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A Conflict between Traditional Flood Measures and Maintaining River Ecosystems? A Case Study Based Upon the River Lærdal, Norway

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Abstract: Floods are among the most damaging of natural disasters, and flood events are expected to increase in magnitude and frequency with the effects of climate change and changes in land use. As a consequence, much focus has been placed on the engineering of structural flood mitigation measures in rivers. Traditional flood protection measures, such as levees and dredging of the river channel, threaten floodplains and river ecosystems, but during the last decade, sustainable reconciliation of freshwater ecosystems has increased. However, we still find many areas where these traditional measures are proposed, and it is challenging to find tools for evaluation of different measures and quantification of the possible impacts. In this paper, we focus on the river Lærdal in Norway to (i) present the dilemma between traditional flood measures and maintaining river ecosystems and (ii) quantify the efficiency and impact of different solutions based on 2D hydraulic models, remote sensing data, economics, and landscape metrics. Our results show that flood measures may be in serious conflict with environmental protection and legislation to preserve biodiversity and key nature types.

Keywords: river; ecosystem; flood; protection; EIA; HEC-RAS; hydraulic modeling; dredging; mitigation; management; impact; fish; wall confinements; floodplains

1. Introduction

River flooding is one of the most damaging of natural disasters, causing potentially significant disruption to critical services such as energy, water provision, infrastructure, and transport. River flooding can also have detrimental effects on the life and health of the local population and disrupt society by hampering transport of goods and persons [1,2]. Flood damage comprises a third of the economic losses inflicted by natural hazards worldwide, and between 1980 and 2018, the global direct economic losses due to floods exceeded $1 trillion and more than 223,000 people lost their lives. Storms continued reaching record levels in 2020 in Europe [3,4].

Future flood risks are likely to increase due to two factors: climate change [5] and land use modifications [6]. First, climate change will affect the water cycle substantially by generating more intense local rainfalls, storm surges will be more frequent and severe [7] and sea level will rise. Although there is considerable uncertainty as to the magnitude of this impact between different regional projection scenarios, climate change has the potential to substantially change human exposure to flood hazards [8,9]. Second, land use will influence flood risk due to human activity, for example, vegetated soils being replaced with impermeable surfaces, leading to increasing overland flow and reduced infiltration [9].

Structural flood mitigation measures are essential to prevent river flooding and therefore are an important focus area for the work of managers and engineers globally. The choice of the most appropriate flood risk mitigation approaches will be vital in the future when considering sustainable river management in terms of natural hazard protection and environmental preservation [10].

Traditional flood measures such as dredging or embankments can have unintended side-effects on the river system. Dredging is used to enhance water transport capacity, and, in its most extreme form, realigns river channels by creating linear, channelized watercourses to convey flood water past critical areas [6]. Several studies have shown that dredging can increase flood risk for communities downstream, destabilize riverbanks, cause erosion, and damage infrastructure [11–16]. Embankments are constructed along riverbanks to prevent the water from entering key residential, agricultural, or urban floodplain areas. However, studies have shown that overbank flow in rivers can improve storage capacity and water quality [6,10,17].

The impact of dredging on fish communities has been shown in several studies, and in many areas, fish population plays an important role in river management [17]. The distribution and abundances of trout and salmon are strongly influenced by their habitat [18]. Modifications in the riverbed can have an impact on spawning and shelter areas, both of which are key factors controlling fish size [19]. Removing gravel can damage vital spawning grounds for species of conservation concern, such as Atlantic salmon, brown trout, European bullhead, and lampreys [6]. Access to shelter in the form of interstitial spaces is crucial in providing protection from predation and reducing energy expenditure [19]. This shelter is especially important in the vicinity of spawning areas where parr density becomes particularly high. Riverbed modification can also influence egg and embryo development, which is dependent on factors like water quality, temperature, and gravel composition [19,20]. Research has shown that models that integrate hydrology, hydrodynamics, and other physical data are appropriate to evaluate the habitat sustainability for fish in river ecosystems [21].

Additionally, IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services) reports an alarming loss of biodiversity, mainly due to alterations in land use [22]. Floodplains are essential ecosystems for supporting biodiversity and providing goods and services to society [23,24], but they are being threatened by human efforts to avoid floods. Modification in lateral connectivity has a strong effect on natural dynamics, habitat heterogeneity, and macroinvertebrate richness [25], but this lateral connectivity is often disrupted. Traditional engineered flood control measures, such as dredging and wall confinements, have significant impacts on river and floodplain ecosystems, therefore threatening the environment biodiversity [20–22].

In Norway, water damage related to weather and natural damage has cost 27 billion NOK (3.2 billion USD) over the last 10 years [26]. Research has shown that if political and economic interests exist and the government is willing to pay, flood measures are often carried out rapidly at the expense of weaker environmental interests [27]. The river Lærdal is an example of this, where the Norwegian Water Resources and Energy Directorate (NVE) has proposed traditional flood mitigation measures, including confinement within walls and dredging of the riverbed. The Lærdal case illustrates a typical situation that will occur in many areas where human settlements and important infrastructure are exposed to floods and where the proposed flood protection measures can severely impact important ecosystems and habitats. The river Lærdal is designated a national salmon river as it is recognized for its importance for the population of Atlantic salmon. The national salmon rivers legislation states that threats to the salmon population should be eliminated or mitigated if elimination is not possible. Further, the Nature Diversity Act protects both biological and landscape diversity, and, in this case, in-stream habitat and riparian vegetation will be removed for flood protection purposes [28].

During the last decade, sustainable reconciliation of freshwater ecosystems with human activity has increased. Traditional methods for flood protection are in conflict with modern methods. For example, embankments disconnect floodplains from the river system. River managers are turning from hard engineering solutions to ecologically based restoration activities in order to improve degraded waterways [29]. The idea of giving space to rivers is crucial in large river restoration. Opperman [10] proposed that a large-scale shift in land use and policy is needed to achieve economically and environmentally sustainable floodplain management. One of the first issues within this framework is reconnecting the main channel with secondary side channels [30,31]. This would increase the capacity to capture and store water, working with nature rather than against it [6]. The EU Water Framework Directive is aimed at enhancing basin-wide management of water resources, which appears to be a step in the right direction in terms of adaptation [32].

This paper aims to (i) illustrate the dilemma between traditional flood measures and maintaining river ecosystems and (ii) quantify the efficiency and impact, utilizing new methodology that includes 2D hydraulic models and remote sensing data. This is applied in the study case of the river Lærdal in Norway where flood protection measures are planned to be implemented.

2. Study Site

The Lærdal basin (1183 km^2) is located in the county of Sogn og Fjordane, in western Norway (Figure 1). Lærdal has experienced historical large flood events [33]. Flooding of the Lærdal river results in flooding of the village of Lærdalsøyri, located at the mouth of the river on a large floodplain. It has a population of 1120 inhabitants and 161 historic buildings that represent one of the best preserved original old wooden house communities in Norway. The authorities have proposed conventional channelization works that include confinement with walls and dredging in the riverbed as a future risk mitigation action. This proposal has caused the discomfort of several stakeholders, because the river Lærdal is a national salmon river, Ola Petter Bø (pers.comm.), and internationally recognized for its recreational and historical fishing for Atlantic salmon and sea trout. Flood risk mitigation measures are therefore considered potential threats to the river ecosystem, and environmental perspectives are particularly important. Conventional flood risk mitigation measures should be challenged. Lærdal is an 81 km long river with an average flow of 36 m^3/s; the peak discharge for the 200-year flood is 920 m^3/s. The river reach analyzed in this study is a 5 km reach on the lowermost part of the Lærdal river that includes several small weirs and flood control walls [34].

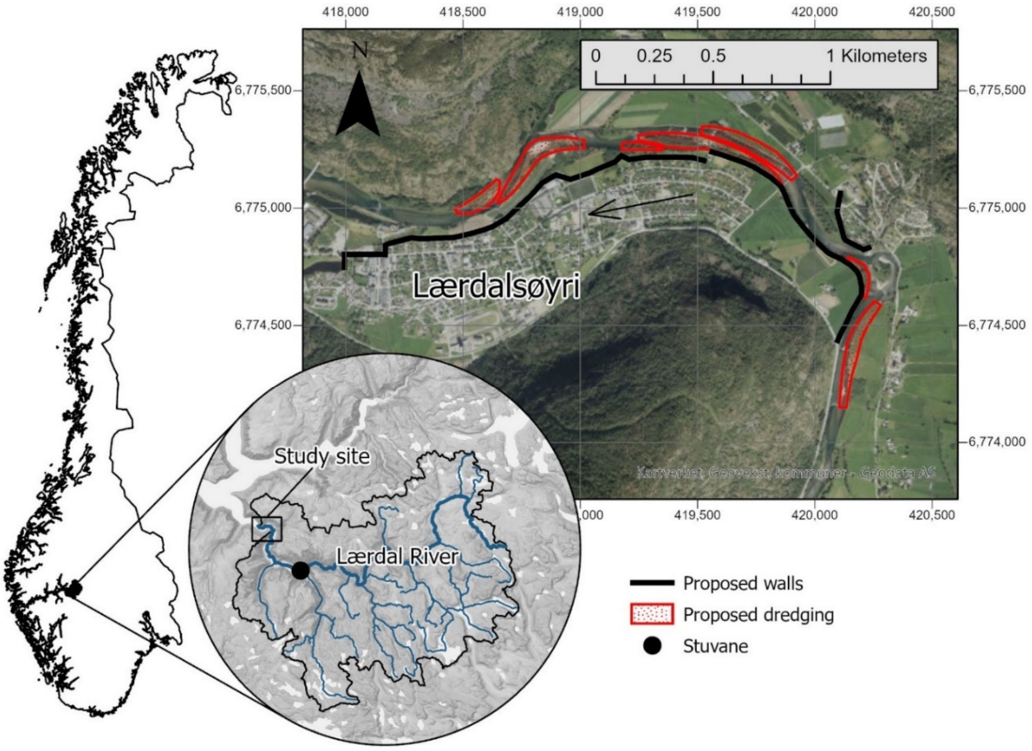

Figure 1. Illustration of Lærdal catchment location in Norway, location of the selected study area in the lowermost part of the river, Lærdalsøyri village, and proposed walls and dredging in the riverbed.

3. Materials and Methods

The methodology followed in order to analyze the flood and environmental impact is divided into three main stages described in the subsequent sections: pre-processing, processing, and postprocessing (Figure 2).

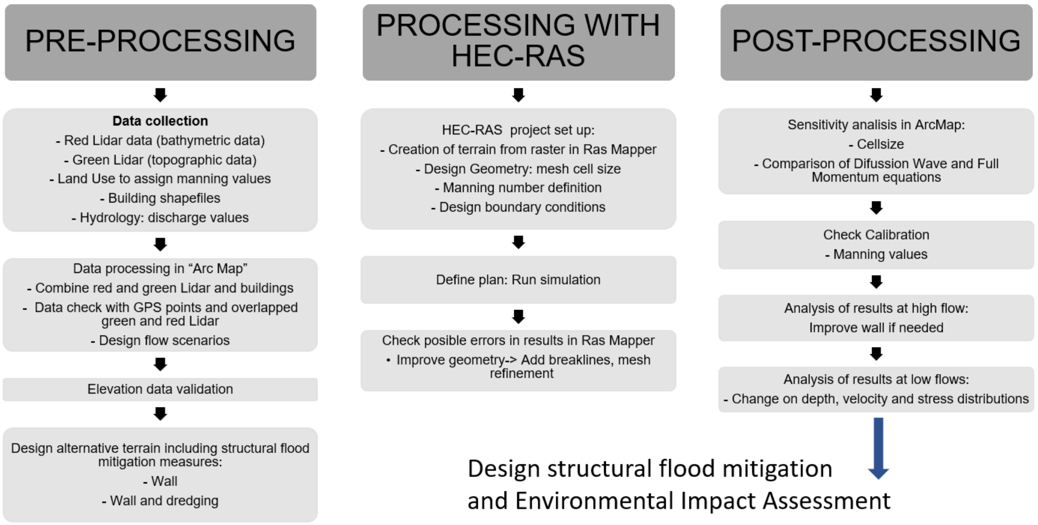

Figure 2. Workflow scheme of the methodology applied including pre-processing, processing with HEC-RAS, and post-processing.

3.1. Pre-Processing

The objective of the pre-processing is to obtain input parameters for simulation in HEC-RAS [35], which includes the terrain elevation (before and after modifications), land use, different flow scenarios, and tidal data.

The core of the preprocessing stage is the creation of the digital terrain model (DTM). The main data source is the river bathymetry attained by green LiDAR. This is a remote sensing technique for mapping relatively shallow water bodies, which is increasingly used for topo-bathymetric surveys providing a high-quality digital elevation model [36]. The data was collected by Airborne Hydro Mapping (AHM) from Austria on 29 May 2018. The survey was carried out with a measured flow of 97 m^3/s on the Stuvane gauge. Data for the bathymetry were delivered by NVE in LAZ format. The measured water edge was used for testing different cell sizes and Manning values. The green LiDAR has been merged with red LiDAR that contains data for the floodplains. These data were made available by the Norwegian Mapping Authority (Kartverket). The coordinate system utilized has been ETRS1989 UTM Zone 32N (xy coordinate system) and NN2000 (z coordinate system).

The coverage and precision of the data were checked prior to the construction of the hydraulic model. The green LiDAR was verified to cover the entire riverbed, with a total of 744,993,985 points and an average point spacing of 0.123 m, which meant additional surveys were not needed. The precision was compared with the red LiDAR where data were overlapped. Additionally, the data were also compared with RTK-GPS points taken during fieldwork in Lærdal in May 2019. The analysis showed that the green LiDAR data have a high resolution and density and are perfectly suitable for our study [37].

The combination of red and green LiDAR data sets had a high point density that allowed for a raster interpolation of 0.35 × 0.35 m resolution. In addition, the elevation model from Høydedata was a DTM (containing only ground surfaces), so the buildings had to be included in the terrain afterwards.

Flood control works are proposed in the form of channelization that includes confinement with walls and dredging of islands and the riverbed (Figure 1 and Appendix A). The terrain modifications were implemented in the model using ArcGIS and RasMapper in HEC-RAS. The channelized version of the terrain results in a lower riverbed than the current river (Appendix A).

The land use distribution was obtained from the Norwegian Mapping Authority (Kartverket), and different Manning values have been assigned according to the literature [38].

3.2. Flow and Tide Data

The gauge station Stuvane located 10 km upstream of our model boundary has been used to obtain the flow values. In the absence of observed data under a flood event, the model was calibrated using the discharge value of the day of the flight when the underwater bathymetry was collected. The measured discharge was 97 m^3/s. A correction was made to compensate for the additional catchment flow contribution between the gauge and the upstream boundary condition. This part of the catchment is unregulated, and after studying the surrounding stations, it was correlated with the gauge in Flåm bru, located in a neighboring catchment, 35 km southwest in the river Flåm. The final discharge used to calibrate the model was 106 m^3/s [37]. The upstream boundary condition is defined 5 km upstream of the mouth of the river where the hydrograph is defined. The downstream boundary condition is in the fjord and defined by a stage hydrograph with the highest average tide at 1.24 m.

The discharge value used in the flood analysis is calculated for a 200-year flood event, 920 m^3/s, estimated by NVE [39].

3.3. Processing with HEC-RAS

Three separate 2D hydraulic models were utilized: (i) without any structural constructions to study the impact of the flood, (ii) with the structural wall confinement to study the flood mitigation, and (iii) with the structural wall confinement and dredging of the riverbed as proposed by authorities.

Two-dimensional hydraulic geometries with a cell size of 3 × 3 m (for the flood model) and 1 × 1 m (for the habitat analysis) (Figure 3) were developed using the HEC-RAS 5.0.7 and HEC-RAS 6 Beta 3 software created by the US Army Corps of Engineers [35]. The cell size was selected as a compromise between computational time and precision. Additionally, a geometry with a cell size of 2 × 2 m was tested for the flood models. The computational interval was set to be controlled by the courant condition with a final value of 0.22 s.

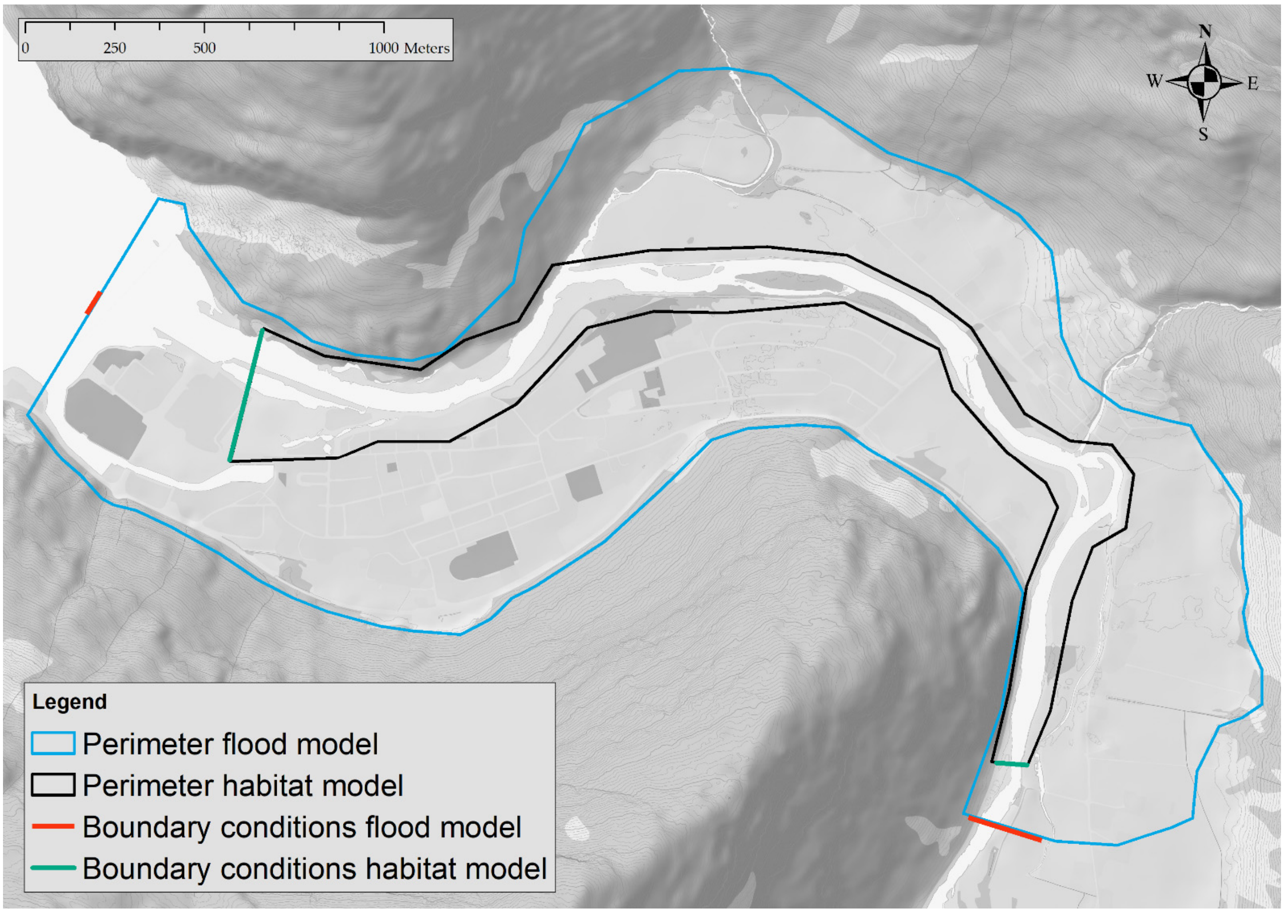

Figure 3. Location of the perimeters and boundary conditions in the HEC-RAS geometry for both the flood model and the habitat model.

3.4. Post-Processing

The water edge line provided for the LiDAR company was used for the sensitivity analysis. Three zones in the domain were selected for testing of varying input parameters, comparing the wetted area between the LiDAR data and HEC-RAS simulation of the same discharge (106 m³/s). The error computed as:

$$Error\ (\%) = \frac{Abs\ (Area_{measured} - Area_{simulated})}{Area_{measured}} \quad (1)$$

The water edge line was also used for the calibration of the model. The model was calibrated by comparing different Manning values in the riverbed and calculating the error as in the previous equation. The final Manning number chosen according to previous studies was 0.035 [37].

3.4.1. Effects on Habitat and River Use

Lærdal is a national salmon river, and the state of the salmon habitat and recreational fishing regulation is protected by law and important for preserving the Atlantic salmon population for the future. We identify low, average, and high flow values (10, 30, and 65 m^3/s, respectively), analyzing daily data recorded in the gauge station of Stuvane from 1987 to 2018. Based on modeling results for these flow values, several aspects of the riverine ecosystem could change due to channelization, focusing on salmonid habitat and other uses of the river such as recreational fishing. Habitat heterogeneity has been used as a proxy to evaluate physical changes that could potentially impact salmonids at different life stages such as juvenile, adult, spawning, and fish migration. Histograms for water depth and velocity were computed to evaluate the changes before and after the channelization for the overall distribution in the riverbed. The Shannon diversity index [40] was used as an indicator for the spatial heterogeneity changes, which was computed using the R package Landscapemetrics [41]. Depth and velocity distributions were contrasted with current substrate, shelter, and spawning availability maps [42] in order to provide an overarching discussion of the potential impacts on salmonids for the different life stages. Recreational fishing impacts were estimated based on meso-habitats, as outlined by Barton et al. [43], and the changes in meso-habitats after calibration were based on an approximation of the method described in Casas-Mulet et al. [44].

In addition, sediment stability has been analyzed under high flow conditions after channelization, bearing in mind the placement of graded sediments on the riverbed to adapt it to the needs of the aquatic fauna as a potential mitigation measure to the effects of channelization. In this regard, to define the minimum diameter of material that will not be washed out by the flow, a sediment stability assessment was made employing the Shields equation as proposed by Guo [45], which allows computing the critical shear stress required for incipient motion of a sediment particle of a specific diameter. The Shields equation is expressed as:

$$\frac{\tau_c}{(s-1)\,\rho g d} = \frac{0.11}{Re_{*c}} + 0.054\left[1 - \exp\left(-\frac{4Re_{*c}^{0.52}}{25}\right)\right] \tag{2}$$

in which:

$$Re_{*c} = \frac{d u_{*c}}{\nu} \tag{3}$$

and:

$$u_{*c} = \sqrt{\frac{\tau_c}{\rho}} \tag{4}$$

where: τ_c: critical shear stress (N/m^2); s: specific gravity of the sediment; ρ: density of water (kg/m^3); g: gravitational acceleration (m/s^2); d: sediment particle diameter (m); Re_{*c}: sediment particle critical Reynolds number; u_{*c}: critical shear velocity (m/s); ν: kinematic viscosity of water (m^2/s).

3.4.2. Cost Calculation

Cost calculations for the wall construction and the riverbed dredging have been made to assess the different structural flood-protection measures. Two cases were assessed: (i) construction of the wall alone (pre-dredging) and (ii) construction of the wall and dredging of the riverbed (post-dredging) (Figure 4). Assuming the wall construction is inevitable, the purpose of this assessment is to compare (1) the volume and cost of the riverbed dredging (ΔV_b) and (2) the additional cost of the wall required to obtain the same flood-protection as the post-dredging scenario by further increasing the wall height instead of dredging the riverbed (ΔV_w). The additional wall cost was calculated with the additional height required (ΔH) by comparing the WSE (water surface elevation) in the models pre-dredging and post-dredging. In the cost analysis, only the areas for dredging preselected by the authorities were considered.

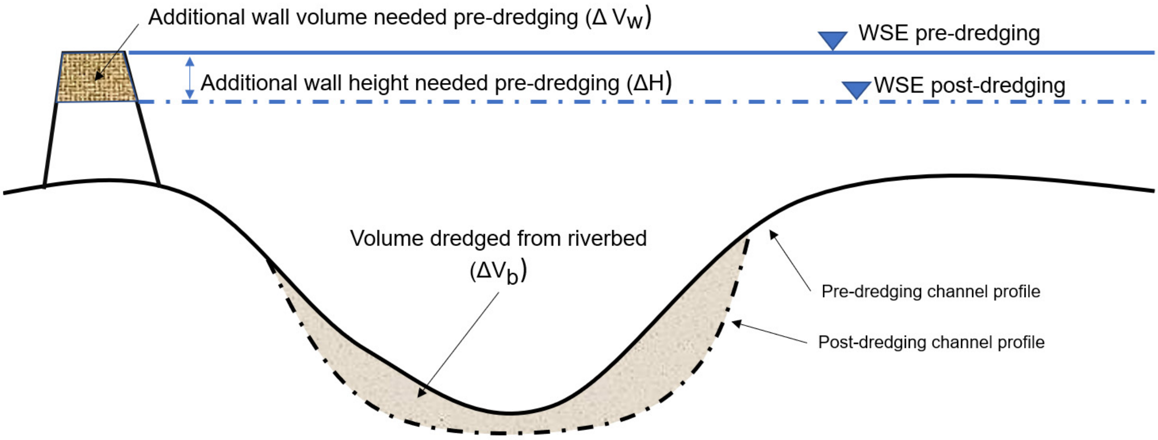

Figure 4. River profile scheme that shows the WSE and channel profile for (i) pre-dredging (continuous line) and (ii) post dredging (dotted line); the additional wall height needed pre-dredging (ΔH); the additional wall volume pre-dredging (ΔV_w); and the volume dredged from the riverbed (ΔV_b).

The unit cost has been extracted from the Cost Basis for Small Hydropower Plants developed by NVE [46]. The fundamental assumption comes from the wall being constructed with an impervious core made of clay or similar material, a geotextile membrane on each of the faces acting as a filter, and an outer riprap layer to protect against the scouring of both upstream and downstream faces with slopes of 2.5:1 (H:V) and 2:1 (H:V), respectively. The additional wall height section was considered immediately below the freeboard segment of the wall. The freeboard segment is assumed to have a height of 1.5 m with a top width of 3.5 m for constructive reasons, leaving the top width of the additional height section to have 10.3 m and a height of either 0.30 or 0.60 m. The resulting unit costs are 692 NOK/m (83 USD/m) for the 0.30 m in height and 1469 NOK/m (176 USD/m) for the 0.60 m in height section.

The dredging cost was estimated to be 85 NOK/m^3 (10 USD/m), without consideration of the possible diversion of the river or other similar measures during the construction period.

The lengths for the additional wall height and the dredging volumes were calculated by comparing the different cases in QGIS [47] with the raster calculator and other similar sampling tools.

3.4.3. Calibration and Sensitivity Analysis

The first simulation was performed at 106 m^3/s, as it could be compared to the water-covered surface the day of the flight. The calibration was performed by changing the Manning values of the riverbed, since it was proven to be the most influential parameter. A final value of 0.035 offered the most suitable results. The calibration shows that a Manning value of 0.035 in the riverbed has an error in the water-covered area of 4%, within a suitable range for the objective of this study [48]. The cell size and equation set were proven not to have a significant effect in the model with less than 2% in the difference in the water covered area. The cell size was finally set to 3 × 3 m for the flood simulations and 1 × 1 m in the habitat simulations.

4. Results

4.1. Flood Results

The results for the flooded area with a discharge of 920 m^3/s (200-year flood) are shown in Table 1. Additionally, the relative decrease in flooded area considering no mitigation measures as reference is displayed in the table. The results indicate that floods of 920 m^3/s inundate an area of 2,130,393 m^2, and the construction of the wall would decrease the inundated area by 28%, while both construction of the wall and dredging in the riverbed would decrease the inundated area by 36% (Figure 5).

Table 1. Flooded area (m^2) and relative decrease of flooded area (%) for the present scenario (no mitigation); only wall (pre-dredging) and wall and dredging (post-dredging). The results are shown for a discharge of 920 m^3/s.

Q = 920 m^3/s	Area (m^2)	Relative Decrease
Present/no mitigation	2,130,393	0%
Only wall/pre-dredging	1,539,782	28%
Wall and dredging/post-dredging	1,358,918	36%

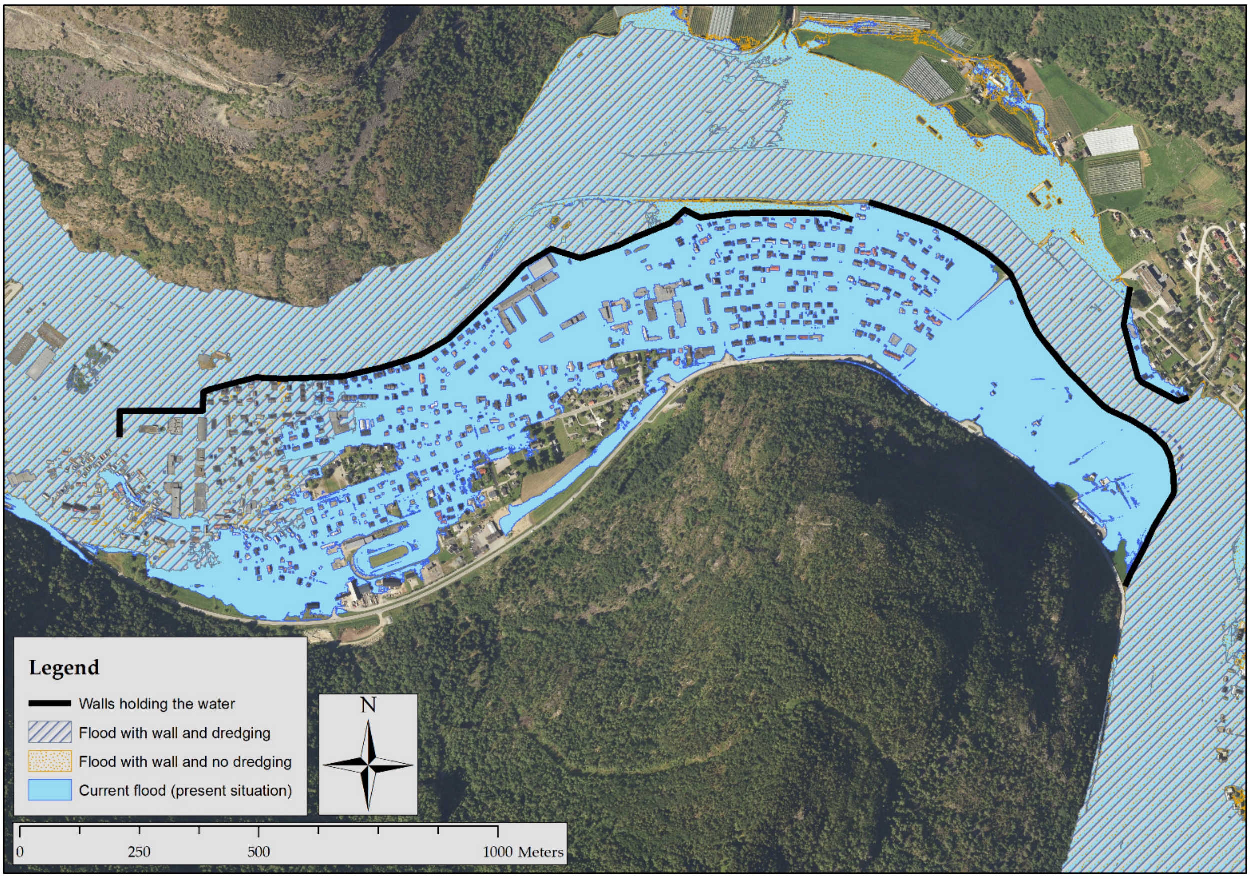

Figure 5. Flooded area at current situation (blue), with wall and no dredging (dotted) and with wall and dredging (stripes) with discharge 920 m^3/s.

The comparison of WSE of the simulation pre-dredging and post-dredging show how much higher the wall needs to be in order to provide the same flood protection in the pre-dredging (only walls) scenario as in the post-dredging (walls and dredging) scenario for Q = 920 m³/s (Figure 6).

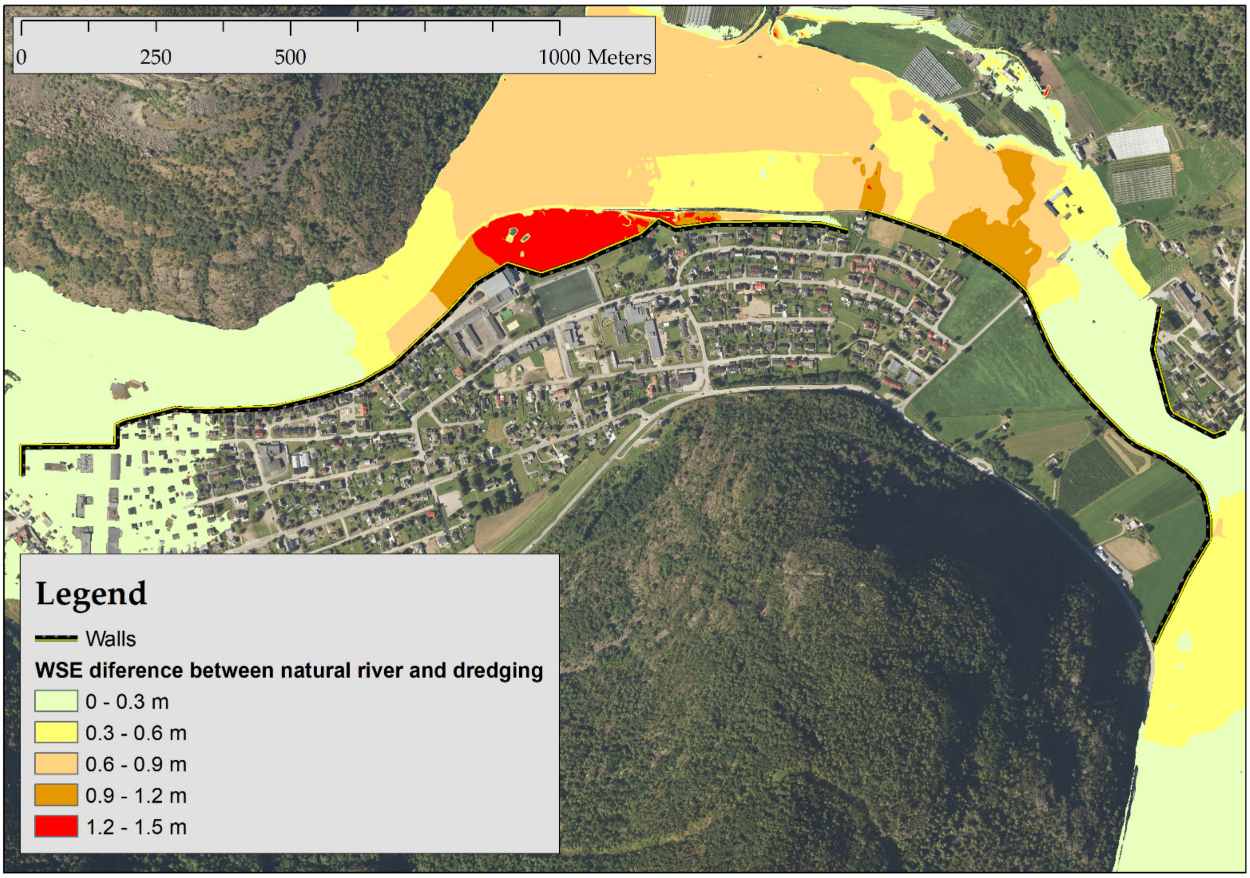

Figure 6. Difference in WSE with natural river and modified terrain with wall and dredging at Q = 920 m³/s.

4.2. Habitat Analysis

Histograms and accumulated depth and velocities are shown in percentages in Figure 7. The results yield a loss in diversity of both depth and velocity. At low (10 m³/s) and average (30 m³/s) flow, 75% of the depth is below 1.5 m prior to modification, which is reduced to 0.5 m after modifications. In conditions of high flow (65 m³/s), it is observed that 75% of depths are below 1.5 m before modifications, which is reduced to 1 m after reduction measures. The sum of the percentage of area for velocity also shows smaller variability for the channelized river (see Figure 7c,d). To further evaluate changes in depth and velocity diversity, the Shannon index was computed for each case. This study found a reduction in average diversity for depth from 2.4 to 1.42 after mitigation measures. Introducing mitigation measures also reduces the diversity of velocity from 1.99 to 1.71.

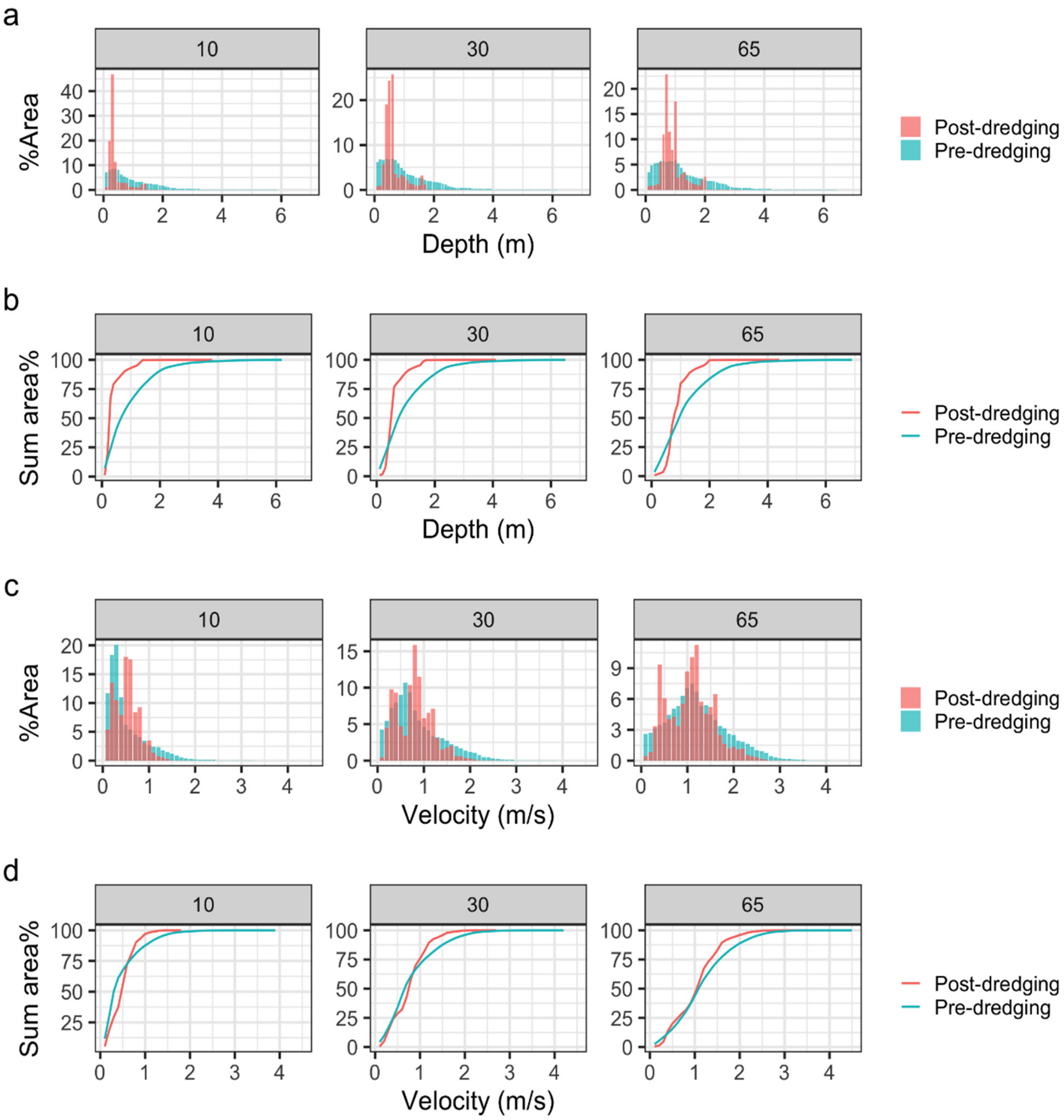

Figure 7. Histogram in % (**a**,**c**) and accumulated area in % (**b**,**d**) for depth and velocities at low, average, and high flows (10, 30, and 65 m^3/s).

From Figure 8, it can be observed that deep areas are concentrated in the lower end of the reach after channelization, while the deep habitats are more scattered along the reach prior to the flood protection works. The maximum depth without measures is 6.13 m, while depth after channelization is maximum 3.64 m, thereby eliminating the deepest pool sections (Figures 7b and 8). Maximum velocity values are also decreased from 4 to 2.5 m/s (Figure 7d).

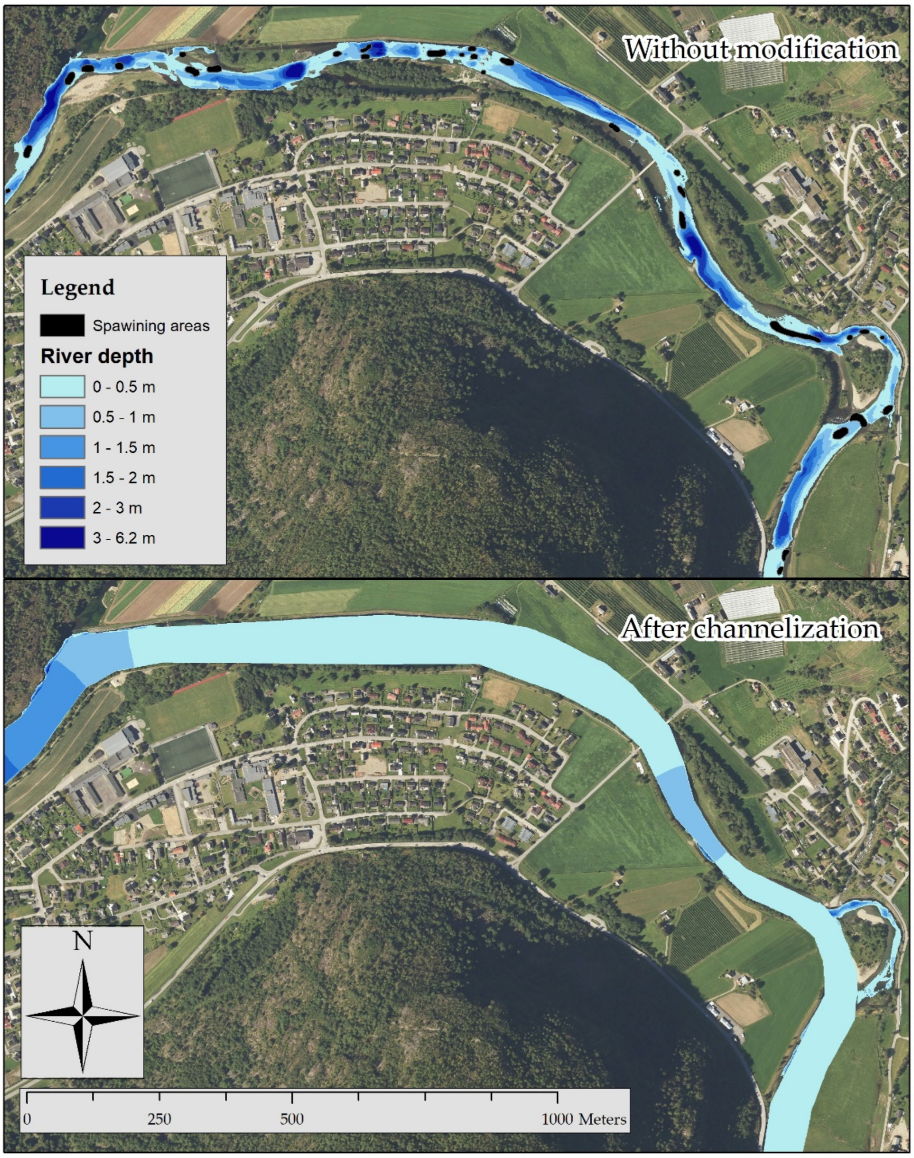

Figure 8. Map of river depths without river modification (top) and after channelization (bottom) at 10 m^3/s.

After channelization, the absolute depth value decreases from 6 to 2 m, pool habitats and deep glides [49] are nearly eliminated from the river, and these are important habitats for recreational fishing, as outlined by Barton [43]. Shallow glides still exist in the reach, but now without deeper holding areas. This indicates that the recreational fishing potential would be reduced as a result of the planned flood protection work.

The modifications in the riverbed show a change in magnitude and distribution of shear stress that could lead to particle movement (Figure 9), predominantly movement of particles up to 5 cm. The dominant substrate type consists of rocks between 6.4 and 38.4 cm [42], with a presence of sand and boulders in other areas within the reach. The change to a most uniform shear stress distribution (Figure 9) could lead to the disappearance of the minority substrate types.

Figure 9. Map of particle movement according to shear stress with flow of 65 m^3/s.

4.3. Cost Calculations

The results from the cost calculation show that the total cost of dredging is 11 million NOK (1.3 mill USD) (Table 2), while the extra cost of the wall would be 5 million NOK (600.000 USD) (Table 3). Therefore, the solution of only using a higher wall would be 2.16 times cheaper than using the walls and dredging.

Table 2. Number of sectors to dredge, total volume, and cost.

Number of Sectors to Be Dredged	Volume of Dredged Material (m^3)	Unit Cost (NOK/m^3)	Total Cost (NOK)	Total Cost (USD)
7	130,104	85.0	11,058,840	1,329,549

Table 3. Extra wall height needed, length, and cost.

Wall Height Increase (m)	Length (m)	Cost (NOK)	Cost (USD)
0.00	458	0	0
0.30	1095	758,316	90,936
0.60	711	1,044,170	125,216
0.90	287	669,412	80,275
1.20	348	1,138,558	136,535
1.50	326	1,399,552	167,833
Total	3225	5,010,008	600,797.25

5. Discussion

Flooding is a natural hazard that is likely to increase with the effect of climate change [5]. Simultaneously, development in floodplains increases the people at risk, while compacted soils and modified upstream areas channel more water down the catchment at a faster rate [6,10]. This will lead to low urban areas being exposed to a greater risk of flooding. Traditional flood measures such as dredging the riverbed and embankments are usually seen as flood protection measures, but it has been shown that its capacity to carry floods is limited and it can have direct and indirect consequences for ecosystems [50,51]. In this paper, we show that there is a conflict between traditional flood measures and maintaining river ecosystems. We also show how 2D hydraulic modeling and LiDAR data can help in providing quantitative data for different flood mitigation measures. This is applied in the study case of the Lærdal river, in Norway, a national salmon river that has experienced historical large floods.

Different 2D hydraulic models were utilized to study the effects of these measures on flooding and potential fish habitats. Different terrain configurations have been created: (a) without any structural constructions to study the impact of the flood, (b) with the structural wall confinement to study the flood mitigation, and (c) with the structural wall confinement and dredging of the riverbed. This research shows how much taller the wall would have to be in order to have the same effect in decreasing the flood risk in the town as dredging the riverbed (Figure 6). Increasing the wall height would have an impact on the landscape in the riverbank, but dredging could be avoided. In this case, we consider that a 2D hydraulic model is more suitable for the case, as it is possible to simulate overtopping over a levee, where the water goes in many different directions [52].

The results of the habitat study show a loss of diversity both in depth and velocity after river channelization. The Shannon diversity index depicts a reduction in the deep areas and loss of deep pools, shown in Figure 8. Despite these changes, juvenile habitat would still be present based on suitable depth and velocity parameters from the literature [18,42]. Shelter, on the other hand, was classified as poor in the study area by Skår [42]; the main reasons were related to the deposition of fine sediments in the interstitial spaces between the gravels and rocks and the low gradient, weirs, and low velocities. Therefore, there are reasons to believe that the conditions after channelization could also lead to sedimentation problems from reduced velocities and hetereogeneity, and consequently poor shelter conditions, particularly under low flow. The reduction of pools and increased homogeneity would potentially also impact shelter and refuge for adult salmonids. Current spawning areas [42] were predominantly mapped in areas that overlap with high diversity areas, such as pools and upstream small weirs; therefore, regardless of possible adequate depth and velocity values for spawning compared with literature values [42], a negative impact is expected from the spatial distribution changes based on the current preferences. Migration paths could be negatively impacted after channelization, as the riverbed channel is shallower, especially under low flows. In addition, the widening of the river and removal of riparian vegetation would decrease the shading on the river, affecting the temperature. Decreased temperature and lower velocities could create more ice during winter, which is an important factor that affects fish migration behavior [53]. There will be a loss of areas for recreational fishing due to the loss of diversity of fishing places, more shallow areas, and the disappearance of the suitable pool and deep glide fishing mesohabitats described by Barton [43].

The cost of the additional wall height would be 5 million NOK (600,000 USD) while the cost of dredging is almost 11 million NOK (1.3 million USD) (Tables 2 and 3). In other words, it is possible to obtain the same level of flood protection for less money without resorting to dredging of the riverbed. Other natural flood risk management alternatives have been considered that can provide high levels of biological productivity and biodiversity [24], for example, opening flood plains upstream. This measure had reduced potential in Lærdal due to the narrowness of the valley.

Dredging can have a different effect depending on the flood values used. This study highlights the importance of having a good understanding of how flood water moves through the system when studying the potential flood protection from dredging [6]. The wall confinement scenario (b) would reduce the inundated area by 28% and the wall and dredging (c) would reduce it by 31% (Table 2). This means that the gain from doing additionally dredging in comparison with the construction might not be the best solution.

However, no impact assessment can cover all the impacts related to the implementation of flood-protection measures, and the analyst needs to make choices as to what to include and exclude [2]. In this paper, we only study the walls and dredging in the proposed plan, given the properties of this catchment. It will be important to consider other natural measures in flood risk assessment in other rivers, understanding the three dimensions of river, catchment, and floodplains [10]. Preliminary data should be analyzed to consider other possible solutions, and these should include upstream storage and dampening effects.

Another limitation of our study is that we have not considered habitat mitigation measures in the channelized river. This would increase the construction costs for the channelization of the river. Our results also show that channelization leads to increased shear stress in the riverbed, increasing the potential for sediment transport, especially of particles under 5 cm, which could result in the natural removal of mitigation measures such as the placement of spawning gravel.

These results show that structural flood mitigation measures can protect the village of Lærdalsøyri. This research seeks to provide tools to assess the impact on the environment of structural flood mitigation measures. The village of Lærdalsøyri is susceptible to flood damage in the future. We evaluated different measures to protect the village from the flood, with the conclusion that constructing a higher wall could avoid dredging in the riverbed, resulting in a most cost-effective solution. An operation like the one suggested would require significant measures to mitigate the negative impacts addressed in the paper. This would significantly raise the cost of the flood protection works.

6. Conclusions

In the future climate, when current scenarios predict increased floods in many regions, adaptation to floods will be necessary, and engineered flood control measures are still a common way to implement flood control. As shown in the case study presented in this paper, such measures may be in serious conflict with environmental protection and legislation to preserve biodiversity and key nature types. It is therefore necessary to look for new methods of flood control. Our studies show that this can be achieved by putting more emphasis on flood control structures away from the riverine habitats, but future work should also evaluate other potential nature-based measures to control future floods.

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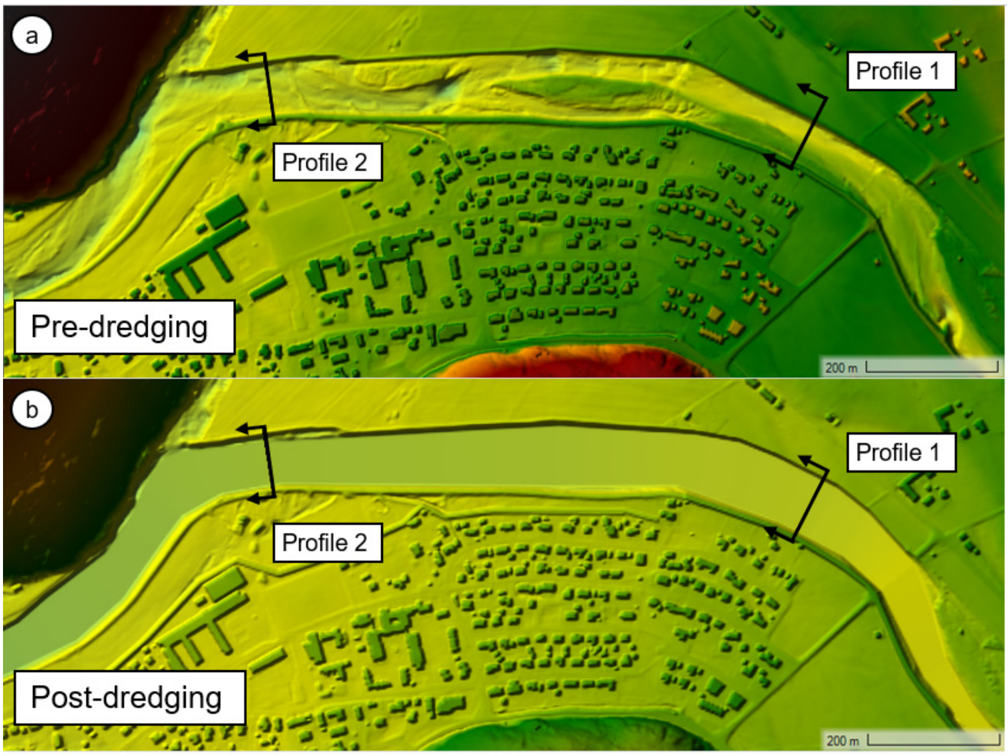
Appendix A. Terrain Pre-Dredging and Post-Dredging



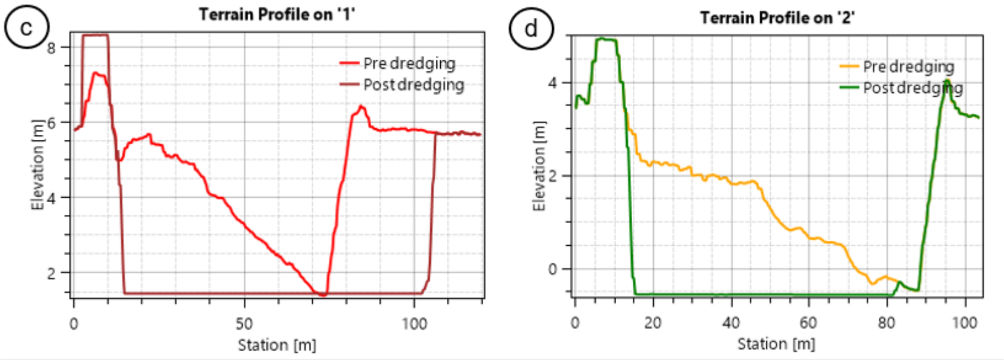


Figure A1. Terrain pre-dredging (**a**), terrain post-dredging (**b**), and profile 1 (**c**) and 2 (**d**) for comparison of both terrains.

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