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Application of airborne LiDAR bathymetry in Norway

NORCE

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Summary

New technologies in remote sensing provide opportunities for effectively sampling information on topography and bathymetry for large areas. With Airborne LiDAR Bathymetry (ALB) terrain and also the river bottom (bathymetry) can be measured with high accuracy. In this report we present our contributions to 1) validation, 2) flood risk analysis and mitigation, and 3) river restoration.

All rivers could be classified to river types according to Hauer & Pulg (2018) from remote sensing data only. ALB data can be much faster than other surveying or mapping methods and has higher accuracy. Ecological information can be acquired from ALB data in higher resolution than with other methods, and also parameters like grain size and shelter have a high correlation with ALB derivates.

The ALB datasets can be used for planning and assessing ecological and flood related questions from the desktop with a strongly reduced requirement for field work compared to data from other data sources, additionally giving a model verification with much higher accuracy and detail degree than other methods. ALB can therefore improve planning safety and speed up planning and modelling process for high- flow, low-flow, morphodynamics and ecological applications.

The Lærdal flood case study shows that advances in remote sensing can be used to develop and model nature-based and integrated solutions for improving flood safety and ecological status.

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1. Introduction

Background:

New technologies in remote sensing provide opportunities for effectively sampling information on topography and bathymetry for large areas. Light Detection And Ranging (LiDAR) is used for determining distances between a laser and an object/terrain by measurning the time the emitted and reflected light takes to return to the sensor (Heritage & Large, 2009). Conventional airborne LiDAR scanning (ALS) is used for scanning land with plane, helicopter or drone/unmanned aerial vehicle (UAV) mounted sensors. It uses red light which cannot penetrate the water surface. Airborne LiDAR Bathymetry (ALB) uses green light and can therefore also measure the river bottom (bathymetry). It is used in river science for various applications like flood risk modelling (Yoshida et al. 20121), morphodynamics and habitat monitoring (Mandlburger et al. 2015), and for assessing residual flow and hydropeaking issues (Skeie 2017; Stranzl et al. 2019). It has also been tested for bottom classification in the sea (Eren et al. 2018) and automatic classification of large boulder elements (Wiener & Pasternack 2022). Also, smaller substrate classes can to an increasing extent be detected by combining remote sensing techniques (Gomez et al. 2021).

In Norway, LiDAR ALS data covers 90 % of the country (NDH 2022), while ALB is only available for a handful of rivers. A comparison of flood modelling results reveals the huge difference in accuracy between ALS and ALB datasets with a large overestimation of wetted area from ALS modelling results (Awadallah et al. 2022). Also, for modelling low-flow conditions, red LiDAR data alone is not sufficient (Stranzl et al. 2018). Cross-section bathymetric data exists only for selected rivers in Norway (NVE 2022). While this database is regularly used for flood zone mapping, for modelling erosions zones in river corridors, low water situations or ecological information, additional planar bathymetric data is essential (Pulg et al. in prep).

Sundt et al. (2021) showed that 3-band multispectral regional models can give a good estimation of river depth with a slight overestimation in his case rivers; in his four case rivers he reached coefficients of determination of 0.47-0.91 (Sundt 2022).

Objectives

The overall objectives with the national ALB project "*Validation and application of Airborne Laser Bathymetry (ALB) technology for improved management and monitoring of Norwegian rivers and lakes (2021-2022)*" are i) Is ALB applicable for Norwegian freshwater systems such as rivers and lakes? ; ii) will ALB as a technology improve data basis and cost-benefit evaluations for management?; iii) will ALB work as a management tool across Norwegian authorities?

In the given report and as contribution from NORCE to the national project the following sub objectives are given:

- WP 1- Validation:
    - Classification of river Lærdal, Bøelva and Hallingdal according to Hauer & Pulg 2018.
    - Field sampling according to field protocol and 3D mapping applying DGPS- RTK drone.

- WP 2: Flood risk analysis and mitigation:

- Evaluate whether ALB data give a better resolution for erosion modelling compared to DGPS data or Red LIDAR.*
- Evaluate whether ALB based erosion risk model can predict real morphodynamics that happened during floods.**
- Case Lærdal: nature-based solutions applying ALB as basis for planning and testing.
    - Development of scenarios for nature-based solutions and hybrid solutions for improving the flood safety and ecological status along the town Lærdal, with ALB as a planning basis
    - Discussion of the benefits of ALB compared to traditional techniques in flood scenarios and the benefits of nature-based solutions compared with traditional flood protection

- WP 3: River restoration:
    - Test scenarios based on the mapped river reaches in Lærdalselva, Bøelva and Hallingdalselva with different restoration scenarios such as widening of river channel, reconnection of side channels, dam/weir removal, gravel addition, sediment management or other relevant techniques.***
    - Practical benefits and deficits of the ALB data are compared to conventional base data such as aerial photos, manual DGPS measures and accessible maps and altitude data.

*adapted allocated to other partners, see next chapter “Limitation”

Limitation

NORCE LFI's contribution consists of delivering field and UAV structure from motion (SfM) data and river classification across different scales and demonstrate applications of ALB for habitat mapping, modelling ecological flood protection cases and contribute with examples on river restoration applying ALB. An important aspect is therefore demonstrating cost-benefit of applying ALB datasets compared to traditional mapping and other base data.

This work is not covering all river types in Norway. Implementation of river classification is a mean to test and validate ALB as a future sampling and monitoring tool. Furthermore, NORCE contribution has been to collect field data as basis for statistical tests and validation between ALB and ground truth (here DGPS and drone-SfM). Due to unforeseen challenges in local hydrology (high discharge during field sampling) the planned field protocol and transect based approach has not been 100 % fulfilled.

Also, an important contribution from NORCE has been to support NTNU and BOKU with their analyses, and thus results given in this report is also reported partly in reports from NTNU and BOKU.

In dialog with the working partners and contracting authorities, tasks were adapted during the project:

Comparison of base data for flood risk analysis* and morphodynamic** assessment was mainly performed by BOKU and NTNU. Also, NTNU already had a readily available publication on weir removals in river Lærdal as an example for for restoration***. Therefore, a new task was introduced where ALB should be tested as a tool for planning and assessing nature based flood risk adaptions in river Lærdalselva. Ongoing work (modelling a weir removal in river Lærdal was already running based on ALB data) was finished and is discussed in the report.

Report structure

The given report is structured based on the objectives above. A detailed overview of deliverables of activities related to the objectives are given in Appendix (Table 9). Chapters are structured beginning with validation (river types, ground truth,

In an effort to answer the three research questions outlined in the introduction, we conducted field work in 3 rivers in 2020, in order to collect ground truth data for comparison with ALB data. The following subchapters describe ground truth sampling, analysis and applications which were performed on the various datasets.

1. Materials and methods

WP 1 Validation, analysis, and conceptual work

River types

In all study sites, river types on reach scale were preclassified from aerial pictures and bed slope and verified with substrate size according to Hauer & Pulg (2018). Table 1 summarizes parameters for the different river types.

Table 1: River types with typical slope, dominating substrate and pool length according to Hauer & Pulg (2018)

River type	Slope (%)	Dominant substrate	Pool length
Cascade	30-6.5	Bedrock/boulders	1 x river width
Step-pool	3-1	Boulders/cobbles	1-4 x river width
Diamictic plane bed	3-0.5	Boulders/cobble/gravel	NA
Plane bed	3-0.5	Cobbles/gravel	NA
Mixed pool-riffle	1.5-0. 1	Boulders/cobble/gravel	5-7 x river width
Pool-riffle	1.5-0.1	Cobbles/gravel/sand	5-7 x river width
Dune-ripple	0.5-0.01	Fine gravel/sand or finer	5-7 x river width

Ground truth and mesohabitat mapping

The rivers Lærdalselva, Hallingdalselva and Bøelva were chosen for mapping ground truth for this study. A field protocol was followed for collecting ground truth, the whole protocol is attached in the appendix (page 72 ff, in Norwegian).

Mapping of physical variables was performed on 15th and 16th November 2021 in Lærdal with clear water and good mapping conditions. UAV data was collected on 16th November. Discharge was 17 m^3/s on 15th November and between 21 and 23 m^3/s on 16th November. The mapped river stretch was 9.8 km long. Along the stretch were 15 cross-sections measured.

Mapping in Hallingdal was done on 13th November 2021 upstream of lake Krøderen on a length of 4.2 km. Due to high water level in the lake (water level was at kote 133 m during the field trip) and steep banks, it was only possible to wade 1- 2 m out into the river. The river is so wide and deep that approximately ¼ of the UAV sampled stretch could not be merged with SfM.

In Bøelva mapping was achieved from 20th to 22nd October 2021 along a 6.9 km long stretch close to the village of Bø. Discharge was gradually decreasing from 15.8 m^3/s on 20th to 12.7 m^3/s on 22nd October. In total, 27 cross-sections were surveyed (5 points/cross section + water line). While most cross-sections were surveyed at the predefined locations, some had to be moved due to lack of signal reception in the upper canyon stretch. The river had a high discharge with colored water during the sampling. Mesohabitat classification was not a problem but sediment and vegetation sampling, as well as UAV orthophoto processing was challenging. Drone mapping took place on 3rd November 2021.

Cross sections and sediment measurements

In each case-river, cross sections with at least five points per cross sections were surveyed with a Trimble R6 RTK GPS. Cross sections were taken from the riverbank as far as possible into the river as long as personnel managed taking the measurements (limited by water depth and flow velocity).

At each cross section, river typology (Hauer and Pulg, 2018), surface pattern (Newsom and Newsom 2000) and mesoclass (Borsányi et al., 2004) was visually registered at each cross section in field. These classifications were later validated by visual analysis of drone orthophotos.

At each cross-section measuring point, the dominating and sub dominating substrate class and embeddedness was registered within a 0.5 x 0.5 m rectangle. Table 2 gives an overview over assessed substrate classes. Embeddedness was classified into one of four intervals (0-25 %, 25-50 %, 50-75 % or 75-100%). In addition, at each cross-section point, the type of vegetation and cover grade was assessed. Water depth at cross section points were calculated as the altitude difference between water surface and measuring point.

Additionally, in each river type, the b-axis of the 50 largest stones within a 2 x 2 m rectangle were measured manually at least at one site.

Water samples were collected within each river for analysis of turbidity and watercolor.

Table 2: Substrate types for field classification (modified Wentworth scale)

Substrat type	Størrelse mm	Kode
Organisk fint	<10	1
Organisk grovt	>10	2
Leir, silt	0.004-0.06	3
Sand	0.061-2	4
Fin grus	2.1-8	5
Grus	8.1-16	6
Grov grus	16.1-32	7
Småstein	32.1-64	8
Liten rullestein	64.1-128	9
Rullestein	128.1-256	10
Stor rullestein	256.1-384	11
Blokk	384.1-512	12
Stor blokk	>512	13
Jevnt fjell	-	14
Ujevnt fjell	-	15

Mesohabitat assessment

Each river was mapped according to a method modified from Forseth & Harby (2013). Mesohabitat length should be at least the river length and was classified according to Borsányi *et al.* (2004). A summary of mesohabitat classes is shown in Table 3. Share of sediment classes and plant cover was visually estimated for each mesohabitat. In each mesohabitat, 3 shelter measurements were performed according to Finstad et al. (2007). The mapping was quality-checked with UAV aerial pictures.

Table 3: Mesohabitat classes according to Borsányi et al. (2004) Steep: >4 %, fast:>0.5 m/s, deep: >0.7 m.

Table I. – Classification decision tree.

criteria	surface pattern	surface gradient	surface velocity	water depth	code
Decision	smooth / rippled	steep	fast	deep	A
				shallow	
			slow	*deep / shallow*	
		moderate	fast	deep	B1
				shallow	B2
			slow	deep	C
				shallow	D
	broken / unbroken standing waves	steep	fast	deep	E
				shallow	F
			slow	*deep / shallow*	
		moderate	fast	deep	G1
				shallow	G2
			slow	*deep*	
				shallow	H

UAV aerial pictures and elevation model

Orthophotos were taken with a DJI Phantom 4 RTK UAV with a 1 inch, 20 megapixel CMOS sensor in RTK mode. Images were postprocessed with SfM software Agisoft Metashape Pro into aerial pictures, DEM and a point cloud without additional ground control points.

ALB pointcloud data handling

ALB data was provided by Kartverket in LAZ format. Different workflows were tested for LAS and DEM creation and ranked after processing time. Different raster creation options tested and compared visually in areas with high diversity and low point density. All conversions were performed with a Intel(R) Core(TM) i7-4770 CPU @ 3.40GHz with Intel(R) HD Graphics 4600 computer.

The fastest method for LAS creation was using LasMerge for merging the pointclouds and exporting to LAS in one step. The raster export options binning: "nearest" and void fill: "natural" gave the smoothest DEM based on visual comparison of different raster export options.

Data management LAZ to DEM

1) LasTools: LasMerge > save as LAS
2) ArcGis filter class 2 (ground) and 26 (bathymetry), Export to raster / binning: nearest /void fill: natural / cell size 0.05 / 0.25 m

For water surface: only class 27, 1 m raster/binning: average, void fill: natural

Comparison of ALB with RTK UAV and manual RTK cross sections

For comparison of acquired data based on RTK GPS and ALB, the maximum water depth of each profile was calculated (the deepest point in each transect, independent if it was covering the full river width or a part of the river), and 75 and 90 percentile of all profiles per river were used to analyze the area that would have been possible to survey manually. Water depth from ALB data was derived by subtracting bathymetry (class 26 in the ALB data, processed to rasters with 5 and 25 cm resolution) from the watersurface (class 27 in the ALB point cloud, processed to 1 m raster with averaged values to correct for outliers in the laser point cloud). In Hallingdal the water level was so much higher during ground sampling that most surveying points were on land in the laserscan. Analysis for this dataset were therefore dropped.

In Lærdal, CloudCompare was used to compare the UAV RTK point cloud with the Terratec ALB point cloud.

Assessment of shelter derivation from ALB data

A random sample of 50 RTK GPS geolocated shelter measurements was used in river Lærdal to test if differences in shelter can be derived from ALB data.

Vector Ruggedness Measurement (VRM) and Terrain Ruggedness Index (TRI) were tested with different spatial resolution on the 25 cm AHM raster dataset. With higher (5 cm) resolution data, artifacts due to non-equidistand point densities (Figure 1) appeared and these analyses were therefore dropped. River Lærdal was selected due to high shelter and substrate diversity.

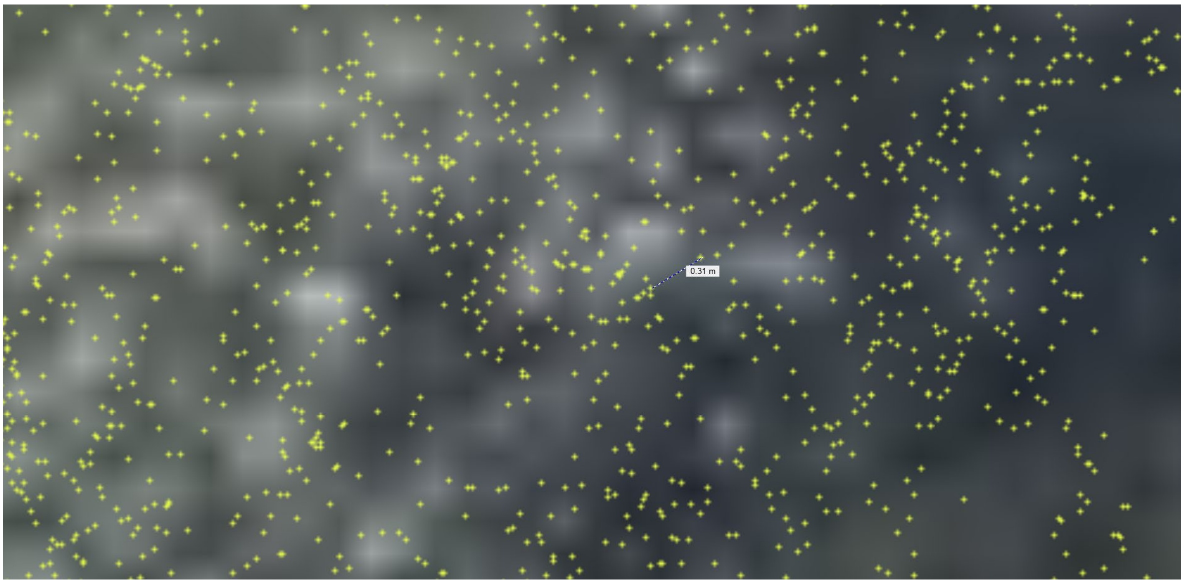

Figure 1: Non-equidistant point densities can lead to artifacts in LiDAR- derived parameters.

TRI is an expression of elevation difference between adjacent DEM cells. The tool follows methodology described in Riley et al. (1999) by measuring the averaged squared difference from center cells and it’s 8 surrounding cells. The square root of this average is the TRI value of the center cell. The analysis is performed on every cell in the raster file.

VRM measures the variation of the 3-dimensional orientation of grid cells and its surrounding cells by means of vector analysis. By calculating dispersion of vectors normal to the grid cells within a neighborhood, ruggedness is decoupled from slope or elevation. Ruggedness values can range from 0 (no terrain variation) to 1 (full terrain variation). The algorithm was first proposed by Hobson (1972) and adapted by Sappington et al. (2007).

WP 2 Flood risk, analysis and conceptual work

ALB data is used as a basis to develop scenarios which will benefit flood- and erosion safety and environment in Lærdal from sjukehusvegen bridge to the estuary for a 200 years flood with climate factor. The 200-year flood in Lærdal is 920 m^3/s (Holmqvist, 2000), with a 40 % climate factor discharge would be 1288 m^3/s. Field work with on-site assessment of possibilities and challenges was performed on 12th and 13th September 2022.

The scenarios were drafted in cooperation with BOKU based on on-site observation and historical orthophotos with the goal to reach ecological and flood safety improvements. Building on NTNU's existing ALB model, BOKU implemented adaptions to the geometry, and NTNU processed the adapted model with HEC-RAS.

WP 3 River restoration.

Weir removal scenario

A theoretical weir removal in river Lærdal was modelled and analyzed based on the AHM ALB data to demonstrate application for restoration and quick adjustments to the base data. The riverbed was interpolated based on bed elevations upstream and downstream of the weir. Changes in velocity, water depth and shear stress were compared for current state and theoretical altered state for a discharge of 50 and 270 m^3/s.

Comparison of base data for ecological assessment

Modelling of average flow (36 m^3/s) of a 560 m long river stretch (Oftepollen) in river Lærdal was compared based on ALB data, RTK UAV data and RTK cross sections. 2d- hydrodynamic models were built based on

1) X-sections every 25 m. These were derived from the AHM ALB dataset and limited to a water depth of 1.15 m in order to reflect the results from WP1 (maximum wading depth with RTK GPS of 1.15 m in Lærdal river). The river between the X-sections was interpolated with Aquaveo SMS.
2) UAV DEM data without corrections
3) AHM DEM data without corrections.

Time use and results were compared to show cost and usage areas of the various data sets. The stretch was modelled with HydroAS (Hydrotec).

Figure 2: Overview over the cross sections for model setup at Oftepollen.

2. Results and discussion

WP 1 Validation, analysis, and conceptual work

River types

Application of ALB data was tested in different classified river types. Which river types can be mapped with ALB and where are the uncertainties?

All case rivers were dominated by fluvial river types, mainly pool-riffle type and fine-sediment type (Table 4). In both river types, ALB delivers planar Z-information beyond the depth that could be surveyed by wading.

Table 4: Overview of the different case studies, classified river types according to Hauer &Pulg (2018), average river gradient (%) and total river length (km) mapped with ALB.

Case study	River class	D10/90	River gradient	River length (km)
River Lærdal	Pool-riffle	13/19	0,67%	9.8
River Hallingdal	Pool riffle; dune-ripple	9/46; 18/27	0,07%/0,004%	1.5/2.5
River Bø	Pool-riffle	22/38; 8/14	0,38%	6.9

In Lærdal the whole scanned river stretch was classified as pool-riffle type, with an average slope of 0.67 %, a sediment composition dominated by sand, gravel and cobble and a typical morphology consisting of pools and riffles. The morphology is affected by ground sills, but in a natural state without the sills, the typology is still expected to be dominated by pools and riffles due to bed slope and sediment composition. Figure 3 shows the scanned river stretch and locations of manually surveyed cross-sections. The substrate sample of the biggest grains has a median b-axis of 16.5 cm, d90 was 19 cm and d10 13 cm (cobble). A longitudinal profile of the river stretch and a boxplot with grainsize distribution are shown in Figure 27. Both slope and the narrow range of sediment composition indicating a fluvial sorting are within typical ranges of a pool-riffle type.

The ALB-measurement alone could generate the energy and the bed slope (Figure 4), it could also reflect the morphology (riffle and pools data visible in the longitudinal profile). BOKU's results show that in fluvial river types like Lærdalselva, the sediment compositions (b-axis) could be derived to a degree where distinguishing plane-bed and pool riffle type is possible (cobbles and finer substrate).

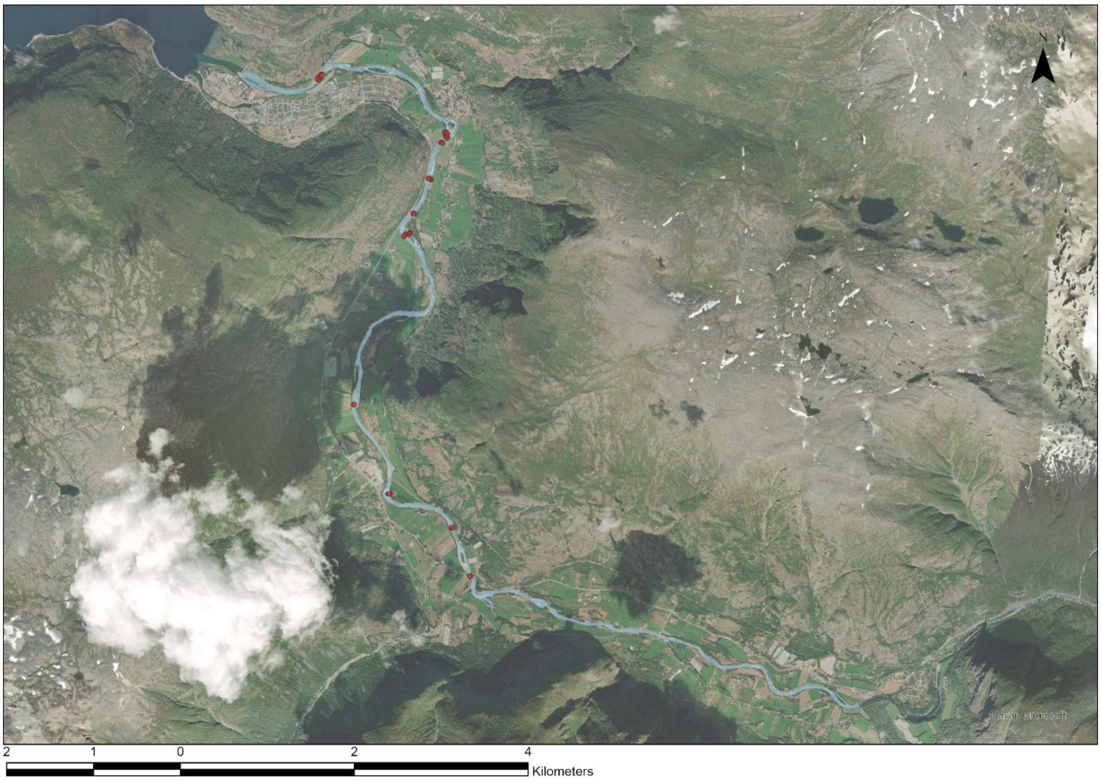

Figure 3: Overview over the river Lærdal stretch (RTK cross-sections red, scanned area blue.)

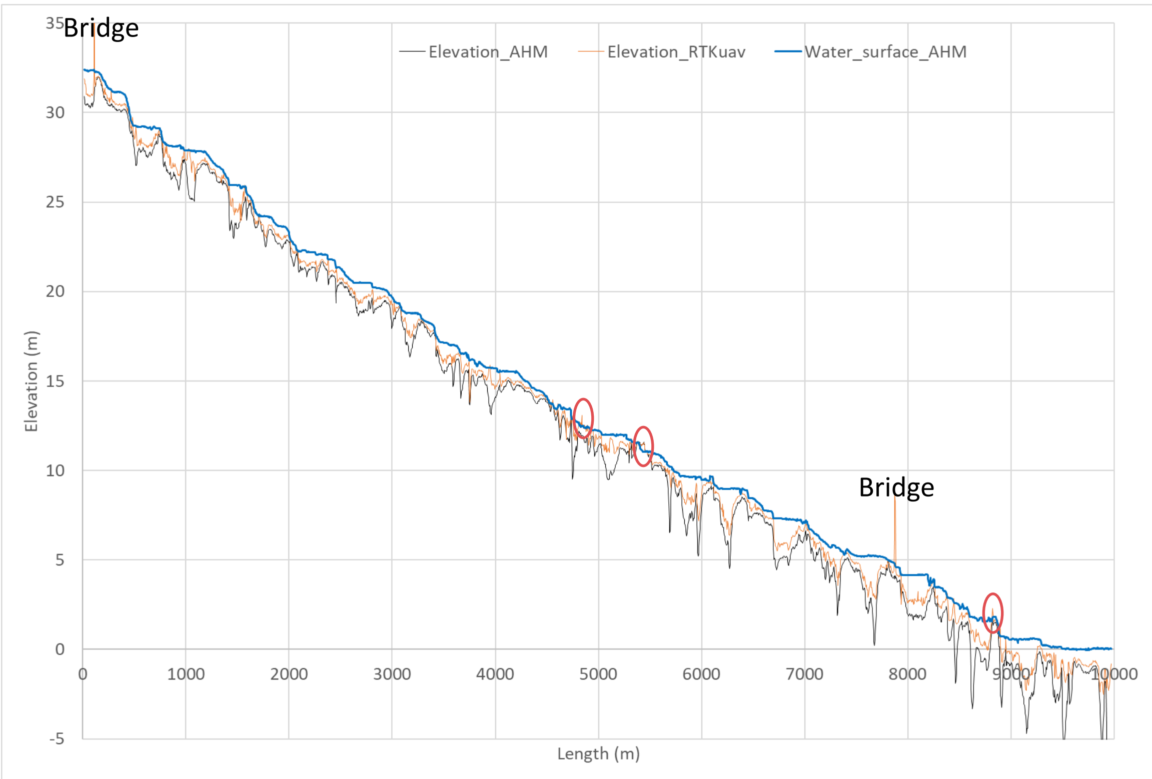

Figure 4: Longitudinal profile of river Lærdal. Water surface in blue, Thalweg from AHM ALB in black, Thalweg from RTK UAV in orange.

In Hallingdal the upper 1.5 km is classified as pool-riffle type, with an average slope of 0.07 %, the lower 2.5 km stretch is a dune-ripple type with 0.004 % slope. Median b-axis length of the two sediment samples in the pool-riffle stretch was 20.5 and 20.45 cm, d90 was 46 and 27 cm and d10 was 9 and 18 cm. The sample in the lower river stretch consisted of sand and fines, confirming the dune-ripple type. A longitudinal profile of the upper river stretch is shown in Figure 6 and a boxplot with grainsize distribution for the upper two samples are shown in Figure 28. The upper river stretch has a slightly lower slope (0.07 %) than the typical pool riffle type (0.1 %) but since grainsize is in the cobble fraction and a typical pool riffle morphology is developed the stretch is classified as pool-riffle type. This can be explained by confinement, making the stretch a forced pool-riffle type.

The ALB-measurement alone could be used to generate the energy- and bed slope data, it could also reflect the morphology (riffle and pools data, Figure 6), but grain size (b-axis) could not be explained with BOKU's method. However, BOKU found that a variability of roughness in ALB data can be used to distinguish fluvial-and non-fluvial rivertypes.

Figure 5: Overview over the mapped stretch in river Hallingdal, manually surveyed cross sections marked in red, scanned area in blue.

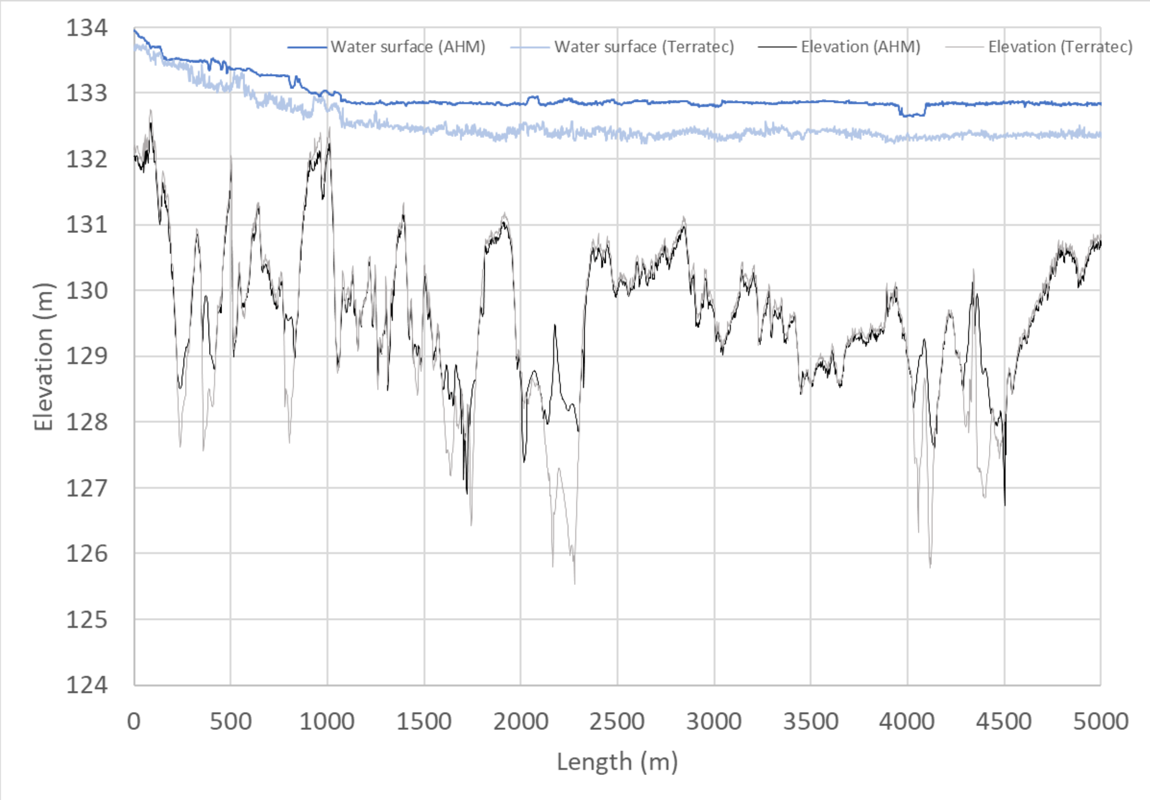

Figure 6: Longitudinal profile of the surveyed stretch of river Hallingdal

In Bøelva the whole river stretch was classified as pool riffle type, with an average slope of 0.38 %. The upper stretch is confined by a gorge and has coarser sediments (cobble with some small boulders). Median b-axis length was 29.75 and 16 cm in the upper two samples, and 8 and 8.4 cm in the lower two samples. D90/D10 was 38/22 and 24/15 cm in the upper and 15/8 and 14/8 cm in the lower samples. Both samples indicate fluvial sorting, especially the lower ones. A longitudinal profile of the river stretch is shown in Figure 8 and Figure 29 and a boxplot with grainsize distribution is shown in Figure 9. Slope is in a typical range for pool-riffle types. However, grainsize distribution of the upper two samples is rather typical for plane-bed type. This deviation can be explained by the valley confinement (gorge stretch) in the upper part leading to higher shear stress and sediment transport capacity, that forces pools by constriction and confinement (forced pool-riffle). Since there was a typical pool-riffle morphology observed on-site, the stretch was not classified as plane bed. The ALB-measurement alone could be used to generate the energy- and the bed slope, it could also reflect the morphology (riffle and pools data, Figure 6), but BOKU could not explain grainsize variation directly (b-axis) with its method of protrusion rate measurements. They showed however, that roughness variability in Bøelva could be used for distinguishing fluvial and non-fluvial elvements.

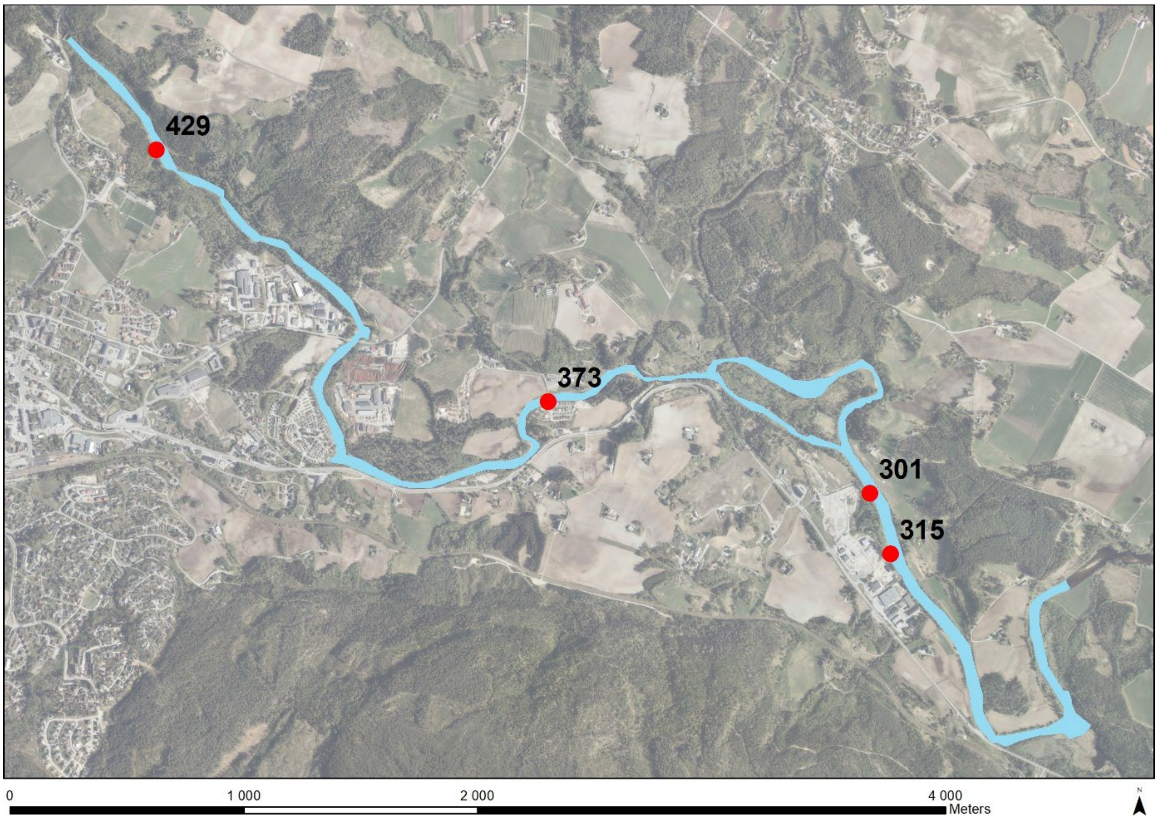

Figure 7: Overview over the mapped stretch in river Bøelva, sediment sample locations marked red, the scanned river stretch in blue.

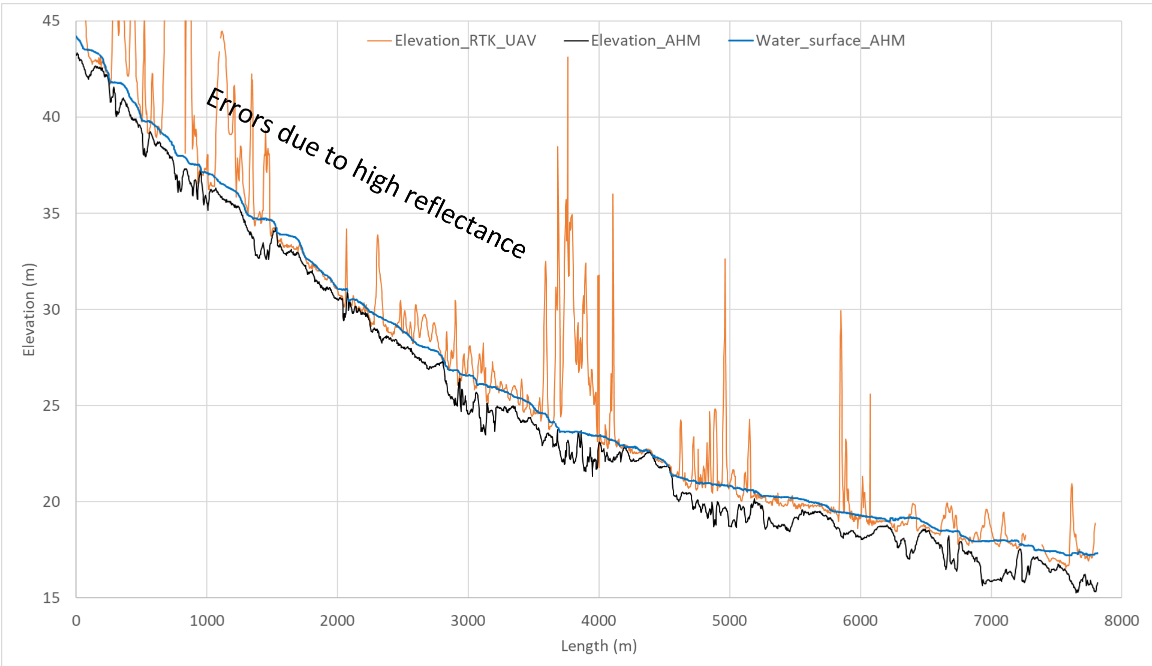

Figure 8: longitudinal profile of river Bøelva. Water surface in blue, Thalweg from AHM ALB in black, Thalweg from RTK UAV in orange.

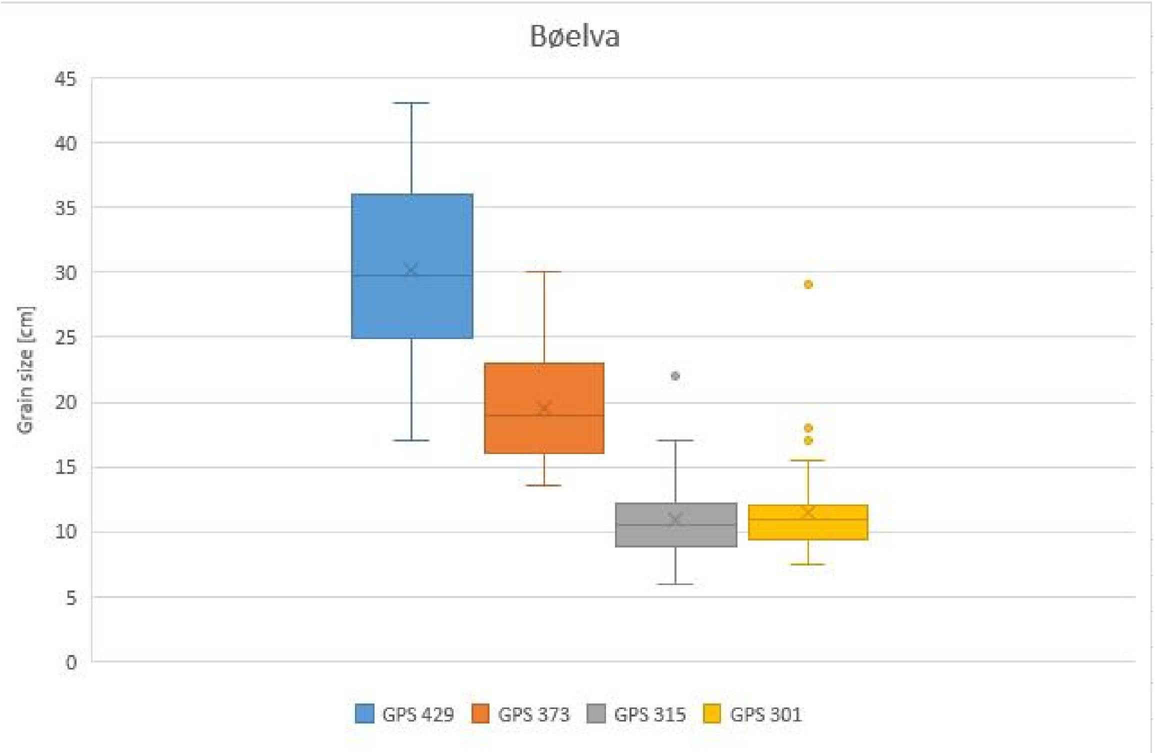

Figure 9: Sediment size variation in river Bøelva.

Ground truth and mesohabitat mapping

Mesohabitat assessment

Lærdalselva

The mapped river stretch in Lærdal is dominated by fast runs (rippled surface and with water velocity >0.5 m and water depth >0.7 m) (43%), pools (32%) and deep glides (24%). Mesohabitat maps are shown in Figure 30 - Figure 32, a summary of mesohabitat compositions shown in Figure 36. Shelter is on average 4,36 and higher in the upper half (average 5,47) than in the lower (average 3,36), see Figure 33-Figure 35. Substrate is dominated by cobble (55%), gravel (25%) and sand (14) in river Lærdal (Figure 37), with 60% cobble, 18% gravel and 11% sand in the upper part and 50% cobble, 30% gravel and 16% sand in the lower part.

Bøelva

The mapped river stretch in Bøelva is dominated by deep glides (51%), fast runs (29%) and pools (14%). A map of the mesohabitat types is shown in Figure 38, a summary of mesohabitat types is shown in Figure 40. Shelter and sediment distribution could not be determined because of high flow and bad visibility.

Hallingdalselva

The mapped river stretch in Hallingdalselva is dominated by deep glides (96%) and has some fast runs (6%) and pools (1%). Mesohabitat types are shown in **Figure 43**. Shelter is on average 0,21 and higher in the pool riffle section (average 0,34) than in the dune ripple section (0,0). Substrate is dominated by sand (62%), gravel (20%) and cobble (12%) in river Hallingdalselva (**Figure 44**), with 55% sand, 18% gravel and 11% cobble in the pool riffle section and 80% sand, 10% gravel and 10% cobble in the dune ripple section.

UAV aerial pictures and elevation model

Aerial pictures and DEM derived from UAV aerial pictures can be found in the delivery folder. A summary of time consumption for acquiring UAV data and the length of the mapped river stretch is shown in Table 7. Average total time consumption (finished DEM and orthophoto) for all three case rivers was 128 minutes per km river stretch, of which on average 20 min/ km were processing time.

Table 5: Time consumption for data collection and processing of UAV aerial pictures

River	Length (km)	Travelling time (min)	Data collection (min)	Processing time (min)	Total time consumption (min)
Lærdal	9.8	360	130	270	760
Bøelva	6.9	600	150	150	900
Hallingdal	4.2	540	150	45	735

Lærdalselva

In Lærdal, the point cloud from UAV RTK bathymetry was compared to the Terratec ALB data (class 26). Figure 48 shows the compared river stretch, and a histogram of Z-error.

In Figure 17, boxplots for 0.2 m binned water depth were created to illustrate linear increase in Z-error due to refraction. Median Z-error was 0.02 m (SD 0.15 m) at 0 m water depth, 0.34 m (0.2 m SD) at 1 m, 0.76 m (0.39 m SD) at 2 m and 1.33 m (0.63 m SD) at 3 m. A table with errors up to 6 m is shown in Table 8. The median error is linear up to a depth of ca. 3m, however, there is a large standard deviation.

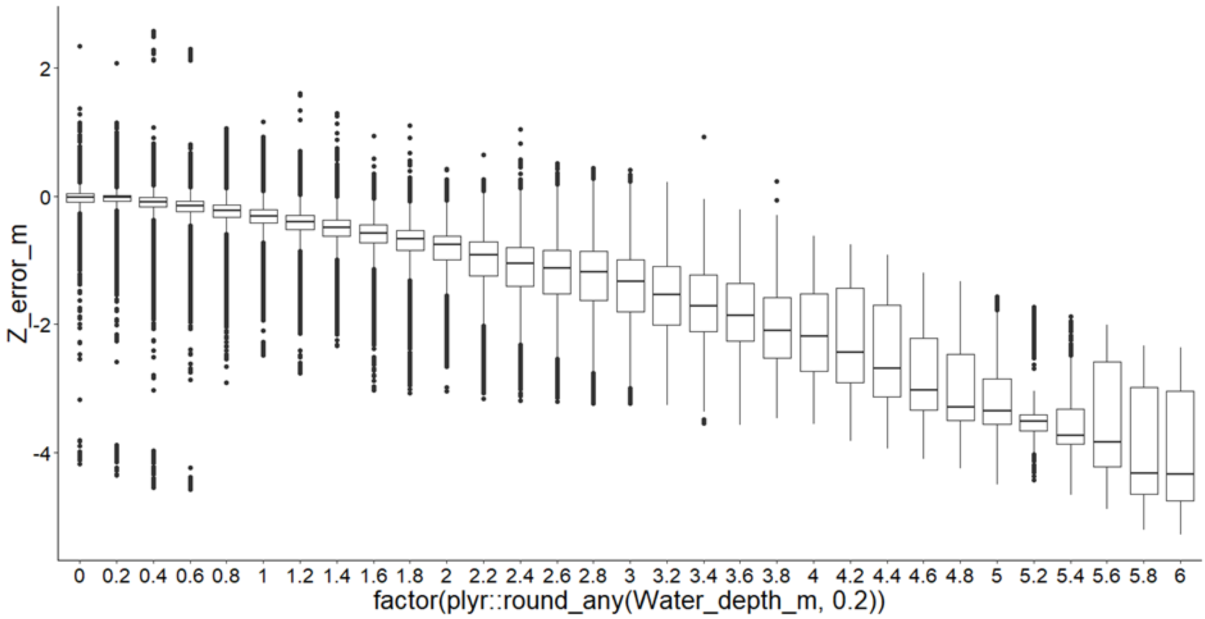

Figure 10: Boxplots of Z- error in 0.2 m water depth bins.

A longitudinal profile (Figure 4) of the surveyed river stretch reveals that Z-values of UAV data are overestimated, meaning the river bed is estimated to be higher than in reality. This is especially the case in deep pools. Also, the error is not constant, and while most pools are visible in the longitudinal UAV profile, some are not detected (like at length 5000 in the profile).

While pool-riffle type rivers can be classified with ALB data based longitudinal profiles, UAV data does not always supply sufficient and consistent depth information, and some pool-riffle stretches could be misclassified as plane bed type. UAV results therefore have 1) shallower water depths, resulting in 2) higher velocities and 3) a generally larger wetted area. The river bed from UAV SfM can also be overestimated above water surface in white water stretches (red circles in Figure 4).

Bøelva

High reflectance due to the dark watercolor led to a lot of errors at DEM generation from UAV data, especially in the areas where ground is not visible in the pictures. A longitudinal profile of the scanned area can be seen in Figure 8, bathymetry from UAV could only be derived in very shallow areas and could thus not be used for analysis. ALB data on the other hand, can penetrate the water to a depth which is sufficient for classifying the pool-riffle character of the river section.

Hallingdalselva

The river was wide and with high humosity and about half of the river stretch could not be processed into aerial pictures and DEM with the given dataset. In the areas where postprocessing worked, the river bottom could be registered to approximately 80 cm water depth. Due to the high water level difference between ALB and UAV flight, a comparison of ground data was not reasonable. A longitudinal profile of the same river stretch shows that ALB data from both companies can penetrate to more than 5 m water depth (Figure 6) at lower water levels.

ALB data handling

Total time consumption for raster creation from ALB data sets was on average 79 minutes per kilometer, which exclusively was processing time. Time consumption for raster creation is summarized in Table 4.

Table 6: Time consumption for raster conversion in minutes. (all calculations performed with Intel(R) Core(TM) i7-4770 CPU @ 3.40GHz with Intel(R) HD Graphics 4600).

Company	River	5cm	25cm	50cm	100cm
AHM	Boelva	2337	285	91	24
AHM	Laerdalselva	7601	1071	310	100
AHM	Hallingdalselva	3164	314	90	15
Hexagon	Boelva	1093			15
Terratec	Laerdalselva	*	210	61	35
Terratec	Hallingdalselva	*	38	14	3

*Too low point density

Comparison of ALB, manual RTK and UAV data

Practical benefits and deficits of the ALB data are compared to conventional base data such as aerial photos and manual RTK cross-section measures. Data will be compared for time consumption, limits of water depth, challenges, and availability in the sub-chapters.

In Table 5, time consumption for preparing base data from the case rivers is divided into river length. The table is further classified based on the different methods tested in this project. Based on the assumption that ALB data will be openly available (set as a precondition in the project), ALB data preparation was faster than preparation of UAV data. ALB data preparation to readily available DEM 25 cm raster was 1.5 times faster, compared to the UAV SfM data counterpart. Further, compared to ready to use cross section data (distance of 100, 50 and 25 m), the ALB data preparation was 5.7, 11 and 23 times faster. Additionally, the ALB preparation only requires computer processing time in the background, while the largest part of time consumption in the other methods goes to data collection.

Table 7: Average total time consumption (travelling, field work, processing) per river length for preparing raster or shapefiles for the case rivers under the assumption that ALB data point clouds are openly available.

River stretch (m)	500	1,000	5000	10000
Method	Time (hours)			
X-sections 25 m	15.0	30.0	150.0	300.0
X-sections 50 m	7.5	15.0	75.0	150.0
X-sections 100 m	3.8	7.5	37.5	75.0
UAV 25 cm resolution	1.0	2.0	10.0	20.0
ALB 25 cm resolution	0.7	1.3	6.5	13.0

Cross-sections with RTK GPS

Table 2 gives an overview of time consumption for acquiring cross sections, including traveling time. In a typical restoration project, transects would have a distance of 20-100 m, depending on detail degree. The sampled transects could thus be used in a 300-1500, 540-2700, and 200-1000 m long river stretches in richer Lærdal, Bøelva and Hallingdal, respectively. The average total time consumption per cross sections (finished shapefile) for all surveyed cross-sections was 43 minutes. In typical projects we estimate a total time consumption of 60 minutes per cross section. One reason for the shorter time consumption in this project can be that many cross-sections in Bøelva and Hallingdal were limited to the riverbank due to the high water level/steep river banks.

Table 8: Time consumption for manual surveying of X-sections with RTK GPS

River	Nr X-sections	Traveling time (min)	Surveying time (min)	Data management (min)	Total time consumption (min)
Lærdal	15	360	150	10	420
Bøelva	27	600	300	10	910
Hallingdal	10	540	120	10	670

Limits of manual RTK surveying (cross sections)

Lærdal

Percentiles of maximum manually surveyed water depth were 0.96 m (75 percentile) and 1.15 m (90 percentile). Areas deeper than the percentiles represent respectively 54 % (380366 m^2) and 35 % (249674 m^2) of the total water surface (697568 m^2) in the surveyed area.

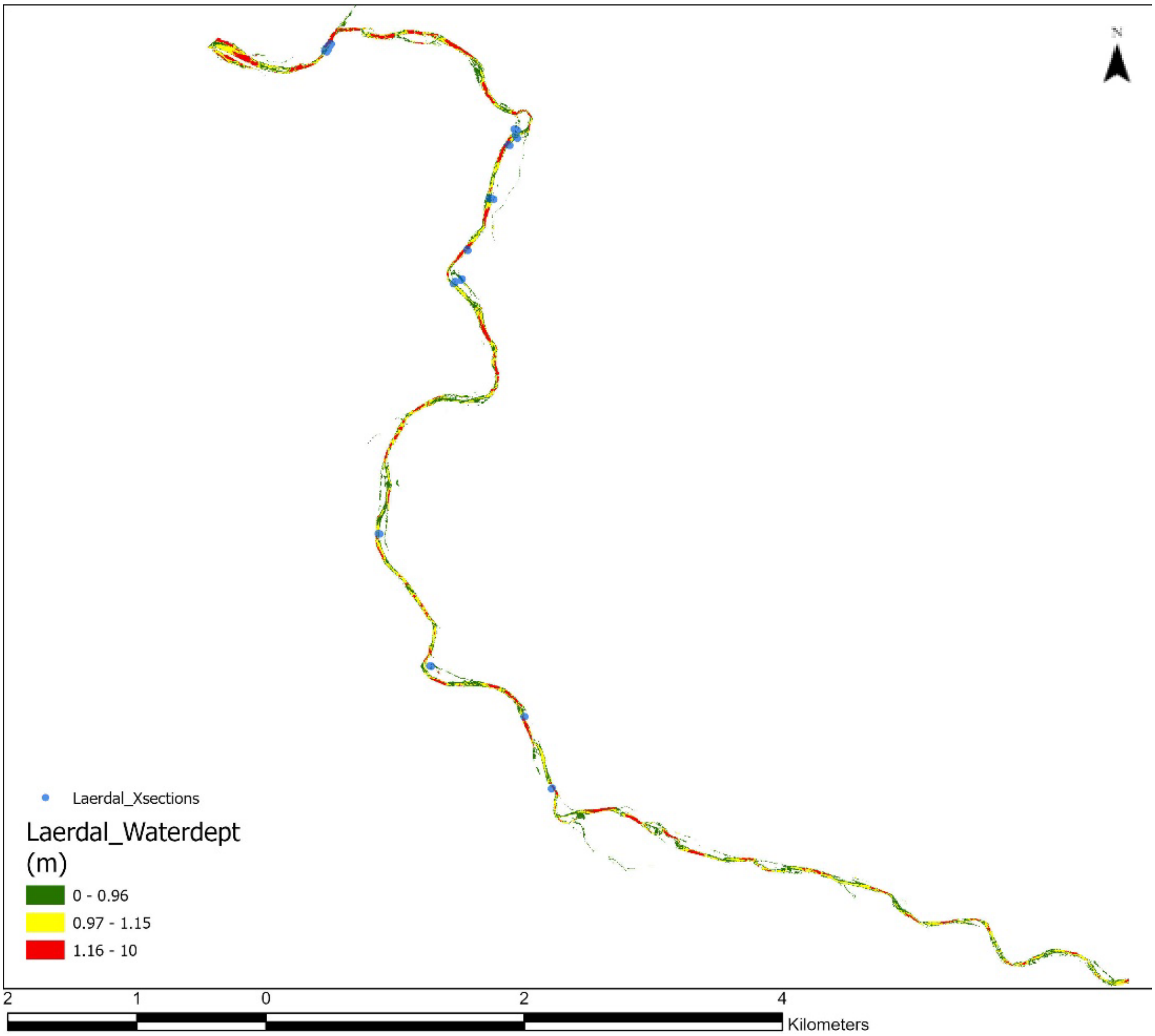

Figure 11: Overview over the whole river stretch in Lærdal with manual X-sections marked blue and estimated manual surveyability marked in green, yellow and red.

Bøelva

75% of all transect points in Bøelva had a water depth of 66 cm or less, while 90 % were shallower than 80 cm. Feedback from the surveyors revealed that heavy currents made measuring in deeper areas impossible. Figure 11 illustrates the areas in Bøelva which were possible to measure (green), difficult to measure (yellow) or impossible/dangerous to measure (red). The blue dots reveal that the surveyors turned around on the border from green to yellow in this transect. Figure 12 shows the cross section for the same transect, the black lines indicate the maximum depth that was possible to measure manually at this location. The deep section between the black lines would in typical cases be interpolated or estimated, potentially leading to a significant underestimation of water depth in the cross section. Figure 13 shows the limitations of manual RTK surveying along the project reach.

In Bøelva, 26 percent of the project reach (84 829 m^2) have a water depth of >80 cm and would be hard or impossible to survey by manual RTK GPS on the surveying day, 53 % would be difficult to survey (174 029 m^2 with a water depth between 66 and 80 cm). The whole water surface of the project stretch in this river is 324 127 m^2.

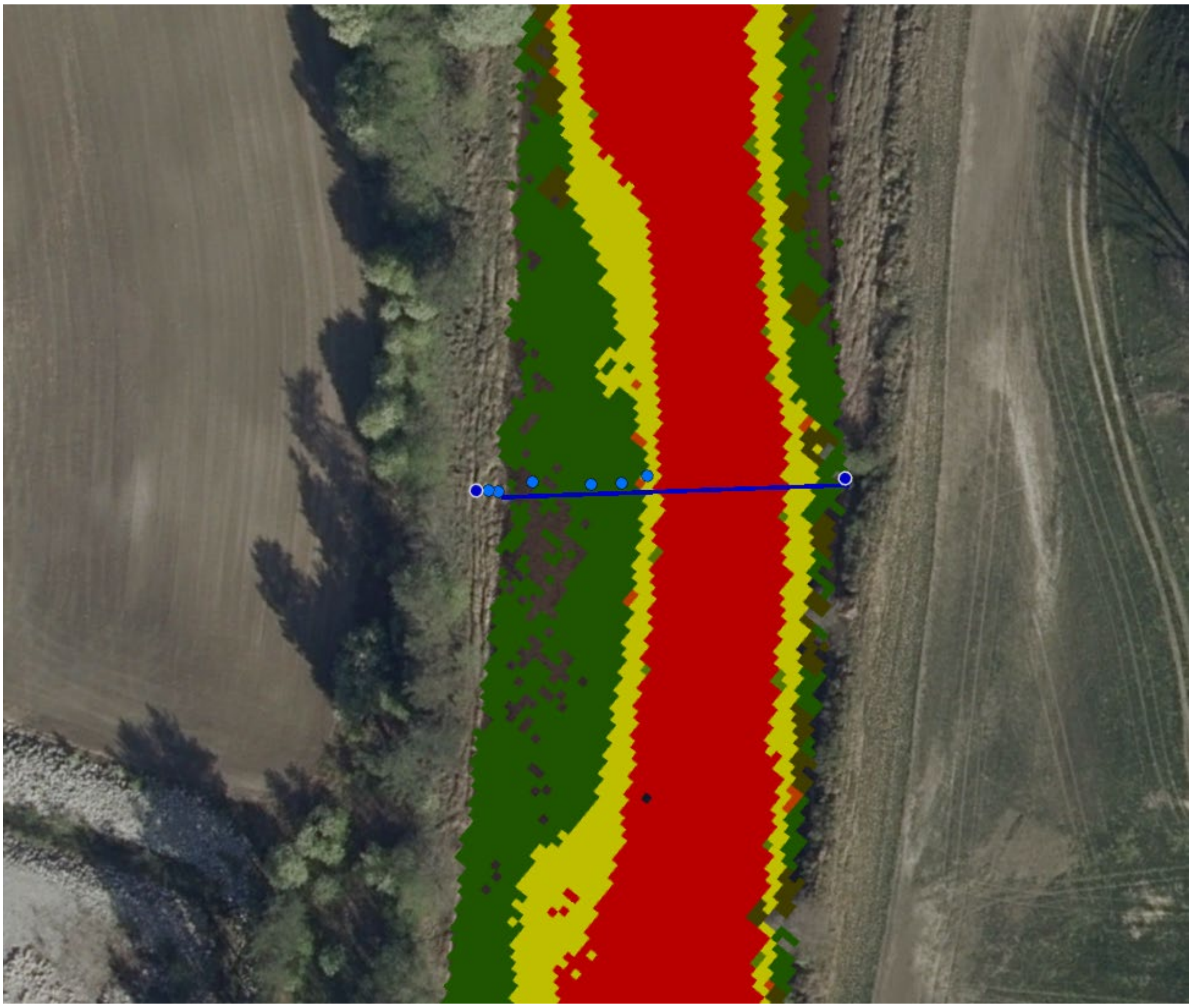

Figure 12: Limits of manual surveying. Manually measured RTK cross section (blue dots) and cross section derived from ALB data (blue line). Green areas were possible to survey manually, yellow areas were difficult to survey manually and red areas were at the limit or impossible to survey manually under the surveying conditions.

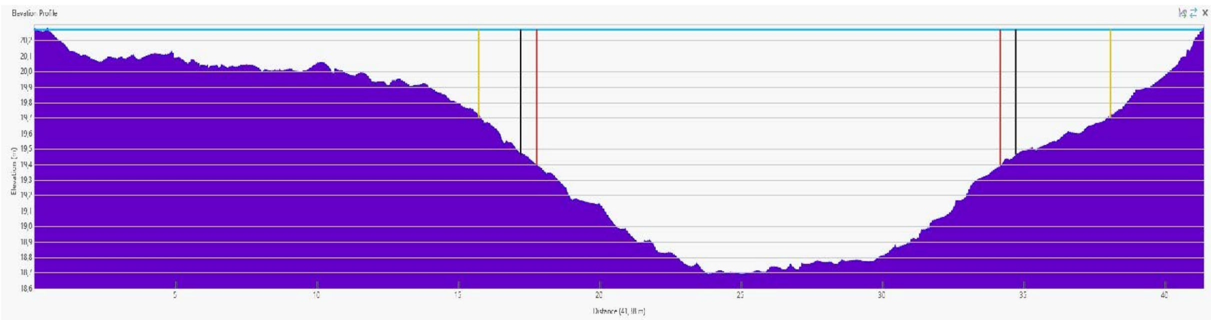

Figure 13: Cross section based on ALB data (blue line in the figre above) of the same river stretch. Black line indicates maximum measured water depth in this specific profile, yellow lines depths that based on the analysis were difficult to survey manually and red lines water depths that were the limit to survey manually under the surveying conditions.

Figure 14: Overview over the whole river stretch with manual Xsections marked blue and estimated manual surveyability marked in green, yellow and red.

Assessment of shelter derivation from ALB data

Terrain ruggedness index (TRI) and Vector Ruggedness Measure (VRM) which were derived from the 25 cm raster resolution AHM ALB Lærdal dataset show a promising correlation to shelter measurements (Figure 14 and Figure 15).

At higher resolution data, the algorithms delivered "rugosity" edges in areas where lower point densities meet higher point densities along the sampling path of the laser beam. Most likely because points along a beam sampling path were closer to each other than the neighboring beam sampling path and resulted in artificial rugosity.

VRM increases significantly as shelter increases ($R2=0.27$, $t=4.21$, $p<0.01$, $s=0.001$), as does TRI ($R2= 0.35$, $T=5.00$, $p<0.01$, $s=0.007$). Location of shelter measurements and VRM are displayed in Figure 16. An aerial picture of a stretch with shelter measurements, TRI and VRM raster results are shown in Figure 45 -Figure 47. It is possible that the correlation would be even stronger with a less strict filtering algorithm by the ALB data provider or with a finer grid in the raster file. Figure 46 shows holes in the ground class of the bathymetry dataset, holes occur mainly with large boulders which decreases roughness. Missing points in the ground/bathymetry point cloud are available in the raw data (class 1/unassigned and class 7/noise) of the LAS file. More research should be put into testing more sensitive filtering algorithms on the existing data in order to not lose roughness information in the LAS files. BOKU showed a clear relation between roughness and grain size, so cross-correlation to shelter values can be expected. These analyses prove that estimating substrate characteristics is possible with high resolution point clouds.

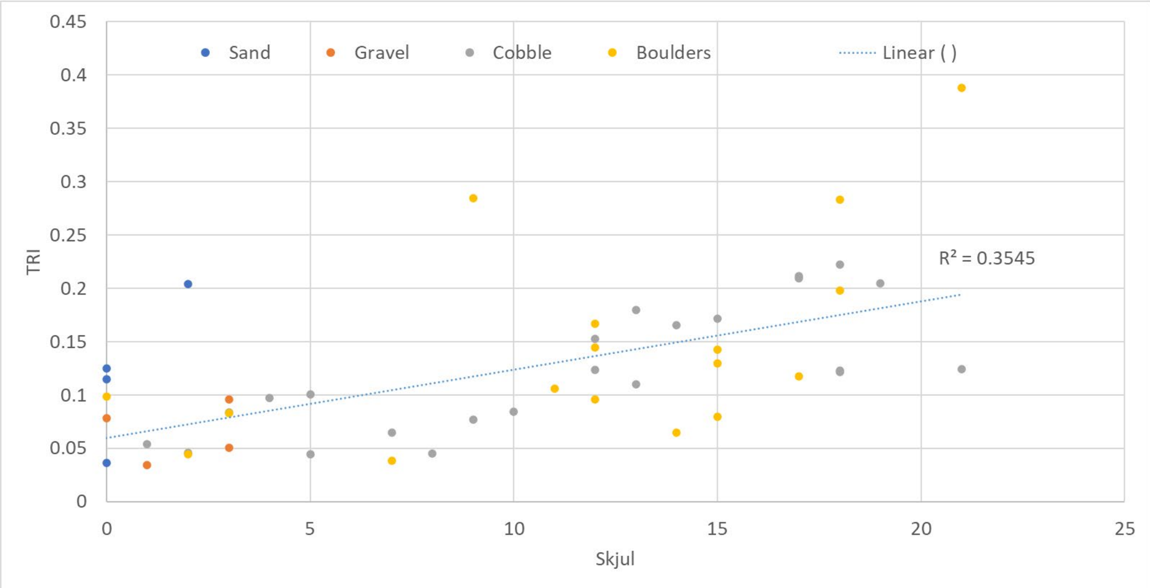

Figure 15: Increased Terrain Ruggedness Index by increased shelter values in Lærdal

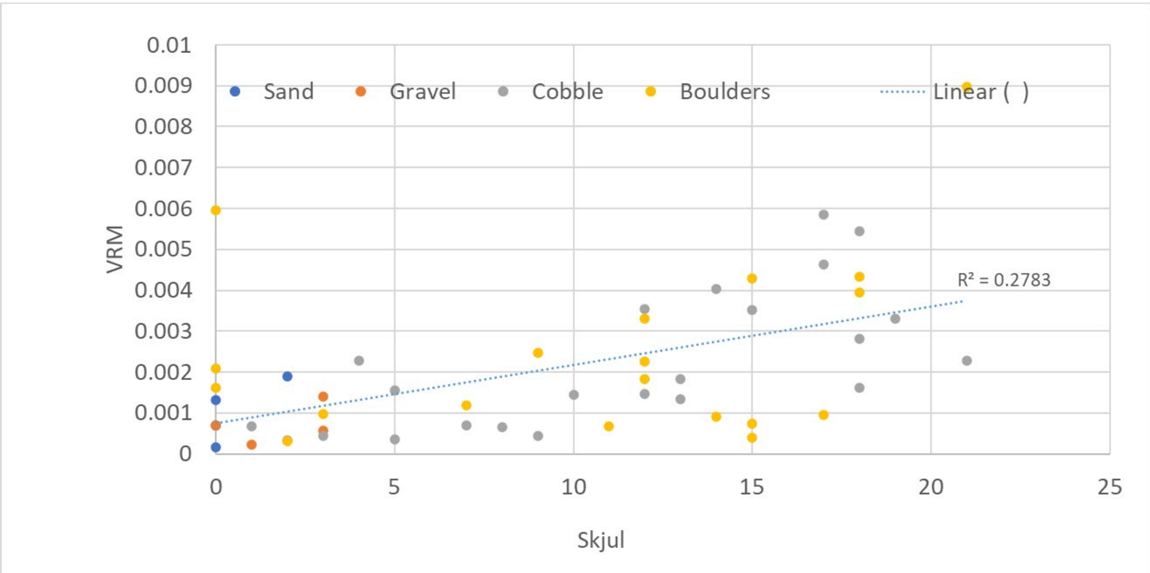

Figure 16: Increased Vector Ruggedness Measurement with higher shelter values.

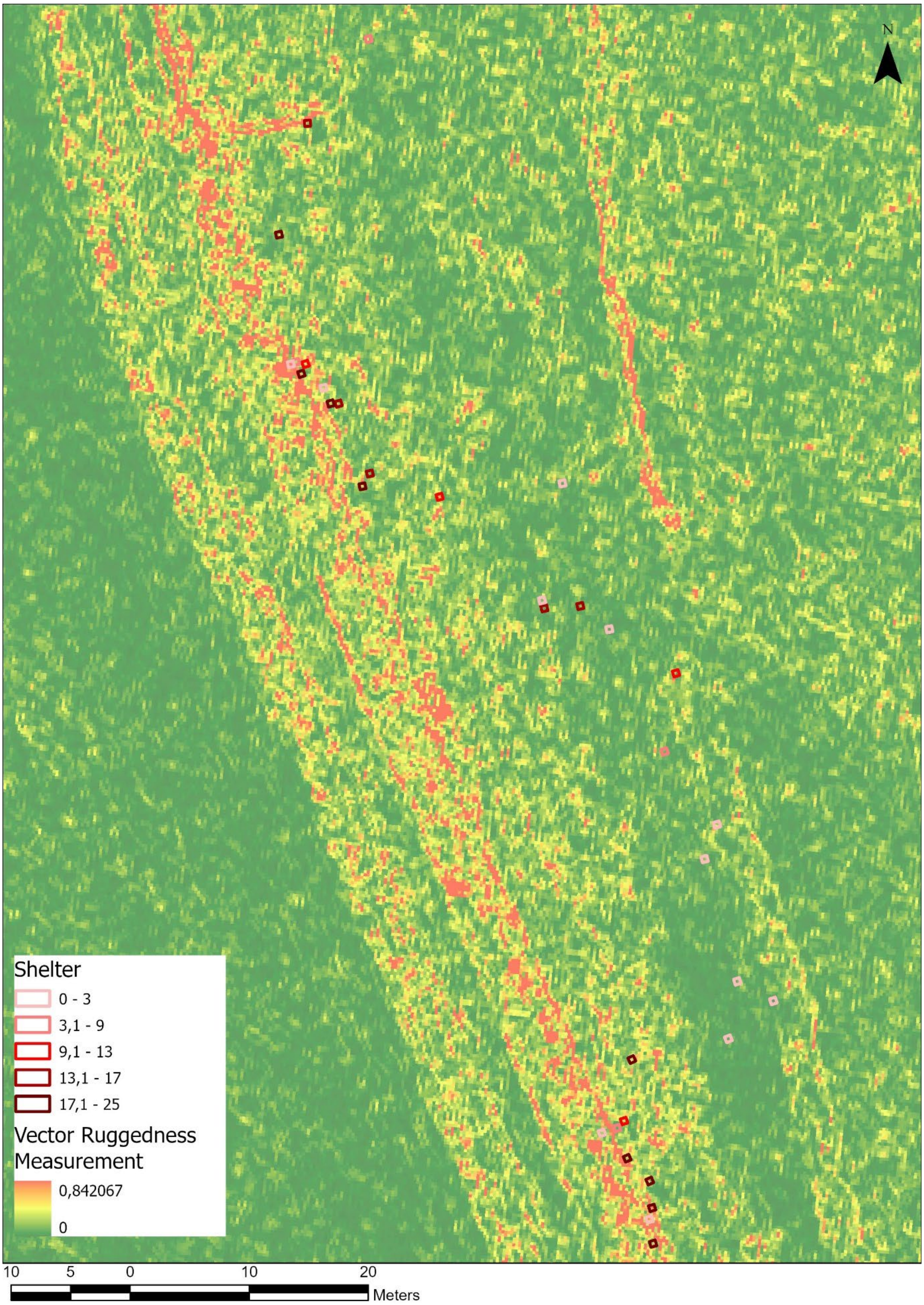

Figure 17: VRM and shelter measurements.

WP 2 Flood risk -Ecological and flood-safety improvement scenarios for Lærdalselva

Options for improvements of the flood- and ecological situations around Lærdal center that were drafted during the on-site visit are shown in Figure 18. These are 1) A levee/flood wall which is moved as far from the river as possible, 2) increased cross sections by reopening historical flood- and side channels, 3) a flood tunnel, if the other measures are not sufficient, and 4) terrain adjustments to increase the cross- section during flood events.

The measures focus on restoring parts of the historical situation in the estuary. On the aerial picture from 1979, some of the historical features are still visible (Figure 19). The tested adaptions follow historical channels and would restore some of the estuary character of the river stretch. For best ecological benefit, the flood channels should be designed as permanently wetted side-channels. The channel on the right bank can also be designed as exclusively being wetted with large floods. This way, the area can be used agriculturally and will locally get more acceptance.

Modifications could be integrated into the existing model based on ALB and LiDAR without additional surveying needed. The high resolution and accuracy give reliable results for flood safety planning, at the same time, ecological effects and benefits can be derived from the modelling results (Figure 27). By overlaying the different scenarios and tweaking their dimensions, integrative solutions can be quickly iterated. A mass estimation for both side channels (64 000 m3 right river bank channel, 49 000 m3 left river bank channel) could be quickly calculated from the DEM.

The first iteration revealed that the input scenario was under dimensioned, and that the left bank side-channel, the right bank flood tunnel, or both need to have larger dimensions. Also, adaptions to the flood levees are necessary. While the first trial did not provide sufficient flood protection, the case highlights the potential for testing out scenarios and demonstrates how easily adaptions can be integrated into an ALB-based model.

Compared to plans of the authorities for river Lærdal which include channelization and dredging of the river bottom in the same river stretch (Juarez et al. 2021), this scenario would provide a more sustainable flood safety situation without the need of redredging after larger floods, and at the same time restore river habitat. This study shows that novel technical developments like ALB can be used to design nature based solutions with benefits for ecology and flood safety. Additionally, precise mass-estimation of planned measures is possible without need for additional surveying.

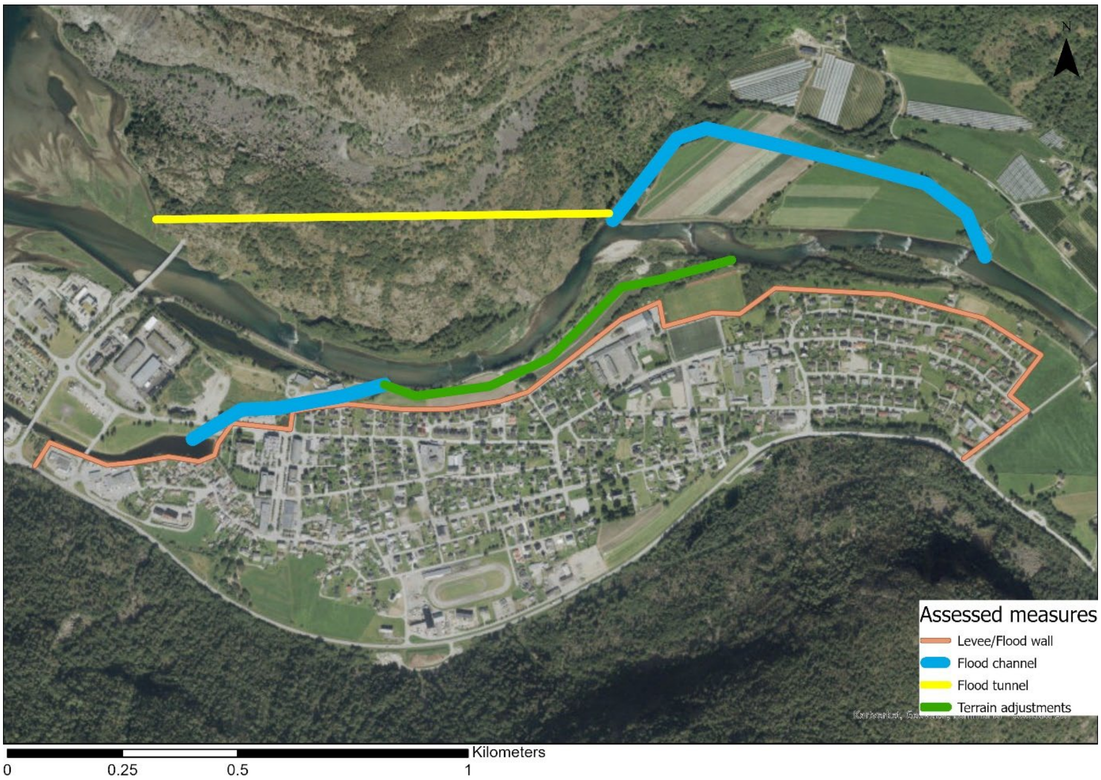

Figure 18: Overview over assessed measures around Lærdal.

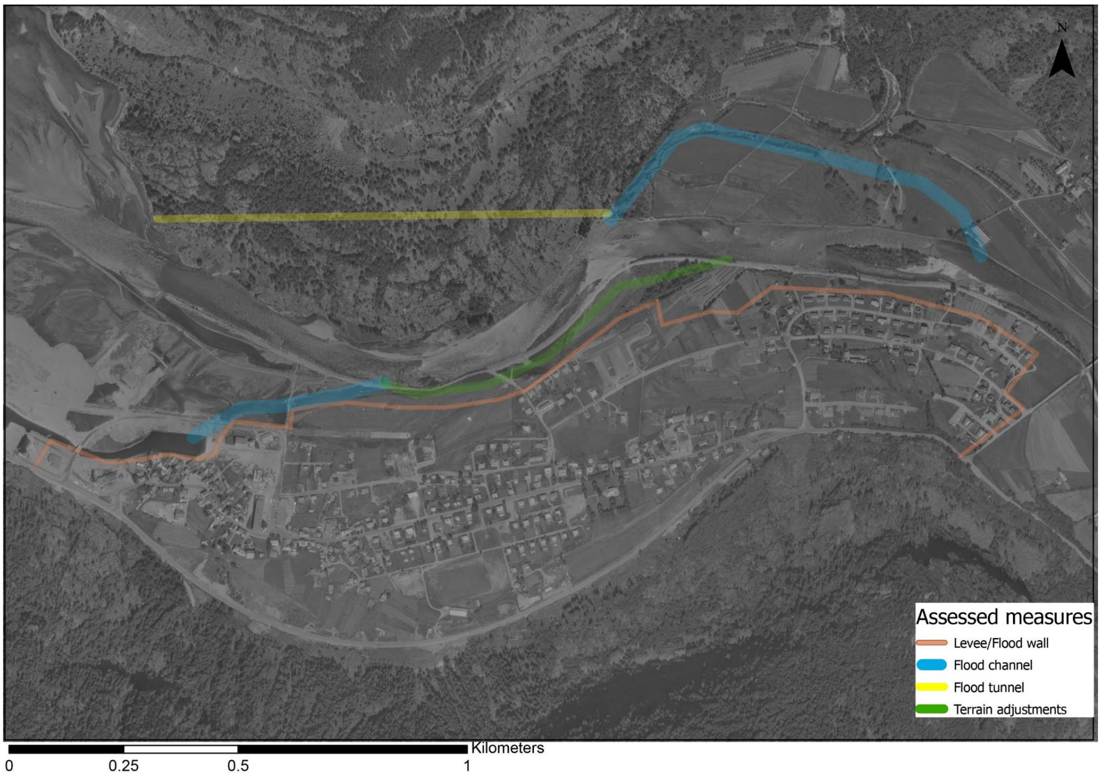

Figure 19: The assessed measures follow historical flood channels which are still visible on the aerial picture from 1979.

WP 3 River restoration - Comparison of base data for planning/modelling restoration measures

Planning of measures is usually performed with 1) fieldwork for data acquisition, 2) processing of data and 3) actual planning processes. Especially in larger rivers this involves significant resources for collecting enough base data. A weir removal scenario was modelled in Lærdalselva for demonstrating application in concrete measures. Additionally, cross-section, SfM and ALB base-data is compared with focus on ecological assessment and implications.

Weir removal scenario

As a typical example of measures in Norwegian streams, a weir removal was planned based on the AHM ALB dataset. Both BOKU and NTNU data show that for higher discharges, differences in water depth and flow velocity are neglectable and no changes in substrate stability occur. This finding is supported by our experience from real weir removals. Typically, these basins above weirs are clogged and so stable that yearly floods are not sufficient to mobilize and thus clean the sediment. Therefore, excavators are used to rip up the clogged sediments and clean it manually.

At mean flow conditions, the benefits of weir-removals are revealed, while water depths do not change a lot, big local differences can be seen when looking at flow velocities (Figure 20). Up- and downstream of the removed weir, flow velocities increase, and also the sides, where most juvenile fish densities occur in natural streams, experience increased velocities. Velocities in the area upstream of the removed weir come into a range, where smaller spawning site placements could be considered. Figure 21 shows increased spawning area and juvenile salmonid densities from weir removal monitoring in Lærdalselva and Årdalselva.

Typically, the boulders from the weir removal would be used to create local variation and should in a real scenario be implemented into the model.

The ALB data provides a reliable data basis for planning measures and assessing consequences. For real case scenarios, also assessing low-flow conditions, is essential. High quality bathymetric data for revealing areas with risk of stranding is of high importance. With ALB data, the weir can iteratively be adapted to find scenarios with improved habitat conditions while minimizing stranding risk in very high detail degree. This planning safety is highly beneficial in regulated rivers but is with climate change getting increasingly important also in natural rivers.

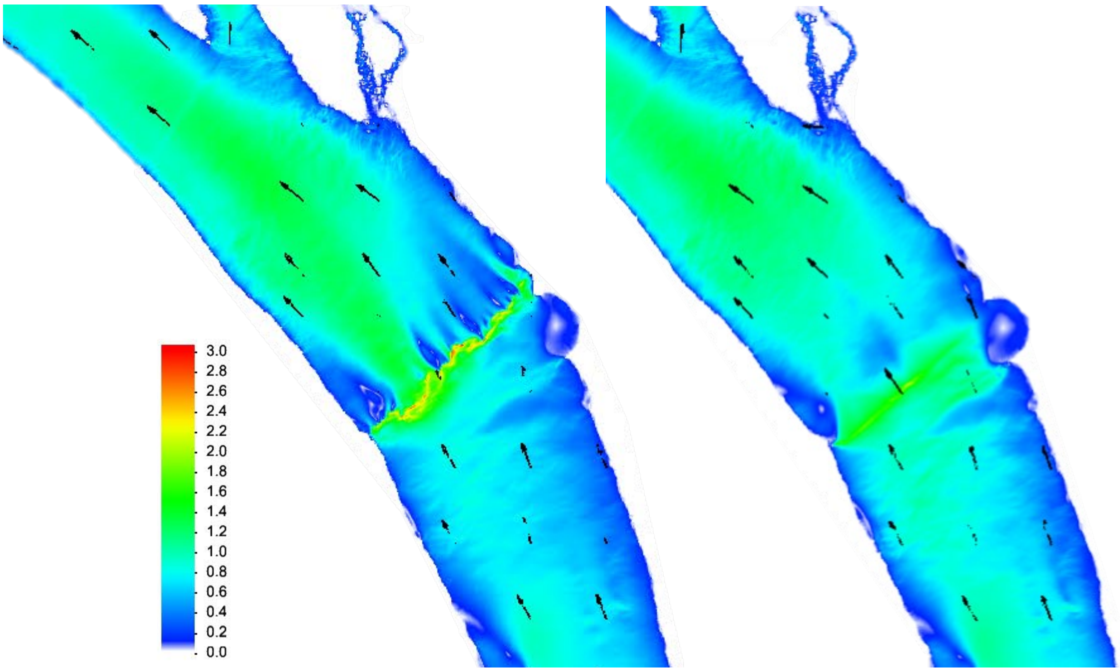

Figure 20: Flow velocities at 50 m3/s for current state (left) and weir removal scenario (right).

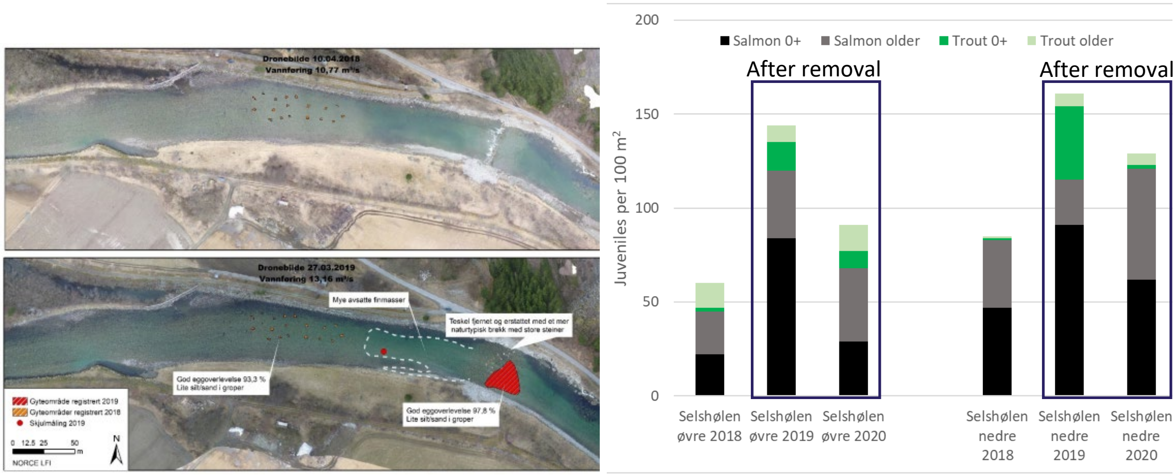

Figure 21: Left: Spawning areas before and after weir removal in Lærdalselva (Source: Gabrielsen & Skår 2019), right: densities of juvenile fish before (2018) and after (2019 and 2020, black frame) weir removal in river Årdalselva

Comparison of base data for ecological assessment

Modelling of a 560 m long river stretch (Oftepollen) in river Lærdal was compared based on ALB data, RTK UAV data and RTK cross sections (25 m between Xsections adjusted to existing morphology, denser profiles in areas of interest, with a measuring depth limit of 1.15 m). This is denser than usual modelling densities based on X-sections, which often are at 50 or 100 m distance.

Water depth of the stretch for the three models are shown in Figure 49 and depth differences in Figure 21. Flow velocities and differences between the models can be seen in Figure 22 and Figure

23. A summary is presented as boxplots in Figure 51 and Figure 52. In all three models, width variation is visible, however depth variation is underestimated in the UAV model (river bed is higher than in reality), and not available in the X-section model (Figure 24 and Figure 53 - Figure 56). This can, especially in rivers with little available shelter have an ecological implication, when key habitats like holding pools are not represented according to ground truth.

Higher river-bed elevation data can also explain that the UAV model has a greater water covered area (Figure 25) and higher flow velocities. The cross-section model has an area of 28 771 m^2, the UAV SfM model 28 466 m^2, and the ALB model: 26 921 m^2.

Compared to ALB data, the UAV based model underestimated water depth and water velocity in the deep and fast parts and slightly overestimates depth/velocities in the shallow and slow parts (Figure 51 and Figure 52). The biggest overestimations of both water depth and flow velocities can however be seen at bins of 0.8-1.1, where the UAV model has approximately twice the area of the ALB model.

An automatic mesohabitat classification performed by BOKU revels that X-section based data delivers very simplified results which need high effort to reflect the current state. Cross-section approach is overestimating the area with riffle stretches. While both ALB and UAV data can detect riffles, runs, pools, backwater and shallow water sections. The UAV data is however underestimating pools and overestimating runs by 9 %. Also riffles, backwater and shallow water areas are more frequently detected with ALB data. Fast runs are equally well detected.

Compared to manual mesohabitat mapping (which was performed on a much coarser scale), both, UAV and ALB derived mesohabitat maps give a more detailed picture than the manually mapped units. All stretches which were classified as pool manually also contain areas classified as pool in the UAV and ALB data, likewise with fast runs. The deep glide manually classified stretches are mainly covered by runs/fast runs in the modelled data. Most riffles were too short to be registered manually according to the mapping method, the one manually mapped riffle is classified as riffle in both modelled results as well (Figure 26). Also, all plunges out of weirs are classified as riffle due to their hydraulical conditions. Biota might not always agree with the classifications derived from hydrodynamic parameters (e.g. the plunge classified as riflle might not be an appropriate habitat for many species).

The underestimation of key habitats like of holding pools, and important juvenile fish habitat like shallow areas and backwater can have implication when drawing ecological conclusions based on non—corrected UAV data derived results. While hydromorphological units can be derived from modelling results, more research is required for registering key habitats like spawning areas, where additionally to flow conditions also substrate parameters need to be detected.

ALB and UAV data give a planar result of meso- and microhabitats, where a lot of small-scale variation is lost in the X-section model. Some of the habitats in in the UAV model are however errors due to white water or reflections on the water surface and do not exist in reality (red markers in Figure 22).

For macroscale analysis like flood modelling, detail degree of cross-sections might be sufficient. For meso- or microscale analysis that affect biota in the rivers, X-section based models do not seem to reflect the essential habitat elements and distribution of water between the channels and flow velocities are not represented realistically. Of course, the density of cross-sections could be increased to at least represent a coarse depth variation, but with an average surveying time of approximately one hour (including traveling time) per X-section in these sized rivers, this would make surveying very costly.

If one uses results from UAV without corrections, this can have important implications for ecological assessments and planning: 1) too little residual flow or stranded key habitats like spawning areas due to overestimation of wetted area, 2) planned measures could in reality have slower water velocities and shear stress than anticipated, 3) missing of pool habitats can lead to wrong conclusions and 4) mass overestimation when planning measures due too high river bed elevation data. Also, for flood modelling, the errors in riffle- and white water sections can have an effect on water level and wetted area. It is thus important to be aware of the limitations of UAV data for ecological assessments and planning.

In smaller streams and side channels which generally are shallower, X-section corrected UAV data can provide planar information if ALB data is not available. This gives a much more detailed bathymetry with vast more applications than X-sections alone.

ALB data delivers superior data basis in large rivers. With available ALB bathymetry and aerial pictures that can be linked to discharge, the whole planning process from model building, adaptions to the geometry and calibration can be performed from the desktop, with a significantly shorter field work for model verification. When using UAV data, additionally to UAV data collection, correction and control measurements would be necessary for realistic UAV data in deeper sections. With only RTK X-sections, a lot of sampling would be necessary to get a realistic depth variation or a mass estimate of planned measures.

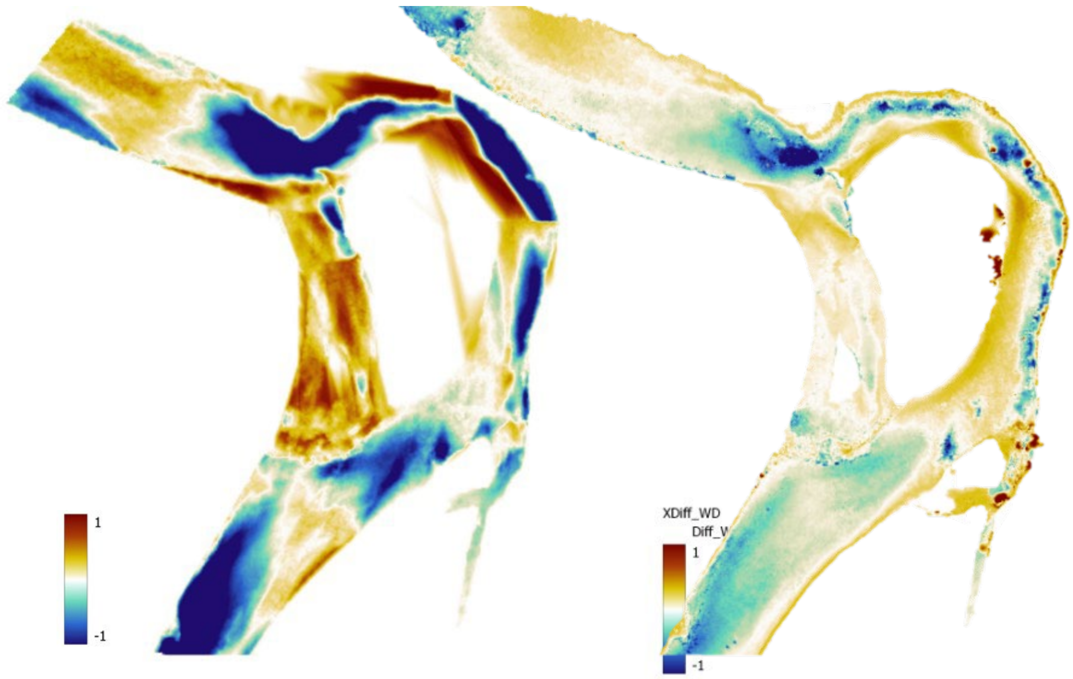

Figure 22: Difference in water depth (m) between X-section model and ALB model (left) and UAV model and ALB model (right), red: other model deeper, blue: ALB deeper.

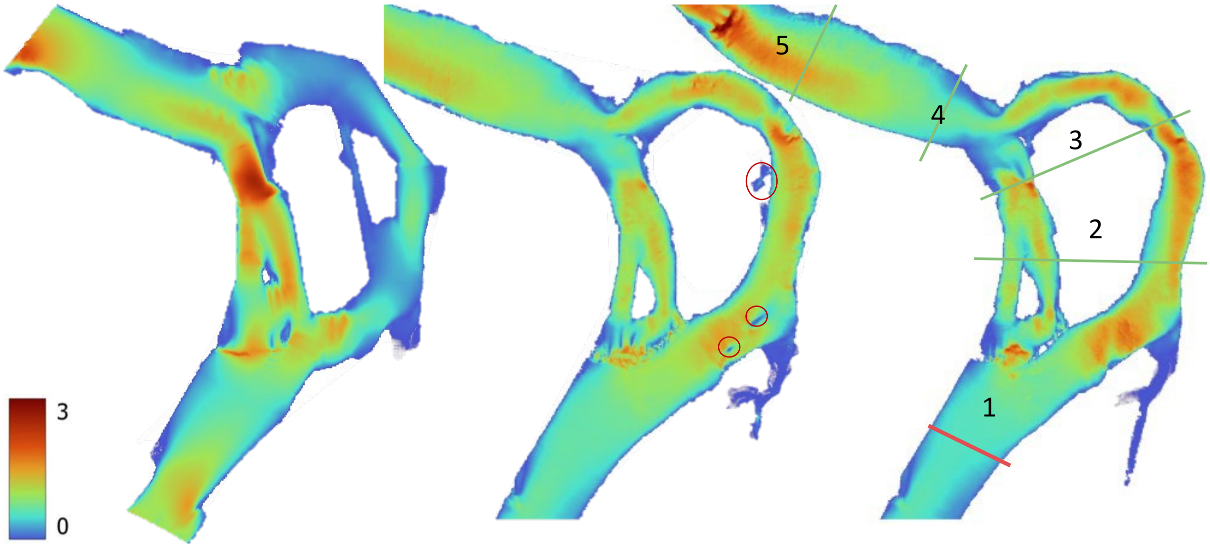

Figure 23: Flow velocities based on X-sections (left), UAV data (middle) and ALB data (right). Cross-sections (with numbers) for the following figures (red lines)

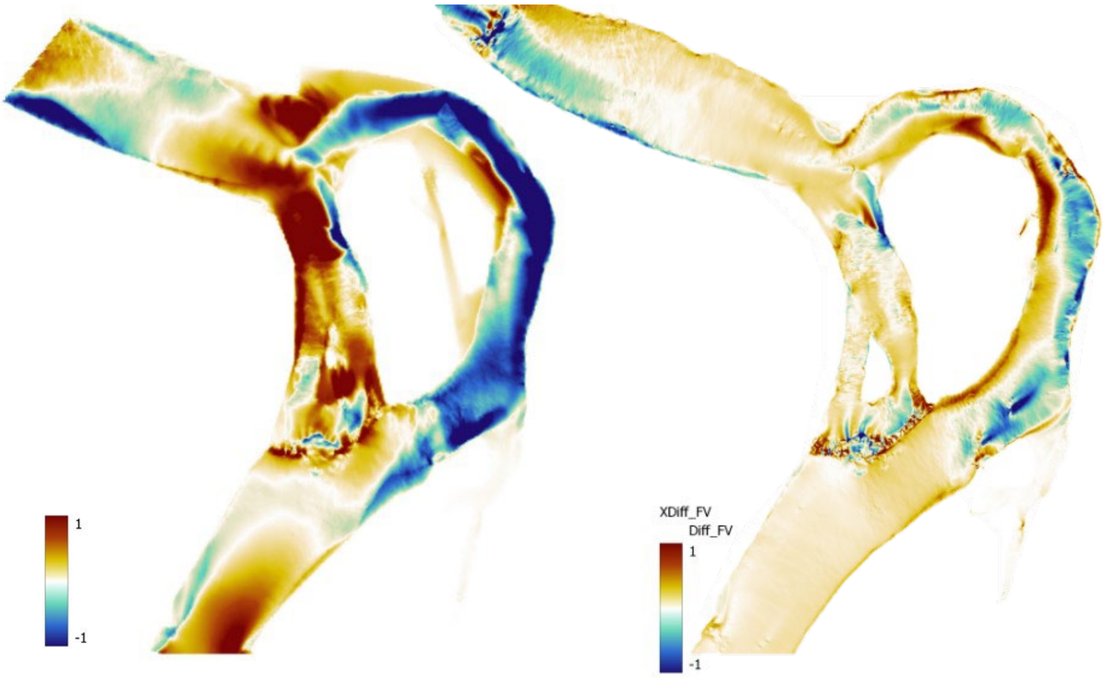

Figure 24: Difference in flow velocity (m/s) between X-section model and ALB model (left) and UAV model and ALB model (right), red: other model faster, green/blue: ALB faster.

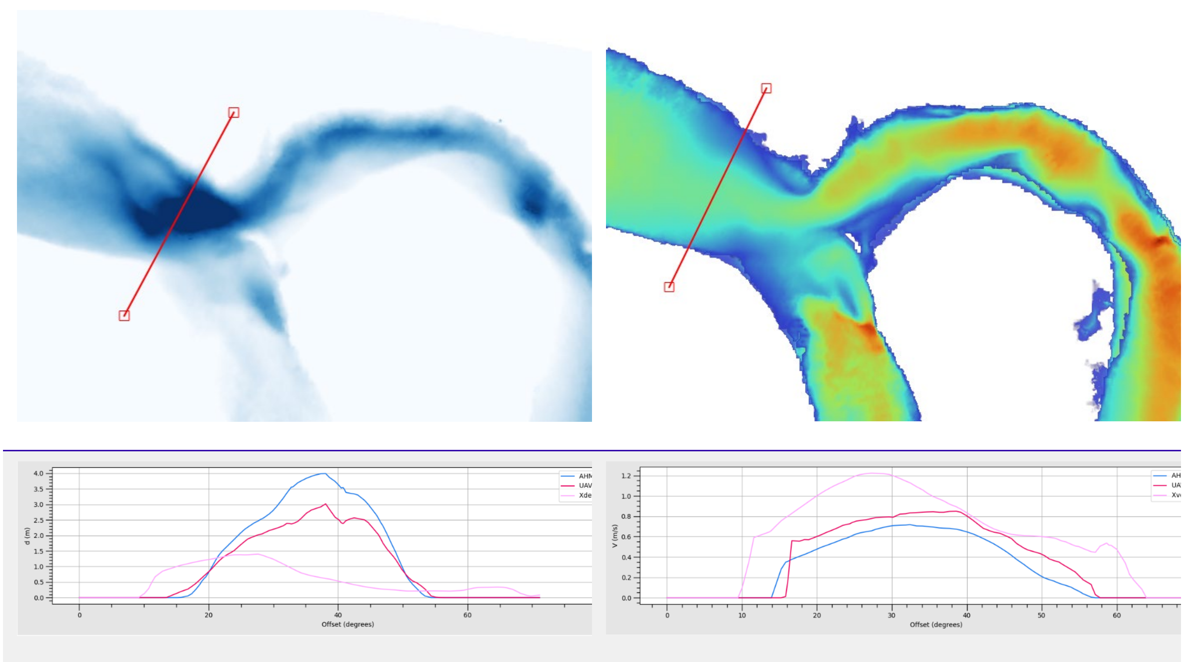

Figure 25: Water depths (left) and flow velocities (right) at profile 4. Diagram coloring: ALB data (blue), UAV data (red), X-section data (pink).

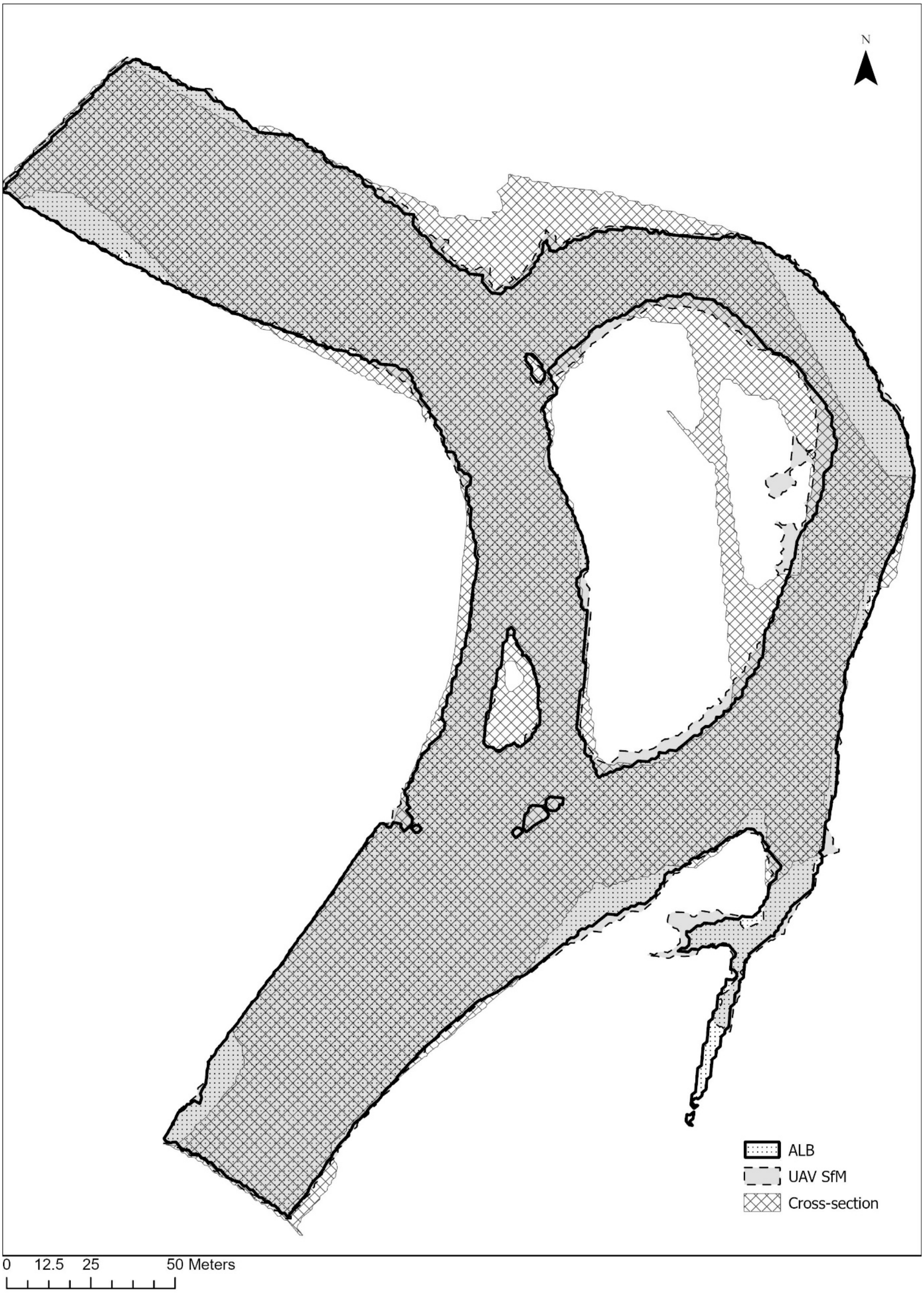

Figure 26: Wetted area for the ALB (dotted, solid line frame), UAV (solid grey, stippled line frame) and X-section (crosshatched) based model.

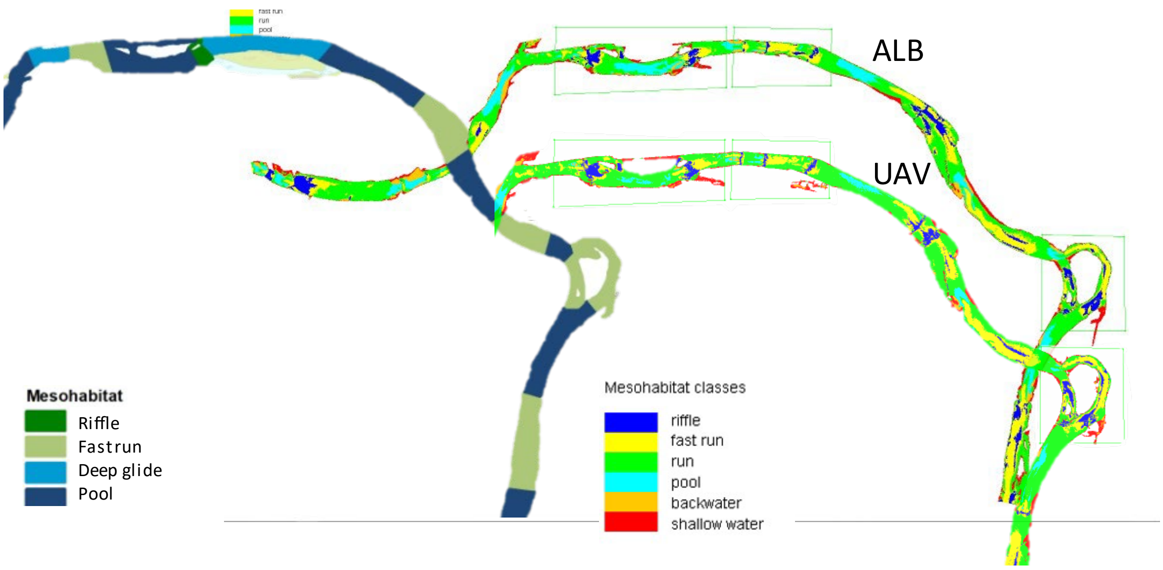

Figure 27: Mesohabitat classes from manual mapping (left), derived from ALB and UAV SfM (right)

3. Summary and conclusion

WP 1 Validation, analysis, and conceptual work

River types

ALB worked in the river types (pool riffle, fine sediment type) in the case rivers. Based on a longitudinal profile and substrate estimate, a classification in all case rivers was possible and was used to verify the river type of pre-classification. Slope of water surface/energy slope, and bed slope could be made out with one longitudinal profile, where pools and riffles were clearly visible. Results from BOKU show that substrate parameters (b-axis) can be extracted from high resolution ALB data in rivers without non-fluvial elements. In rivers with non-fluvial elements, b-axis derivation was not possible, however differentiation between fluvial and non-fluvial river types was possible with analyzing roughness variation. More research is required for automatic substrate classification and findings indicate that more information could be derived also in non-fluvial stretches when boulders don’t get filtered in the laser datasets.

Ground truth and mesohabitat mapping

Mesohabitat assessment

The amount of ground truth data that could be sampled varied in the different case rivers due to limited visibility under water and high water level. In a follow–up project, timing of ALB surveying and ground truth sampling could be better coordinated to assure comparable conditions. The sampling also revealed the depth limitations of cross-section sampling.

UAV SfM sampling worked well in river Lærdal which has clear water and analysis reveal the superior performance of ALB regarding accuracy and consistence. With cross-section correction data, UAV SfM bathymetry could be an alternative for smaller-scale surveys in clear and smaller streams, which delivers planar information and higher detail degree compared to cross-section data alone.

Application of UAV data was limited in the rivers Hallingdalselva and Bøelva with coloured water and a wider channel where bottom if at all could be registered between a few and 80 centimeters. ALB could under the same conditions register ground in several meters water depth. Differences were found in Hallingdal, where Terratec data was flown at lower water level than the AHM survey and reaches deeper areas in very deep pools.

If openly available, ALB data can be acquired much faster (1.5 times as fast as UAV data, 7.5, 15 and 30 times faster than 100, 50 and 25 m distance cross section approach respectively) than cross-section or UAV based data. Compared to the other methods which require field work, it also only requires processing time, which with improving data systems will decrease over time. ALB data is additionally more accurate and detailed with consistent and planar bathymetric information.

ALB data based models can deliver ecological information like abiotic mesohabitat distribution at a higher resolution than traditional mapping (Hauer et al. 2009) in fluvial river types. Hauer et al. (2009) pointed out that current state models will not provide realistic results in rivers with very high roughness / non-fluvial river types.

Assessment of shelter derivation from ALB data

While mesohabitats are important, automatic algorithms for analysis of key parameters for salmonids like shelter or substrate type based on ALB data are not yet widely available. We show a significant correlation between shelter and roughness indices derived from rasterized ALB point cloud and BOKU showed that bottom grain sizes can be estimated based on the raster files in fluvial river types. Both results indicate that misclassification (holes in the bathymetry data at boulder locations due to a too strict filter algorithm) of bottom substrate in the available ALB point cloud likely led to weaker correlations.

For non-fluvial rivers, other methods like roughness surface generation (Wiener & Pasternack 2022) could be used for classifying large boulders, where detailed DEMs are subtraced from smoothed DEMS and boulders are “pointing out”. For finer grains, Gomez et al. (2022) showed that machine learning algorithms that incorporate several derivatives of laser scans had a determination rate of 86 % on land for grainsizes up to coble (256 mm). It could be tested with ALB with shelter, larger grainsizes and in the river as well. More research should therefore be put into 1) improving point cloud classification and 2) extracting substrate parameters based on raster and directly from point cloud data from high point density ALB data.

WP 2 Flood risk - Ecological and flood-safety improvement scenarios for Lærdalselva

The ALB datasets can be used for planning and assessing ecological and flood related questions from the desktop with a strongly reduced requirement for field work compared to data from other data sources, additionally giving a model verification with much higher accuracy and detail degree than other methods. ALB can therefore improve planning safety and speed up planning and modelling process for high- flow, low-flow, morphodynamics and ecological applications.

The Lærdal flood case study shows that advances in remote sensing can be used to develop and model nature-based and integrated solutions for improving flood safety and ecological status.

Additionally, precise mass-estimation of planned measures is possible without need for additional surveying. A more detailed study in Lærdalselva which includes the whole catchment would have great potential for improving both flood safety and ecological status on a much larger scale.

WP 3 River restoration - Comparison of base data for planning/modelling restoration measures

Weir removal scenario

The ALB data based model is detailed enough to reveal changes in flow velocities at lower discharges at a local level and can be used for iterative optimization of habitat measures to boundary conditions like low-flow. At the same time, the ALB data can be used to assess sediment stability to check the need for additional measures like ripping and to rule out unwanted erosion. Results highlight that both, flood, and low flow conditions have to be considered in restoration projects. Monitoring results confirm the positive effect of changed hydraulic conditions after weir removal on spawning area and juvenile density. Especially the low flow conditions will become increasingly important with climate change.

Comparison of base data for ecological assessment

For planning river restoration and habitat measures, ALB data improves planning safety, and delivers a detail degree which can be used for planning microhabitat adaptions, key habitats like spawning areas and assessment of ground stability. Increased effort would be necessary for achieving comparable results with RTK transects (much denser cross-section data) and UAV SfM (bathymetry correction with ground control points and manual depth measurements in deep pools).

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5. Appendix

WP 1 Validation, analysis, and conceptual work

River type classification

Figure 28: Longitudinal profile of river Lærdal and variation in grainsize.

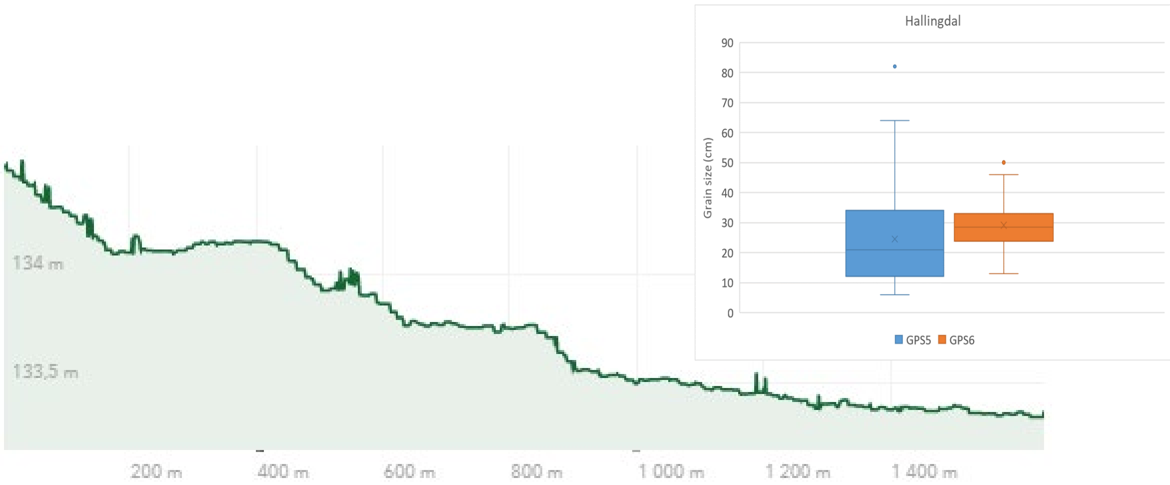

Figure 29: longitudinal profile of the steeper section of river Hallingdal and variation in grainsize. The lower part of the river stretch is flat.

Figure 30: Longitudinal profile of river Bøelva.

Mesohabitat assessment

Lærdal

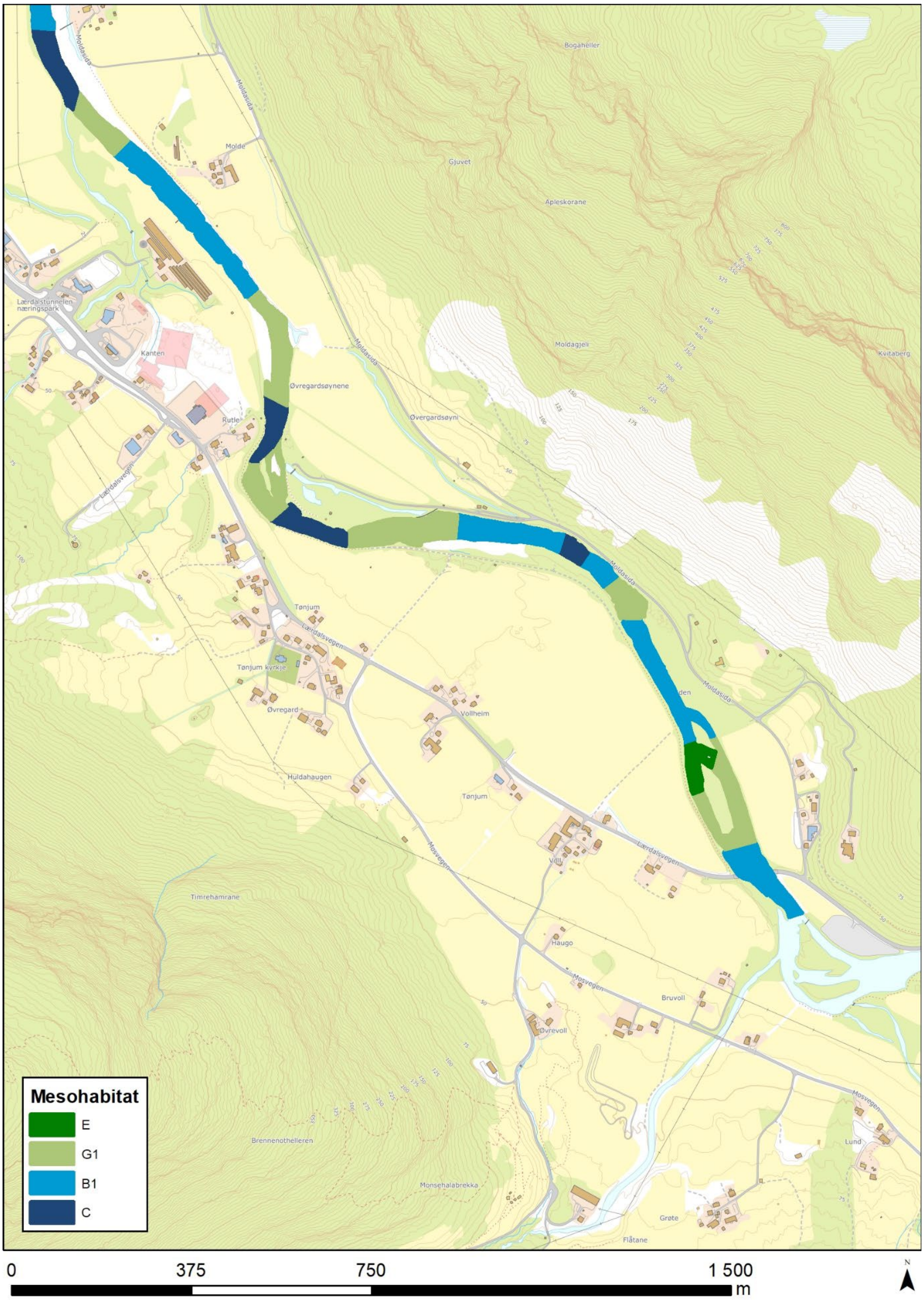

Figure 31: Mesohabitat classes in the upper part of the mapped Lærdal river stretch (E: run, G1: fast run, B1: deep glide, C: pool)

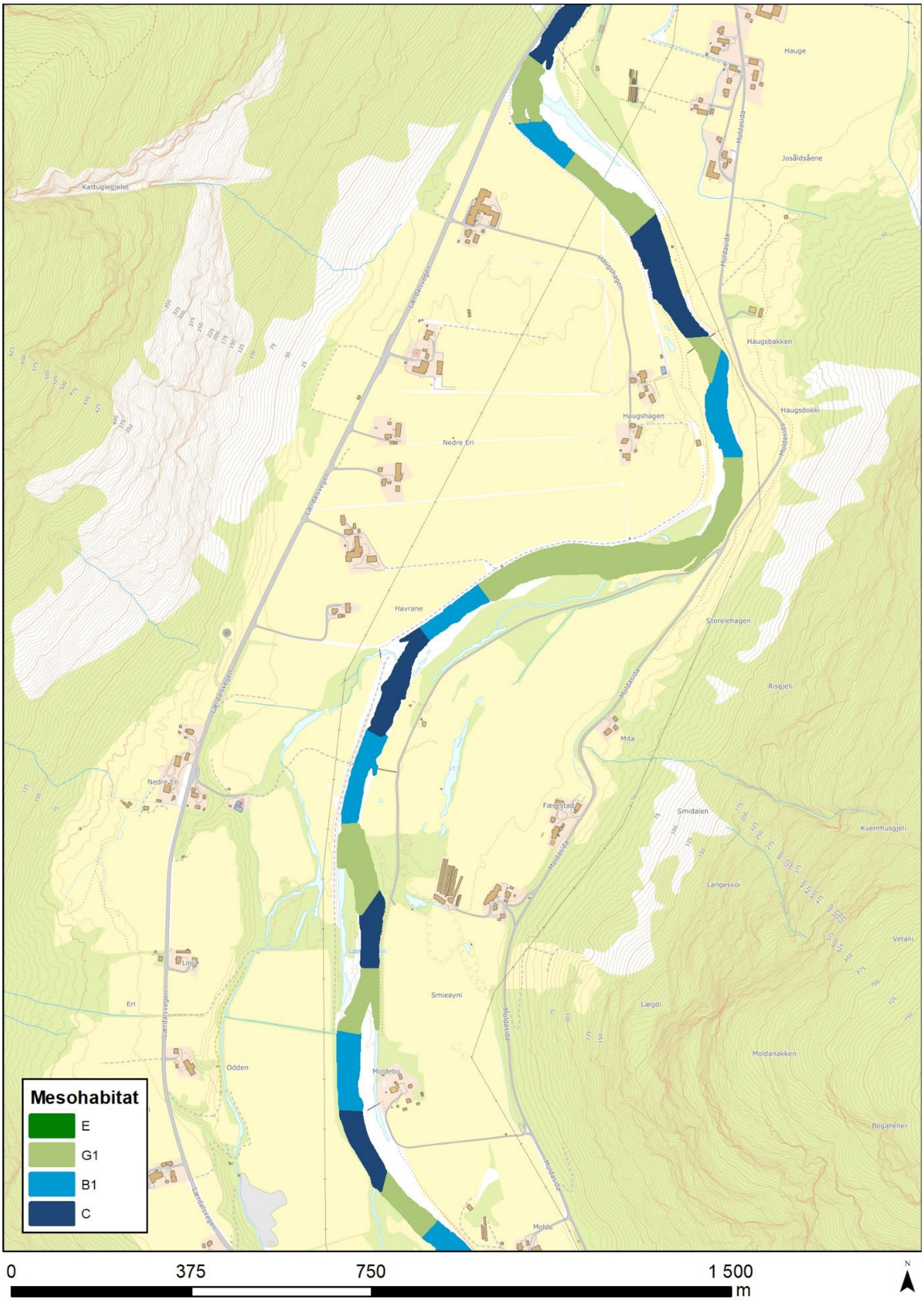

Figure 32: Mesohabitat classes in the middle part of the mapped Lærdal river stretch (E: run, G1: fast run, B1: deep glide, C: pool)

Figure 33: Mesohabitat classes in the lower part of the mapped Lærdal river stretch (E: run, G1: fast run, B1: deep glide, C: pool)

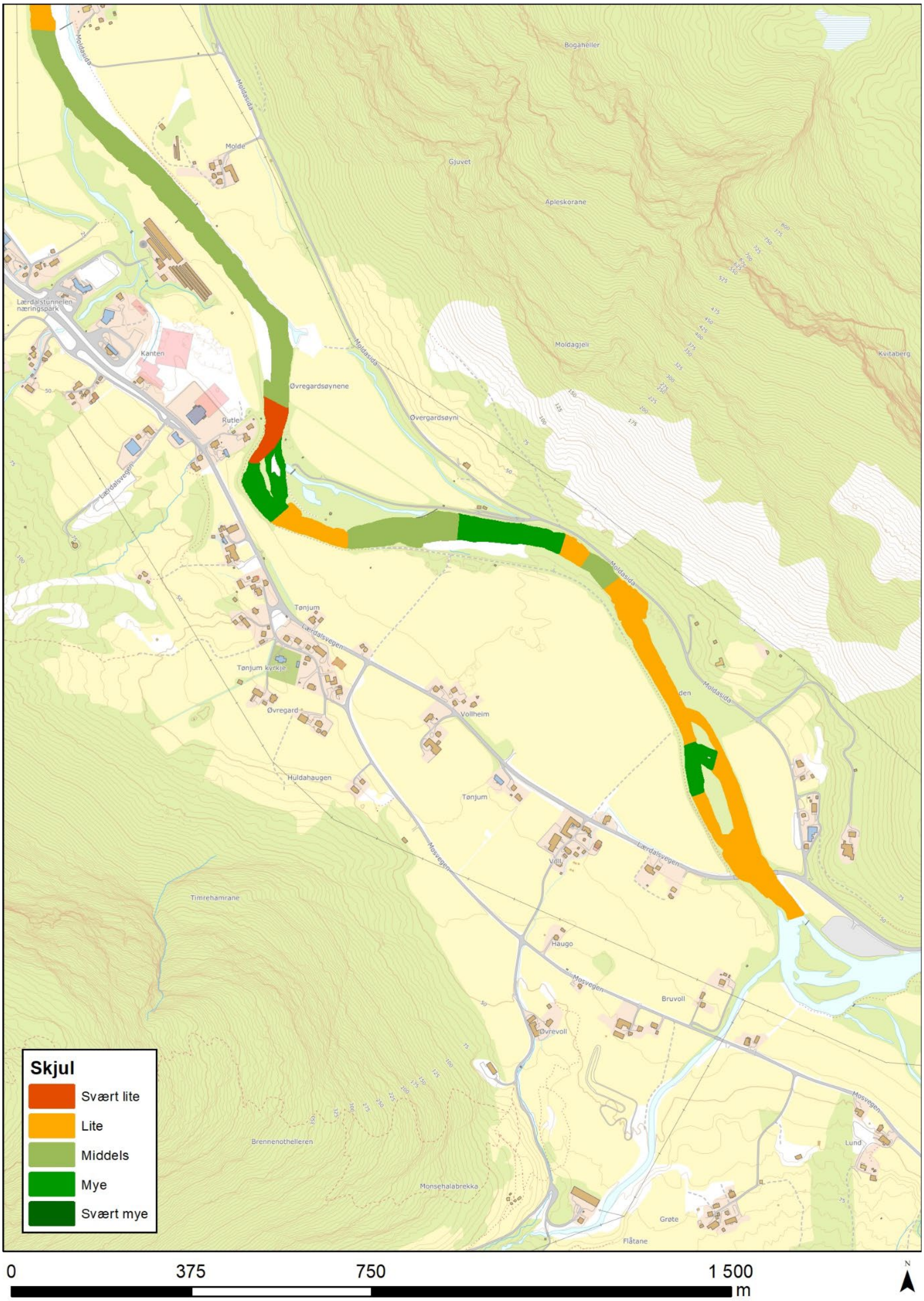

Figure 34: Shelter in the upper part of the mapped Lærdal river stretch

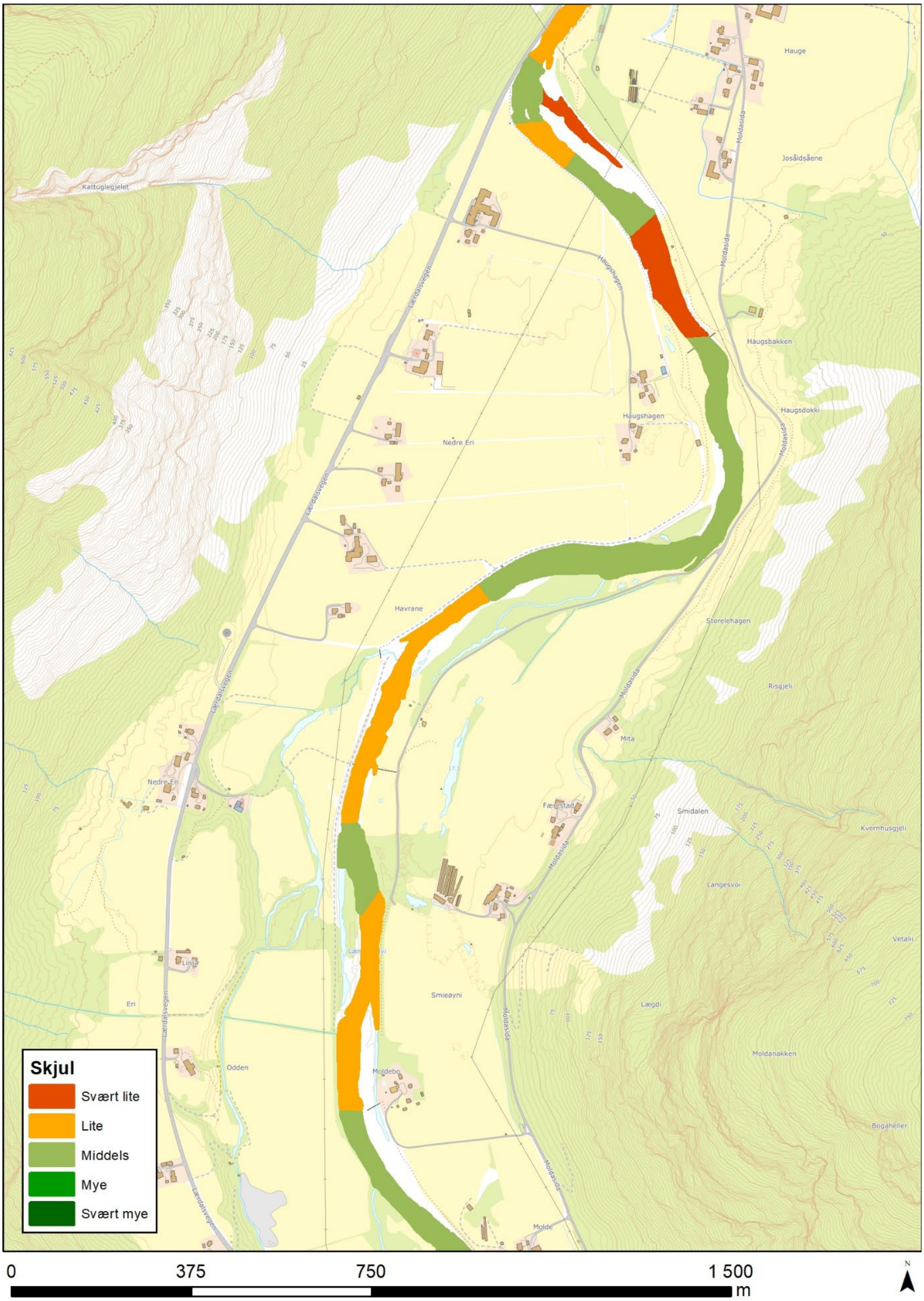

Figure 35: Shelter in the middle part of the mapped Lærdal river stretch

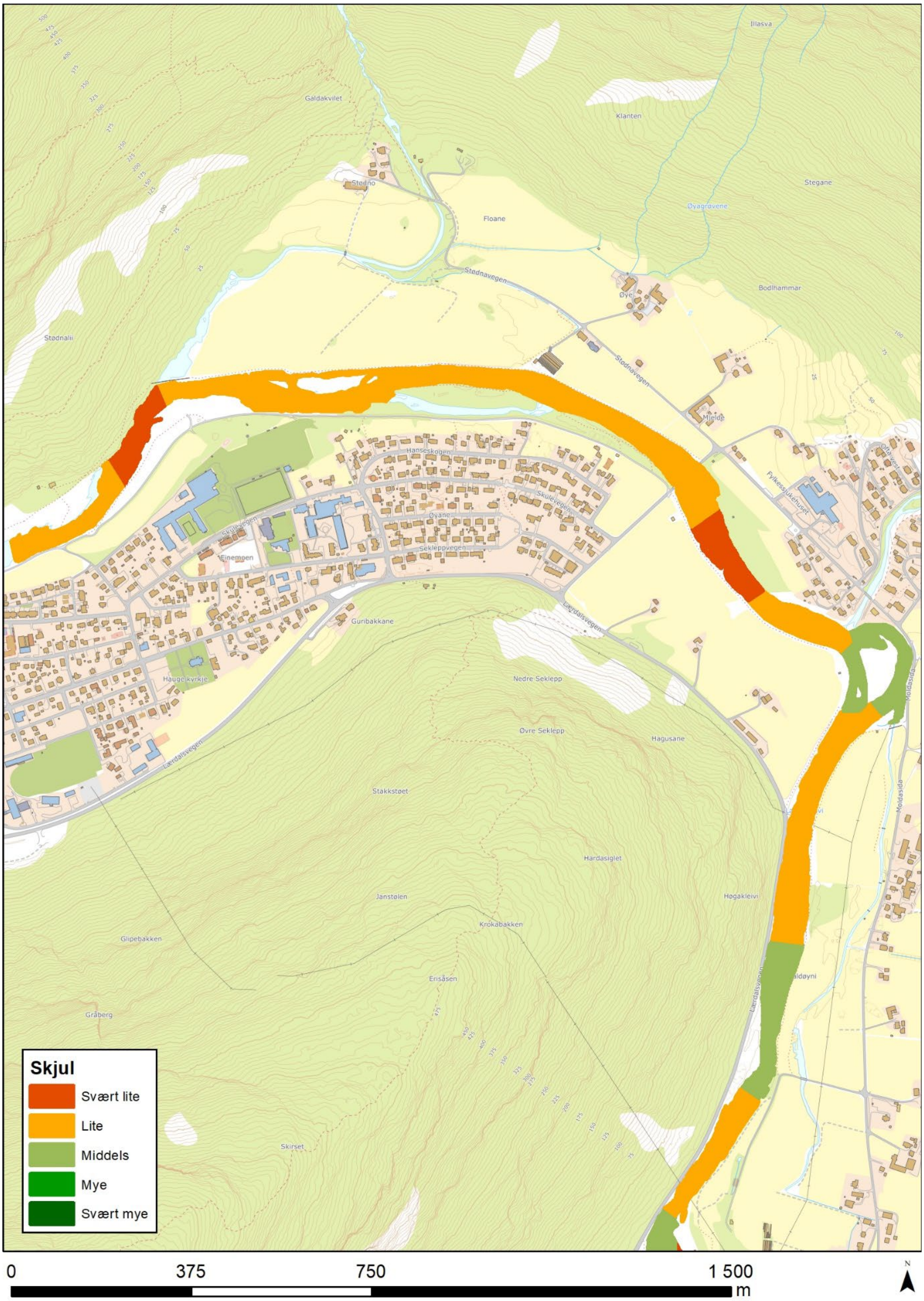

Figure 36: Shelter in the lower part of the mapped Lærdal river stretch

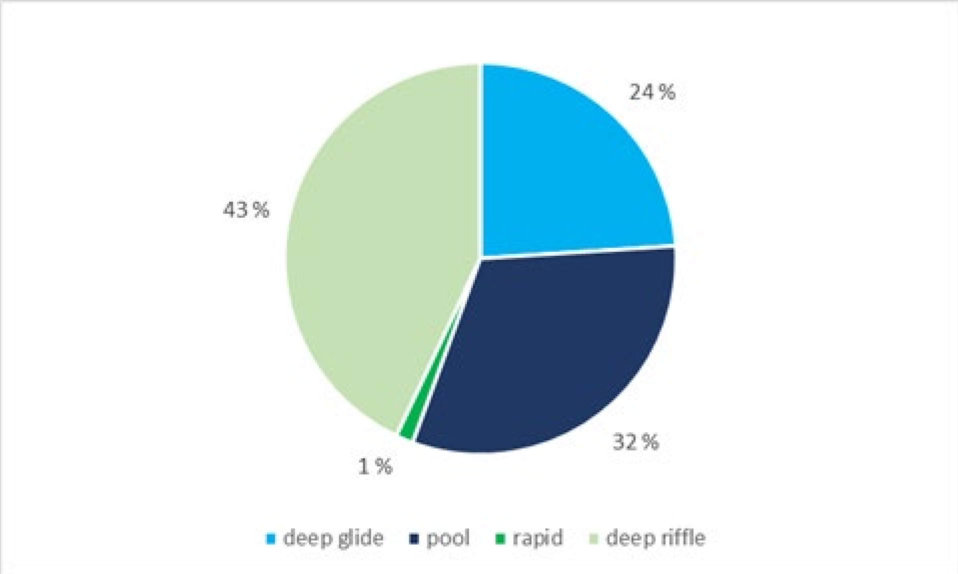

Figure 37 Mesohabitats Lærdalselva

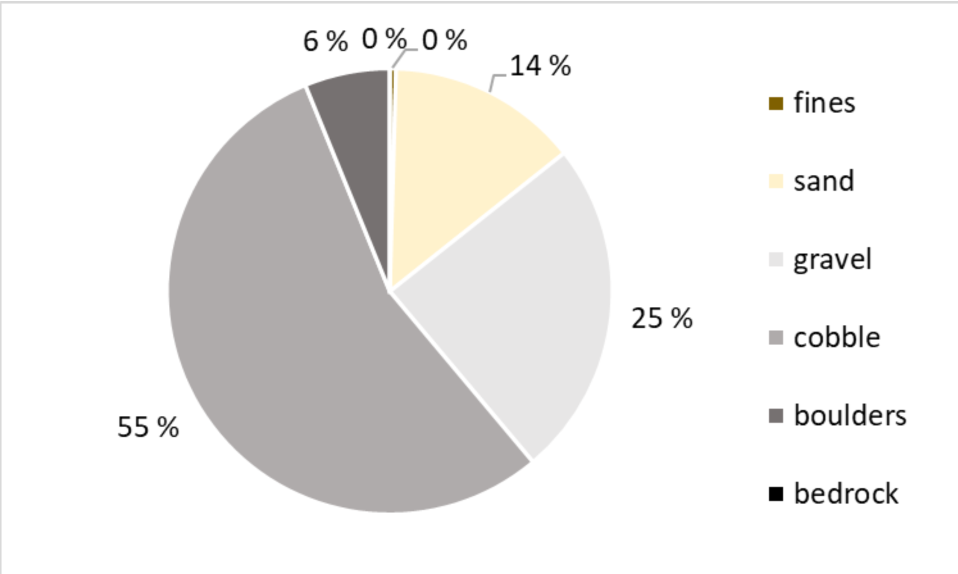

Figure 38. Sediment distribution Lærdalselva

Bøelva

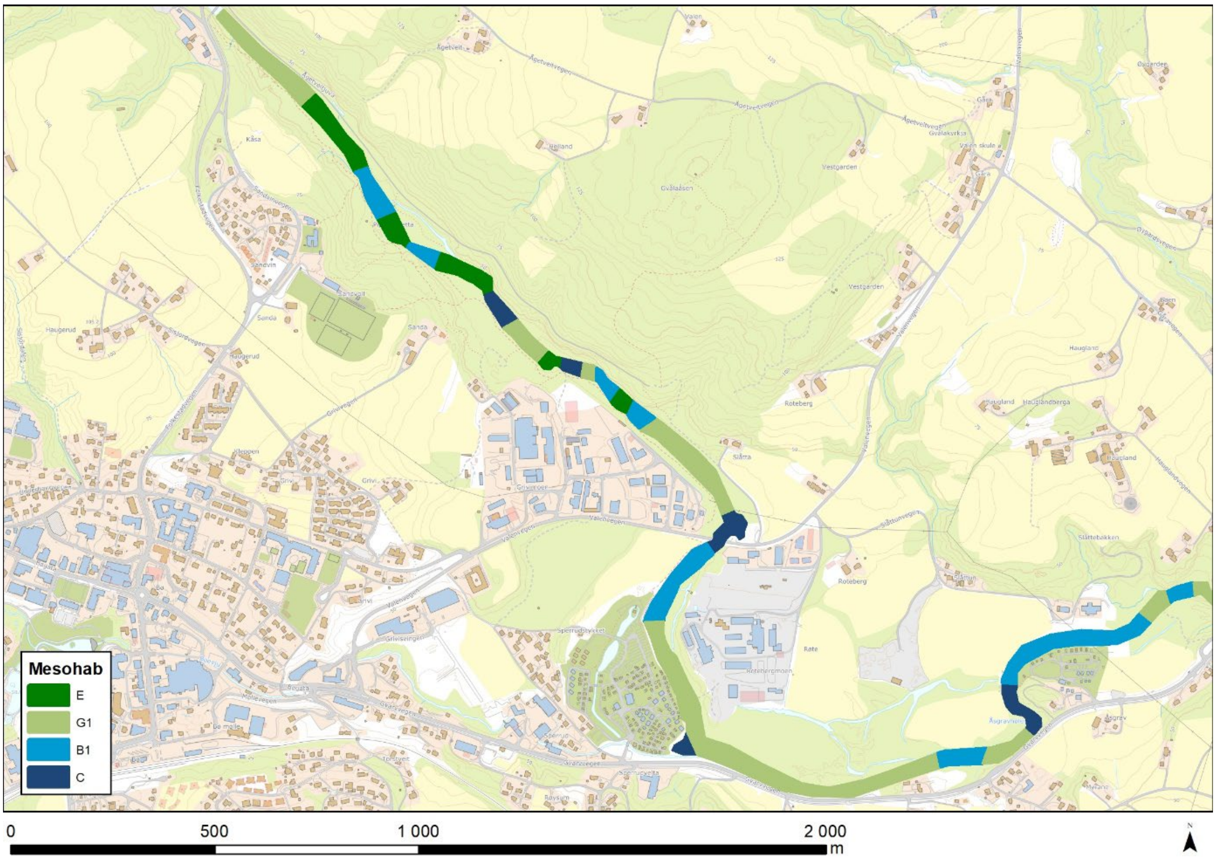

Figure 39: Mesohabitat classes in the upper part of the mapped stretch of river Bøelva (E: run, G1: fast run, B1: deep glide, C: pool)

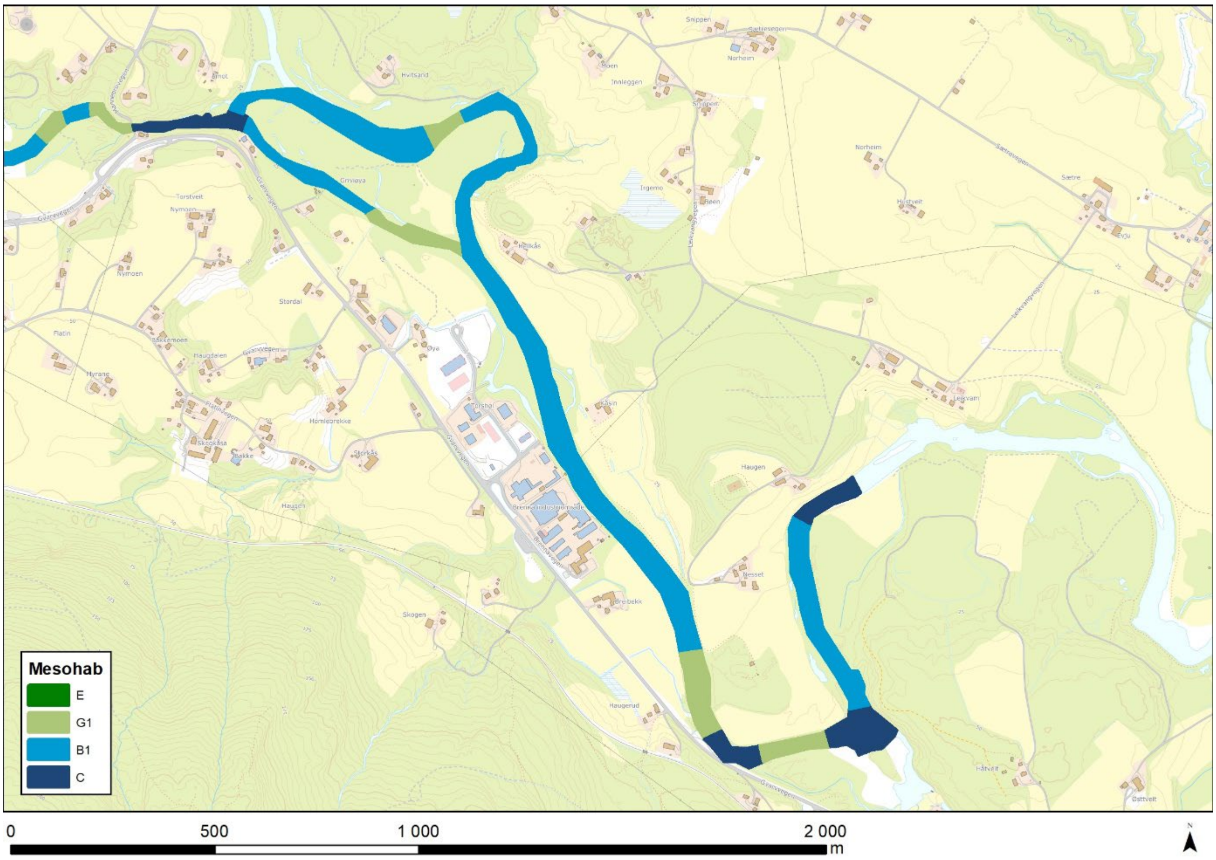

Figure 40: Mesohabitat classes in the lower part of the mapped stretch of river Bøelva (E: run, G1: fast run, B1: deep glide, C: pool)

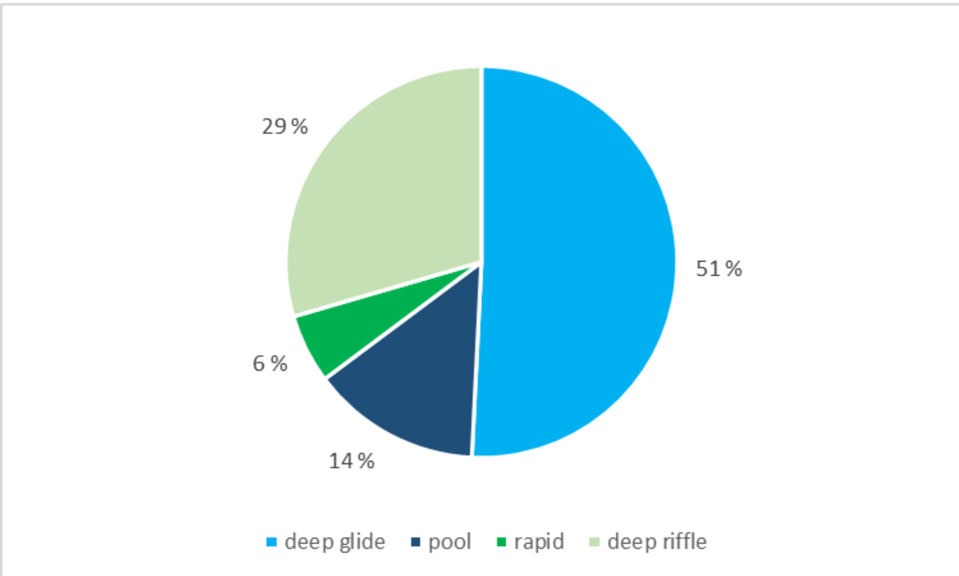

Figure 41 Mesohabitat distribution in river Bøelva

Hallingdalselva

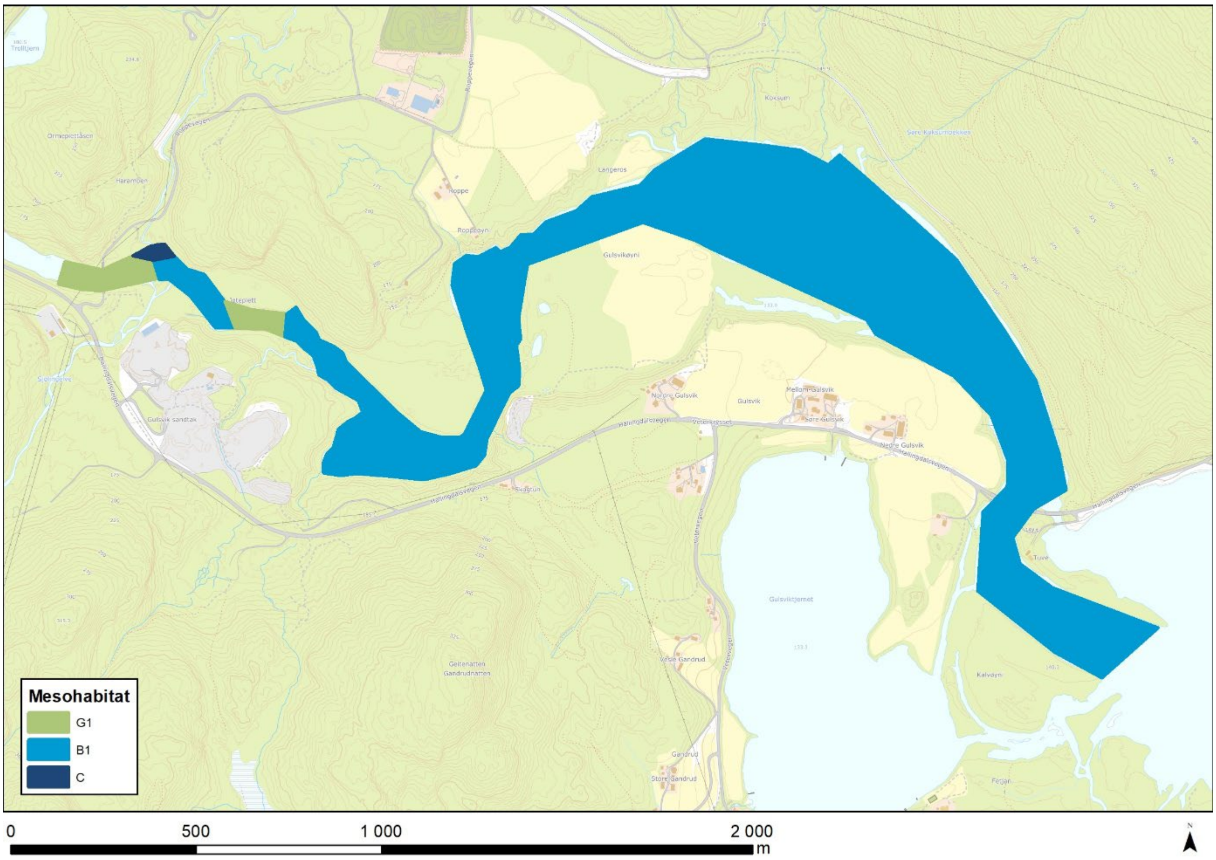

Figure 42: Mesohabitat classes in the mapped stretch of river Hallingdal (G1: fast run, B1: deep glide, C: pool)

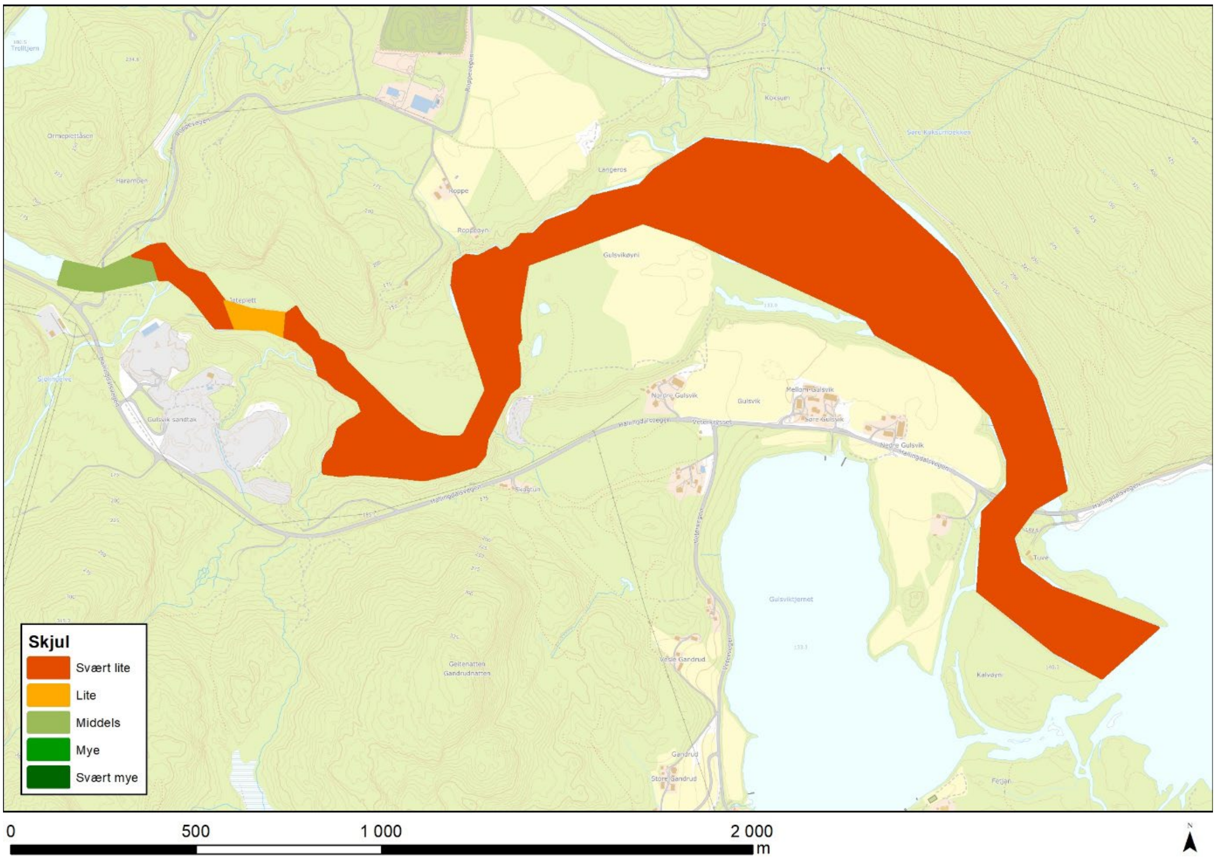

Figure 43: Shelter in the mapped stretch of river Hallingdal

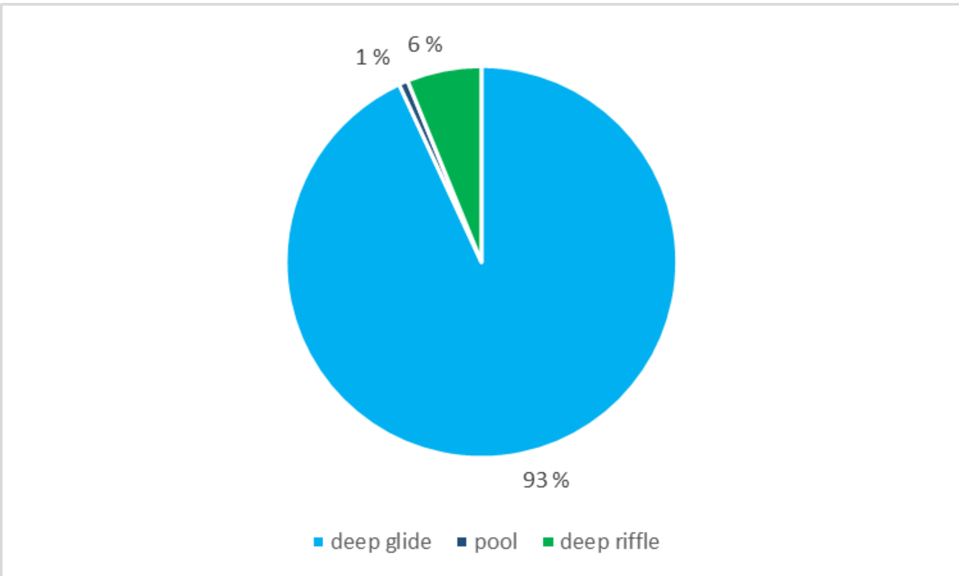

Figure 44 Mesohabitats Hallingdalselva

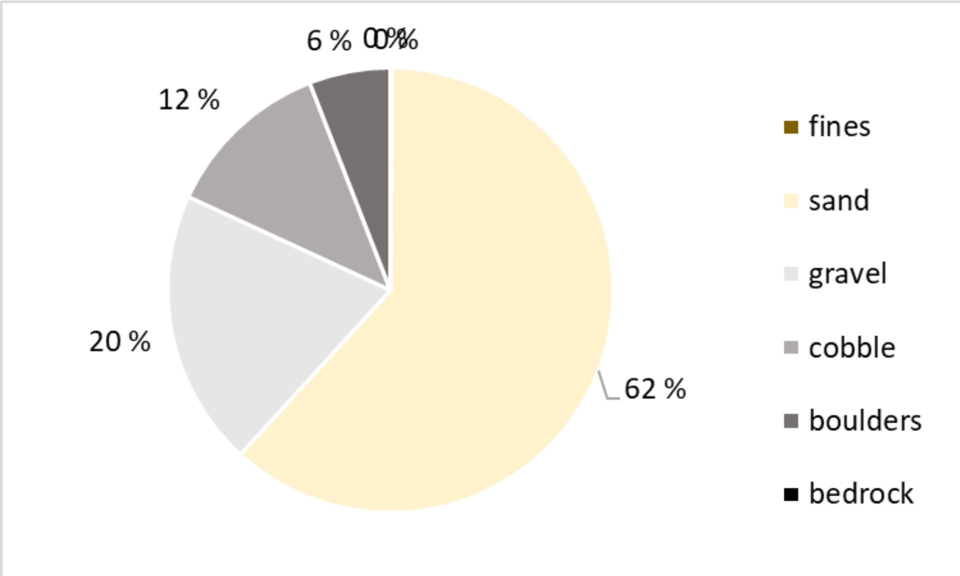

Figure 45 Sediment distribution Hallingdalselva

UAV aerial pictures and elevation model

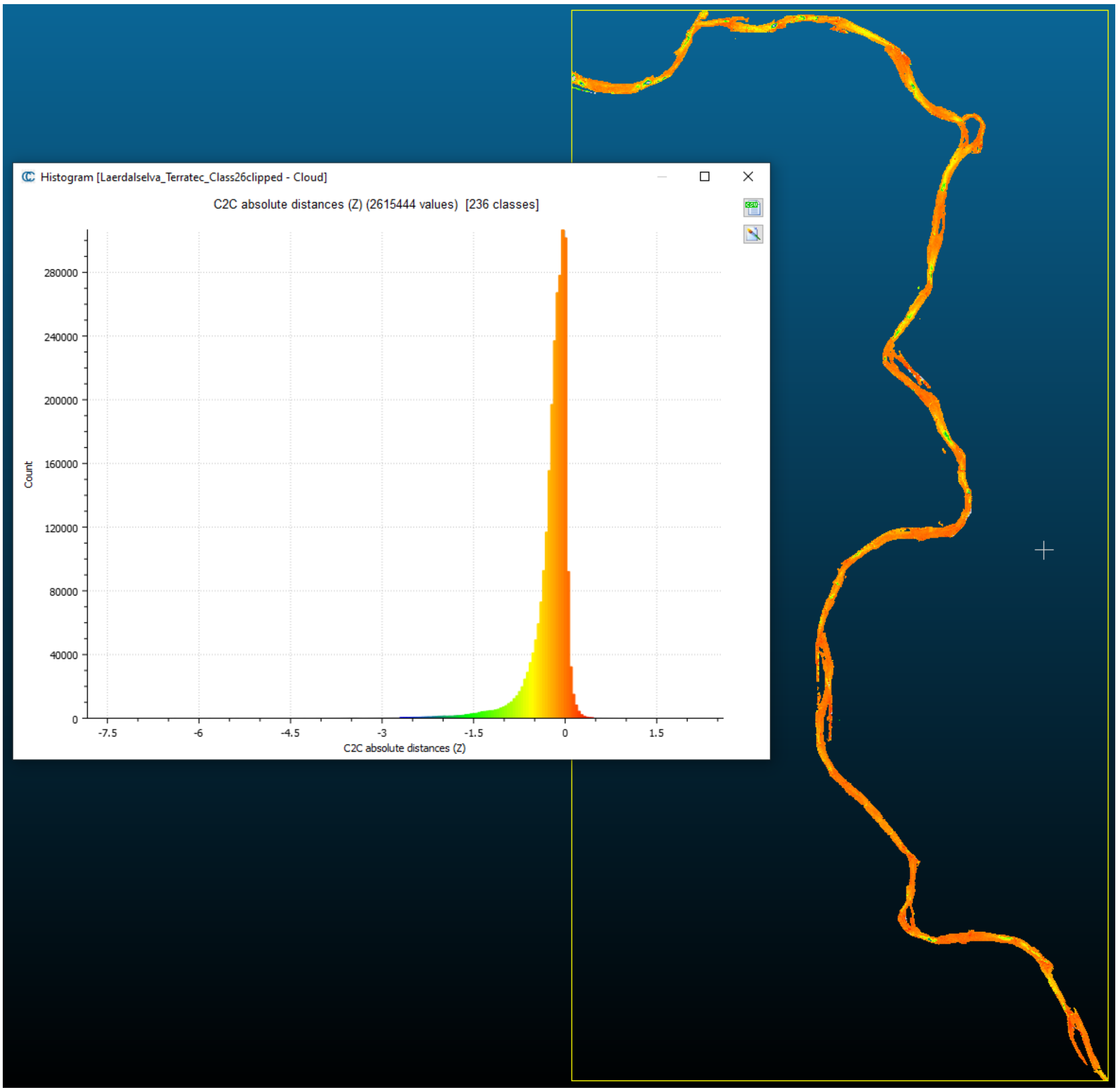

Figure 46: Total Z-error (m) from UAV compared with the Terratec ALB data (class 26). Negative values mean the Z-value of the UAV data is higher (underestimating depth). High negative values occur in pools in the river.

Table 9: Error table for UAV and Terratec ALB data.

Water depth (m)	Median Z error (m)	Mean Z error (m)	SD (m)
0	-0.023	-0.02809	0.149003
0.2	-0.02233	-0.05289	0.139599
0.4	-0.08733	-0.10747	0.128069

0.6	-0.1535	-0.17075	0.138361
0.8	-0.221	-0.24619	0.169505
1	-0.314	-0.33746	0.199408
1.2	-0.4055	-0.43876	0.23433
1.4	-0.488	-0.53808	0.279023
1.6	-0.573	-0.64219	0.317313
1.8	-0.662	-0.7556	0.364243
2	-0.761	-0.86777	0.390189
2.2	-0.913	-1.02055	0.45096
2.4	-1.051	-1.15311	0.505374
2.6	-1.128	-1.23897	0.566822
2.8	-1.184	-1.31701	0.615432
3	-1.3345	-1.45871	0.637748
3.2	-1.53283	-1.57315	0.660515
3.4	-1.71	-1.69179	0.620822
3.6	-1.8685	-1.80331	0.638565
3.8	-2.1	-2.00799	0.678805
4	-2.188	-2.11538	0.735854
4.2	-2.434	-2.28575	0.78004
4.4	-2.6925	-2.46838	0.789318
4.6	-3.032	-2.79574	0.683858
4.8	-3.2995	-3.02154	0.651973
5	-3.3555	-3.13194	0.639825
5.2	-3.523	-3.35991	0.593153
5.4	-3.7455	-3.49428	0.631274
5.6	-3.845	-3.5067	0.87364
5.8	-4.3285	-4.01801	0.837824
6	-4.341	-4.02874	0.899038

Assessment of shelter derivation from ALB data

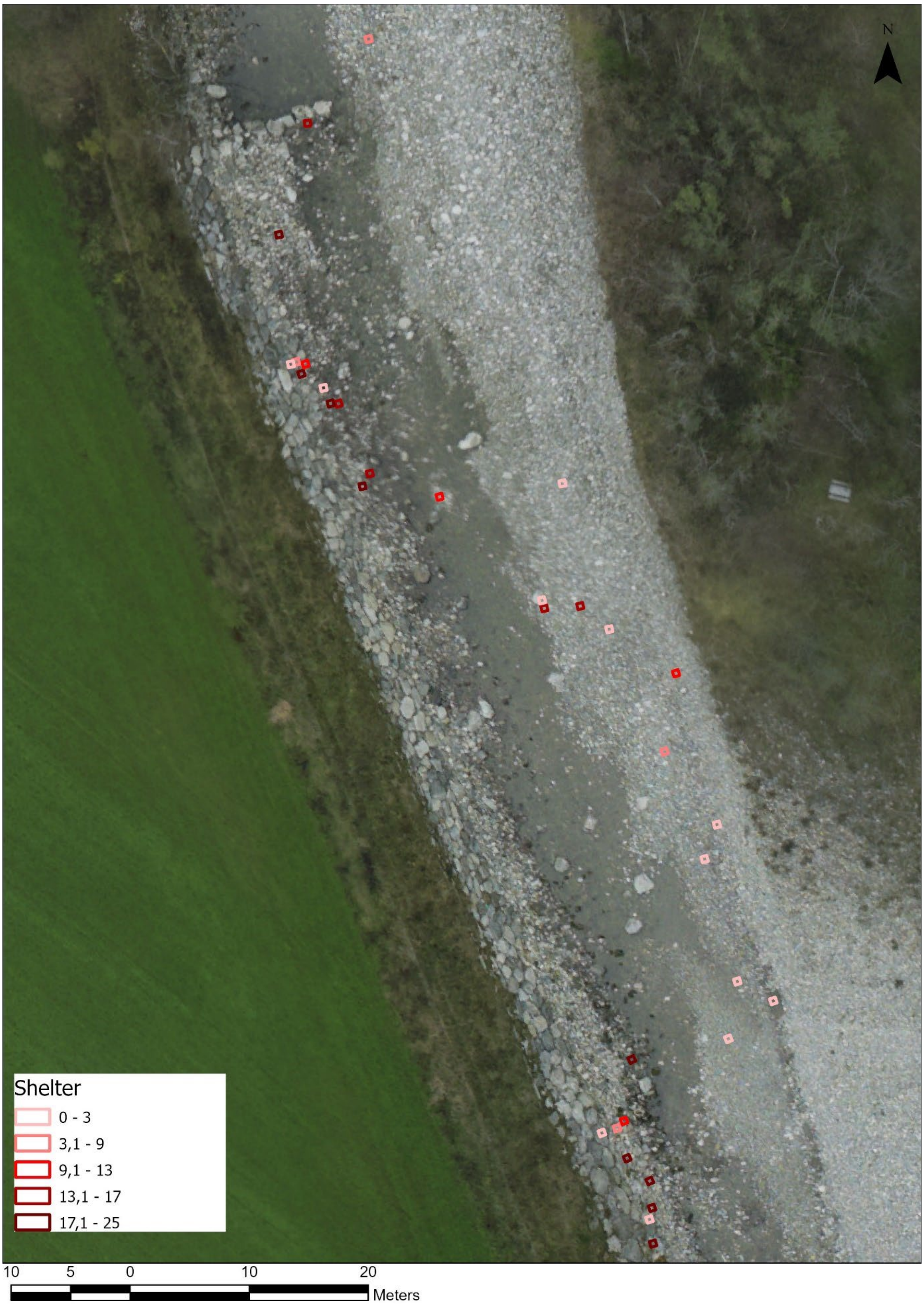

Figure 47: Areal picture of selected area with shelter measurements.

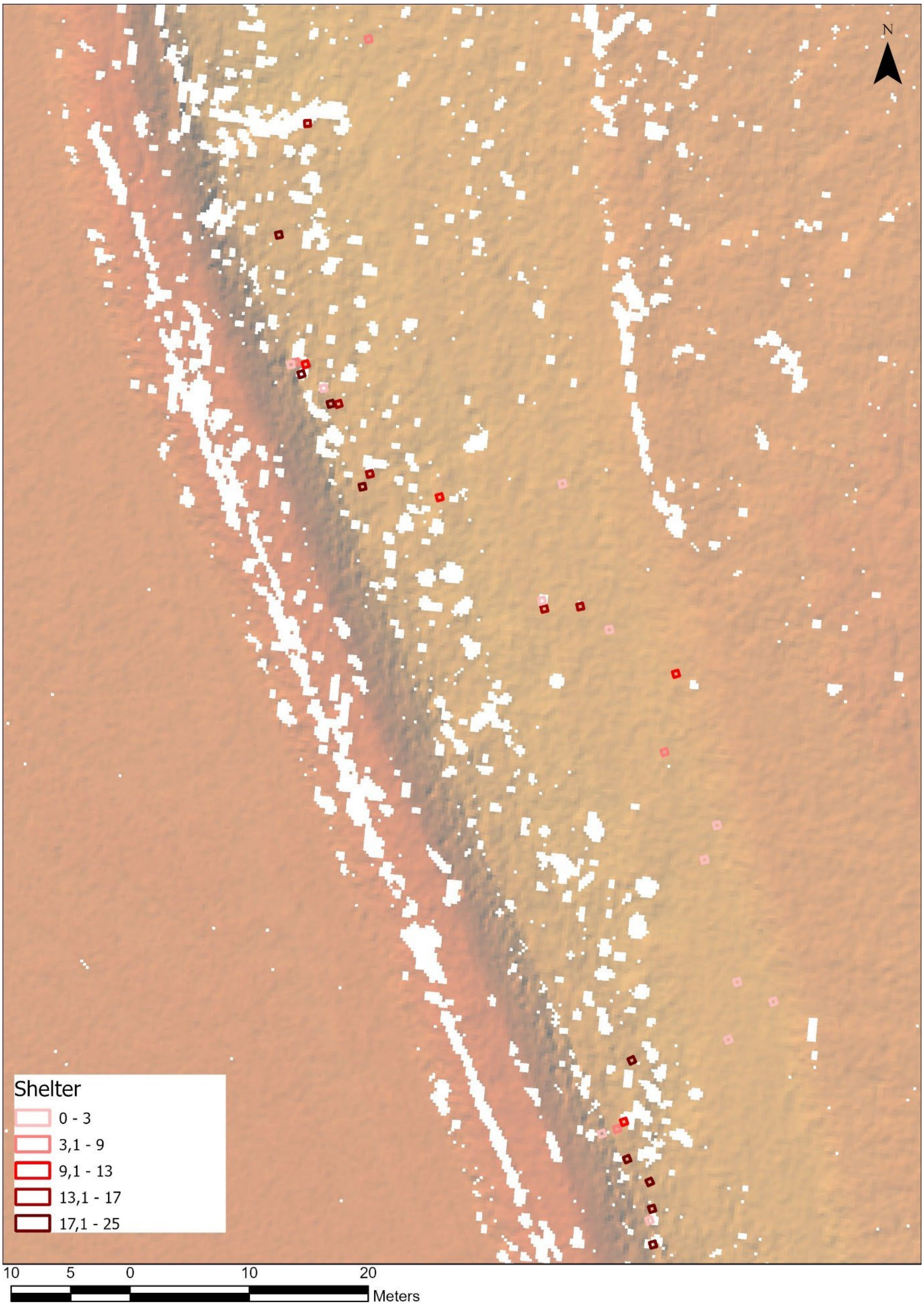

Figure 48: Holes (white) in the ground/bathymetry point cloud and shelter measurements. The missing points are classified in the class "unassigned" or "noise" in the raw data point cloud. (illustrated in hillshade where "red" means higher elevation)

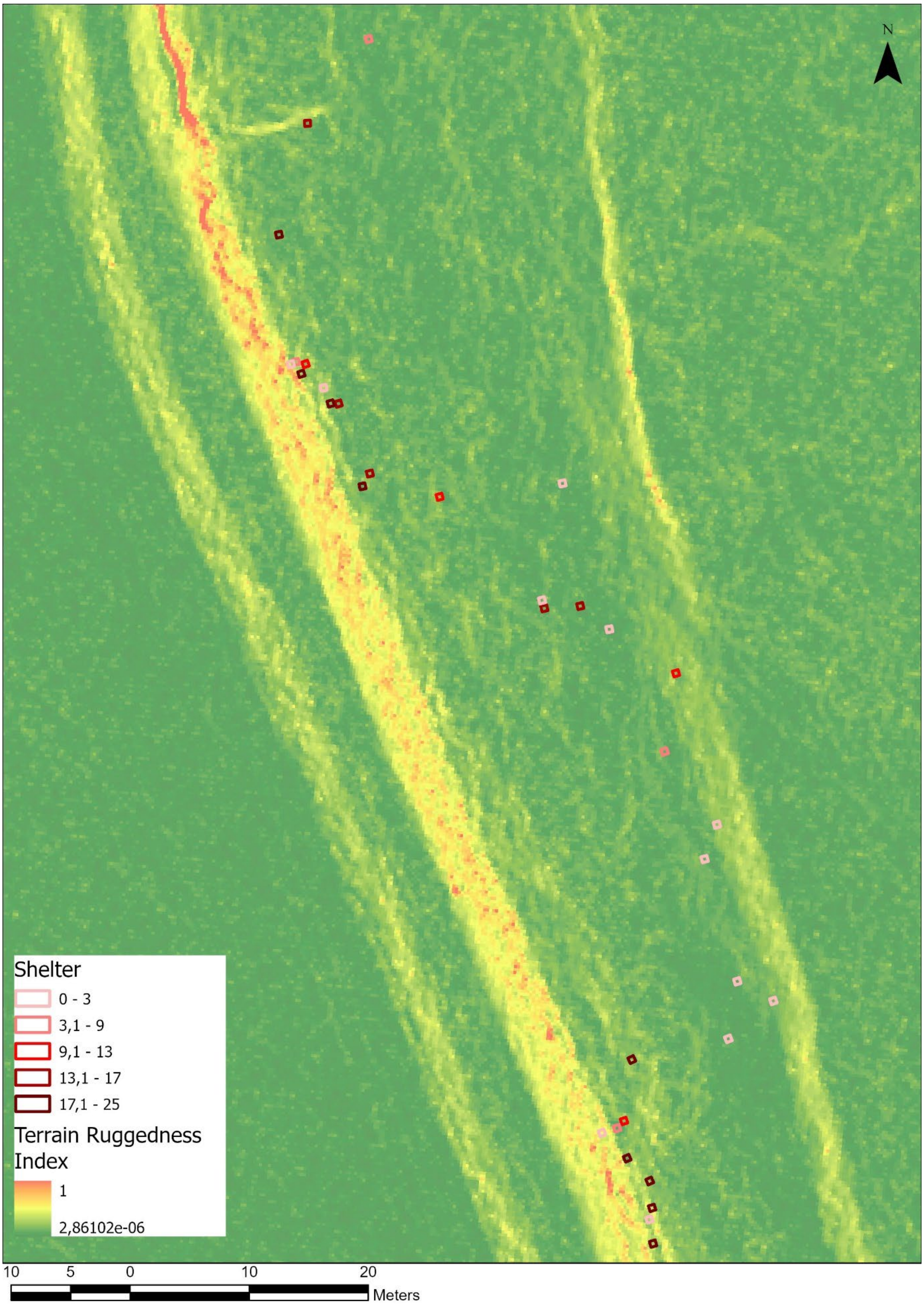

Figure 49: TRI and shelter measurements

WP 3. River restoration - Comparison of base data for planning/modelling restoration measures

Comparison of base data for ecological assessment

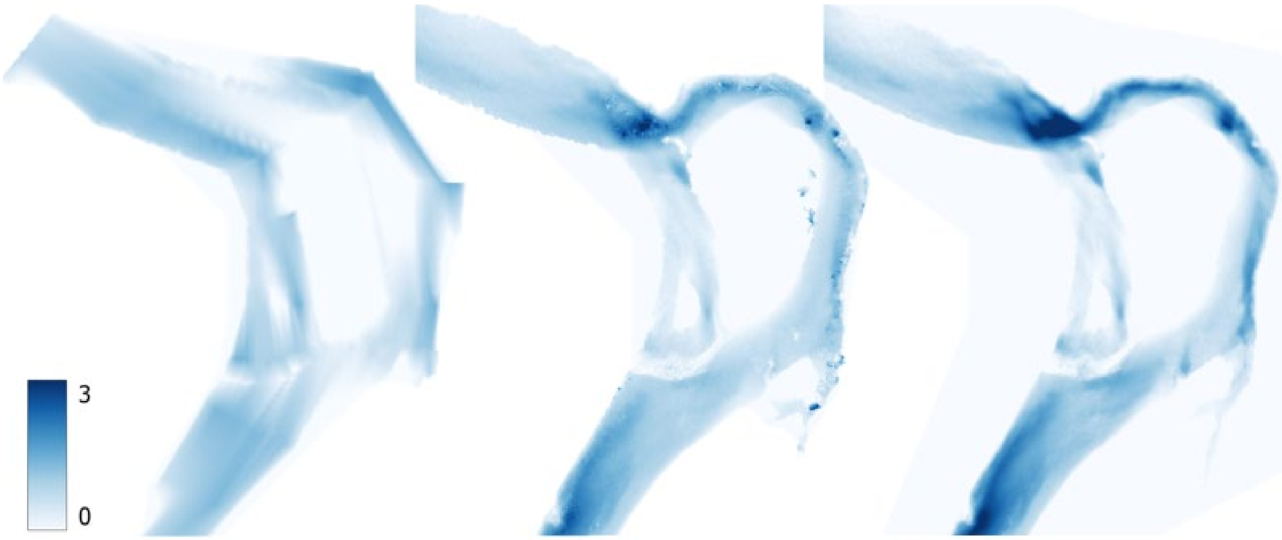

Figure 50: Water depths based on X-sections (left), UAV data (middle) and ALB data (right)

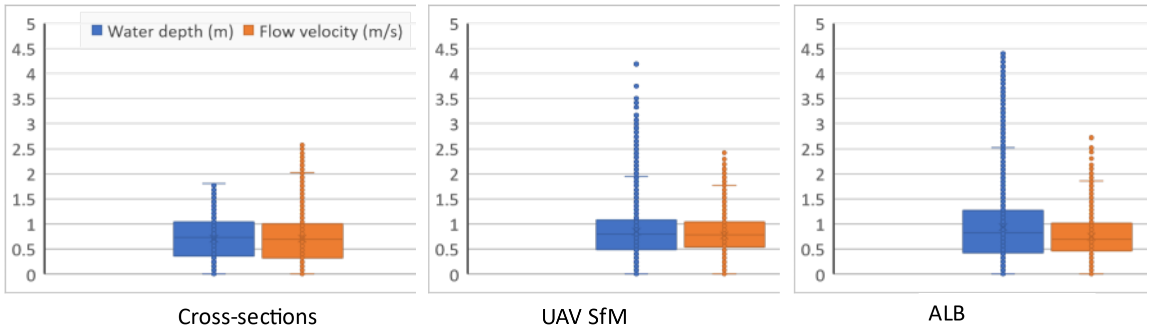

Figure 51: Water depth (blue) and flow velocity (orange) for the X-section, UAV SfM and ALB based model.

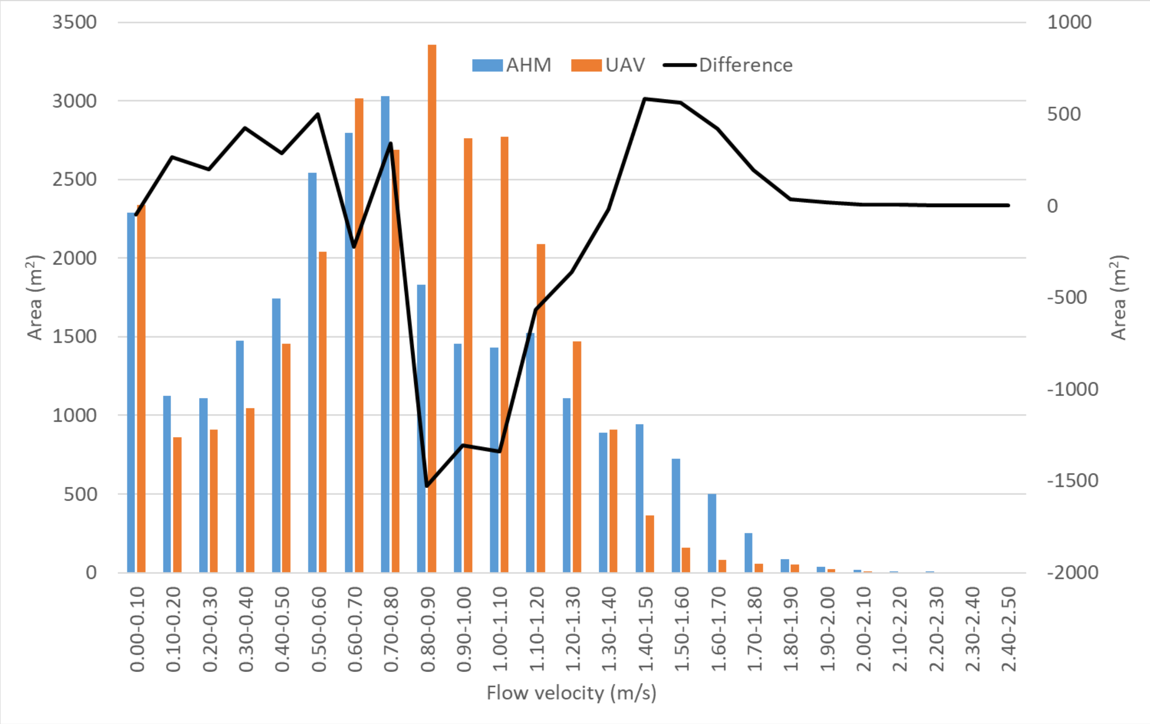

Figure 52: Area of the ALB (blue) and UAV (orange) model in water velocity bins. Difference in the area in each bin (black line)

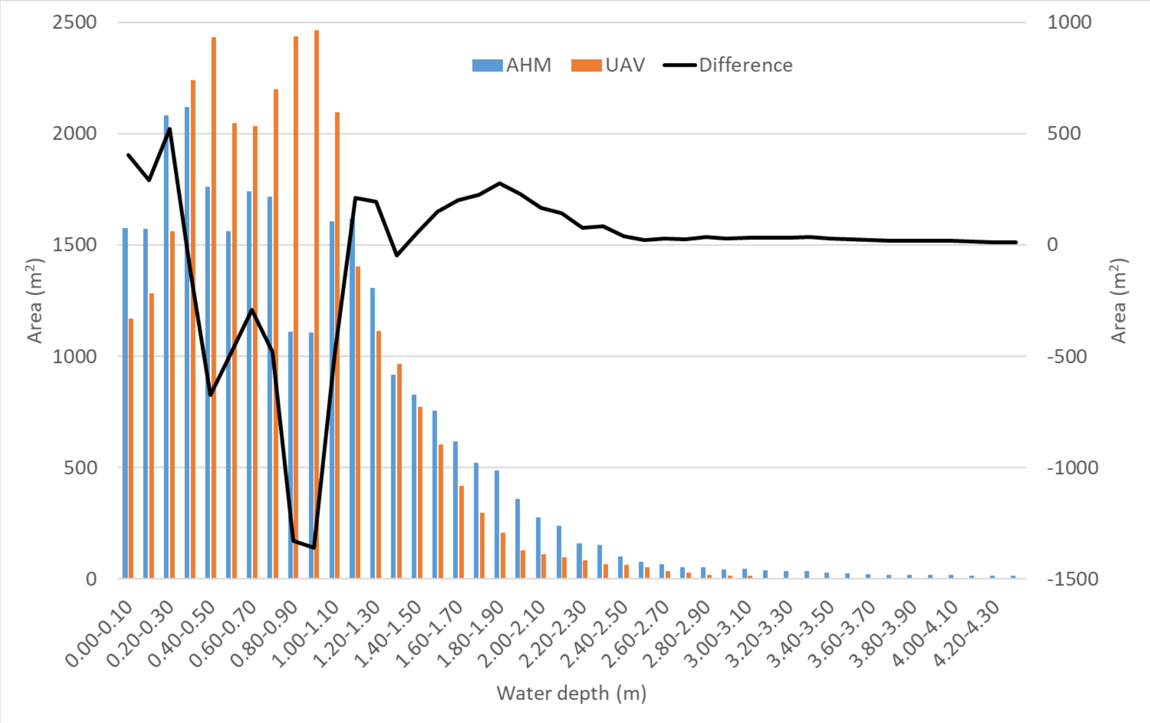

Figure 53: Area of the ALB (blue) and UAV (orange) model in water depth bins. Difference in the area in each bin (black line)

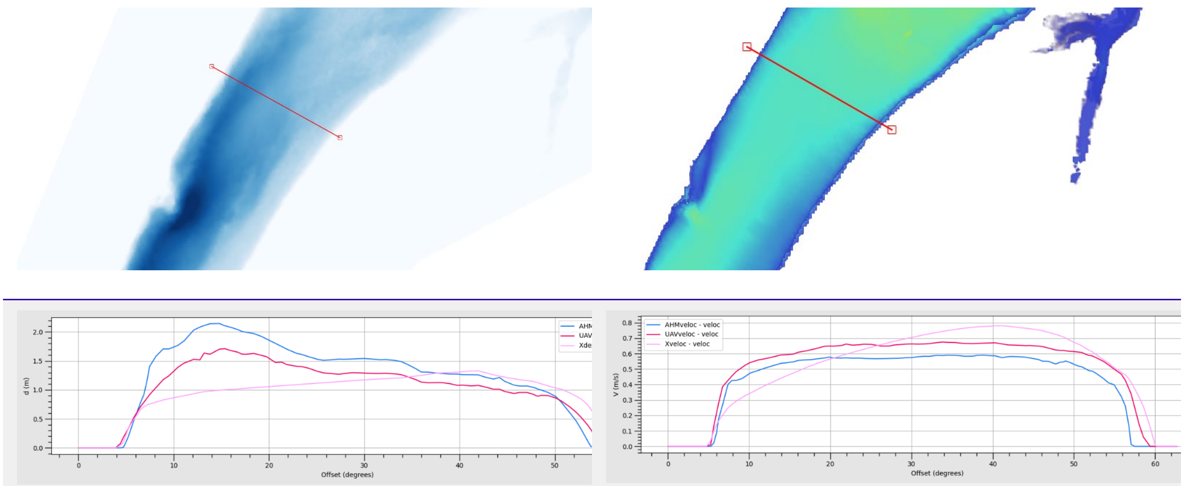

Figure 54: Water depths (left) and flow velocities (right) at profile 1. ALB data (blue), UAV data (red), X-section data (pink).

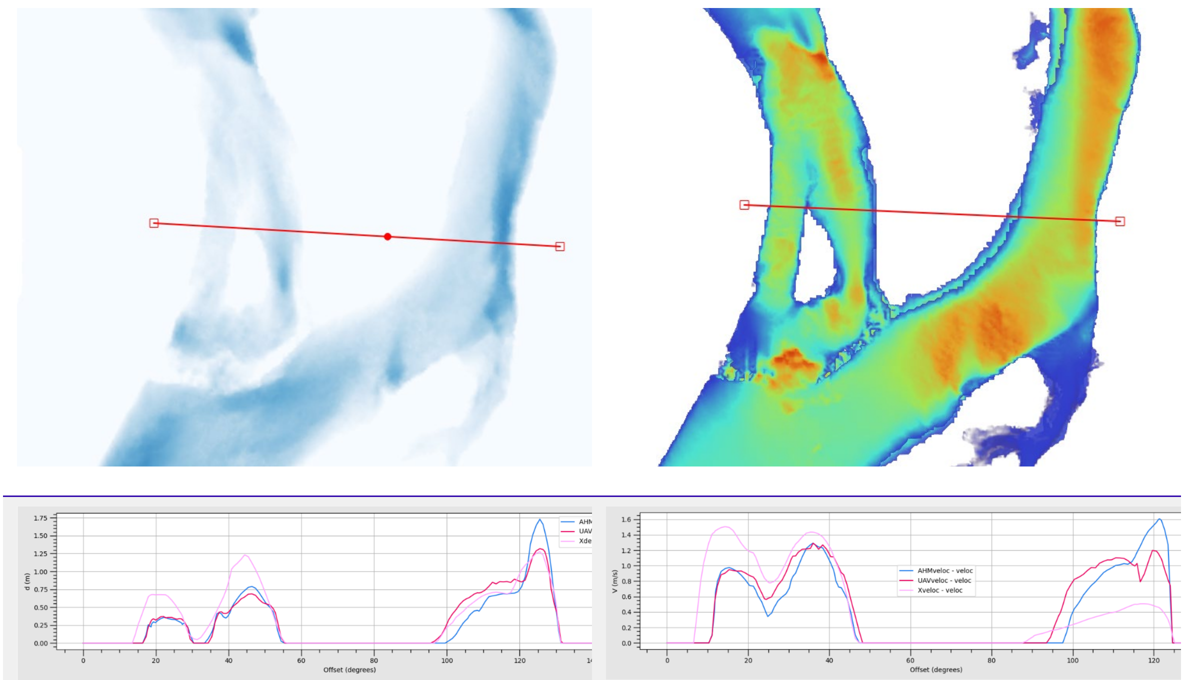

Figure 55: Water depths (left) and flow velocities (right) at profile 2. Diagram coloring: ALB data (blue), UAV data (red), X-section data (pink).

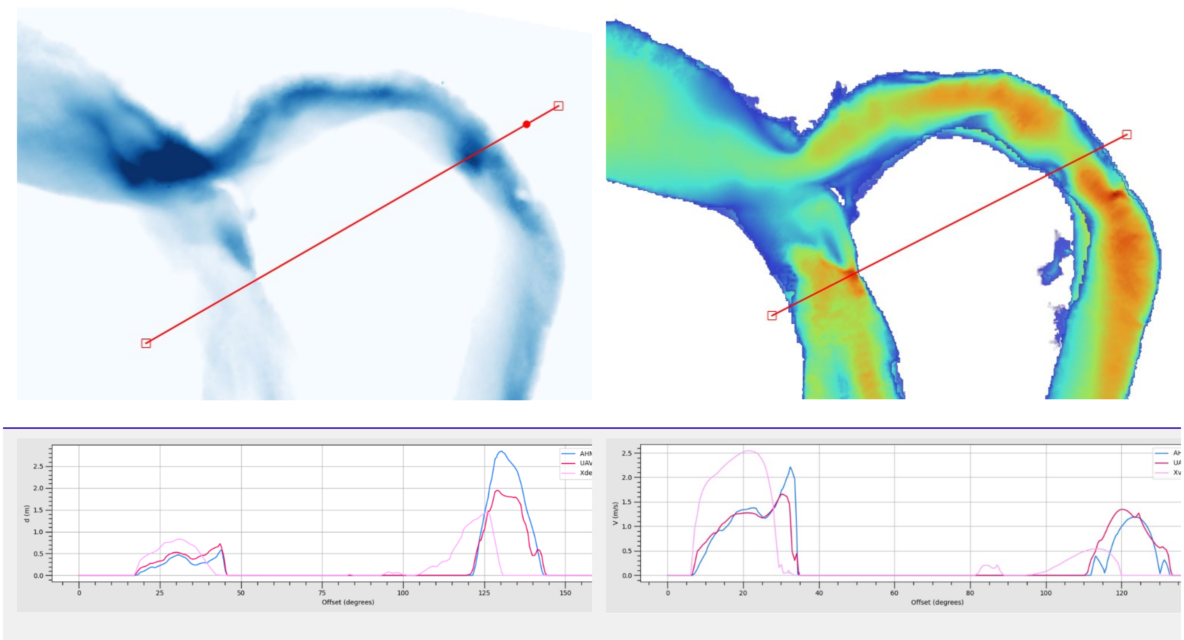

Figure 56: Water depths (left) and flow velocities (right) at profile 3. Diagram coloring: ALB data (blue), UAV data (red), X-section data (pink).

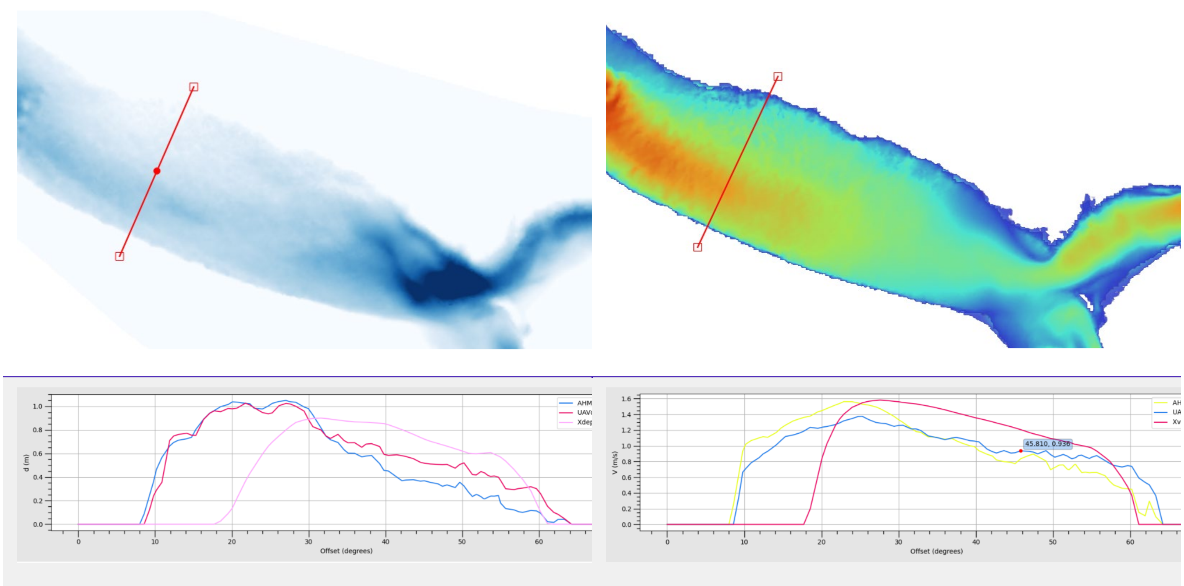

Figure 57: Water depths (left) and flow velocities (right) at profile 5. Diagram coloring: ALB data (blue), UAV data (red), X-section data (pink).

Overview over work-packages and contributions of NORCE

Table 10: Workpackages and contributions of NORCE

Contribution and Work Package	Work delivery and WP	Status
WP 1- Validation (Contribution 1.1)	**Desk study: River classification and river gradient change**. 1. Pre-river classification of case studies Lærdalselva, Bøelva Hallingdal (Krøderen) to be classified according to Field protocol (v.10.October 2021) based on www.norgeibilder.no. 2. Optional (not included): Leira-Tangeelva, Glomma are potentially studied later depending on ALB results, also testing of existing data in Tokkeåani may be chosen as supplement. **Field work: Ground truth mapping based on river classification and measuring field parameters.** 3. River classification: River classification and measuring field parameters* according to Field protocol v.10.October 2021 implementing (Hauer & Pulg (2018) classification system and Borsányi (2004) meso habitat mapping. River classes and location of transects to be adjusted in field when needed. Flow conditions as similar to ALB flight as possible when planning field work. *Field work are based on three levels: River typology (strata); Transect (tverrsnitt) Point measurements in each transect (parameters);Field work (contribution 1.1) to be conducted and finalized within 31.12.2021, or before ice coverage and winter season. **Date:** Compilation and finalization of data systematization to be delivered within 1.february 2022.	1. Draft delivered 2. 2. Not conducted 3. Draft delivered
WP 1- Validation (Contribution 1.2)	**UAV package** 1. 3D terrain mapping based on aerial photos taken by DGPS- RTK drone and photogrammetry during low flow (equal or lower than ALB flying conducted). 2. Field sampling to be conducted and finalized within 31.12.2021, or before ice coverage and winter season. **Date:** Compilation and analysis to be finalized 1st September 2021.	1. Draft delivered 2. Data delivered
WP 1- Validation (Contribution	Development of methodology 1. Development of a remote sensing based methodology, flow chart for classifying river	1. Draft delivered 2. Test of deriving sediment and

2.1)	types according to Hauer & Pulg. (2018, 2021) and the new Nordic River Typology. Main criteria will be energy slope, sediment composition and planform. 2. Classification of river stretches and comparison of ALB data in different river types. Which river types can be mapped with ALB and where are the boundaries? Cooperation with BOKU for developing an algorithm for testing automatic classification based on ALB. BOKU will test automatic substrate classification using ALB data. 3. The work is tested for the mapped stretches in Lærdal, Bøelva og hallingdal and validated by comparing ground data to ALB data. 4. Needed field sampling to be conducted and finalized within 31.12.2021, or before ice coverage and winter season. **Date:** Compilation and analysis to to be finalized 1st October 2021.	skjul parameters from ALB data in river Lærdal (due to high variastion in skjul and sediment composition). Draft delivered 3. Draft delivered 4. Conducted
WP 2.1 Flood risk analysis and mitigation (Contribution 3)	**Analysis:** 1. Do ALB data give a better resolution for erosion modelling compared to DGPS data or Red LIDAR? 2. Can an ALB based erosion risk model predict real morphodynamics that happened during floods? The work is tested for relevant mapped stretches (1) and requires that morphodynamics are documented. Work aligned and collaborated with NTNU and BOKU. NORCE responsible for this alignment. Needed field sampling to be conducted and finalized within 31.12.2021, or before ice coverage and winter season. **Date:** Compilation and analysis to to be finalized 1st October 2021.	1. Mainly BOKU, Norce contributes with field sampling and scenarios. Draft delivered. 2. Mainly BOKU, Norce contributes with field sampling and scenarios. Draft delivered.
WP 2.3 River restoration. (Contribution 4)	**Restoration and mitigation scenarios are developed for chosen river reaches based on ALB data.** 1. Test scenarios based on the mapped river reaches in Lærdalselva, Bøelva and Hallingdalselva with different restoration scenarios such as widening of river channel, reconnection of side channels, dam/weir removal, gravel addition, sediment management or other relevant techniques. 2. Practical benefits and deficits of the ALB data are compared to conventional base data such as aerial photos, manual dgps measures and accessible maps and altitude data.Work aligned and collaborated with NTNU and BOKU. NORCE responsible for this alignment. Needed field sampling to be conducted and finalized	1. In cooperation with BOKU and NTNU, developing of scenarios ongoing. Workpackage will likely be delayed due to need for field sampling and changes in personell at NTNU.

	within 31.12.2021, or before ice coverage and winter season. **Date:** Compilation and analysis to to be finalized 1st October 2021.	2. Draft delivered.
Reporting (Contribution 5)	**Final report** 1. Final report to be finalized and delivered, included all field data and appendixes, 1st November 2021. Data compilation, analysis, results, discussion and conclusion.	1. Standardized report from NORCE. Draft delivered

Field protocol

This chapter gives an overview over the field protocol which was used for sampling ground truth. The protocol is written in Norwegian and pasted as it was delivered and used.

Skala	Metode	Tetthet/ replikanter	Sted
1. Topografi/Ground truth			(alle = Bøelva Hallingdalselva Lærdalselva)
Tverrprofilpunkter x-y-z-verdier	håndholdt DGPS	Minst 5 punkter per profil	Alle (Lærdal ?)
Arealtopografi - dronebasert	Picture to motion	Hele arealet, 2-4 cm oppløsning Gjennomfæøres ved svært lav vannføring	Alle elver (?) Mål om 10 transekter per type (blir vanskelig i Hallingdalselva)
Sedimentopppmåling	Hauer& Pulg 2018	modifisert Wolman count, hvert 50 m I felt. vi prøver også basert på dronebilder	Alle elver I hver type
2. Elvetype	Hauer& Pulg 2018	Defineres basert på topografiske data, reach scale	Alle
	Felles nordisk elvetypologi fra 2022	Defineres basert på topografiske data, reach scale	Alle
3. Mesohabitat			Alle elver (Lærdal ?)
Habitatarealer	Forseth&Harby 2013	Mesohabitatarealer (minimumlengde = elvebredde) skjulmålinger på transektpunktene	

Sediment	Dekninsgrad etter Braun-Blanquet	Wentworth kalsser i 10 % steg visuell vurdering på sted kvalitetssikret med dronebilder	
Vegetasjon	Dekninsgrad etter Braun-Blanquet	visuell vurdering på sted kvalitetssikret med dronebilder	
Microhabitat			
Siktedyp	Secci skive Standardisert fotografi	Øverst og nederst i elvetypen Ovenfor og nedenfor relevante tilløpsbekker Dypeste sted.	
Sedimentprøver på grusbanker	Siktekurve	Utvalgte steder som gjenspeiler sedimentsammensetning per elvetype sand – grus – rullestein	Alle elver?

Grønn laser – sampling elv – utkast feltprotokoll *in situ* undersøkelser 14.09.2021

Bakgrunnsinformasjonen er fra prosjektbeskrivelser, ppt presentasjonen ‘Status per juni 2021’, samtaler med prosjektansvarlig Morten Stickler, og prosjektmøte 07.09.21 med diskusjoner.

Hovedmålsettingen er å undersøke hvor nøyaktig (± variasjon/avvik) fjernanalyse via grønn laser bestemmer bunntopografien (~ dyp) i elver, og hvilke faktorer som påvirker dette (dyp, partikkel- og luftboble innhold vannfarge, overflatestruktur/turbulens). In situ feltmålinger brukes som ‘sanne’ verdier.

Her fokuseres på rennende vann/elver.

Oppdragsgiver bestemmer aktuelle elver og avgrenser aktuell undersøkelsestrekning.

Undersøkelsestrekning stratifiseres på forhånd til fem elveklasser (Hauer & Pulg 2018) basert på ortofoto (+ ev tilleggsinformasjon)

Det foreslås en stratifisert, balansert design hvor de fem elveklassene til Hauer and Pulg (2018) er fem strata som bør være likt representert (balansert) i datainnsamlingen. Denne stratifiseringen er styrende for det videre arbeid.

For senere sammenligning gjøres også en tilsvarende forhåndsklassifisering etter Borsányi *et al.* (2004), etter overflatestruktur og –gradient. Det antas at disse to klassifikasjonsmetodene i hovedsak vil samsvare, men det bør en selvstendig evaluering av dette/grad av overlapp for de to metoder.

Den mest overordnede (grovmaskede) typeinndeling relevant for norske elver tar hensyn til nåtidige fluviale prosesser (elvesletter) og tidligere glasiale/ras prosesser (bratte elvedaler; blokk fra ras/isbre), og innebærer en enkel inndeling i fem klasser (cascade, plane-bed-dimictic, plane-bed-fluvial, riffle-pool-mixed og riffle-pool-flivial (Hauer & Pulg 2018)). Inndelingen kan (i hovedsak) gjøres på forhånd via flyfoto. En noe mer nyansert inndeling (10 mulige klasser, grupperes i fem elvetyper) som også kan gjøres på forhånd via flyfoto og som er brukt en del i norsk sammenheng, baserer seg i hovedsak på klassifisering av overflatestruktur og gradient (ev. med støtte fra feltundersøkelser av dyp og vannhastighet (Borsányi *et al.* 2004)). Denne overlapper antagelig også i stor grad med typologien til Orr *et al.* (2008) som er basert på gradient.

(Minimum) Ti transekter per stratum med fem målepunkter i hvert transekt

Transektene stratifiseres til å fange opp dypere områder med urolig/brutt overflate innen hovestrata, ettersom dette sannsynligvis svekker presisjonen tikl grønn laser. Transekt-stratifiseringen gjrøes forsøksvis på forhånd basert på flyfoto, men justeres i felt.

Alternativt kan transektene fordeles uniformt (randomisering vil være lite hensiktsmessig med såpass få transekter per stratum)

Vanndekket lengde måles over hvert transekt, og det er fem målepunkter per transekt, med punkt på 50 % percentil, dvs. midten, i 25-75 percentilene, og i10-90 percentilene. Alle punkter innmåles ved differensiell GPS.

I punktene måles dyp (cm) og visuelt klassifiseres overflatestruktur, mesohabitat, dominerende og sub-dominerende substrat, embeddedness, vegetasjon type og -dekning

Målinger/klassifiseringer for responsvariable gjøres i de geo-refererte punkter/midt i en tilhørende definert (imaginær) areal-størrelse på 1 m^2 (Tab. 1). Relevante responsvariable (Tab. 1): elvetype (kategorisk, klasser, brukes som stratifiseringsvariabel), dyp (kontinuerlig, cm), gradient (kontinuerlig, cm, avledes i etterkant fra rød laser data (?), overflatestruktur (kategorisk, klasser), mesohabitat (kategorisk, klasser), substrat partikkel størrelse (kategorisk, klasser), vegetasjon (klasser; type, dekningsgrad).

Siktedyp (kontinuerlig, cm) og vannfarge (kategorisk, klasser) angis med en måling/klassifisering per stratum.

Måling av vannhastigheter er tidkrevende og mindre relevant for prosjektet, og utelates derfor. Måling av skjul? Visuell gradering av embeddedness mye raskere og like informativt?

Tabell 1. Mulige responsvariable

Elvetype (klasse)	Kategorisk	Visuelt fra flyfoto	Elvestrekning (m)	Stratifiseringsvariabel
Dyp (cm)	Kontinuerlig	Laser, *in situ:* multibeam, manuelt i GPS punkter	GPS punkt	Grønn laser kan generere for ulike arealer, bør testes. *In situ* i GPS punkt.
Gradient (cm/m)	Kontinuerlig	Generert fra laser	100 cm (fra 0,5 m oppstrøms til 0,5 nedstrøms GPS punkt)	Proxy for overflatestruktur, turbulens, luftbobler
Overflatestruktur (dominerende klasse)	Kategorisk	Klassifiseres visuelt *in situ* for areal $1m^2$ omkring GPS punkt	Se vedlagt klassifisering	
Mesohabitat (dominerende klasse)	Kategorisk	Klassifiseres visuelt *in situ* for areal $1m^2$ omkring GPS punkt	Se vedlagt klassifisering	Representativt arealet omkring GPS punkt diskutabelt?
Substrat1 (dominerende partikkel størrelse)	Kategorisk	Klassifiseres visuelt *in situ* for areal $1m^2$ omkring GPS punkt	Se vedlagt klassifisering	Måling av skjul?
Substrat2 (sub-dominerende partikkel størrelse)	Kategorisk	Klassifiseres visuelt *in situ* for areal $1m^2$	Se vedlagt klassifisering	Sammen med Embeddenes indikasjon på skjul

		omkring GPS punkt		
Embeddedness	Kategorisk	Klassifiseres visuelt *in situ* for areal $1m^2$ omkring GPS punkt	Se vedlagt klassifisering	
Vegetasjon type	Kategorisk		Ulrich?	
Vegetasjon dekning	Kategorisk			
Siktedyp (cm)	Kontinuerlig	Måles *in situ* på dypeste blankstryk/stille		Proxy for partikkelinnhold (og luftbobler). 3 gjentatte målinger. Bør denne også måles i alle punkter med luftbobler?
Vannfarge (klasse)	Kategorisk	Klassifiseres visuelt *in situ* samtidig med siktedyp		

Datainnhenting *in situ* i punkter/arealer bestemt ved differensiell GPS gjøres manuelt for alle relevante responsvariable (Tab 1).

Multibeam måler kun dyp. Multibeam er mulig å bruke (uten for mye støy) dypere elve-områder enn minst 1-2 m, dvs områder som er for dype til å vade for manuell innhenting av data. Det vil skape analytiske vanskeligheter om data for metodene blandes. Det foreslås derfor at sampling og data gjøres separat for de to metodene, hvor differensiell GPS brukes på vadbare elveområder, mens multibeam brukes på dyp-områdene. Disse områdene angis når man er i felt med differensiell GPS. Nødvendige undersøkelser med multibeam vurderes deretter. De respektive data analyseres separat mot grønn laser data.

Siktedyp (partikkelinnhold) og vannfarge endrer seg lite/ikke med elvens forløp over kortere avstander (unntatt ved innløp sideelver/vesentlige rasfenomener) og angis for tre målinger i de dypeste elvepartiene på aktuelle sutartum. Derimot vil luftbobler endre seg mye med gradient, og sannsynligvis påvirke grønn laser effektivitet. Bør dette måles inn (som Secchi-dyp), i alle målepunkter hvor siktedyp blir redusert av luftbobler?.

Vedlegg A Elvetyper

Elveklasser fra (Hauer & Pulg 2018):

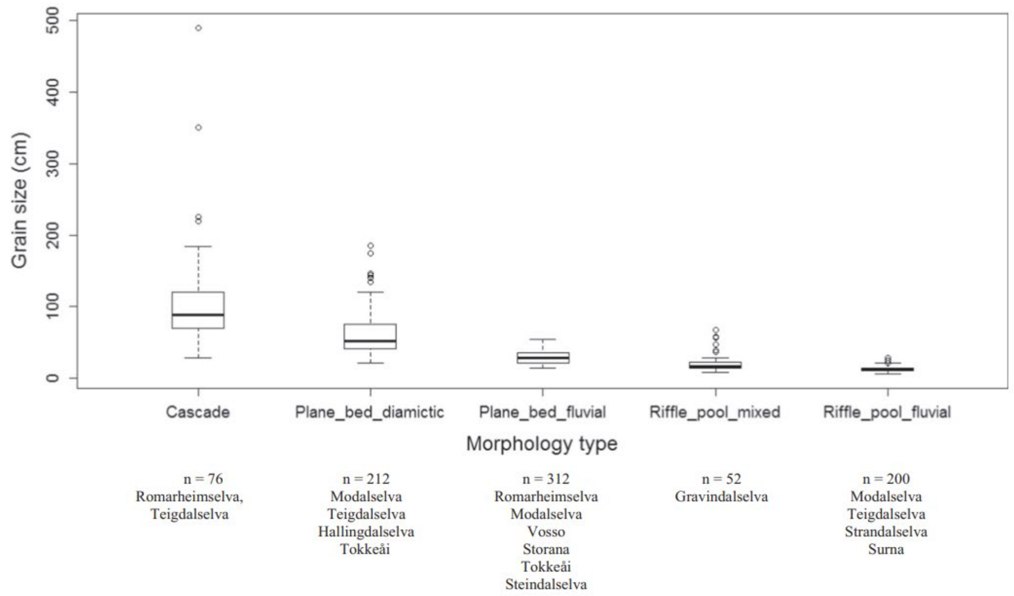

Fig. 6. Box plots of cumulative D_{max} measurements for different river channel patterns in Norwegian mountain rivers. n = number of sampled sediments in the clustered box plot analysis.

Elveklasser fra (Borsányi *et al.* 2004):

Table I. – Classification decision tree.

criteria	surface pattern	surface gradient	surface velocity	water depth	code
Decision	smooth / rippled	steep	fast	deep	A
				shallow	
			slow	*deep / shallow*	
		moderate	fast	deep	B1
				shallow	B2
			slow	deep	C
				shallow	D
	broken / unbroken standing waves	steep	fast	deep	E
				shallow	F
			slow	*deep / shallow*	
		moderate	fast	deep	G1
				shallow	G2
			slow	*deep*	
				shallow	H

Vedlegg D Substrat klasser

Tabell 3. Type av substrat og partikkelstørrelse klassifisert i felt (modifisert Wentworth skala).

Substrat type	Størrelse mm	Kode
Organisk fint	<10	1
Organisk grovt	>10	2
Leir, silt	0.004-0.06	3
Sand	0.061-2	4
Fin grus	2.1-8	5
Grus	8.1-16	6
Grov grus	16.1-32	7
Småstein	32.1-64	8
Liten rullestein	64.1-128	9
Rullestein	128.1-256	10
Stor rullestein	256.1-384	11
Blokk	384.1-512	12
Stor blokk	>512	13
Jevnt fjell	-	14
Ujevnt fjell	-	15

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