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Flood mitigation options to reduce flooding risks in Bjørkelangen town

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Norwegian Institute for Water Research

REPORT

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Summary

We assessed three different flood mitigation options, based on simple models, to reduce flooding problems in Bjørkelangen town. The mitigation options i) small debris dams, ii) re-meandering of Lierelva, and iii) restoration of Liermåsan and Bliksrudmåsan were considered for current and future flow scenarios in a climate change context. We evaluated flood reduction potential for peak flow episodes with return periods of 100 years. Restoration of Liermåsan and Bliksrudmåsan may store approximately 4-5% of the total water volume comprising maximum daily peak flow and approximately 2-3% in context of future climate change. Importantly, however, the total water storage capacity increases non-linearly with increasing area of peat land and establishing peat land in 5% of the catchment would create a 10% flooding reduction. Construction of small debris dams in forested areas at approximately 1,000 sites may store approximately 5% of the total water volume comprising the 1-day peak flow and approximately 2-3% in context of future climate change. Re-meandering of Lierelva was not found to have significant effects on flood mitigation in Bjørkelangen. Restoration of Liermåsan and Bliksrudmåsan should receive highest priority due to a combination of highest cost-efficiency and high flood mitigation potential.

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2. Stream restoration	2. Restaurering av vassdrag
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Flood mitigation options to reduce flooding risks in Bjørkelangen town

Preface

This report considers different mitigation measures according to prevent flooding in Bjørkelangen town. The results are based on modelled peak discharge events and modelled changes in peak discharge events in the current and in future climate change scenarios.

The work was financed by Haldenvassdraget Vannområde and was conducted according to the contract. The work frame was designed and defined by Jes Jessen Rasmussen and Jose-Luis Guerrero, and all modelling was performed by Jose-Luis Guerrero.

Below is a list of NIVA employees involved in completing the work and report deliverable:

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Summary

In this report, we assessed three different flood mitigation options, based on simple models, to reduce flooding problems in Bjørkelangen town. The mitigation options i) small debris dams, ii) re-meandering of Lierelva, and iii) restoration of Liermåsan and Bliksrudmåsan were considered for current and future flow scenarios in a climate change context. We evaluated flood reduction potential for peak flow episodes with return periods of 100 years in current and future hydrological scenarios. A return period is the estimated average time between floods of a given magnitude. The modelled future daily maximum peak flows depended on the applied climate change scenario, but worst-case scenario (RCP 8.5) included 60-70% higher maximum daily peak flows within the coming century compared to the current hydrological regime.

Restoration of Liermåsan and Bliksrudmåsan showed a potential for storing approximately 4-5% of the total water volume comprising maximum daily peak flow and approximately 2-3% in context of future climate change. Importantly, however, the total water storage capacity increases non-linearly with increasing area of peat land. Liermåsan comprises approximately 3% of the total catchment but establishing peat land in 5% of the catchment would create a 10% flood reduction. Converting 10% of existing land use to peat land would create a 38% flood reduction. Restoration of Liermåsan and Bliksrudmåsan was considered as **the most cost-effective measure** targeting flood mitigation in the catchment of Bjørkelangen and holds the additional benefits of reducing in-stream nutrient concentrations, improving conditions for terrestrial and semi-aquatic biodiversity, and carbon sequestration.

Construction of **small debris dams** in forested areas at approximately 4,500 sites would provide retention capacity of approximately 10% of the total water volume comprising the daily peak flow. The daily peak flow is the total volume of water that discharges through a defined point in the stream system during 24 h, for a given return period.

In context of future climate change with expected increased peak flow, the total water storage capacity in the dam impoundments approximated 5% of the total water volume comprising maximum daily peak flow. The number of dams was not linearly correlated with total water storage capacity, and strategic investments in establishing the 1,000 debris dams with highest storage capacity would ensure a total water storage capacity of approximately 5% of the total water volume comprising maximum daily peak flow (2-3% in context of future climate change).

Re-meandering of Lierelva was not found to have significant effects on flood mitigation in Bjørkelangen unless the restored section gets reconnected with its floodplain allowing substantial amounts of water to be stored during peak discharge events. Additionally, re-meandering would have positive impacts on stream biodiversity, ecological quality of the stream, and ecosystem function and nutrient control.

We briefly considered value-for-money and potential added benefits for the three flood mitigation measures listed above, along with four additional measures, and we emphasize that there appears to be no one-trick solution to fully mitigate future floods in Bjørkelangen town. The option providing highest flood reduction potential, and simultaneously holding several added benefits and high cost-efficiency, was **restoration of Liermåsan and Blikrudsmåsan and potentially re-creating other peat areas**. Consequently, we recommend restoration of these peatlands receiving highest priority in a future flood mitigation mosaic solution in the Bjørkelangen catchment.

Sammendrag

Tittel: Muligheter for flomreduksjon i Bjørkelangen
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I denne rapporten ble tre ulike tiltak for flomreduksjon evaluert for å vurdere hvordan hver av disse kan bidra til å redusere flomproblemer i Bjørkelangen. Evalueringen ble utført ved hjelp av enkle modeller og de tre mulige tiltakene var i) fordrøying av vann i skogsområder med kvistdammer, ii) remeandrering av Lierelva nord for Bjørkelangen, iii) restaurering av Liermåsan (herunder stoppet torvuttak). Potensialet for flomreduksjon ble evaluert i forhold til nåværende og fremtidige hydrologiske scenarier (som resultat av klimaendringer) og ble utført med utgangspunkt i maksimum daglig vannføring innenfor en 100-års periode. Maksimum daglig vannføring ble estimert til å økes med opptil 60-70 % avhengig av det anvendte klimaendringsscenariet i løpet av det kommende århundret. Verst tenkelige scenario klimaendringer var RCP8.5.

Restaurering av Liermåsan og Bliksrudmåsan viste et betydelig flomreduksjonspotensial, tilsvarende ca. 4-5 % av det totale vannvolumet fra maksimal daglig vannføring og 2-3 % i framtidsscenarier med klimaendringer. Det er viktig å bemerke at den totale lagringskapasiteten øker ikke-lineært med økt areal av torvmose. Liermåsans areal svarer til ca. 3 % av det samlede vannområdet, men etableres torvmose på et areal tilsvarende 5 % blir potensialet for flomreduksjon økt til 10 %. Hvis 10 % av det eksisterende arealet kunne omdannes til myr ble det samlede flomreduksjonspotensialet estimert til hele 38 %. Samlet sett vurderes tiltaket som **det mest kost-effektive** og har dessuten markante tilleggsfordeler i form av reduksjon av næringssaltkonsentrasjoner, etablering av viktige habitater for semi-akvatisk biodiversitet samt netto-lagring av kullstoff.

Kvistdammer viste betydelig potensial for flomreduksjon, og etablering av 4.500 kvistdammer ble estimert å kunne lagre ca. 10 % av det totale vannvolumet fra maksimal daglig vannføring. Gitt forventede klimaendringer svarer dette til ca. 5% av det totale vannvolumet. Antallet av kvistdammer var imidlertid ikke lineært korrelert med den samlede lagringskapasiteten, og en strategisk etablering av de 1.000 kvistdammer med størst lagringspotensial ble estimert å kunne bidra med en samlet lagringskapasitet på ca. 5 % av det totale vannvolum fra maksimum daglig vannføring (2-3 % i verst tenkelige scenario for klimaendringer).

Remeandrering av Lierelva forventes å ha mindre effekt som flomreduksjonstiltak, med mindre koblingen mellom vann og land gjenetableres. Det vil si at det restaurerte vassdraget må dimensjoneres etter naturlige forhold og dermed tillate at de ripariske områdene oversvømmes under kraftig vannføring. Det er klare tilleggsfordeler ved re-meandrering av Lierelva, for eksempel økt biodiversitet, bedre økologisk tilstand og tilbakeholdelse av næringssalter ved kraftig vannføring.

Vi betraktet også kost-effektiviteten og mulige tilleggsfordeler for disse tre flomreduksjonstiltakene, samt fire øvrige restaureringsmuligheter. Vår konklusjon er at ingen av enkelttiltakene alene vil løse behovet for fremtidig flomsikring av Bjørkelangen, men at tiltaket med størst potensial for flomreduksjon, og samtidig også en høy kost-effektivitet, er **restaurering av Liermåsan og Bliksrudmåsan samt etablering av ytterligere myrområder**. Dette tiltaket anbefales å få høyest prioritet i en samlet fremtidig løsning på flomproblematikken i Bjørkelangen for å kunne oppnå en komplett flomsikring av Bjørkelangen i en fremtid med klimaendringer.

1 Introduction

Lake Bjørkelangen is one of several lakes embedded in the Halden river system and receives water mainly from the Lierelva to the North. The river catchment (Figure 1) has an area of approximately 273 km^2. Much of the agricultural area in the catchment is situated in low terrain, being a product of decreasing the lake's water level during the 1940's and 50's. This agricultural area is flooded during periods with high precipitation, which might become increasingly common due to climate change. Similarly, the city of Bjørkelangen, just North of the inflow of river Lierelva to lake Bjørkelangen, experiences flooding. Consequently, Haldenvassdraget Vannområde is interested in flood mitigation measures that prevent flooding of Bjørkelangen town.

The water quality in the river system is negatively affected by the intensive agriculture in the catchment, with especially phosphorus loads being problematic for the lakes in the Halden river system. Targeted measures for treating wastewater from urban areas and scattered settlements have decreased urban phosphorus inputs to 800kg per year, but the anthropogenic inputs of phosphorus are still 6—8 tonnes per year. It has been assessed that these phosphorus inputs come mainly from agriculture and are mainly generated when the agricultural areas are flooded during high precipitation events. Consequently, flood mitigation measures should ideally also mitigate eutrophication.

Large peatland areas are situated just north of Bjørkelangen town. These are a centre for industrial peat extraction. Peat extraction activities are, however, being phased out, and the part of the peatland closest to Bjørkelangen is already becoming recolonised by plants. The peatland is highly drained with multiple channels produced to secure the peat extraction activity. Previous reports have pinpointed restoration of the peatland as highly efficient flood prevention measure (Hauge et al., 2017) and suggested a method for the actual restoration process (Land, 2018).

The main purpose of this feasibility study was to assess flood reduction measures in the Bjørkelangen catchment. This was done through the application of simple flood models using three potential mitigation measures:

1. Delaying of the flood pulse using **small debris dams** made of branches in forest areas
2. **Re-meandering** of a section of the river Lierelva
3. **Restoration** of a part of the peatland area (Liermåsan and Bliksrudmåsan).

As a supplement, we used expert judgement to assess the potential of reducing phosphorous loads based on these three mitigation measures as well as evaluating their cost efficiency. Moreover, we assessed potential reduction of phosphorous loads and cost efficiency of four additional flood mitigation measures of interest to Haldenvassdraget Vannområde. The additional four mitigation measures considered here were: i) Daylighting small culverted streams, ii) Handling excess water from impervious surfaces in Bjørkelangen town, iii) Reducing the water level in lake Bjørkelangen, and iv) establishing a wetland in Kjelle.

2 Methods

2.1 Describing present discharge scenarios

In order to assess the potential impact of the proposed flood-prevention measures, we made use of publicly available datasets:

- A high resolution, 1x1m Digital Elevation Model (DEM) (www.høydedata.no)
- The NIBIO AR5 land use database (https://www.nibio.no/tema/jord/arealressurser/arealressurskart-ar5)
- The Norwegian Meteorological Institute (www.met.no) Nordic Gridded Climate Dataset (NGCD), a gridded 1x1km precipitation and temperature dataset covering the whole country
- Discharge data from NVE for the stations in the Bjørkelangen catchment
- Future climate data from Norsk Klimaservicesenter

The first step was to quantify the magnitude of the yearly peak average daily discharge for different return periods using frequency analysis. The conceptual basis was to fit a sample of peak yearly discharges to a given statistical distribution that could then be used to estimate peak discharge for different return periods (exceedance probabilities). The discharge information required to perform frequency analysis in the Bjørkelangen catchment was obtained from two stations upstream of lake Bjørkelangen: i) Lierelva (station code 1.200.0) and ii) Berg (station code 1.198.0) (Figs. 1 and 2). Ultimately, we only used the data for Lierelva because the catchment at Berg was deemed too small (1.21 km^2) and with insufficient data (Fig. 2) to allow fitting with acceptable uncertainty.

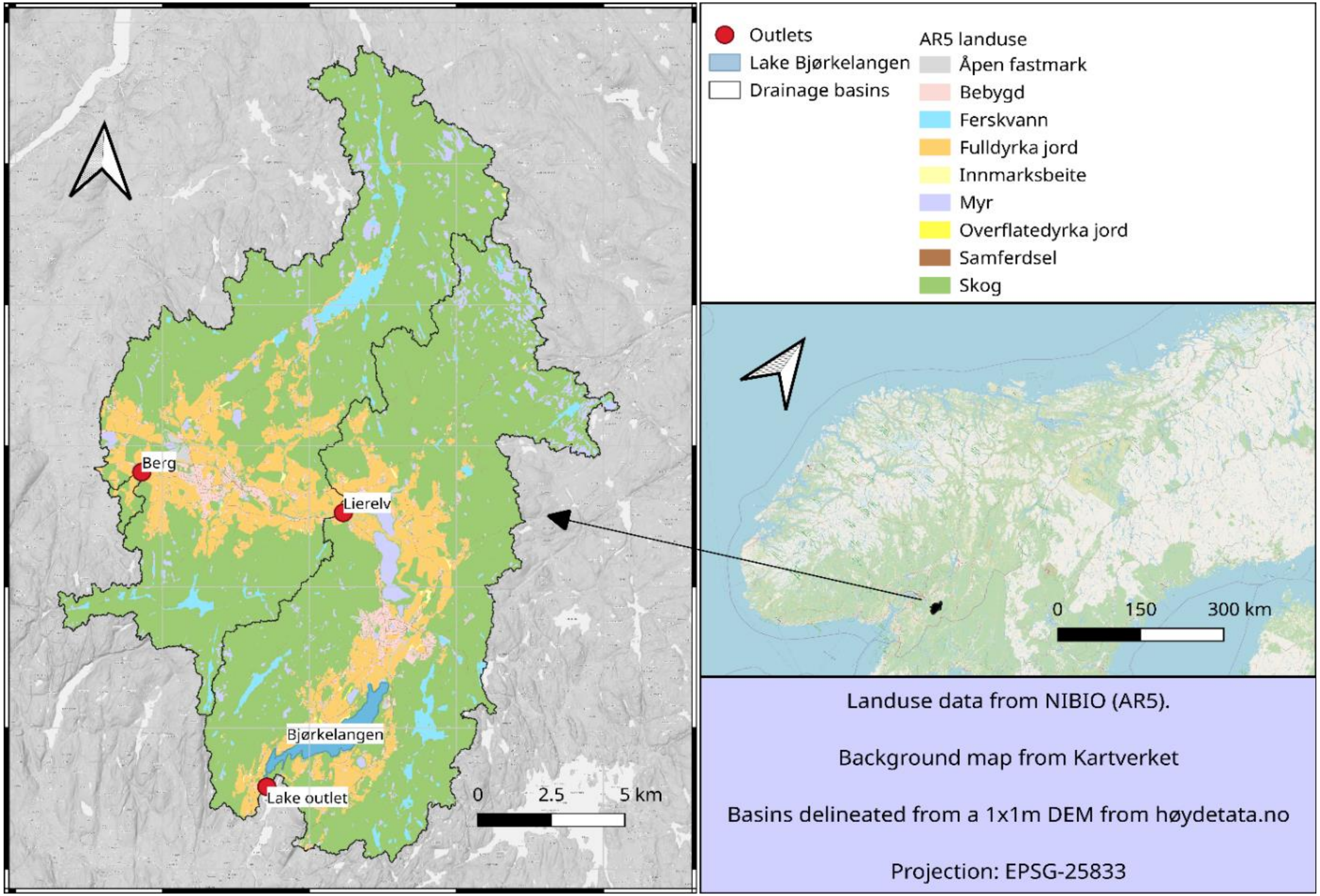

Fig. 1. *Bjørklangen land use map. The red dots mark the outlet of the lake and the location of NVE discharge-measuring stations. The basins upstream of those points are given as black polygons.*

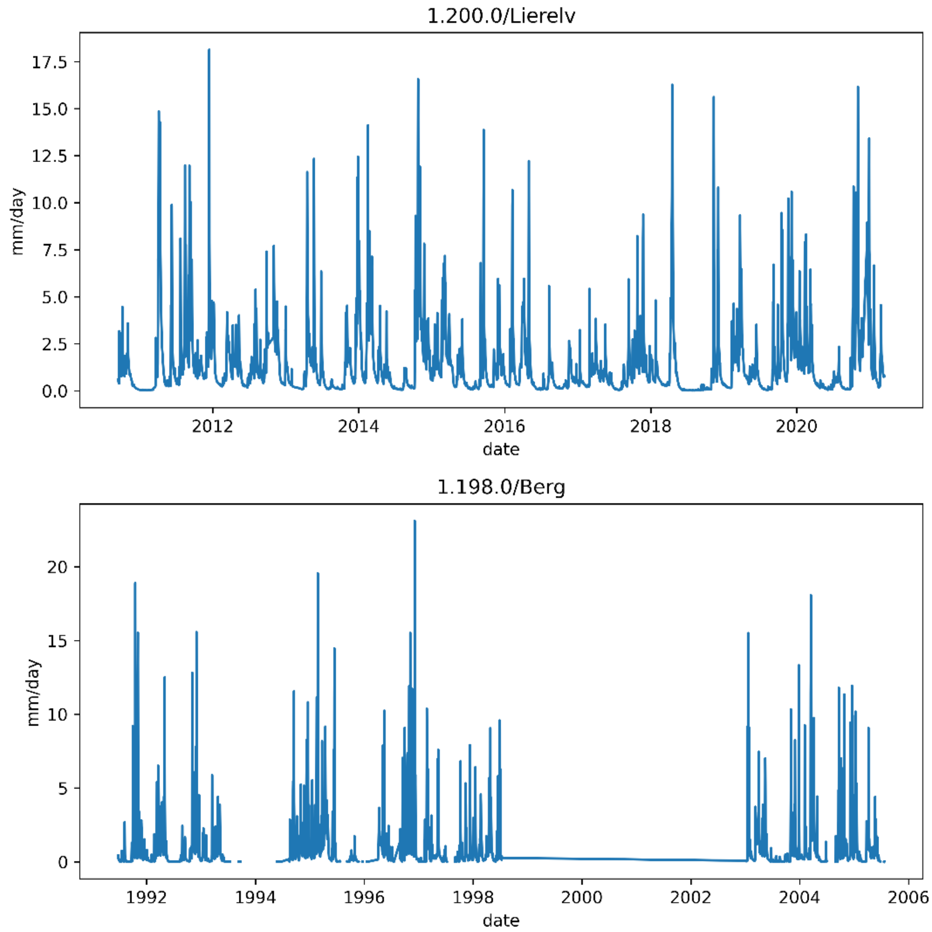

Fig. 2. *Discharge (y-axis) in mm/day at the two NVE stations upstream of lake Bjørkelangen. The NVE discharge is given in m3/s and was converted to mm/day using the catchment areas derived from the 1x1m DEM. The NVE dataset was averaged to a daily timestep.*

The total upstream catchment at the Lierelva discharge station has an area of 132.25 km^2. The available discharge data pans from 2011 to present, yielding 10 years of nearly continuous daily discharge data (Fig. 2). The limited length of this monitoring period potentially introduces uncertainties in the computation of design floods for future predictions. Therefore, we first attempted to extend the timeseries using a simple hydrological model driven by precipitation and temperature.

Precipitation and temperature data were available for the period 1971-2020 (Nordic gridded climate dataset, Lussana *et al*., 2018a; 2018b). The HBV hydrological model (Seibert, 1996) was used to extend the discharge timeseries. To do this, the model parameters were first calibrated using the measured discharge at Lierelva. After this, the longer precipitation and temperature timeseries were fed to the model in order to generate a longer discharge timeseries using the calibrated parameter values.

The usefulness of extending the discharge timeseries for flood frequency analyses depended on the performance of the model when simulating peak flows. Said performance was evaluated using the Nash-Sutcliffe efficiency (Nash & Sutcliffe, 1970), which favours the fit of high flows, as an objective measure when calibrating the model.

We found that the model could not adequately simulate peak flows. When using the extended timeseries, the peak flows for even the largest return periods approximately equalled the peak flows from the monitored timeseries (Fig. 2 and 3). This is unlikely and probably reflects the inability of the model to do a robust simulation of peak flows. Consequently, the simulated discharge timeseries should not be used for flood frequency analysis, and we decided to use only the observed discharge (Fig. 2) available at the Lierelva monitoring station to perform the flood frequency analysis. However, the statistical robustness of frequency analyses depends on the sample size. We deemed the 11 years of available data, i.e. 11 sample points, to be too short and increased the sample size by selecting the largest floods within a 6 months window, thus doubling the sample size. This was not ideal, since it might violate the assumption that the samples are independent and identically distributed, which is at the heart for frequency analysis: the same mechanisms might not apply for floods at different times of the year, and reducing the time window to 6 months increases the chance of the events being dependent. However, we assessed that this solution was preferable over basing the flood frequency analysis on a smaller sample size. Additionally, we performed a flood frequency analysis on the measured discharge data without the modelled extension of the data to compare results.

The basic principle in computing a return period is to fit a sample of yearly peak flows of a defined intensity to a statistical probability distribution and use the fitted distribution to predict the flows for different return periods. We tested the fit of several distributions commonly used for extreme value statistics and gave an assessment of the uncertainties in the estimated peak flows.

The distributions, which are typically used for estimating return periods, that were fitted to the data were:

- Exponential (EXP)
- Generalised Extreme Value (GEV)
- Generalised Logistic (GLO)
- Generalised Pareto (GPA)
- Gumbel (GUM)
- Pearson III (PE3)
- Weibull (WEI)

To assess which distribution provided the best fit to the sample of peak discharges, we used the two-sided Kolmogorov-Smirnov (KS) test. The goodness of fit was assessed using the KS statistic indicating how much the two distributions differed from each other and the significance level. In addition to the uncertainty in the selection of the distribution, there is additional uncertainty in the results for a single distribution. The latter can be assessed through bootstrapping (Efron and Tibshirani, 1993) providing an uncertainty range for the predicted peak flows for a given distribution.

2.2 Describing future discharge scenarios under climate change

Flood frequency analysis relies on the assumption that current and future floods belong to the same population. This assumption might be violated under a changing climate as different flow generation mechanisms might become dominant. Therefore, we also include an analysis of the expected future hydrology, i.e. discharge, for the Bjørkelangen catchment. The basis of the analysis is a gridded dataset (1x1km) of climate and hydrological projections for Norway (Wong *et al*. 2016) which uses 10 different climate models and two emission scenarios, or Representative Concentration Pathways (RCP), to estimate temperature, precipitation, and runoff. The projections encompass the period until 2100 and include an intermediate scenario with peak emissions around 2040 and a subsequent decline (RCP 4.5) and the business-as-usual scenario where emissions continue to rise all throughout the 21st century (RCP 8.5). The results from this dataset were areally-averaged to the Bjørkelangen catchment.

These peak flows and their uncertainty ranges can then be used to quantify the required retention capacity in the catchment to prevent flooding in a future context. Once this was done it was possible to assess if the flood mitigation activities tested in this report are likely to be sufficient to mitigate flooding during future peak yearly flows.

2.3 Small debris dams

We assessed the flood mitigation potential of small debris dams in mountainous forest areas in the Bjørkelangen catchment. The storage capacity of small debris dams is normally difficult to assess from a DEM (Digital Elevation Model) given their usually low resolution, where one single pixel can be larger than the desired size of the dam. However, the 1x1m DEM used in this report (provided by Kartverket) has a high spatial resolution, allowing an adequate quantification of the storage capacity of small debris dams.

Normally, raw DEM data needs to be processed before use in hydrological computations, and the river network burned into the raster: The elevation of raster cells that are directly under or close to the path of a river is lowered. This step guarantees that the synthetic flow paths derived from the DEM follow the actual river path. However, this was not done in our work because of the lack of a high-resolution river network: The available river network was at least partially derived from a 50x50m raster, thus producing a scale mismatch. Therefore, we based our computations on a synthetic (i.e. derived from the raw DEM) river network as explained below.

We started processing the DEM by filling sinks in the elevation model, thus assuming all sinks were artifacts. Once the sinks were identified and removed, we computed a flow direction raster, assuming the water from one cell only flowed in the direction of steepest descent to one and only one adjacent cell. From this flow direction raster, it was possible to compute the number of cells upstream of every cell in the raster, thus generating the flow accumulation raster. From the latter, it was possible to generate a synthetic river network by setting a threshold beyond which the cells are considered a part of the river. This might not exactly coincide with the actual river but is a good indicator of it.

The synthetic river network and the DEM provided the basis for this analysis, and the procedure required several subjective definitions or assumptions. These choices are explained below:

1. A cell in the flow accumulation raster was considered part of the river network if it had more than 10,000 upstream cells (1 hectare).
2. A dam could only be placed in a forested area, at least 100m away from cultural elements/other land uses to avoid conflicts of interest.
3. A dam could have a maximum width of 20m and a height of 1m (pragmatic constraints).
4. All dams were placed perpendicularly to the flow path. The direction of the flow path was determined from the vector defined by two points: the location of the dam and the river cell 15 pixels upstream of the dam.

The water detention capacity for dams placed in all the cells fulfilling the listed conditions was computed using the elevation data. This generated a set of potentially overlapping dams: the storage area of a given dam impinges on the location of a few upstream dams. Therefore, in order to compute the total retention capacity, we randomly sampled the potential locations in a way such that there were no overlapping areas between dams. We repeated the experiment twenty times to get a robust quantification of the potential storage capacity.

2.4 Re-meandering of Lierelva

The accepted physical basis for fluid dynamics is the Navier-Stokes equations. Increasing levels of simplification yield the Saint-Venant equations: one-dimensional, no-vertical acceleration, shallow channel (Darrigol 2002). At the other end of the spectrum, flow in natural channels can be described using uniform-flow formulae (which can be traced back as simplifications of the Navier-Stokes equations) based on observational data.

The Manning equation belongs to the group of uniform-flow formulae which is still the basis of most open-channel flow computations due to its proved reliability and simplicity. Manning’s equation relates flow in an open channel to its slope and its conveyance. The conveyance is a function of a resistance factor, the channel’s cross-sectional area, and a power function of the hydraulic radius (Chow, 1959). In other words, the flow depends only on the channel shape if the resistance factor is constant.

Manning’s formula describing uniform flow in open-channels often takes the form:

$$Q = \frac{KAR^{2/3}S^{1/2}}{n}$$

where Q is discharge (m^3/s), k is the friction coefficient($s/m^{1/3}$). A is the cross-sectional area (m^2), R (m) is the hydraulic radius, S is the slope of the channel (m/m), and n is a coefficient describing channel roughness (which depends on channel material and condition).

A large body of literature addresses the estimation of the resistance factor for different types of channels (Vieux, 2001). Manning’s equation becomes less reliable when its underlying assumptions are violated. However, Manning’s friction coefficient not only represents resistance to the flow, as intended from its formulation, but is a lumped factor that accounts for a variety of conditions affecting it (Mohanta *et al.*, 2018). One such condition is that of a straight channel: the conveyance is reduced with a meandering channel and there exists a wide array of methods that allow computing the resistance coefficient based on channel sinuosity. Most of them require observational data that are unfortunately lacking for Lierelva.

As such, we made use of a simple method, assuming unmodified riverbed characteristics (constant n) where the only factors considered were the reduced slope in a meandering channel in comparison to a straighter one, and a change in the roughness coefficient due to an increase in sinuosity. The effects of re-meandering a section of Lierelva on water retention capacity was therefore evaluated using the Manning equation. Based on subjective assessments of maps, we assumed that the total length of the restored reach would approximate to 3.8 km.

2.5 Restoration of Liermåsan and Bliksrudmåsan

Catchments where peat is prevalent have more porous soils, store more water and have shallower water tables compared to watersheds dominated by mineral soil types. Kværner and Kløve (2006) show that peatland, especially peatland located near a river outlet, can be effective for flood attenuation.

In the case of Liermåsan and Bliksrudmåsan, where peat extraction activities are performed and where the peatland is drained by drainage canals to facilitate the peat extraction process, water retention capacity is reduced. Hence, a highly drained peat area might have water retention characteristics comparable to less porous soil types.

Since the restoration of these peat lands would include a total stop of the peat extraction activities and a closure of the drainage canals, re-establishing the naturally highwater retention capacity, we decided to evaluate the flood retention potential of restoring the peatland by comparing the water retention capacities of healthy peatland to a soil type/land use with higher permeability. For this, we needed a method that explicitly accounts for soil typology in water retention and discharge calculations.

A commonly used method to quantify flood generation based on soil types is the United States Department of Agriculture Soil Conservation Service curve number (SCS-CN) method, which is widely used due to its low data and parameter requirements. This model ignores rainfall intensity and duration and instead relies only on data representing total precipitation volume.

The application of the SCS-CN method is limited to single events with a maximum duration of 24 hours, and factors such as frozen soils are disregarded. Still, it is often used if the objective is to quantify runoff generated during a flood event as a fraction of the total precipitation, as was our objective here.

The SCS-CN method is based on the formula:

$$Q = \frac{(Q - I_a)^2}{P - I_a + S}$$

where P is total rainfall, I_a is the Initial abstraction (or fraction of precipitation that contributes to runoff) and S is the maximum retention. The formula is often simplified to:

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S}$$

thus assuming that the initial abstraction is equal to 0.2S. The maximum retention parameter is obtained from the curve number using the following relationship：

$$S = \frac{25{,}400}{CN} - 254$$

where S is in mm and CN is non-dimensional and varies from 0 to 100. There is a large body of literature relating the curve number to soil types, land uses, hydrological conditions, and antecedent moisture. Different adaptations of the SCS-CN method exist, that account for a wider range of conditions, e.g. a time varying CN (Misra and Singh, 2004; Mishra *et al*., 2014). The CN number can be obtained from tables based on hydrological conditions, land use, treatment and four hydrological soil groups (A, B, C and D): A) low runoff potential, B) average infiltration conditions, C) soils with low infiltration when wetted, and D) soils with high runoff potential (NRCS, 2004) none of which adequately describe peat soils.

Menberu *et al*. (2014) filled this knowledge gap and derived curve numbers for peat dominated catchments. The study is particularly relevant since one of their test catchments was located 40km north of Oslo, i.e. close to lake Bjørkelangen's catchment.

The SCS-CN number varies according to defined land use types (Table 1), and the actual flow generation capacity strongly depends on the hydrological soil group. The soil map database in Norway mostly contains agricultural land (Mathiesen *et al*., 2018). Consequently, assigning SCN-CN numbers to a given area (e.g. Liermåsan area) relies on an assumption that the soil types in agricultural areas and non-agricultural areas are similar. As most of the agricultural areas are located in lowland areas in the river corridors in the catchment of Lake Bjørkelangen, we suggest that the assumption is reasonably safe.

The NIBIO soil map (jordbonnskart; Mathiesen et al. 2018) shows that soils in the Bjørkelangen catchment have either 'high' or 'very high' water retention capacity. This would correspond to soil group C or D (Table 1) of the SCN-CN method.

***Table 1**. SCN-CN numbers for different land uses and soil types (hydrological soil groups) (USDA 1986)*

Land use	Curve number for hydrologic soil group			
	A	B	C	D
Forest	30	55	70	77
Built-up (65% impervious)	77	85	90	92
Agricultural	64	75	83	85

To comply with the aim of quantifying the effects of restoring Liermåsan and Bliksrudmåsan, we compared the expected daily peak flow from a 24-hour rain event when transitioning from existing land use (i.e. hydrological soil group C or D) to an area dominated by peat. This convoluted approach was necessary because of the lack of information on the SCS-CN number for degraded (highly drained) peat such as it exists in Liermåsan and Bliksrudmåsan.

Ideally, we would compare the SCS-CN numbers for peat (from Menberu *et al*., 2014) to those for well-drained peat. However, to the best of our knowledge, the latter is not available in the literature and would have needed to be measured onsite.

Considering that the lower the SCS-CN number, the higher the water retention capacity, we chose to make our estimates conservative by selecting the SCN-CN numbers for forest and hydrological soil group C and D to best reflect the current conditions at Liermåsan and Bliksrudmåsan.

As such, we compared the numbers from Menberu *et al*. (2014) to a worst-case-scenario, i.e. the soil type/land cover in the catchment with the highest potential retention capacity amongst the dominant types of soils present in the catchment (Table 1).

Additionally, Menberu *et al*. (2014) recommends using lower initial abstraction capacities (I_a in the above formulae) in peat dominated catchments. We used their recommendations when performing the comparisons (0.036S). Hereby, we evaluated the effects of restoring Liermåsan and Bliksrudmåsan (fixed area of 4.4 km^2) as equivalent to transitions from other land uses to peat dominated soils. This provided a rough estimate of the ability of soil type transitions to dampen peak floods.

3 Results and discussion

3.1 Describing present discharge scenarios

The results of the flood frequency analyses are presented in Fig. 3. The statistical robustness of the fit for GEV, GPA, WEI, PE3 and GLO distributions was nearly identical (Table. 2), but still produced a wide range of possible discharge for longer return periods (Fig. 3).

Table 2. *Kolmogorov-Smirnov test results between the listed distribution and the empirical (observed) distribution. The statistic is an indicator of the difference between the two distribution (the lower the better) and the p-value indicates the significance level (the higher the better).*

Distribution	Statistic	p-value
GEV	0.15	0.965
EXP	0.25	0.497
GUM	0.20	0.771
WEI	0.15	0.965
GPA	0.10	0.999
PE3	0.15	0.965
GAM	0.20	0.771
GLO	0.15	0.965

The uncertainty of each fit was estimated using bootstrapping (example provided in Fig. 4 with the PE3 model as case). The results for all distributions are summarized in Table 3, presenting expected peak flows for the different distributions considering the uncertainty in the fit. In short, the expected discharges for a return period of 100 years ranged from 18.21 mm/day to 22.58 mm/day translating into a total discharge of 2.41e6 to 2.99e6 m^3/day at the Lierelv station. Using the upper limits of the confidence intervals increased the maximum expected discharges to 2.89e6 to 4.15e6 m^3/day at the Lierelv station, depending on the fitted distributions, during a flood event with a return period of 100 years.

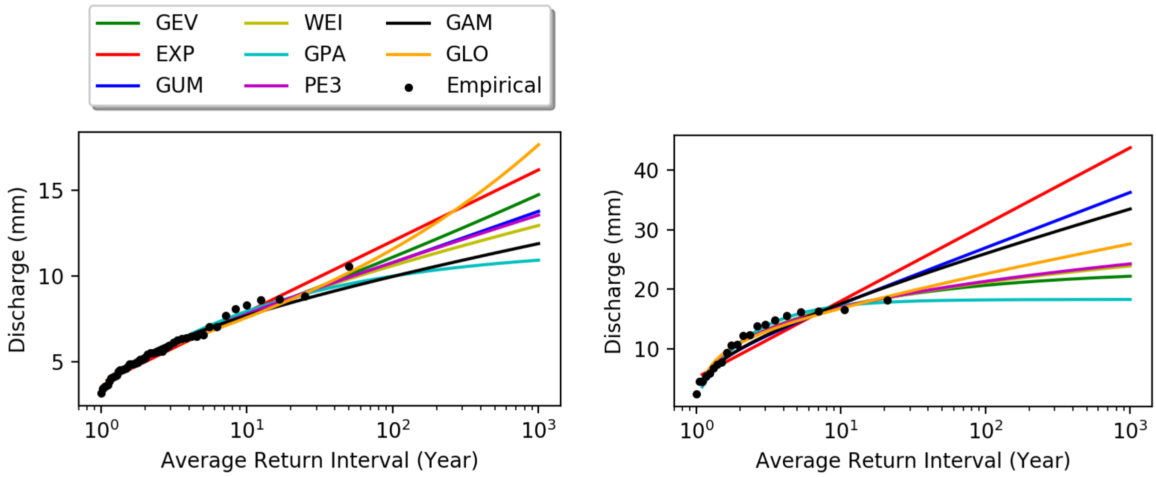

Fig. 3. *Return period (x-axis) for peak yearly flow (y-axis). Discharge (mm) at the Lierelv station. The black dots represent the empirical distribution of yearly maximum flows. The full lines represent the fitted distributions. The left figure shows extended discharge timeseries (using the HBV model), and the right figure only the observed discharge was used.*

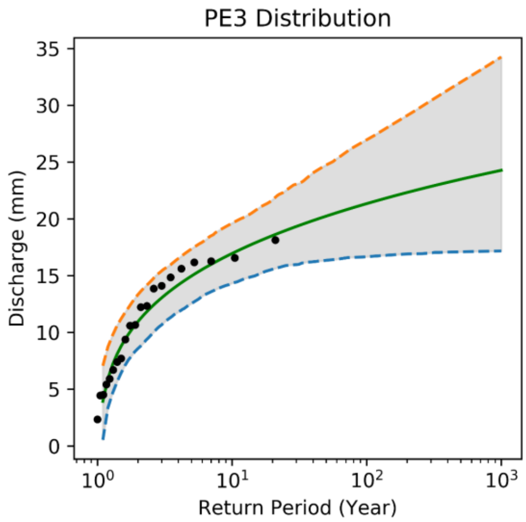

Fig. 4*. Bootstrapped (0.025 and 0.975) confidence intervals for the floods (y-axis) for a given return period (x-axis). The black dots show the empirical distribution from observed values and the green line the fitted GEV distribution. The grey area gives the interval range and the dotted lines show the 95% confidence interval.*

3.2 Predicted changes in discharge in a future climate

Temperature, precipitation, and discharge are expected to change in the future, irrespective of the scenarios and models used to predict them (Fig. 5). The average yearly temperature is predicted to increase under all scenario/model combinations (Fig. 5, bottom). Precipitation is also expected to increase under a warming climate, albeit at a slower rate (Fig. 5, top). The situation is predicted to become more nuanced with respect to discharge (Fig. 5, middle). In the near future, yearly discharge might decrease but it will probably stabilize on the longer term: the increase in temperature (more evaporation, less discharge) is predicted to somehow be compensated by the increase in precipitation (more discharge).

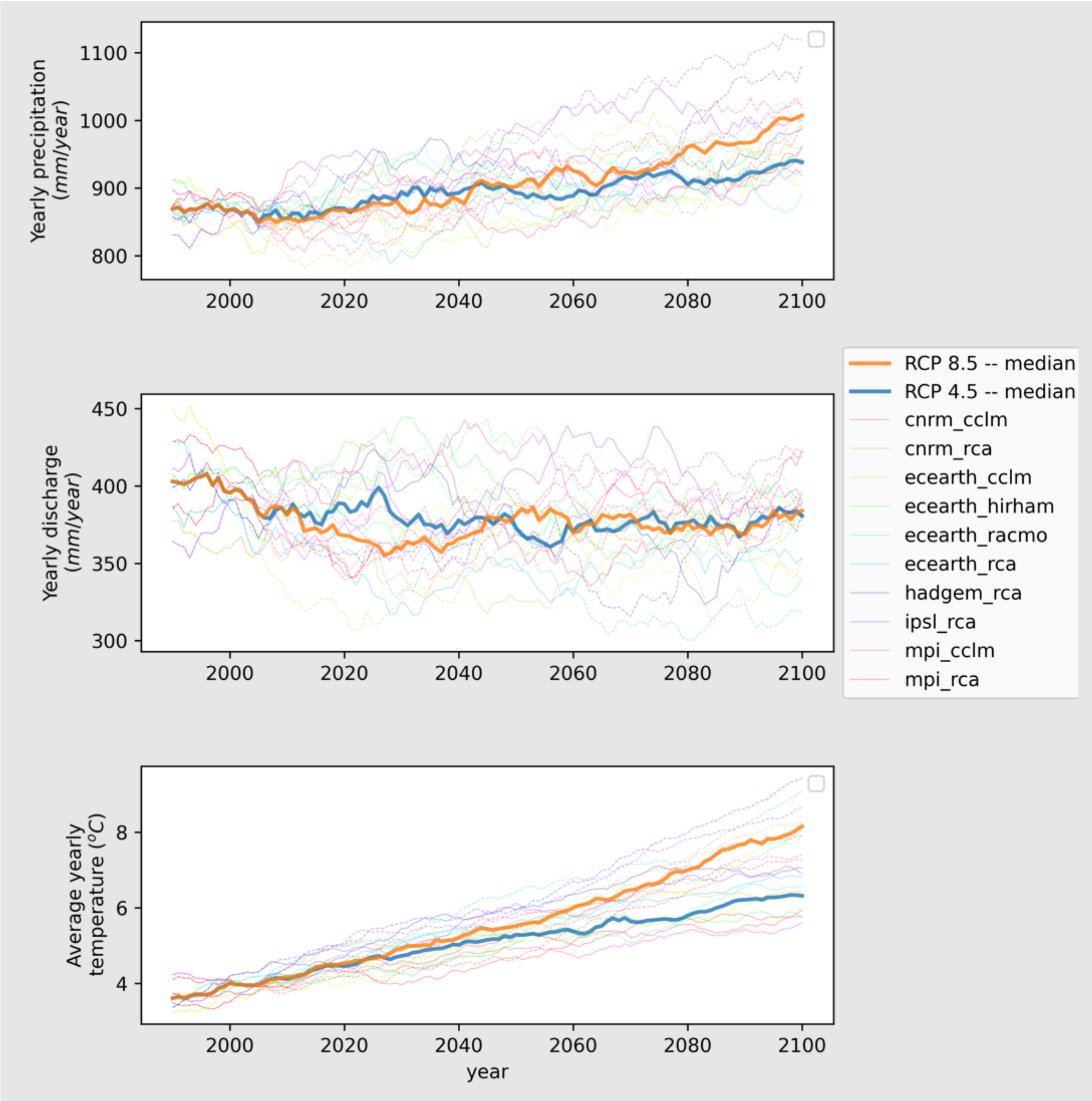

Fig. 5. *Total yearly precipitation (top, mm/year), total yearly discharge (middle, mm/year), and average yearly temperature (bottom, mm/year) in lake Bjørkelangen's catchment for different climate scenarios (full line: RCP 4.5, dashed line: RCP 8.5). The median for the RCP 4.5 and RCP 8.5 scenarios is presented with bold lines. To eliminate high-frequency variations, the precipitation, temperature and discharge are given as averages over a 20-year moving window.*

Although the total yearly discharge might decrease, the variability in peak yearly discharge is predicted to increase, which may accommodate more extreme peak flow events (Fig. 6). In the worst-case scenario, i.e. the largest discharge predicted by any model (Fig. 6), peak floods are expected to increase by 50% to 60% compared to the selected reference period of 1996 to 2005.

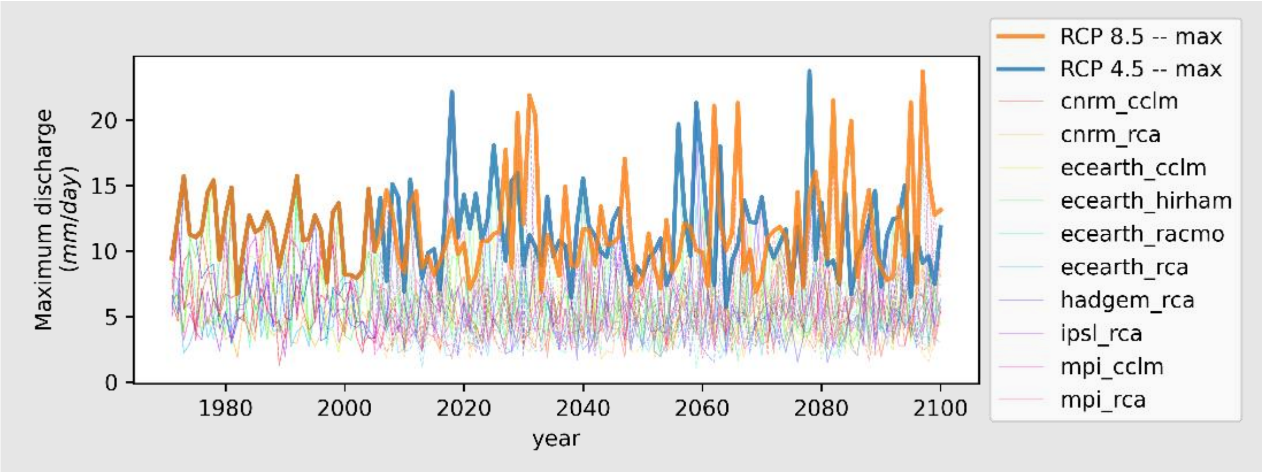

***Fig. 6**. Maximum daily discharge (mm/day) per year for 10 different models and two climate scenarios. The bold lines represent the maximum predicted discharge across all models (i.e. RCP 4.5 and RCP 8.5).*

Considering more conservative estimates, i.e. an average increase for every model for the RCP 4.5 and RCP 8.5 scenarios instead of worst-case scenarios (Fig. 7), peak flows may increase by 30% compared to the reference period. Clear differences in the predicted discharge scenarios exist between the two climate change scenarios. In case of RCP 8.5, the predicted peak yearly discharge increases through the entire century, whereas with RCP 4.5, the peak yearly flow will reach a maximum in 2080 and then decrease. This might be explained by the fact that the increase in precipitation is higher for the RCP 8.5 scenario overriding the expected increase in evaporation with increased temperature whereas this overriding effect is lower for the RCP 4.5 scenario. Note, however, that the highest peak flows are expected to occur sooner in the RCP 4.5 scenario, thus requiring more rapid actions to mitigate flooding in the future.

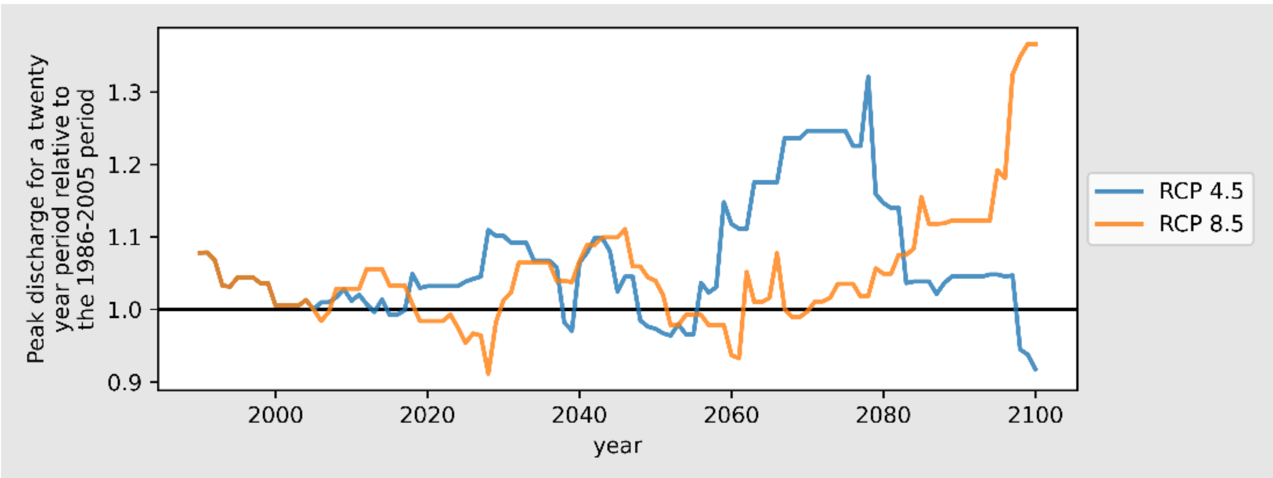

***Fig. 7**. Ratio of peak daily discharge (average predicted discharge for the climate change models) for a twenty-year window relative to the 1986-2005 period for two different climate scenarios.*

It is important to note that this increase in peak flow is independent of the increase for different return periods described above. Frequency analysis assumes that future floods belong to the same population as the sample that was used to predict them. This is not the case under a changing climate. In other words, climate change is predicted to cause more hydrological changes than just a general factor-increase of peak discharge events. Although effects of climate change may not be fully multiplicative (i.e. discharges derived from flood frequency analysis multiplied by the factor of expected discharge increase under climate change), we consider the worst-case scenarios in the following discussion of flood-prevention potential of the suggested mitigation actions (i.e. RCP 8.5). Note, that applying the RCP 4.5 scenario as benchmark for future hydrological changes would only lead to marginally lower daily peak discharge events (Fig. 7).

3.3 Small debris dams

Considering the dams should only be placed within a forested area, 100 m away from other land use types, the number of potential locations in the catchment of lake Bjørkelangen was approximately 101,000 pixels from the elevation raster, representing approximately 101 km of waterways within the catchment. When adding the constraints of a maximum length of 20 m for a 1 m high dam, the number of potential locations was reduced to around 16,000 (Fig. 8).

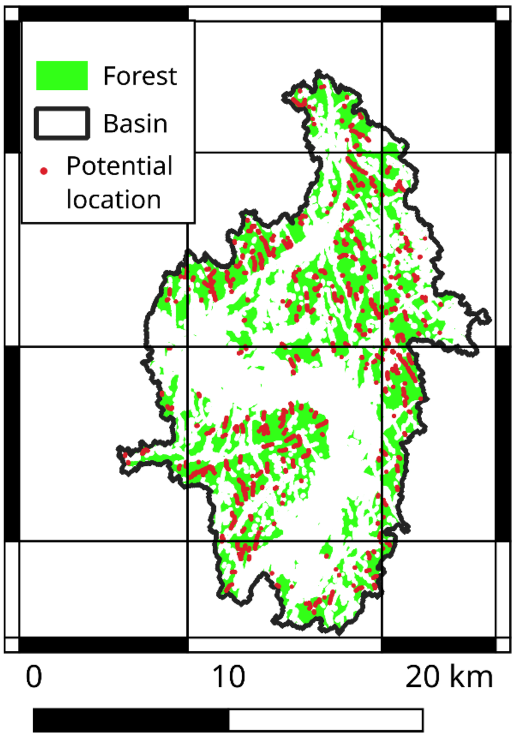

Fig. 8. *Potential locations of small debris dams (red points) within the catchment of lake Bjørkelangen (black polygon), fulfilling the selection criteria (1: at least 100m away from other land use types within a forest (green area), 2: with a height of 1m, and 3: a maximum length of 20m for the small debris dams.*

The average length of the dams for all potential locations was 13.5 m, with an average surface area of the impoundment pond upstream of the dam of 568m^2, and an average storage volume of 284m^3 water (Fig. 9). The total storage volume of water in all the dams, ignoring potential overlaps between dams, was 4.7 M m3, or approximately 50% of the peak daily discharge for flows occurring with a return period of 100 years.

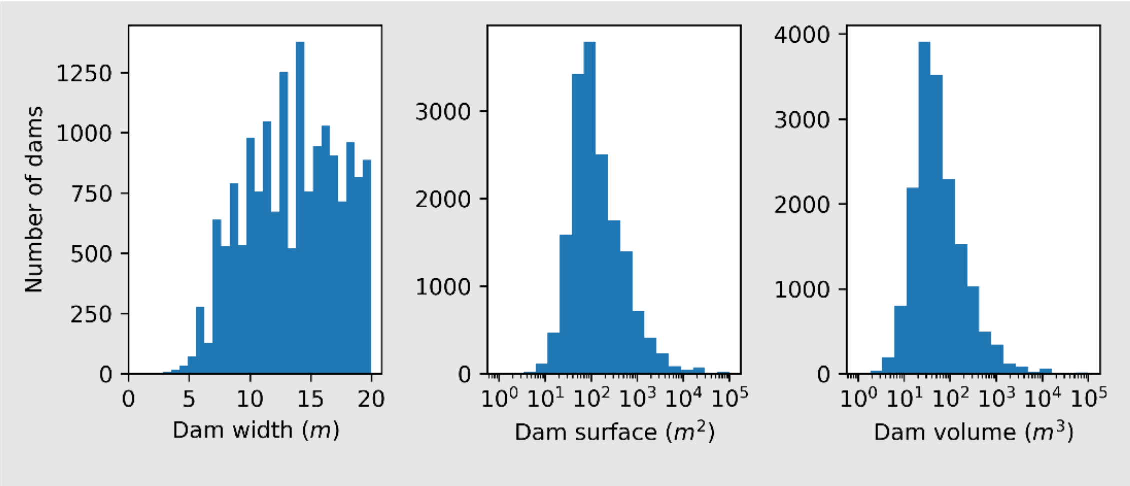

Fig. 9. *Dam width (left), surface area (centre), and volume (right) for all the potential locations for dams within the catchment of lake Bjørkelangen.*

It was, however, impossible to place dams at all potential locations since the storage areas would occasionally overlap. After randomly placing the dams until no more area was available (i.e. avoiding overlap of water storage area) and repeating the randomised location process twenty times, we found that **an average of 4,450 dams could be placed** (minimum of 4384 and maximum of 4518) **with an average storage capacity of 1.08 M m^3** (minimum of 0.86 M m^3 and a maximum of 1.33 M m^3), **corresponding to approximately 10% of the peak daily flow for a 100-year return period**.

Most of the dams had a relatively low storage capacity, and **most of the storage capacity could be achieved by selecting dams with the highest storage capacity** (i.e. <1000 of the largest debris dams). Such a selection would provide >50 % of the total storage capacity, amounting to 5 % of the maximum peak daily discharge with a 100-year return period.

In the context of future climate, and assuming that the predicted relative increase in discharge is multiplicative with the discharges from the flood frequency analysis, the total storage capacity obtained by establishing all dams (i.e. 4,450) would represent approximately 4-5 % of the peak daily discharge for a 100-year return period under the RCP 8.5 scenario at the end of the 21st century.

3.4 Re-meandering of Lierelva

A section of the Lierelva is currently channelized (Fig. 10), and Haldenvassdraget Vannområde considers re-meandering this part of the Lierelva as flood mitigation measure. The section of the stream is situated just north of Bjørkelangen town.

The stream section currently has a length of 3.8km with a sinuosity of 1.14. The average slope was of 0.009% (Fig. 10). We defined the target sinuosity of a re-meandered stream section as 4.21, since another section of the Lierelva located approximately 2 km further upstream has a naturally meandering shape with a sinuosity of 4.21 (Fig. 10). The approximately four-fold increase in sinuosity entails an approximately four-fold increase of the total length of the re-meandered stream section.

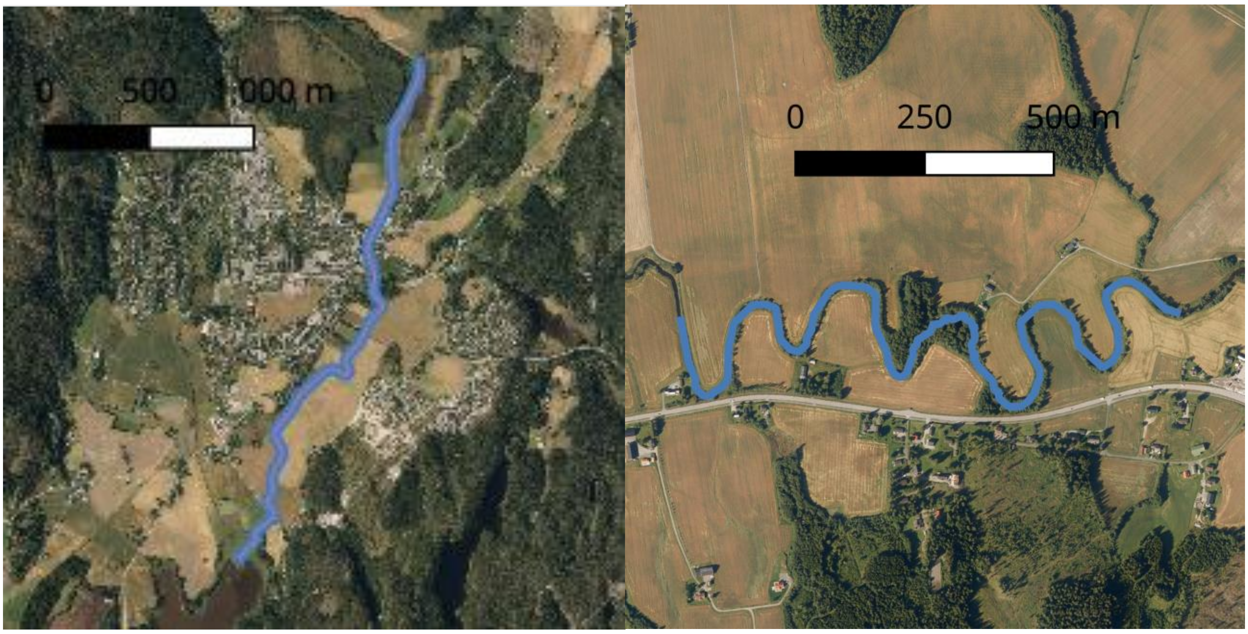

Fig. 10. *River section considered for re-meandering (left figure, blue line) and river section with target meandering profile (right figure, blue line). Orthophotos from Kartverket.*

Re-meandering of the 3.8 km of Lierelva to achieve a sinuosity of 4.21 would decrease the discharge capacity of the reach by a factor of 1.97, assuming the substrate composition and other physical elements influencing flow conveyance remains constant. A variety of more complex methods can be consulted to compute the impact of sinuosity more precisely (Mohanta *et al*., 2018), but the decrease in average slope remains the most important parameter governing discharge capacity, and more complex calculations of discharge capacity would likely not yield significant changes of the estimates based on the methods used here (Manning's formula; Mohanta *et al*., 2018).

The main effect of re-meandering a straight stream channel to a meandering shape is an increase of total stream length, and thereby a reduction of the slope of the restored reach, as well as increased roughness of the channel. Both reduce the potential for flow conveyance (according to Manning's formula, see chapter 2.4). **In terms of flood prevention**, and from a purely mechanical perspective, **re-meandering provides no direct benefit along the re-meandered reach**: higher water levels will be required to drain the same volume of water.

In terms of *downstream* flood prevention, the picture is different: The benefits of re-meandering include an increased chance of flooding the riparian zones of the re-meandered stream section during peak flow events. Consequently, a re-meandering strategy that targets flood mitigation downstream should optimally include an additional restoration of floodplains, and/or re-connection with the floodplain, to optimise the total storage capacity in the riparian zone. This is, however, out of the scope of this report.

Note, also, that re-meandering of a straightened stream channel, and potentially including a restoration of the attached floodplains, has additional benefits in terms of improved conditions for biodiversity, ecological quality, and water quality (Kupilas et al. 2016, Kupilas et al. 2020).

3.5 Restoration of Liermåsan and Bliksrudmåsan

We found a non-linear decrease in flood generation as more soil (forest with hydrological soil type C and D, see chapter 2.5) was converted to peat land, if converting from 0-10% of the land in the catchment at Lierelva station (Fig. 11). In more detail, restoring Liermåsan and Bliksrudmåsan by aborting peat excavation activities and disconnecting drainage systems, the SCS-CN number would be reduced from 70-77 (depending on the selection of hydrological soil type C or D) to 59-63 (values found by Menberu et al. (2015) for peat dominated basins), in addition to modifying the initial water retention capacity (see chapter 2.5).

Converting 10% of the land to peat would reduce the volume of floods by 38%. Note, however, that the established correlation between land conversion and expected flood reduction potential is not linear, as converting 5% of existing land use to peat would only reduce expected flood volumes by approximately 10% (Fig. 11). As indicated by Land (2018), peat restoration needs to primarily consider current hydrological regime, amount of remaining peat, and potential for peat-associated plants to recover lost territory to optimise restoration success. Apart from the peat excavation activity in Liermåsan and Bliksrudmåsan, parts of the current agricultural land in this region may be modified former peat land holding some potential for peat restoration (Land, 2018).

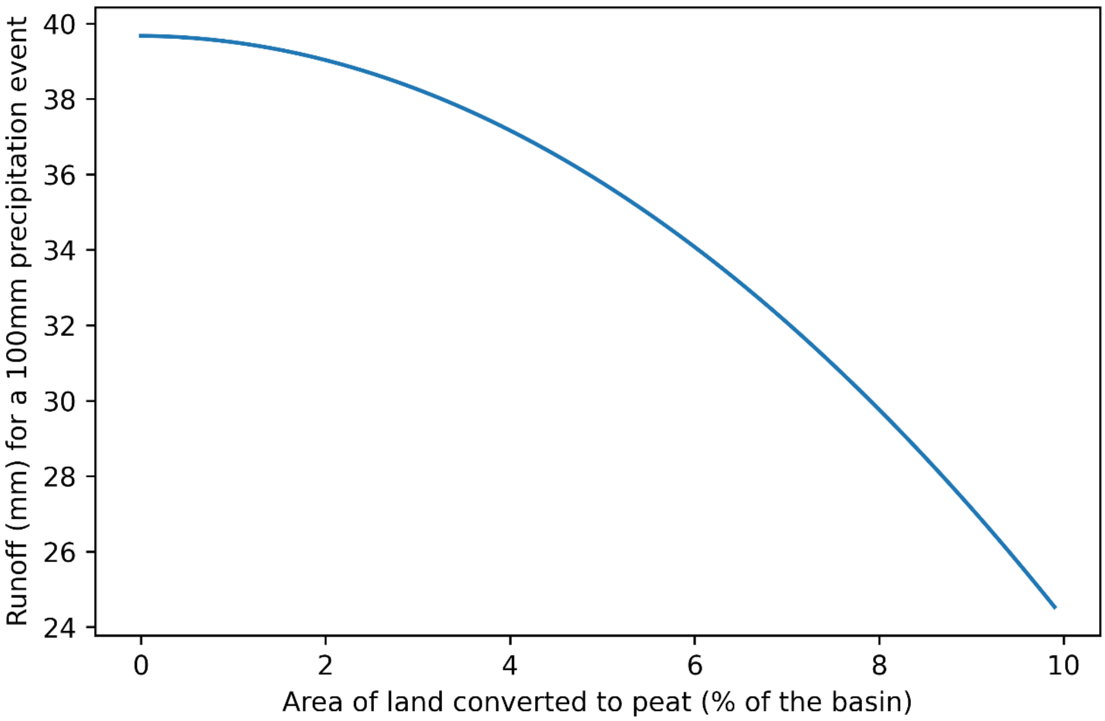

***Fig. 11**. Amount of runoff water to the stream during a 100mm rain event. The runoff was computed using the dominant land use types in the catchment (Table 1) and the SCS-CN method as described in chapter 2.5 of this document and the values recommended by Mohantas et al. (2014) for peatlands. This method assumes that the total storage capacity of the peatland is never exceeded and that all water is infiltrated.*

The Liermåsan and Bliksrudmåsan have a combined area of approximately 4.4 km^2 (Kilden – Arealinformasjon (nibio.no); store norske leksikon (snl.no)), representing 3.3% of the total catchment area of Lake Bjørkelangen. This translates into **a flood reduction potential of approximately 4.3%** of a peak flood with a return period of 100 years, provided the storage capacity of the peatland is not exceeded. Adding changed hydrological scenarios in a future with climate change and increased peak flood volumes might reduce the flood reduction potential of restoring Liermåsan and Bliksrudmåsan to 2-3% depending on the climate change scenario.

These estimates are affiliated with uncertainty, as we are assuming that the current peat excavation and drainage scenarios in Liermåsan is representative of average agricultural land in terms of infiltration capacity and ability to generate runoff (or similar through drainage canals). Furthermore, the estimates rely on the assumption that infiltration capacities are never exceeded, which realistically would be at least occasionally violated. Nevertheless, the estimates serve to illustrate a relatively high flood reduction potential per unit effort e.g. compared to establishing 4,500 debris dams in the forested areas.

Several additional benefits are affiliated with restoring peat areas or converting previous peat areas (e.g. currently agriculture or other land use types) to flood-prone natural peat areas. Peat areas act as carbon sinks, especially those with permanently flooded conditions, which contribute remarkably to remove CO_2 from the atmosphere (Beaulne *et al.*, 2021). Additionally, flood-prone peatland provides large bio-reactive surfaces for nutrient removal during flooding, serving as a natural and efficient way of removing N and P from stream water (e.g. Walton *et al.*, 2020). Conversely, there will be an affiliated financial loss of income from reduced or removed industrial peat excavation, and if agricultural land is to be transformed to peatland.

3.6 Evaluating flood reduction potential and added benefits for a suite of flood mitigation options

As part of the project, we aimed to assess (based on expert judgement) the flood mitigation potential and additional benefits from performing the mitigation options mentioned in the call text. The expert judgement is based on knowledge gained from scientific reports, reports, and articles (e.g. Roni and Beechie, 2013; Flavio et al., 2017; Lammers and Bledsøe, 2017). The following mitigation options were considered:

1. Small debris dams in forested areas
2. Daylighting small, culverted streams
3. Handling water from impervious surfaces in Bjørkelangen town (e.g. rain gardens)
4. Lowering the water level in Lake Bjørkelangen
5. Re-meandering a part of Lierelva immediately upstream of Bjørkelangen town
6. Restoring the peat land in Liermosen
7. Establishing a wetland in Kjelle

Below we provide a step-by-step consideration of flood mitigation potential and potential added benefits for these flood mitigation options. In terms of added benefits, we consider P-reduction potential and improved conditions and habitats for biodiversity.

3.6.1 Small debris dams

As presented in chapter 3.3, small debris dams in forested areas have some mitigation potential in terms of flood prevention. More precisely, we estimated that establishing all 4,500 dams would reduce flow volumes of peak flows with 100-year return periods by approximately 10% and 4-5% in context of worst-case climate change scenarios within the coming century. We argue that the potential for pollution mitigation will be negligible since most of the pollution is estimated to originate from the agricultural production in lowland areas. Moreover, the dams would occupy a significant fraction of the forest space that probably needs to be taken out of production. Benefits in terms of biodiversity improvements will probably be negligible since this mitigation action relies on artificial constructions of pond-like areas in locations where ponds rarely occur in the natural scenario, but we expect no negative effects on salmonid fish production as steep mountainous streams are not relevant spawning or rearing habitats.

3.6.2 Daylighting small, culverted streams

Daylighting small, culverted streams has little effect on flood prevention unless daylighting is supplemented with establishing adjacent wetland areas or floodplains that can be flooded during heavy precipitation events or snow melt. However, the culverts may be under dimensioned compared to current hydrological regimes, consequently acting as hydrological bottlenecks in the stream corridor creating local floods. In these cases, daylighting culverted streams would increase local flood protection with likely lower financial costs compared to replacing the existing culvert with a new and bigger one.

Although the retention capacity and the total area of bioactive surfaces of the daylighted stream section will be slightly increased, we expect minimal influence on pollution mitigation at the catchment level. However, this clearly depends on the size of the culvert that is removed as daylighting larger stream sections (e.g. several hundreds of meters) may generate sufficiently large areas with bioactive surfaces to prompt measurable pollution reduction.

Importantly, overall biodiversity and ecological quality may significantly benefit from removing culverts, as they function as migration barriers for especially fish, but also other aquatic organisms such as plants and invertebrates. As such, removing culverts will provide access to upstream parts of the stream system that were previously inaccessible to the downstream organisms.

3.6.3 Handling water from impervious surfaces in Bjørkelangen town

Establishing green roofs, raingardens etc. to circumvent the rapid transport of water from heavy precipitation events to Lierelva probably has some potential to mitigate flooding downstream of Bjørkelangen town, but the mitigation potential of flooding in Bjørkelangen city will most likely be minimal since the majority of excess water during flooding events originates from the upstream catchment. Hence, **flood mitigation actions should be focused on the upstream part of the catchment if the aim is to avoid flooding in Bjørkelangen town**. We expect no direct benefits from handling water from impervious surfaces in Bjørkelangen town on pollution or biodiversity since i) the majority of N and P originates from agricultural practice in the upstream catchment and ii) since the mitigation action does not (or only marginally) influence habitat or water quality in the stream system.

3.6.4 Lowering the water level in lake Bjørkelangen

Permanently lowering the water level in lake Bjørkelangen provides an option for reducing flooding episodes in Bjørkelangen town, but it comes with a cost of increasing flooding risks in communities and agricultural areas downstream of lake Bjørkelangen. Periodically lowering the water level in lake Bjørkelangen between peak discharge events would provide an option for reducing flooding episodes in Bjørkelangen without compromising agricultural production downstream of lake Bjørkelangen. Importantly, however, permanent and especially periodic reduction of the water level in lake Bjørkelangen would significantly impair aquatic and semiaquatic biodiversity in the lake due to destabilised habitat availability and reducing habitat quality. There is no evident potential for pollution reduction by permanently or periodically reducing the water level. On the contrary, increasing the water retention time in lake Bjørkelangen during peak discharge events when nutrient concentrations are highest would most likely increase the internal pool of especially phosphorus compared to the current water level management in lake Bjørkelangen.

3.6.5 Re-meandering a part of Lierelva immediately upstream of Bjørkelangen town

As discussed in chapter 3.4, re-meandering of the channelized part of Lierelva immediately upstream of Bjørkelangen town has little influence on flooding risk, unless riparian areas (wetlands or floodplains) are managed to become flooded during heavy precipitation incidents or snow melt. We did not account for the mitigation impact of the additional storage instantiated by the creation of a longer channel, as we would need more information on current river morphology and the shape of the re-meandered river, which was beyond the scope of this project.

Although the retention capacity and the total area of bioactive surfaces of the re-meandered part of the stream will be increased, we expect relatively low influence on pollution mitigation at the catchment level. Nevertheless, coupling re-meandering with re-establishing substrates should realign the potential for ecological development towards the natural trajectory of the stream. In other words, re-meandering the section of Lierelva is expected to improve biodiversity and ecological quality if the water quality is good or high due to increased quantity, quality, and heterogeneity of available habitats.

3.6.6 Restoring the peat land in Liermåsan and Bliksrudmåsan

Halting peat extraction activities in Liermåsan and Bliksrudmåsan and closing the drainage canals would provide a measurable risk reduction of flooding in Bjørkelangen town (chapter 3.5). As discussed above, there is a non-linear correlation between flood reduction potential and area converted to natural peat land. In terms of establishing costs, this mitigation option is by far the most cost-efficient and has potential for substantially reducing the flooding risk. Moreover, this mitigation option is affiliated with more and stronger added benefits in terms of reducing nutrient concentrations and providing a carbon sink that can store increasing amounts of carbon with time. Restoring peat land probably has limited effects on stream biodiversity but can improve terrestrial and semi-aquatic biodiversity in the riparian area.

3.6.7 Establishing a wetland in Kjelle

Establishing wetlands along the main stream corridor has potential to reduce flooding risk, but the risk reduction potential depends on the spatial scaling of the project and the geological setting of the area (i.e. soil infiltration capacity). Principally, the risk reduction potential of establishing a wetland in Kjelle can be compared with the reported effects of restoring Liermåsan due to the generalised approach applied to evaluate reduction of flooding risk. Similarly, added benefits include potential for reducing nutrient concentrations, and biodiversity improvements for terrestrial or semi-aquatic species.

4 Conclusion

We found that restoration of Liermåsan and Bliksrudmåsan was affiliated with highest cost-efficiency in terms of flood protection potential, significant nutrient removal potential, highest potential biodiversity benefits, and containing, as the only flood mitigation measure, an additional benefit of continuous carbon sequestration (i.e. acting as carbon sink). Restoration of Liermåsan and Bliksrudmåsan should follow the recommendations of Land (2018) in order to optimise (time to) restoration success of a fully functional and biodiversity rich peat area acting as carbon sink.

Restoration of Liermåsan and Bliksrudmåsan showed a potential of storing approximately 4-5 % of the total water volume comprising maximum daily peak flow and approximately 2-3 % in context of future climate change. Importantly, however, the total water storage capacity increases non-linearly with increasing area of peat land. Liermåsan and Bliksrudmåsan comprises approximately 3% of the total catchment but establishing peat land in 5% of the catchment would create a 10% flood reduction. Converting 10% of existing land use to peat land would create a 38% flood reduction. Consequently, peat land restoration holds strong potential for flood mitigation in the catchment of Bjørkelangen and holds the additional benefits of reducing in-stream nutrient concentrations and improving conditions for terrestrial and semi-aquatic biodiversity.

We found that construction of small debris dams in forested areas at approximately 4,500 sites would provide retention capacity of approximately 10% of the total water volume comprising the 1-day peak flow. In context of future climate change with expected increased peak discharge, the total water storage capacity in the dam impoundments approximated 5% of the total water volume comprising maximum daily peak flow. The number of dams was not linearly correlated with total water storage capacity, and strategic investments in establishing the 1,000 debris dams with highest storage capacity would ensure a total water storage capacity of approximately 5% of the total water volume comprising maximum daily peak flow (2-3% in context of future climate change). Although not affiliated with noteworthy direct added benefits (pollution reduction and biodiversity improvements), small debris dams have the benefit of land use requirements not conflicting with a broad suite of different land use interests as they are restricted to the industrial forestry areas.

Re-meandering of Lierelva, by itself, may have significant positive effects on flood mitigation in Bjørkelangen town if the re-meandered section additionally is re-connected with the floodplains. Re-meandering creates a longer water course with lower slope and consequently decreases discharge capacity (holding back more water). Ideally, this should be exploited by allowing riparian areas to become flooded during heavy rain or snow melt events. Importantly, re-meandering is expected to significantly improve biodiversity and ecological quality if the water quality does not restrict new species from colonising the created habitats.

Of the three flood mitigation measures considered in detail in this report, **the restoration of Liermåsan and Bliksrudmåsan along with mapping additional areas holding potential for establishing peat land should hold highest priority among decision makers** in order to successfully combating the increasing flooding problems in Bjørkelangen. Establishing small debris dams may be considered a viable supplemental flood mitigation measure as well as re-meandering Lierelva, but re-meandering Lierelva needs to be supplemented with establishing flood prone wetlands in the riparian areas.

The modelling of flood reduction potential from restoration of Liermåsan and Bliksrudmåsan relies on the premise that the soils are always permeable for water penetrating through the soil matrix. Natural peat lands are characterised by chronically wet soils, and the water saturated and anaerobic conditions prevailing in peat soils is exactly what causes peat lands to act as carbon sinks. Hence, our model results of water storage capacities in restored peat land areas may overestimate the flood reduction potential. On the other hand, hydrologic functions of peat mimics those of a sponge (unless it is frozen) with a continuous release of water from the soil matrix during dry periods and a significant passive uptake of water during flooding events.

The modelled strong flood reduction potential of creating functional peat lands outperforms the flood reduction potential of re-meandering Lierelva and creating small debris dams in the upstream catchment, but to fully protect Bjørkelangen from future floods they need to be combined. Nevertheless, we emphasize that restoring Liermosen and re-creating peatland in additional lowland areas upstream Bjørkelangen most likely need to become part of future combinations of flood protection measures to be able to fully protect Bjørkelangen from future floods.
We also emphasize that the flood protection measures most likely need to be deployed upstream Bjørkelangen city and not inside Bjørkelangen city or as reduced water levels in lake Bjørkelangen as the last option conflicts with biodiversity protection and obligations to secure good ecological quality in lake Bjørkelangen.

It should be noted that the methods evaluated in this document focussed on estimating the total amount of water flowing during a day. This quantity might be a good proxy to assess the storage capacity required to contain slowly rising water levels. Flooding incidents, however, might travel as fast waves (especially in the case of flash floods) and more water retention capacity might be required to contain them. Fast flood waves might not currently be a common occurrence, but the situation might become different as precipitation patterns are altered under a changing climate. To identify the measures required to mitigate such floods would require a different kind of modelling running at high temporal resolution, e.g. an hydraulic model for the catchment of Bjørkelangen driven by a high frequency hydrological model, which could then be used to quantify the expected magnitudes of flood waves as they travel through the basin.

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