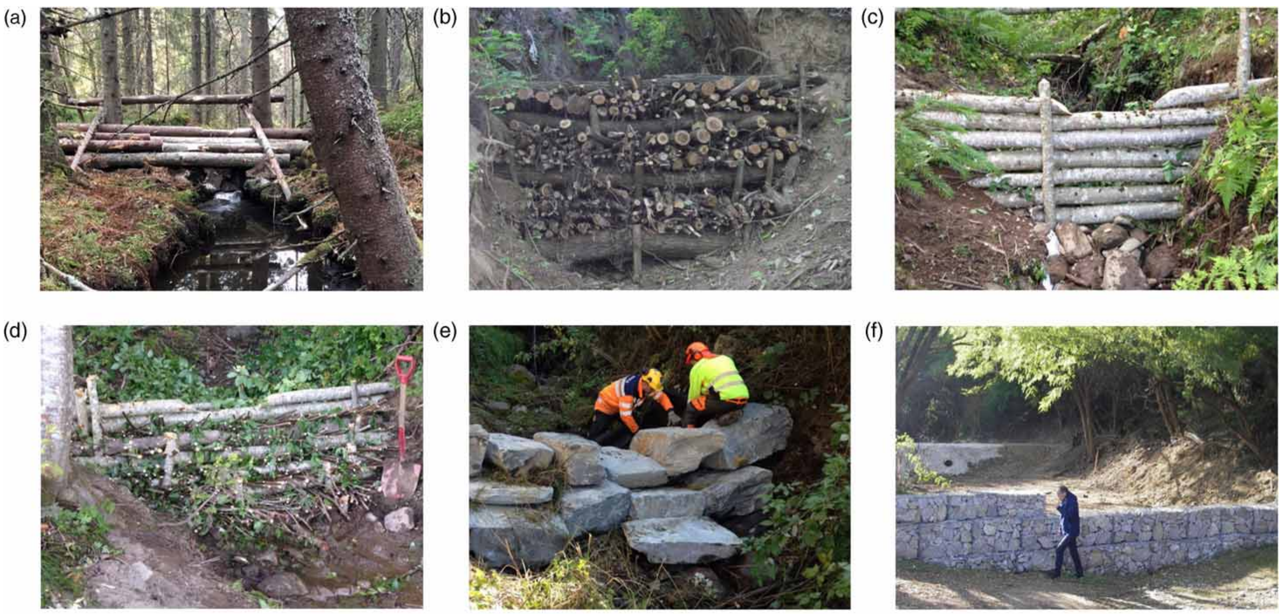

Figure 1 | Examples of online Natural Flood Detention Facilities including (a) leaky woody dam, (b) brushwood dam, (c) log dam, (d) log and branch dam (d), (e) stone check dam, (f) gabion dam. Dams a, c, d and e are made in Norway, b and f in Slovakia. Photo (e): S. Myrabø.

In the UK, small-scale detention systems in the landscape are termed Runoff Attenuation Features (RAF), and defined as a 'man-made landscape intervention that intercepts and attenuates a hydrological flow pathway to provide multiple benefits, including flood management and improving water quality' (Quinn *et al.* 2013). An RAF is a small scale, low-cost, soft-engineered flood reduction measure for small rural catchments. Different materials can be used in construction, such as treated wood, soil, stone and brushwood. RAFs have been tested in several areas in the UK. The trials explored how natural techniques can help manage floods by storing more water in the landscape and reducing its rate of flow downstream (Nisbet *et al.* 2015). Even though the measures do not prevent all flooding, they are expected to reduce the downstream impact of heavy rainfall and to deliver a range of other benefits to the local environment and the community.

In the Belford catchment in North-eastern England, conventional flood defences were unsuitable because of the high cost, a lack of space for flood walls and banks, and the low number of properties at risk (Wilkinson *et al.* 2010). Instead, a network of 30 RAFs was constructed (Quinn *et al.* 2013). Different types of RAFs were installed including overland flow interception, online ditch barriers, large wood debris dams and offline ponds. Study results indicated that online features should be used where the upstream catchment is smaller than 2 km^2. Modelling of the performance of a network of RAFs showed a positive impact on flood hazard in small catchments, with a 15%–30% reduction in the peak flow. RAFs were shown to be more effective under short-duration, flash-flood events. The critical consideration was that flood mitigation was provided by a collective network of RAFs. As soon as the structures were full, they became ineffective if a new rain event occurred before the features had drained (Dadson *et al.* 2017). A lack of observational data meant, however, it was impossible to verify modelling results (Quinn *et al.* 2013). The study concluded that there is no standard approach for siting or constructing RAFs, and rather their location and design depend on local factors including terrain and landowner preferences.

The town of Pickering in northern England also experienced several significant floods in recent years. The largest flood, in 2007, cost the city approximately 70 million GBP (Cronin 2016). Several types of natural flood mitigation measures were implemented to protect the town. One of these was the construction of 129 large leaky-timber debris dams high in the catchment to slow the flow in the Pickering Beck. The dams have different sizes, with water-holding capacities varying between 0.1 and 110 m^3, depending on dam design. It takes three persons one day to build such a dam. During a significant storm in 2015, the positive impact of these measures was observed with an associated reduction in flood damage downstream in Pickering (Environment Agency 2016). However, the need to collect more data to assess the performance of the measures was identified, especially regarding their impact during extreme rainfall (Dadson *et al.* 2017).

Brushwood dams were also developed in Slovakia to protect the Torysa river (Kravčík *et al.* 2012). The protection efforts were based on creating a network of small dams that would achieve the same effect as one large dam. The purpose of the dams was to delay runoff to reduce flood peaks and to increase recharge to the groundwater. Slovakia has adopted a Landscape Revitalization and Integrated River Basin Management Program, which aims to revitalise forest and rural landscapes by retaining as much rainwater as possible where it falls locally. About 80,000 detention structures have been constructed to retain 10 billion m^3 of runoff. These measures provide protection against floods, reduce soil erosion, help to mitigate climate change and preserve biological diversity.

In Norway, the concept of detention systems in natural landscapes was tested by the railway company BaneNOR (Braskerud *et al.* 2014). The detention measures were particularly relevant upstream of gutters and culverts under the railway tracks to reduce erosion and clogging. BaneNOR constructed brushwood dams, log dams and gabion dams (see Figure 1). Equipment for monitoring temperature and water flow in the structures was installed, but only operated for one year from 2013 to 2014, without any significant rainfall being recorded.

International studies report the beneficial impacts of small-scale Natural Flood Detention Facilities (NFDFs) in natural landscapes. While the experience of UK researchers was that there is no standard approach for the siting and design of NFDFs (Quinn *et al.* 2013), the present study seeks to identify a set of criteria that can streamline the planning process. The study aims to assess the needs for and feasibility of implementing NFDF in natural landscapes to reduce flooding in downstream urban areas.

METHODS

Study methodology

The methodology used in this study is based on an integrated stormwater management system that developed under the City of Oslo's project 'Thematic map for Stormwater and Urban Flooding' (Figure 2) (Solheim *et al.* 2021). The methodology for

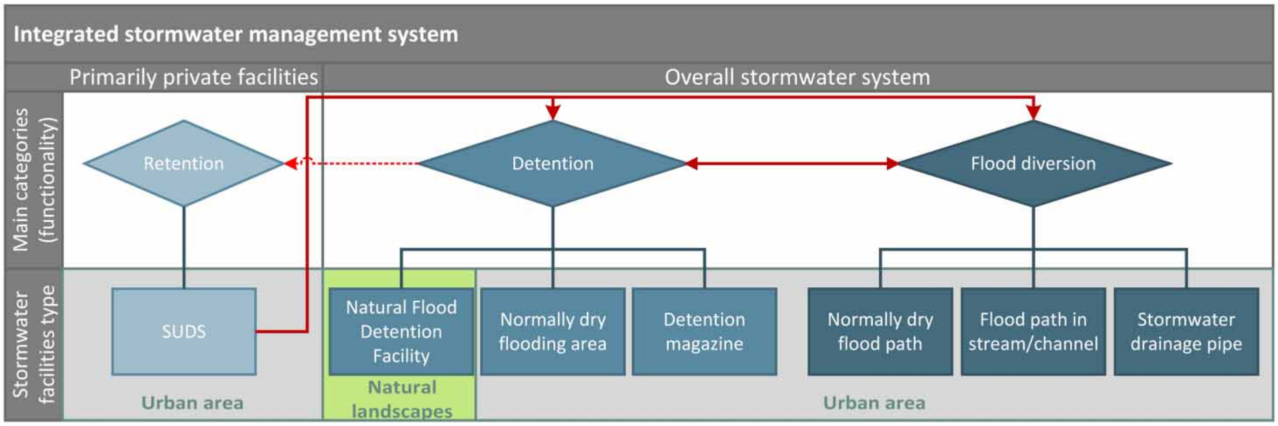

Figure 2 | Design of an integrated stormwater management system in Oslo, based on the S3SS (1 retention, 2 detention and 3 flood diversion).

such a comprehensive view on stormwater management is based on the stormwater three-step strategy (S3SS) developed in 2013 (City of Oslo 2013) and the results from a previous study in Oslo that highlighted the importance of an integrated stormwater system for increasing the rate of pipeline network renewal (Kvitsjøen *et al.* 2021b).

The integrated stormwater management system consists of three main functional categories: retention, detention and flood diversion. Different types of stormwater facilities are grouped according to functionality. Five types will be implemented in urban areas in Oslo, including normally dry flooding areas, detention magazines, normally dry flood paths, flood path in-stream/channels and stormwater drainage pipes. The possible use of NFDF in the natural landscapes upstream of the city is viewed as a stormwater facility type for reducing flooding in urban environments by detention of the short-term precipitation events. An overview of the decision tree which was tested in the study is presented in Figure 3.

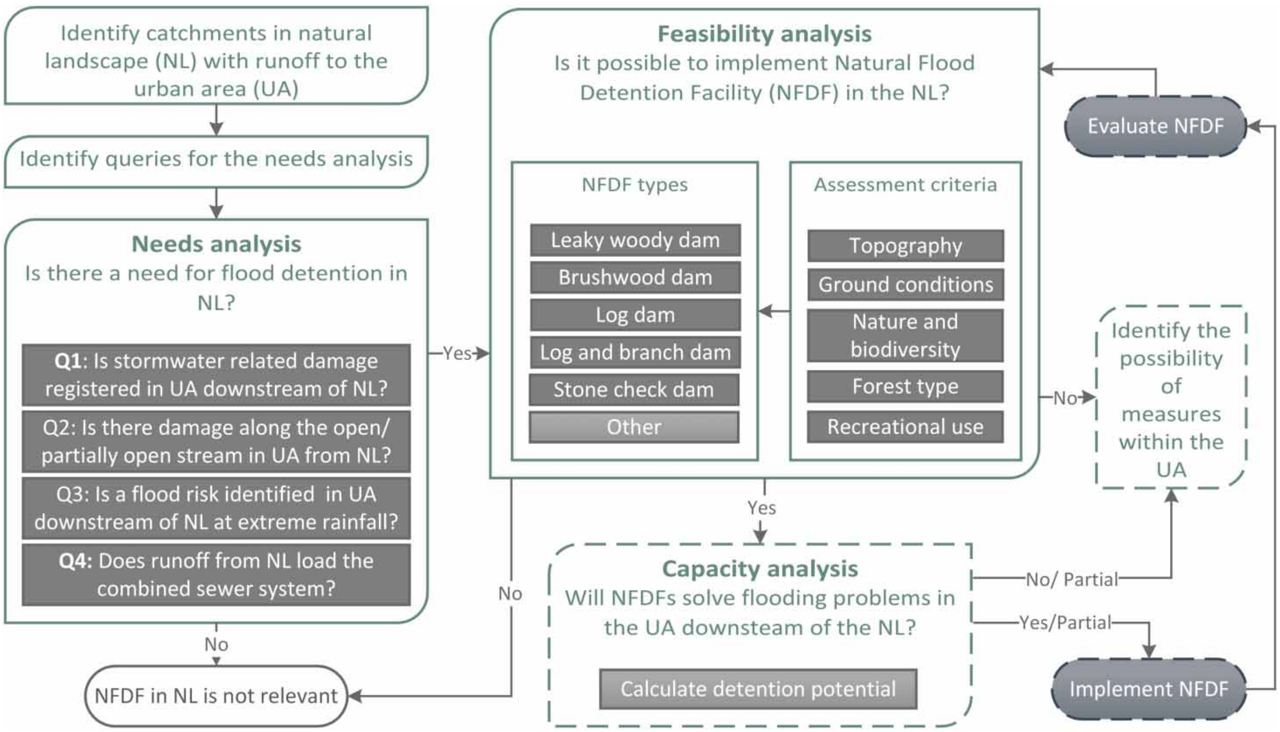

Figure 3 | Decision tree for identifying the need for and feasibility of implementing NFDFs in natural landscapes (NL) upstream of an urban area (UA). Boxes with dotted lines are not undertaken in this paper.

Initially, all catchments with natural landscapes which drain through the city were identified using ArcMap (ArcMap 2021). The responses to Q1–Q4 queries were determined using available registered and calculated stormwater-related damage data (Finance Norway 2020; Kvitsjøen *et al.* 2021a).

A needs analysis was carried out in ArcMap by analysis of response to Q1–Q4. A positive answer to at least one of these four queries may be sufficient to initiate further investigation of the catchment. If there were positive responses to more than one query, the catchment was assigned a higher priority. The catchments with identified needs were then subjected to a feasibility analysis. If no actions were required, NFDF was not considered to be relevant.

Based on a review of the literature, professional experience and field inspection, the feasibility assessment was based on five assessment criteria for local conditions: (i) topography, (ii) ground conditions, (iii) nature and biodiversity, (iv) presence of forest and type and (v) recreational use (Braskerud *et al.* 2014; Borch & Erikstad 2015; Lancaster *et al.* 2021). These five criteria were tested for a variety of small scale online NFDFs, including leaky woody dams, brushwood dams, log dams, log and branch dams and stone check dams (see Figure 1). The various NFDFs assessed in this study cover a wide range of possible small-scale measures in natural landscapes, but the list is not exhaustive and can be further developed.

If the local conditions are not suitable for the establishment of NFDFs then it is necessary to identify other potential flood reduction measures within the urban area. However, if the local conditions are suitable for implementation of NFDF, the next step in the analysis is to investigate the degree to which NFDF can reduce flooding problems in the downstream urban area. If the NFDFs completely or partially solve downstream flooding problems, the use of NFDF is warranted. If flooding problems are only reduced marginally then it is necessary to consider other flood prevention measures within the urban area.

The study did not include a capacity analysis and the subsequent steps described in Figure 3 were not undertaken. The steps which were not undertaken are shown within dotted lines.

Study area

The study area was the areas of natural landscape (NL) upstream of the Norwegian capital Oslo. The study covered an area of 307 km^2. A thin sediment cover over the bedrock dominates the terrain in the study area, and the variation of the elevations is from 100 to 500 masl.

The study area is mainly covered by cultivated forest, which appears as a natural forest. It is an important recreational area for residents of the city, and is used for both hiking and fishing.

There are several dams upstream of the city that control the flow of water in the biggest rivers running through the city to the Oslo fjord. The dams are designed to withstand a 1,000-year flood, and the assessment of river flood protection measures was excluded from this study.

Approximately 55% of Oslo's entire 2,250 km wastewater network is a combined sewer system (CSS). Nearly 67% of the original 353 km of open streams and rivers through the urban area have been piped or buried. Some of these watercourses are now part of the drainage and sewer system, but others have been entirely buried. In addition to the nine main watercourses that flow through the city, several smaller streams have their source in the study area. Runoff conveyed by these streams can potentially have an impact on flooding in the city and can overload the combined sewer system. A study of urban flood risk in Oslo (Kvitsjøen *et al.* 2021a) concluded that there is an exceptionally high risk of damage along both piped streams and smaller open smaller streams in the city.

A needs analysis for NFDF was completed for the entire study area. Based on the results of the needs analysis, a feasibility analysis was carried out for two case catchments that contribute runoff to urban areas, namely the Risbekken and Prinsdal catchments (see Figure 4). The Risbekken catchment, with an area of 0.57 km^2, is located on the northern edge of the city. The Prinsdal catchment (0.45 km^2) is located on the southern edge of the city.

Identification of catchments

In this study, a catchment was defined as a small area in a primarily natural landscape which generates runoff that flows into the city. Some of these flowpaths are active streams with year-round runoff, while others only during rainfall and snowmelt.

The identification of relevant catchments was carried out using the Hydrology toolbox and Geometric network function in ArcMap (ArcMap 2021). As a starting point, preliminary flowpaths were calculated using a digital elevation model (DEM) with a resolution of 0.5 m$\times$0.5 m. Cross-sections of the flowpaths were calculated. If a drainage line crossed the city boundary border multiple times then only those crossings associated with the highest flows were selected. Finally, the catchments for all selected flowpaths were identified.

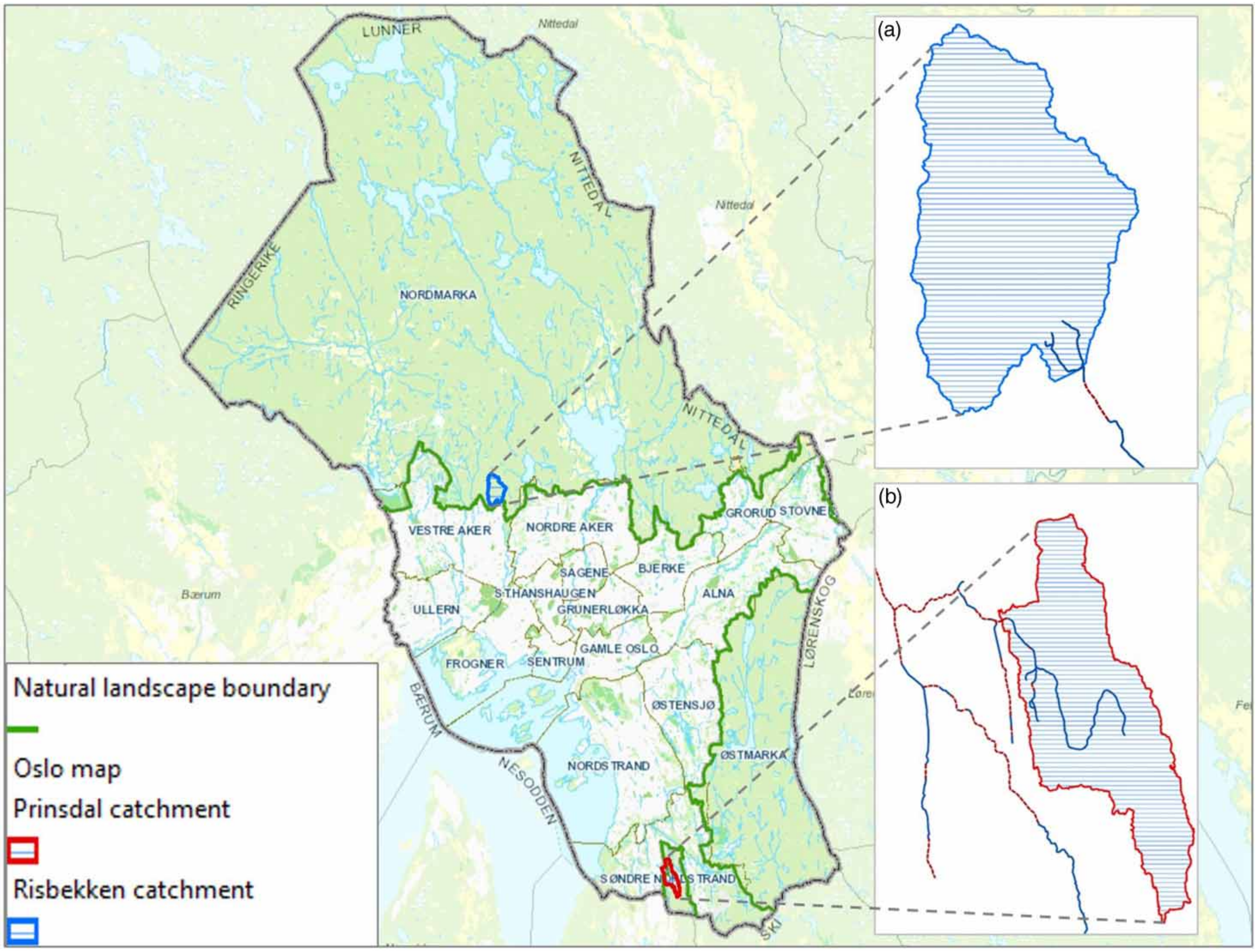

Figure 4 | The study area, Risbekken catchment (a) and Prinsdal catchment (b).

Queries for the needs analysis

The scope of this study was limited to investigating whether runoff from natural landscapes potentially cause damage to building infrastructure within the urban area and/or overloads the combined sewer system. Based on available registered and calculated stormwater-related damage data (Finance Norway 2020; Kvitsjøen *et al.* 2021a), the following four queries were identified:

- Q1 - Is stormwater related damage registered in the urban area (UA) downstream of natural landscapes (NL)?
- Q2 - Is there damage along an open/partially open stream in the urban area conveying runoff from natural landscapes?
- Q3 - Is a flood risk identified in the urban area downstream of natural landscapes under extreme rainfall?
- Q4 - Does runoff from upstream natural landscapes overload the combined sewer system?

Needs analysis

A needs analysis was performed by the Spatial Join functionality in ArcMap (ArcMap 2021) by assessing the responses to queries Q1–Q4 (see Table 1).

The Q1 sub-analysis investigated catchment runoff that may have caused registered damage to buildings 100 m downstream of the NL boundary. Catchments that may have caused registered damage to buildings located 50 m from open/ partially open streams and 1 km downstream of the NL boundary in the urban area were identified by the Q2 sub-analysis. The results from a previous study of the flood risk to buildings in Oslo (Kvitsjøen *et al.* 2021a) were used to identify catchments in the study area that could lead to damage during extreme rainfall comparable to the one experienced in Copenhagen (155 mm in 2

Table 1 | Thresholds and background data used in four sub-analyses of the needs for NFDFs in the natural landscape (NL)

Query adapted to the damage type	GIS data layer	Thresholds in the analysis
General for Q1–Q4	Historical streams, hydrological flowpaths from the NL, catchment boundary in the NL	
Q1: Registered building damage	Registered insurance claims	100 m downstream of the NL boundary
Q2: Building damage along streams	Registered insurance claims	50 m from streams and 1 km downstream of the NL boundary
Q3: Calculated building damage at CPH[a]	Calculated damage risk	100 m downstream of the NL boundary 50 m from streams and 1 km downstream of the NL boundary
Q4: Runoff to CSS	Combined sewer (CS) manholes	100 m downstream of the NL boundary 50 m from stream routes and 1 km downstream from the NL boundary

Q1–Q4 queries are adapted to the damage type.
[a]CPH the 'Copenhagen rain incident', see text.

hours) on 2 July 2011 (Lindholm *et al.* 2013) (CPH) (Q3). The Q4 sub-analysis investigated whether runoff from the study area affects the inflow to the combined sewer system through street gullies, based on an assessment of the connection of flow pathways from the study area to CSS manholes. The thresholds adopted for the Q3 and Q4 sub-analyses were combinations of the Q1 and Q2 thresholds.

Feasibility analysis

In the feasibility analysis, a set of assessment criteria was considered for the five NFDFs: leaky woody dam (Quinn *et al.* 2013; Yorkshire Dales Rivers Trust 2018), brushwood dam, log dam, log and branch dam and stone check dam (Braskerud *et al.* 2014) (see Figure 1).

Five assessment criteria for local conditions were adopted, including: (i) topography, (ii) ground conditions, (iii) nature and biodiversity, (iv) presence of forest and type and (v) recreational use. Furthermore, each of the assessment criteria were classified based on their suitability as either well-suited (++), moderately suitable (+) and unsuitable (0) for each of the NFDF options.

The feasibility study started with an examination of the map data for a selection of catchments. ArcMap was used to determine the size of catchments and terrain design (ArcMap 2021). Information about protected areas, forest type and land use was obtained from the map database of the Norwegian Institute of Bioeconomy Research. An overview map from the Oslo Freshwater Fisheries Management was studied to identify watercourses that contain fish. Red-listed species were identified using data provided by the Norwegian Biodiversity Information Centre. Field inspections of a selection of catchments were performed to verify the map data and to collect additional information.

Due to significant local variations for different catchments, there have been no thresholds for water volumes for the NFDF options presented. The purpose of this study is to generalize parameters for an overall analysis. Several parameters such as slope, cross-section, local immersions, NFDF number and size, infiltration, evaporation, and time of concentration will affect the total volume that NFDFs can detain. It is beyond the scope of this paper to describe the whole water balance.

RESULTS AND DISCUSSION

Need for runoff detention in the natural landscape

The needs analysis resulted in the selection of catchments that contribute to one or more stormwater-related problems in the city, either caused or intensified by runoff from the natural landscapes (NL) (see Figure 5).

The runoff from 21.4 km^2 of natural landscapes contributes to registered building damage at the outer edge of the urban area (Q1). Results also indicate that runoff from 40.2 km^2 of natural landscapes contributes to the damage registered along streams in the city (Q2), while runoff from 40.7 km^2 of natural landscapes contributes to combined sewer loads

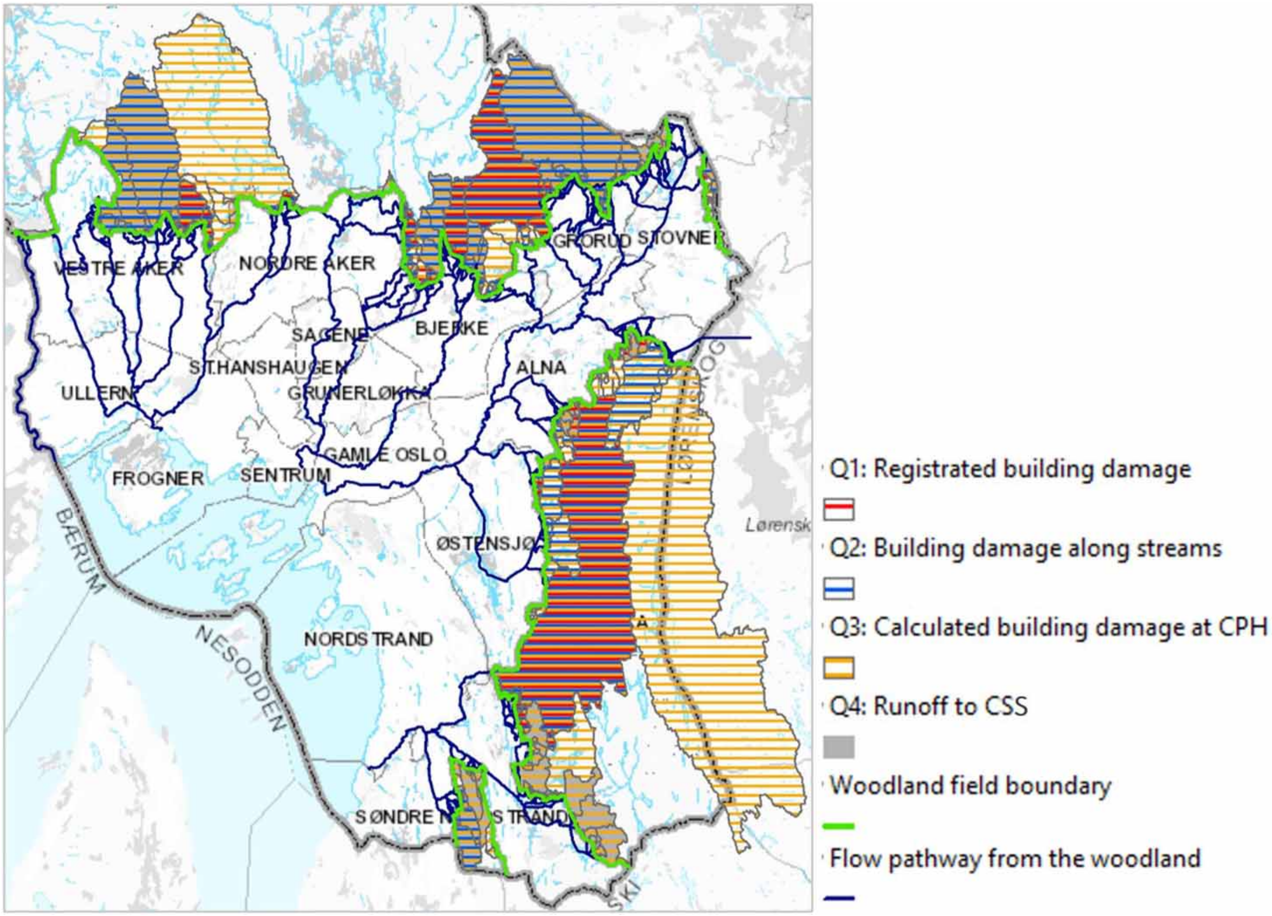

Figure 5 | Candidate catchments for NFDFs, based on the analysis of stormwater-related damage in urban areas downstream of natural landscapes. Multi-coloured catchments have more than one damage type.

(Q3). The Q4 sub-analysis disclosed that runoff from an area of 85.8 km^2 of natural landscapes can lead to urban flooding during extreme rainfall. This constitutes 28% of the total area of natural landscapes upstream of the city boundary.

The size of the catchments identified in this analysis varied from 200 m^2 up to 25 km^2. The UK study shows that online NFDFs are most effective in small catchments up to 2 km^2 in area, whereas offline NFDF can be effective in catchments up to 10 km^2 (Quinn *et al.* 2013). The catchments which are candidates for NFDF were able to be further subdivided into smaller catchments based on the dense network drainage lines within the catchments (see Figures 6(b) and 7(b)).

The needs analysis identified an opportunity to solve some of the flooding problems experienced in the city at a reasonable cost using local, natural stormwater management solutions (Kravčík *et al.* 2012; Quinn *et al.* 2013; Braskerud *et al.* 2014; Nisbet *et al.* 2015). Oslo's stormwater three-step strategy (S3SS) states that surface water must be handled at its origin (City of Oslo 2013). Although this strategy was primarily developed for urban areas, water flow from the upstream natural landscape to the city can be reduced by application of the S3SS outside the city boundary as well.

The needs analysis results also found that upstream runoff does not affect all urban areas adjacent to the natural landscapes. In urban areas where the primary source of flooding is local runoff other solutions such as Low Impact Development and Green Infrastructure can be applied (Kvitsjøen *et al.* 2021b).

Assessment scheme for feasibility analysis

Although the primary function of NFDF is to delay runoff, it is important to consider the potential co-benefits as well. The assessment scheme was based on a literature study, professional experiences in the city of Oslo and field inspections (see Table 2). The suitability of each of the five NFDFs under different local conditions were assessed and assigned a suitability rating. A detailed review of the NFDFs assessed in the study can be found in the MSc thesis (Borge 2021).

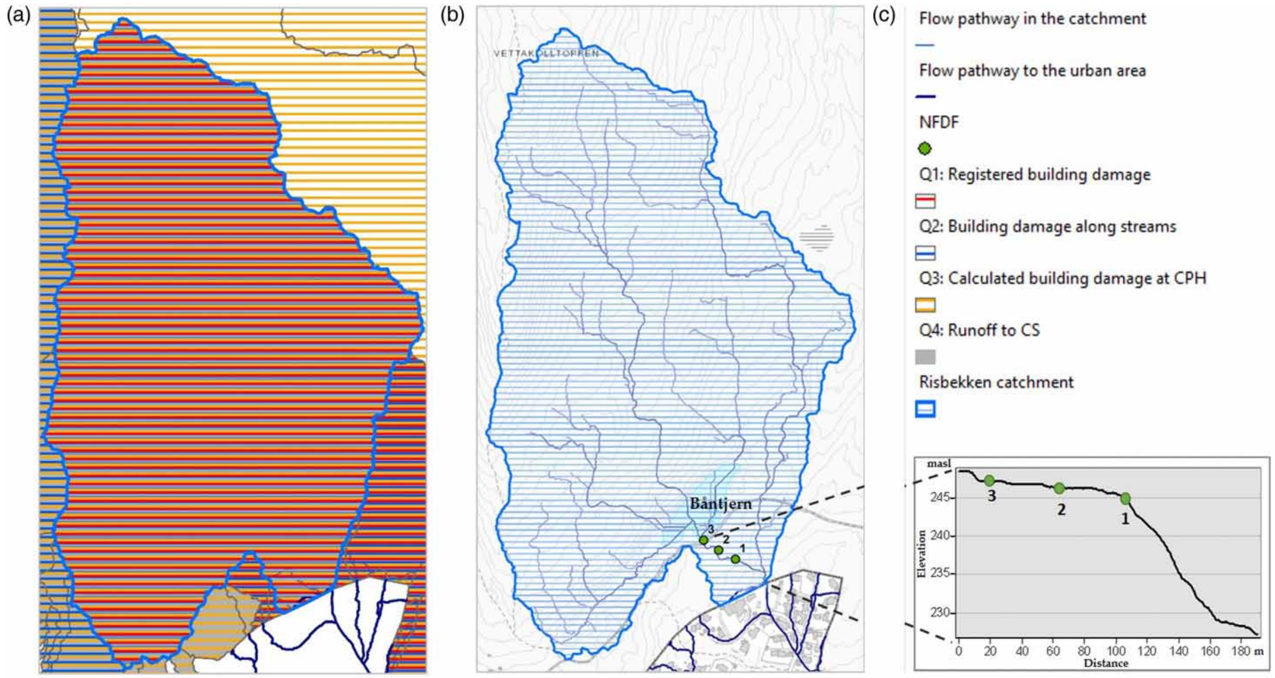

Figure 6 | (a) Identified need for measures, (b) flow pathways with the proposed spatial location of NFDFs and (c) a longitudinal bed profile with the location of NFDFs in Risbekken West with catchment area of 0.57 km^2.

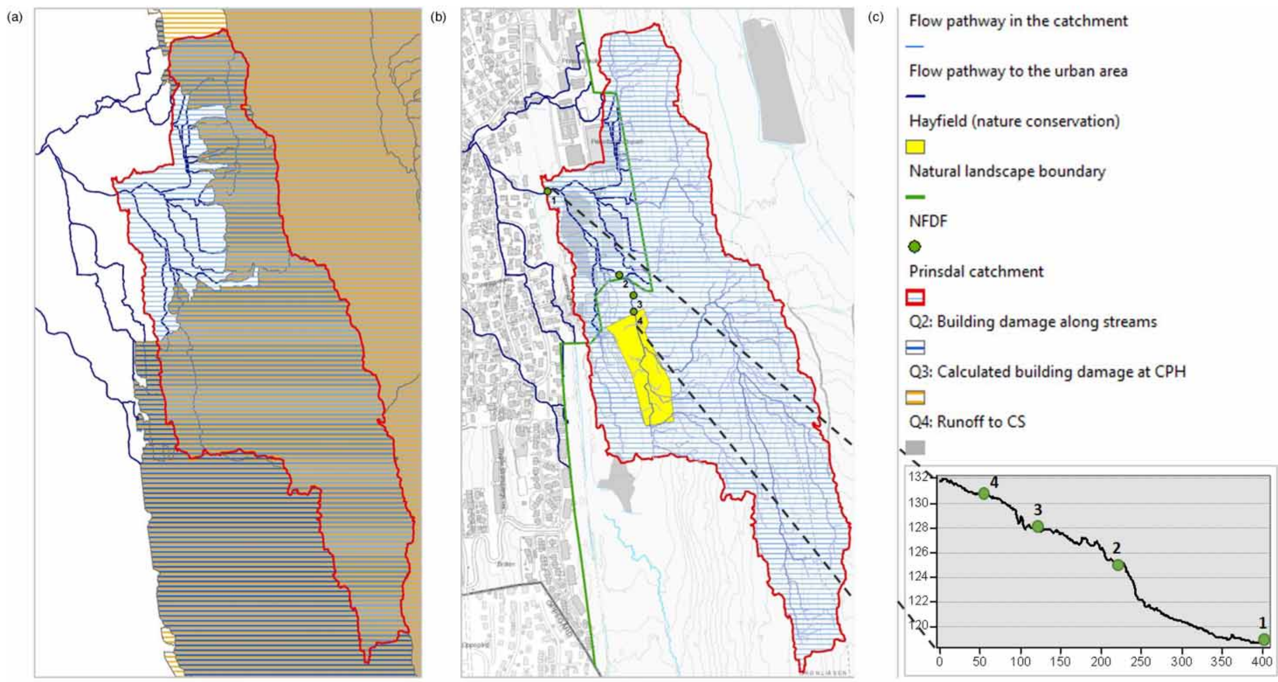

Figure 7 | (a) Identified need for measures, (b) flow pathways with the proposed spatial location of NFDFs and (c) a longitudinal bed profile with the location of NFDF in Prinsdal with catchment area of 0.45 km^2.

Topography

As the purpose of NFDFs in this study is to manage runoff from short-term rainfall events, the significance of evapotranspiration and infiltration is thus minor, but the topography plays a crucial role in determining available surface storage volumes. On gentle slopes, it is possible to store larger volumes of water for a given dam height.

Table 2 | The assessment scheme for the feasibility analysis shows the assessed suitability of the five NFDF types under different local conditions

Assessment criteria	Assessment index	Leaky woody dam	Brushwood dam	Log dam	Log and branch dam	Stone check dam
Topography	Gentle slope	++	++	++	++	++
	Varying	++	+	++	+	+
	Steep	0	0	0	0	0
Ground conditions	Rock	++	+	++	+	++
	Wetlands	++	+	++	+	++
	Sediments	+	++	+	++	+
Nature and biodiversity	Nature conservation	0	0	0	0	0
	Agriculture	+	+	+	+	+
	Fish	++	0	0	0	+
	Amphibians	+	++	++	++	+
Forest type	Conifers	++	++	++	++	++
	Broadleaved forest	++	+	+	+	+
Recreational use	Hiking trail	++	0	++	0	++
	Forest road	++	0	+	0	++

The assessment criteria are: well-suited (++), moderately suitable (+) or unsuitable (0).

Several of the NFDF types can be constructed in varying terrains. In particular, brushwood dams can be installed in a cascade to reduce water flow. Log and branch dams can withstand greater water flows than brushwood dams, depending on how many branches are used and how well the branches are anchored. When constructing stone check dams in varying terrains, large stones should be used to avoid erosion and collapse. Gabion dams are an alternative to large stones, since the wire mesh allows stable structures to be constructed using smaller stones. Furthermore, it is easier to transport small stones than big stones in terrains where machinery cannot be used. As the point of NFDF is to detain as much water as possible, building an NFDF in steep terrain is ineffective.

The results from the field inspection of possible locations for different NFDFs conducted in this study corresponded well with experiences reported in the UK (Quinn *et al.* 2013) and Slovakia (Braskerud *et al.* 2014). Topography is a key consideration when assessing the feasibility of NFDFs. A range for slope is intentionally not presented in this study. The terrain assessment must be made in each case based on the local terrain variations, number of possible NFDFs and the objective of NFDF. This is done under field inspections where the access to natural building materiel is an important part of the decision.

Ground conditions

Prevailing ground conditions have a significant effect on the stability of NFDFs. Due to ground conditions in the study area and the purpose of NFDFs, the soil structure will be less influenced by the infiltration. To avoid the features being undermined and eroded at their outer edges it is necessary to ensure that the outer toe of the dam and its sides must be secured to reduce erosion and prevent collapse. Erosion most often occurs in areas with sedimentary soils. NFDFs, for example brushwood dams, can help to capture sediment and reduce erosion (Braskerud *et al.* 2014; Lancaster *et al.* 2021). Wetland areas are well suited to retaining water. As such areas typically are already inundated, wetlands are able to withstand extra water stress better than normally-dry areas. NFDF can also have a positive impact on wetlands that previously were drained in order to plant forests. It is beyond the scope of this paper to describe construction details and design values.

It is important to consider what other benefits can be achieved by installing NFDF besides flood reduction. Brushwood dams and log and branch dams are moderately suitable for areas with rocky ground. In Norway, there is often year-round water flow in such areas, even in catchments less than 1 km^2. In such locations, it is not advisable to build facilities at the base of the stream that can affect the normal water flow and the natural water balance. However, if it is beneficial that the area becomes more humid then such interventions could have a positive effect. The type of NFDF required to impact on humidity need to have a significant retention capacity. Brushwood dams are not the most robust option when it comes to retaining large volumes of water. Therefore, brushwood dams and log and branch dams are classified as only moderately suitable. On the other hand, these two NFDFs are well suited to areas in which one aims to capture sediments. In areas with sedimentary soils, the three other NFDF types are only moderately suitable as they usually do not affect the normal water flow in the stream. Brushwood dams are also suitable on sites where the ground consists of finer sediments, and thus help to reduce erosion of the stream bed. As the brushwood dam or the log and branch dam fill with sediment the terrain is stabilised. This is particularly beneficial in areas with a risk of landslides or quick clay landslides.

Nature and biodiversity

The first consideration is if the entire catchment or part of the catchment is a protected area. In nature conservation areas, it is not usually permissible to intervene in nature in any way (Ministry of Climate and Environment 2009).

When NFDFs are being considered in agricultural areas the landowners need to be involved in the planning process (Environment Agency and Newcastle University 2011). Therefore, all NFDF types are marked as moderately suitable under this index.

NFDFs must not interfere with natural conditions, and it is therefore beneficial to involve a biologist in the planning assessment (Lancaster *et al.* 2021). In sites where there are fish in a stream with year-round water flow, it is important that NFDFs do not obstruct fish migration. In such catchments, a leaky woody dam is best suited, as it is built above the normal water flow level in the stream. It is also possible to build log dams and stone check dams with lowered centre sections.

Some types of NFDF can contribute to both mitigating floods and increasing biological diversity (Borch & Erikstad 2015). NFDFs can cause areas to become moister for more extended periods. This can have a positive impact on amphibians and other species living in and around wetlands. The structures that are particularly suitable for increasing the moisture in an area are brushwood dams, log dams, and log and branch dams. It is also important to consider potential adverse impacts on a forest of prolonged flooding.

Forest type

There are several aspects to consider in relation to forest type. Generally, broadleaved forests can absorb and delay runoff better then coniferous forests (Calder *et al.* 2009). On the other hand, the structures are likely to clog faster in a broadleaved forest as a result of leaf fall. A leaky woody dam is best suited to a broadleaf forest setting, as it allows the normal water flow in a stream to pass unhindered which limits the potential to trap leaves and branches under normal flow conditions. In streams that flow to culverts, installing NFDFs can trap debris that otherwise would clog the culverts. This problem is not as significant in areas consisting mainly of conifer. All types of NFDF are well-suited to areas of coniferous forest.

Recreational use

The Norwegian Water Resources Act states that all measures must avoid harm or inconvenience to public or private interests (Ministry of Petroleum and Energy 2010). While NFDFs can reduce peak flows, outflows from NFDFs can erode transport and recreation routes and water can accumulate along these routes for extended periods. Therefore, it is essential to consider paths and roads in the area when planning NFDFs, so that the measures do not disrupt recreational activities. NFDFs built in flowing water are marked as moderately suitable, as these will retain water even during minor rainfall events. Along hiking trails, several of the NFDFs can be designed as bridges for hikers. Brushwood dams and log and branch dams are not suitable for walking on, as they primarily consist of smaller branches and narrow logs. If the structures are to be used as bridges, it is vital to ensure the safety of the hikers by installing suitably sized logs or other measures to allow hikers to safely cross the structure.

Maintenance

Without maintenance, the effectiveness of the measures will gradually be reduced over time (Lancaster *et al.* 2021). It is important to inspect the NFDFs after extreme rain and prolonged precipitation events, as some structures can become clogged or even collapse. The wood used in the structures should also be checked for signs of decay. Experience from Slovakia shows that vegetation invades the captured sediments and thus protects against further erosion (Braskerud *et al.* 2014). Maintenance of NFD were excluded as separate criteria in the assessment scheme because it is not essential for the choice of the suitable NFDF type.

Feasibility analysis for case catchments

The assessment of different local conditions suggests that NFDFs are unsuited to steep terrains and nature conservation areas. Thus, catchments that are unsuitable for NFDFs can be screened by inserting these two indexes in the GIS data layers prior to the needs analysis. This will reduce the number of catchments to be assessed in the feasibility analysis phase.

Based on the results of the needs analysis, several catchments were considered when selecting the two case catchments for the feasibility analysis. Catchments that contributed to several damage categories in downstream urban areas were prioritized. The needs analysis prioritised the Risbekken catchment due to four positive outputs to the queries in the assessment (Q1–Q4) (see Figure 6(a)). While no building damage (Q1) was registered due to runoff from the Prinsdal catchment, there were positive outputs to the other three queries (Q2–Q4) in the needs analysis (see Figure 7(a)). Thus, it was also relevant to analyse the feasibility of installing NFDFs in the Prinsdal catchment.

The collected data for two case catchments, which was based on map study and field inspections, is presented in Table 3. A detailed review of the collected data can be found in the MSc thesis (Borge 2021).

The analysis of the terrain from the map agreed with the field observations for the western part of the Risbekken catchment. Consequently the NFDF recommendations based on the map analysis matched the recommendations based on field inspections (see Figure 6(c)). For the eastern part of the Risbekken catchment, more locations for NFDFs were identified through field observation than through the desktop study. If a map analysis only had been used as the basis for selection of NFDFs for the eastern part of Risbekken catchment then feasible locations for NFDFs would have been overlooked.

In the Prinsdal catchment the map analysis and field observations provided similar terrain information (see Figure 7(c)).

In the Risbekken catchment, the map analysis of ground conditions largely corresponded to the field conditions that were observed. In the case of the Prinsdal catchment, the field observations provided more detailed information on the composition of sediments. Field inspections can also locate smaller culverts that may not be registered in a municipal GIS database. This was the case in the Prinsdal catchment.

The assessment of nature and biological diversity criteria can be a challenge because, for example, some fauna may not have been mapped or conversely mapped fauna could not be confirmed by field inspection. In the Prinsdal catchment, frog eggs were found during a field inspection, which indicated the presence of amphibians at the site. The area, marked as a natural conservation area on the map, was re-classified as a hayfield during field inspection (see Figure 7(b)). In the Risbekken catchment, fish migration was registered on the map, but this was difficult to confirm by field observations.

Likewise, property boundaries are clearly shown on maps, but cannot be readily seen on field inspections.

Map analysis and field observations agree well with regard to forest type, forest roads and hiking trails.

While the results of the map analyses provided information on possible locations for NFDFs, the recommendation of specific locations and the types of facilities requires local knowledge. Performing map analysis prior to field inspections contributes to more efficient observations. The study confirmed the findings of Norconsult regarding the need for field inspections when planning NFDFs (Lancaster *et al.* 2021).

Table 3 | Data registration by study of map data (M) and field inspections (F) for the Risbekken and Prinsdal catchments

	Case catchment	
Assessment criteria	**Risbekken**	**Prinsdal**
Topography	Steep/varying (M+F)	Varying (M+F)
Ground conditions	Rock with sediments (M+F)	Sediments (M)/fine-grained sediment consisting of sand, silt, and clay, with some sections of bare rock. Parts of the stream are in pipes (F)
Nature and biodiversity	Fish (M)	Agriculture, partly nature conservation (M)/hayfield, amphibians (F)
Forest type	Young coniferous forest (M)/older spruce trees with some younger broadleaved trees (F)	Young broadleaved forest (M)/some older conifers, but mainly broadleaved trees (F)
Recreational use	Hiking trail (M+F)	Hiking trail (M+F)

During a field inspection, the mapping should be verified and supplemented with local observations. It is also possible to ascertain if there is access to local construction materials and anchorage points. This is important to limit transport of materials and to enhance the environmental benefits of the measure.

The planning for NFDFs requires interdisciplinary cooperation to ensure that appropriate input is provided for all the planning considerations.

In the western part of the Risbekken catchment, it is proposed to place NFDFs between the small lake Båntjern outlet and the point at which the watercourse steepens (see Figure 6(b) and 6(c)). While several NFDFs could also be established upstream of lake Båntjern these were not considered in this study.

The feasibility analysis of NFDF options for Risbekken West was performed using the assessment scheme (see Table 2) with input of data from Table 3. The result of this analysis is summarised in Table 4.

In Risbekken West, leaky woody dams and stone check dams received the highest total score for local conditions. A leaky woody dam is well suited for this area because it best fits the landscape and does not hinder fish migration. Any stone check dams should be built with a lowered centre section. While there are not many large stones along the stream, these could be transported from a nearby location. NFDFs in Risbekken West can also be designed as combined facilities where leaky woody dams are combined with stones that do not clog the stream and permit normal water flow. The other three assessed NFDFs are not suitable for the area, mainly because they interfere with fish mobility in the stream, which was a decisive criterion for choosing NFDFs for this catchment.

Parts of the Prinsdal catchment extend downstream of the natural landscape boundary (0.09 km^2), and the proposed locations of the NFDFs are within both the natural landscape and the urban area. No facilities were proposed to be located within the nature conservation areas of this catchment (see Figure 7(b)).

The feasibility analysis of NFDF options in the Prinsdal catchment was performed using the assessment scheme (see Table 2) with input of data from Table 3. The result of this analysis is summarised in Table 5. In the Prinsdal catchment brushwood dams, log dams, and log and branch dams are the most suitable NFDFs. In addition to reducing flood risk downstream, these facilities are expected to also have other beneficial effects such as increasing biodiversity in terms of amphibian populations and preventing clogging of downstream culverts with forest debris. Stone check dams may also be an option because

Table 4 | Feasibility analysis of NFDFs for Risbekken West

Assessment criteria	Assessment index	Leaky woody dam	Brushwood dam	Log dam	Log and branch dam	Stone check dam
Topography	Varying	++	+	++	+	+
Ground conditions	Rock	++	+	++	+	++
	Sediments	+	++	+	++	+
Nature and biodiversity	Fish	++	0	0	0	++
Forest type	Conifers	++	++	++	++	++
Recreational use	Hiking trail	++	+	++	+	++

Table 5 | Feasibility analysis of NFDFs for Prinsdal

Assessment criteria	Assessment index	Leaky woody dam	Brushwood dam	Log dam	Log and branch dam	Stone check dam
Topography	Varying	++	+	++	+	+
Ground conditions	Sediments	+	++	+	++	+
Nature and biodiversity	Nature conservation	0/++	0/++	0/++	0/++	0/++
	Agriculture	+	+	+	+	+
	Amphibians	+	++	++	++	+
Forest type	Broadleaved woodland	++	+	+	+	+
Recreational use	Hiking trail	++	+	++	+	++

Table 6 | Reliability of data in the study

Factors	Data reliability High	Medium	Low
GIS map layers	x		
Data collected during field inspections	x		
Registered building flood damages		x	
Calculated building flood damages		x	
Runoff to combined sewer systems			x

stones are readily available in the area. None of the suggested NFDFs are located on the hiking trails, but log dams and stone check dams may be support the establishment of new hiking trails.

Based on the results of this study, the city of Oslo initiated a pilot project to construct several NFDFs upstream of the city. The first dam was established in Lunnedalen (see Figure 1(a)), which has local conditions similar to Risbekken West (Borge 2021). The dam was built from local material as a leaky woody dam (that included stones) by two people in 3.5 hours using only manual labour and a chainsaw. This experience confirmed the low resource use and investment costs for such facilities, which agrees with international experiences (Cronin 2016; Lancaster *et al.* 2021). However, the flood reduction effect of the measures remain to be evaluated, and flow gauges to be installed.

Reliability

A large part of the feasibility analysis was based on the assessment of GIS map layers. Access to high-quality GIS data in the study area ensures high reliability in the assessment. Another important factor in the reliability of the feasibility analysis is the data collected during field inspections which can supplement the map analyses. However, there were some uncertainties in data reliability for the study as summarised in Table 6.

The needs analysis is less reliable than the feasibility analysis due to the uncertainty of the registered cause of building damages. There was also some uncertainty regarding the reliability of calculated building damages from a previous flood risk study because the results were based on an uncalibrated hydraulic model (Kvitsjøen *et al.* 2021a). The quality of the results from the needs analysis could be improved if the calculated damage data was obtained from a calibrated hydraulic model.

The greatest uncertainty in the study related to the impact of runoff from natural landscapes on the combined sewer systems. The estimation of inflows to combined sewer systems from upstream natural landscapes and the impact of these inflows is best undertaken using a calibrated hydrological and hydraulic models. Such models would also be a useful tool for assessing the effectiveness of NFDFs.

Notwithstanding the uncertainties in the data, this was not critical constraint on the assessment because the primary purpose of the needs analysis was to rationalise the number of catchments subject to more detailed planning.

CONCLUSIONS

This study has developed a methodology for the systematic assessment of the needs for runoff detention in natural landscapes and the feasibility of Natural Flood Detention Facilities (NFDFs) based on five assessment criteria. The aim of the developed approach is to streamline the planning process for NFDFs.

The results from the needs analysis demonstrated that it is possible to efficiently select candidate catchments for NFDFs across large natural landscape areas. The study identified catchments in the natural landscapes upstream of Oslo that contribute to runoff to the city.

A scheme was developed to systematically assess the suitability of five small-scale NFDFs depending on local conditions. An analysis of the assessment criteria concluded that topography is a key criterion when establishing effective NFDFs. It can also be challenging to build NFDFs in nature conservation areas.

A feasibility study was performed for two case catchments, the Risbekken and Prinsdal catchments, to demonstrate the assessment scheme. As well as topography, the nature and biodiversity criterion were also key considerations when choosing appropriate measures in both catchments.

An assessment of how well the data obtained during field inspections corresponded to available map data was also undertaken. It was concluded that while the map analysis provided information on possible locations for NFDFs, the final decision on the location and the type of facility should be based on field inspections. Performing map analysis before field inspections contributes to more efficient field observations. The study also concluded that interdisciplinary cooperation is needed to effectively plan NFDFs, since the assessment criteria cover different areas of competence.

Following this study, the Oslo municipality started a pilot project in Lunnedalen to gain practical experience with NFDFs. It is recommended in the present study that hydraulic modelling be undertaken to assess the effectiveness of NFDFs in reducing the downstream flood risk and improvement of combined sewer system capacity. Another recommendation is to establish flow measurements to evaluate the function of NFDFs during rainfall events.

It is concluded that using NFDFs in suitable locations could be a cost-effective and environmentally friendly flood reduction measure with multiple benefits. The costs and benefits of NFDFs should be further investigated to identify the NFDFs' role in an integrated stormwater management system. While it is not expected that natural flood detention will solve all flooding problems in urban areas, it is expected that natural flood detention can positively contribute to future resilient stormwater management and to the implementation of the EU Strategy on Adaptation to Climate Change (European Commission 2021).

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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