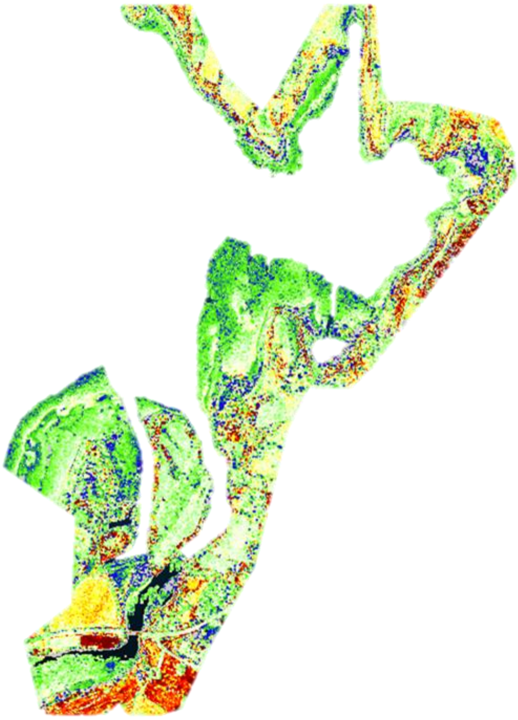
Norwegian University of
Science and Technology

Assessment of the suitability of Green LiDAR in mapping lake bathymetry



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FOREWORD

The project has been funded by the Environment Agency of Norway (Miljødirektoratet) as a supplement to the "Validation and application of Airborne LiDAR Bathymetry (ALB) technology for improved management and monitoring of Norwegian rivers and lakes" collaboration project.

We would like to thank Steinar Sandøy at the Environment Agency for very useful discussions regarding the design of the study and the selection of methodological approaches in the project, and Christian Malmquist at the Norwegian Mapping Authority for continuous support and clarifications of questions regarding sensors and the available datasets, as well as useful comments to the draft report.

SUMMARY

LiDAR stands for Ligth Detection And Ranging technology and is a measurement technique for detailed mapping of the Earth’s surface. The LiDAR sensors can be divided into two main types, the Red LiDAR which is based on the use of electromagnetic waves in the infrared wavelength spectre (1064 nm) and can be used to map terrestrial areas. In contrast to Red LiDAR, the Green LiDAR penetrates water surfaces by using another wavelength spectrum, i.e. the green spectrum of electromagnetic waves (532 nm). Green LiDAR is a more complex and costly technology and has so far been less applied in Norway. Due to the field of application of Green LiDAR, it is sometimes denoted as bathymetric LiDAR, in contrast to the topographic LiDAR (Red Lidar).

The overall objective of the study has been to assess the suitability of Green LiDAR to map the bathymetry of lakes. This has been carried out by use of Green LiDAR data from three different lakes, i.e. Selbusjøen and Benna in Trøndelag and Krøderen in Viken, being the only lakes in Norway with Green LiDAR bathymetry data available. The assessment has been made by systematically compare the performance of different LiDAR sensors, as well as multibeam echosounder (MBES), against each other in those lakes where two or more datasets are available and spatially overlap.

The residuals while comparing multibeam echosounder measurements (MBES) with Green LiDAR measurements and Green LiDAR measurements against each other are generally very small, i.e., in most cases, much less than 10 cm, based on the mean and median residuals. When comparing different Green LiDAR sensors, the residuals are close and normally distributed around 0 cm, indicating no systematic error. The outliers in the datasets (large residuals, filtered out in some of the figures) have the highest representation in the outer ranges of the coverage, i.e. in very shallow water and close to the maximum penetration depth of the sensors.

Under perfect flying conditions and clear water, Green LiDAR seems capable of measuring down to around 20 meters below the lake surface as in Lake Benna, while in most lakes probably far less than 20 meters. Green LiDAR seems be more suitable for mapping shallow parts of lakes, while MBES is more suitable for the deeper parts. In moderately deep areas, the two technologies seem both suitable and useful.

OPPSUMMERING

LiDAR står for "Ligth Detection And Ranging technology" og er en måleteknikk som kan benyttes for detaljert kartlegging av jordas overflate. LiDAR-sensorer kan kategoriseres i to hovedtyper. Rød LiDAR er basert på bruk av elektromagnetiske bølger i det infrarøde spekteret (1064 nm) og kan benyttes til kartlegging av terrestriske areal. Grønn LiDAR kan i motsetning til den røde LiDAR penetrere vannoverflaten ved å benytte et annet elektromagnetisk bølgespekter, det vil si det grønne bølgespekter (532 nm). Den Grønne LiDAR-en er en mer kompleks og kostbar teknologi å bruke og har så langt blitt anvendt i begrenset omfang i Norge. På grunn av anvendelsesområdene til den grønne LiDAR-en omtales den noen ganger som «batymetrisk» LiDAR, mens den røde LiDAR-en omtales som «topografisk» LiDAR.

Målet med dette studiet er å undersøke egnetheten til den grønne LiDAR-en til å kartlegge batymetrien (bunntopografien) til innsjøer. Dette er blitt gjort ved å innhente data fra tre ulike innsjøer, nærmere bestemt Selbusjøen, Krøderen og Benna. Disse er pr nå også de eneste innsjøer som er blitt innmålte med grønn LiDAR. Analysen er gjort ved å systematiske sammenligne presisjonen i LiDAR-dataene i innsjøene, samt data innhentet med multi-stråle ekkolodd (MBES), i de innsjøer hvor to eller flere datasett finnes og de romlig overlapper hverandre.

Avvikene mellom datasettene, det vil si MBES datasett mot grønn LiDAR datasett, og ulike grønne LiDAR datasett mot hverandre, er i de fleste tilfeller veldig små, det vil si ofte mindre enn 10 cm, når gjennomsnittlig avvik og medianverdien av avvik legges til grunn for sammenligningen. Når avvikene mellom de ulike grønne LiDAR datasettene sammenlignes, er disse ofte ned mot 0 cm, og normalfordelt rundt denne verdien, noe som indikerer at det ikke er noen systematiske feil i dataene. De største avvikene ('outliers', og filtrert ut i noen figurer) finnes som regel i ytterpunktene av datasettene, det vil si i de grunneste og i de dypeste områdene som er innmålt.

Under perfekte værmessige forhold og klart vann kan grønn LiDAR penetrere ned til omlag 20 meters dybde, slik som i Benna. I de fleste tilfeller er imidlertid penetrasjonsdypet langt mindre. Grønn LiDAR er derfor mer egnet til å kartlegge de grunnere områdene av innsjøer, mens MBES er mer egnet for de dypere områdene. I de moderat dype områdene av innsjøer kan begge teknologier være egnet og nyttige.

1 Introduction

LiDAR stands for **Li**gth **D**etection **A**nd **Ranging** technology and is a measurement technique used to generate detailed elevation maps of the Earth's surface. LiDAR sensors can be divided into two main types, the most common is the Red LiDAR which is based on the use of electromagnetic waves in the infrared wavelength specter (1064 nm) and are used to map terrestrial areas (Harpold, 2015). Red LiDAR does not penetrate water and can hence not map the surface of areas covered by water. In contrast to Red LiDAR, the Green LiDAR penetrates water surfaces by using another wavelength spectrum, i.e. the green spectrum of electromagnetic waves (532 nm). This is a more complex and costly technology and has so far been less applied in Norway. Due to the field of application of Green LiDAR, it is sometimes denoted as bathymetric LiDAR, in contrast to the topographic LiDAR (Red Lidar).

Green LiDAR technology is typically applied by the use of an air-borne platforms such as a drone, for the light-weight sensors, or more commonly from fixed wing airplanes or helicopters (Szafarczyk and Tos, 2022). The use of Green LiDAR data has the potential to measure the bathymetry of lakes and reservoirs with a very high spatial resolution and very good precision and can cover large and complete/continous areas during one measurement campaign. Green LiDAR has limitations in how deep into the water it can measure, dependent on characteristics of the water such as the concentration of organic material, particles and algae and other types of vegetation. The quality of the data is also dependent on substrate quality, e.g. such as the vegetation and humic content on the bottom (Kastdalen and Heggenes, 2023). The penetration depth is in the literature indicated as three times the secchi depth (Szafarczyk and Tos, 2022), while in the main report from the ALB-project estimated to approximately one secchi depth for the rivers and lakes where the sensors were employed.

Measured data needs very intensive processing before it is ready to use, such as georeferencing of raw data, refraction corrections, noise removal and point classification. During comparison of different Green LiDAR datasets correction with respect to water levels at the respective sampling dates might also be needed.

Green LiDAR has most commonly been used in marine environment, but has also been used in rivers internationally (e.g. Kinzel et al., 2007; Mandlburger et al., 2015) for hydromorphological mapping. Recently, Green LiDAR had been tested in rivers in Norway for flood inundation estimations (Awadallah et al., 2022) and environmental assessments (Kastdalen and Heggenes, 2023). Alfredsen et al. (2022) sums up various studies carried out at NTNU the last few years with a focus on application in river system engineering. In this study, Green LiDAR data from lakes have been analyzed, which is the first study of its kind in Norway.

Green LiDAR can potentially have several areas of application in lakes and reservoirs within the field of environmental sciences. The technology can potentially be used to efficiently map the shallow parts of a lake's bathymetry (bottom surface) and derive information about the slope, exposure and surface and substrate characteristics. This gives a dataset suited to identify potential areas for spawning, feeding and rearing areas of lakes, if physical habitat preferences are known. It can also form the basis for physical habitat mitigating measures in lakes and reservoirs, potentially negatively affected by regulations or other physical modifications. As a basis for computational analysis in lakes and reservoirs, Green LiDAR will be very useful in establishing a bathymetric model for simulating commonly physical and chemical variables such as water velocities and depths, water temperatures and ice formation, sediment deposition and suspension, and basic water quality parameters (e.g. BOD, oxygen concentration, nitrogen and phosphorus concentration and turbidity).

Green LiDAR mapping involves massive data collection, which is a pre-requisite in developing data based artificial intelligent (AI) algorithms. These datasets can hence be a very valuable source of information to be applied to other unmapped lakes, possibly in combination with Red LiDAR data from the shoreline of the lakes, as has been tested out in a master study at NTNU (Ahmed, 2022). In this master study AI, based on Green and Red Lidar data from a few selected rivers, was used as the basis to predict river bathymetry in rivers where green LiDAR data was not available, with promising results.

The overall objective of this study has been to; **Assess the suitability of Green LiDAR to map the bathymetry of lakes.** This objective is reached by carrying out the following research tasks:

1. Evaluate the depth penetration of Green LiDAR sensors.
2. Assess the precision of the sensors by a systematic comparison of the residuals between the different sensors operated in the same lakes.
3. Investigate the strength of the depth penetration by assessing the point densities of the sensors over depth.
4. Assess to what extent the sensor penetration is dependent of the water quality (expressed by color and other water quality parameters).
5. Provide input to the technical specification of new air-borne Green LiDAR mapping campaigns of lakes/reservoirs, e.g. with respect to preferred climatic and hydrological conditions for the lowest residuals (least noise), highest penetration as well as point densities.

The assessment is carried out by use of Green LiDAR data from three different lakes, i.e. Selbusjøen and Benna in Trøndelag and Krøderen in Viken, currently the only lakes in Norway with Green LiDAR data available.

2 Data and Method

2.1 Data Overview

Three lakes have been used to evaluate the performance of Green LiDAR sensors to measure the lake bathymetry, i.e. Selbusjøen, Krøderen, and Benna (see Figure 1), and the spatial coverage of each of the sensors in each of the lakes. More detailed maps of spatial coverage are given in the introductory parts of the Sections 3.1-3.3.

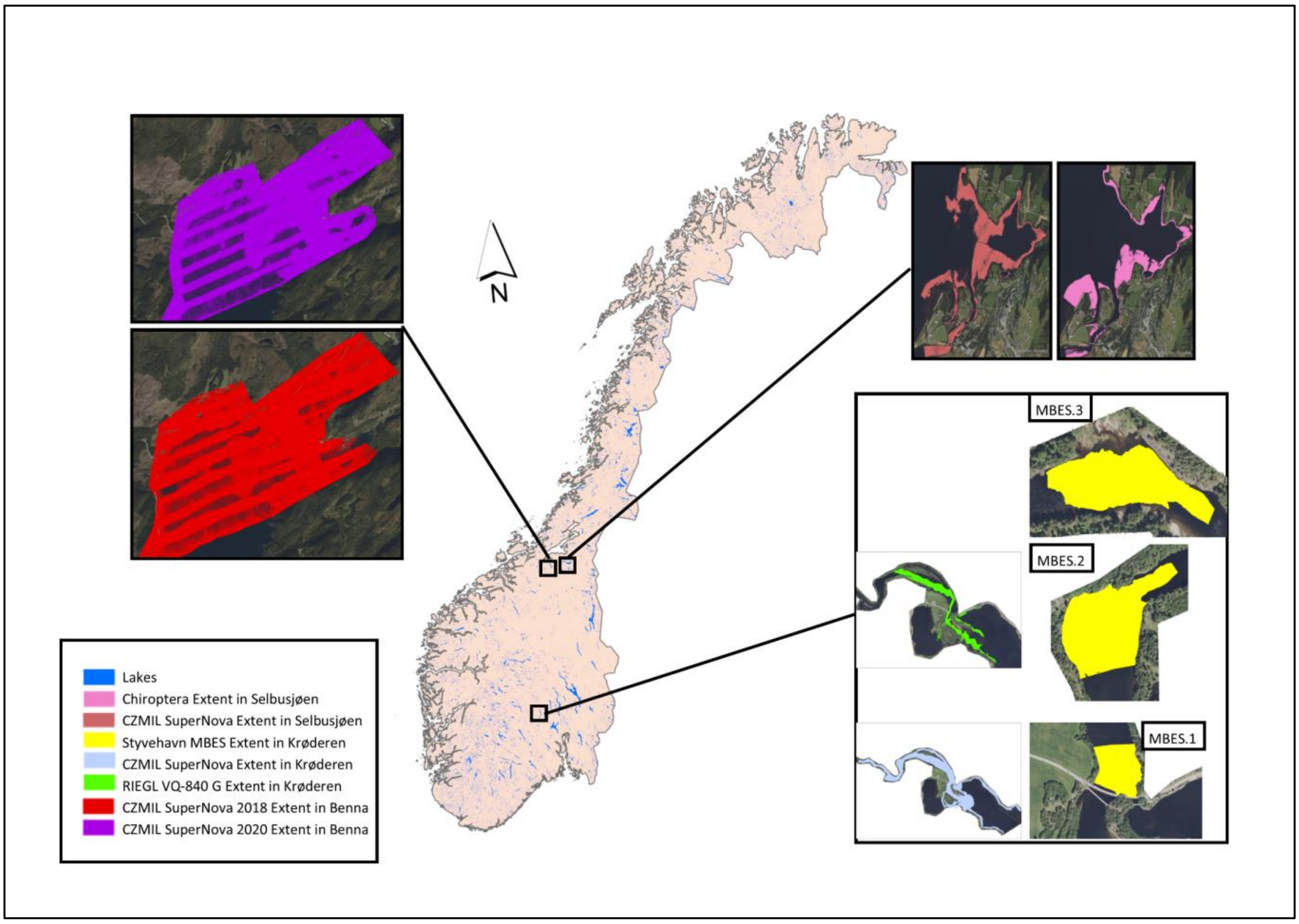

Figure 1. The study area locations in Norway and sensors bathymetry extents in the selected lakes Selbusjøen, Krøderen, and Benna. See more detail presentation of the coverage of each sensor in the test lakes in the Sections 3.1-3.3.

Multibeam echosounder (MBES) is a type of sonar that is used to map the underwater areas with high resolution acoustic waves emitted from a transducer. The time it takes for the sound waves to reflect off the lake bed and return to the receiver is used to calculate the water depth, and based on this, the formation of the surface of the lake bed can be assessed. MBES emits acoustic waves in a fan shape and can by this cover larger areas of the lake bed than single beam echosounders that will only map lines along the lake bed. As MBES emits and receives signals in the same instrument (transceivers) the instrument is not capable of depths less than 1 meter, which is the depth minimum for boat mounted MBES. MBES can normally produce reliable estimates of water depths down to several hundred meters and is capable of covering much deeper areas of lakes than Green LiDAR is.

As such, MBES and Green LiDAR are potentially complementary, as the shallow areas are probably well covered by LiDAR, and the deeper areas by MBES, with some areas of overlap.

In the technical specifications for the procurement, the allowed systematic errors were 10 cm in vertical domain and 30 cm in horizontal domain of the Green LiDAR. The point density must be better than 2 points/m^2 within the sensor's operating range. The MBES dataset was collected using the NMA Hydrographic standards with a systematic vertical error better than 14 cm.

Table 1 gives an overview of which sensors that were used in which lakes, the date of sampling and water level, if available. From the table we can read that CZMIL SuperNova was used in all three lakes, while in Selbusjøen, Chiroptera and MBES (multibeam echsounder) were used for the mapping. RIEGL VQ-840 G, RIEGL VQ-880 G, and MBES were utilized for mapping Krøderen. The water level during the CZMIL flight was not recorded (at Grenstad), but probably around 50-60 cm lower than during the Chiroptera flight. As the datuum of Grenstad is uncertain, the water levels are not related to the elevations given in the Green LiDAR datasets. The water levels during the MBES measurements in Selbusjøen (in December) are probably close to the water level when the CZMIL measurements took place. In Krøderen, the water levels were 132.7, 132.4, and 133.06 masl (meters about sea level) during the CZMIL, VQ840, and MBES surveys, respectively. The water level in Bennna has limited variation, and the relevative diffences between the measurements in 2018 and 2020 are most likely small.

The conditions during the CZMIL SuperNova survey in Selbusjøen were little wind, as shown in Figure 2, while more turbide water was observed during the Chiroptera flight (personal observation by mapping team).

Table 1. Sensors used for surveying the specified lakes, the dates of mapping and the water level at the time of the measurements, in masl (meters above sea level). Norbit MBES surveyed only a small area of Selbusjøen and did not overlap the Green LiDAR measurements, and is hence not further included in the analysis.

Lake	Sensor	Date	Water level at measurement date [masl]
Selbusjøen	CZMIL SuperNova	16/07/2021	N/A
	Chiroptera	14/09/2021	Uncertain
	Norbit MBES	02/12/2021	Uncertain
Krøderen	CZMIL SuperNova	16/07/2021	132.7
	RIEGL VQ-840 G	24/08/2021	132.4
	RIEGL VQ-880 G	03/09/2021	N/A
	Norbit MBES	09/11/2021	133.06
Benna	CZMIL SuperNova (2018 & 2020)	28/10/2018	Unknown
		10/08/2020	Unknown

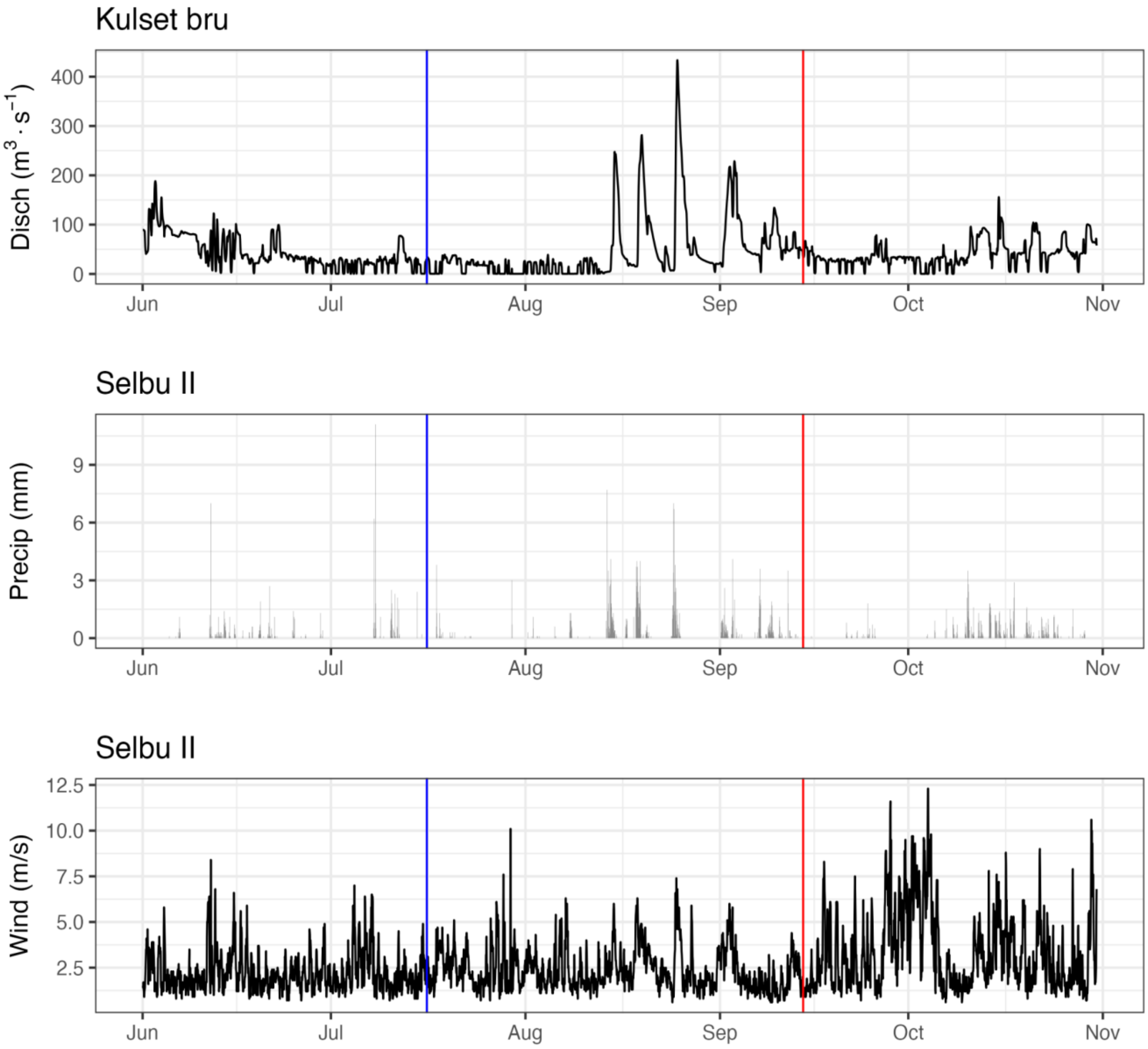

Figure 2. Physical conditions for Selbusjøen during mapping dates. The blue vertical line shows the CZMIL SuperNova flight on 16.07.2021, while the red vertical line shows the Chiroptera flight on 14.09.2021.

2.2 The method applied for the assessment

Standard arithmetic methods were followed for evaluating the performance of the Green LiDAR in lake bathymetry using the point clouds from sensors. The point clouds were filtered according to the utilized classification method in each flight (class 26 and class 40 in these study areas), where only bed-level points were considered. The residuals in lake bottom elevation were calculated according to the following equation:

$$\text{Residual} = Z_n - Z_m$$

Zn and Zm are the bathymetric bed elevations for sensors n and m, respectively. Accordingly, the negative residual value indicates a lower bathymetric elevation in sensor n than the bathymetric elevation in sensor m; therefore, sensor n estimates deeper points than sensor m. Contrarily, the positive residual value indicates shallower measurements for lake bed elevations from sensor n than sensor m.

The residuals were calculated by extracting the point clouds elevations values from the higher coverage sensor as a source to the lower coverage sensor as a destination. The extracted values were calculated using the nearest point, then the residuals were calculated.

In this case, the comparison was made for selected sensors according to the spatial distribution of each point cloud for lake bathymetric data, in view of the fact that the method used for comparison is based on the spatial overlap between the compared point clouds. Therefore, spatial modifications for divergent parts of point clouds distribution for Lake Benna and Krøderen were done to achieve corresponding comparable bathymetry points.

CloudCompare software (CloudCompare, 2023) was used to compare bathymetric point clouds. It is a 3D software designed for comparing, processing, and displaying dense point clouds based on octree structure for advanced data analysis. The program is able to store and process more than a 100 million point cloud.

3 Results and discussion

The results for the comparison of the different sensors and the MBES data are first presented individually for each of the lakes, i.e. Selbusjøen, Krøderen and Benna, in each of the Sections 3.1-3.3. Each of the sensors in each lakes are compared one-by-one and presented as maps showing the residuals between the sensors compared, histograms for the full datasets used in the comparison, correspondence plots and histogram plot for elevations ranges (typical 1 meter elevation ranges). Table 2 summarizes basic statistics from the comparison of sensors in the three lakes with Green LiDAR and MBES data.

Table 2. Summary of the compared sensors in each lake and statistical values of the residuals.

Location	**Sensor comparison**	**Mean (cm)**	**Standard Deviation (cm)**	**Median (cm)**
Selbusjøen	CZMIL and Chiroptera	- 1.93	13.41	- 2.0
Krøderen	CZMIL and MBES	0.16	18.56	3.2
	CZMIL and VQ840	0.49	7.49	1.0
	MBES and VQ840	5.55	6.67	5.0
	VQ880 and MBES	-10.5	14.5	- 10.0
	VQ880 and CZMIL	- 8.0	15.0	- 9.0
	VQ880 and VQ840	- 7.8	10.1	- 8.8
Benna	CZMIL2018 and CZMIL2020	- 3.52	15.0	- 3.0

3.1 Selbusjøen

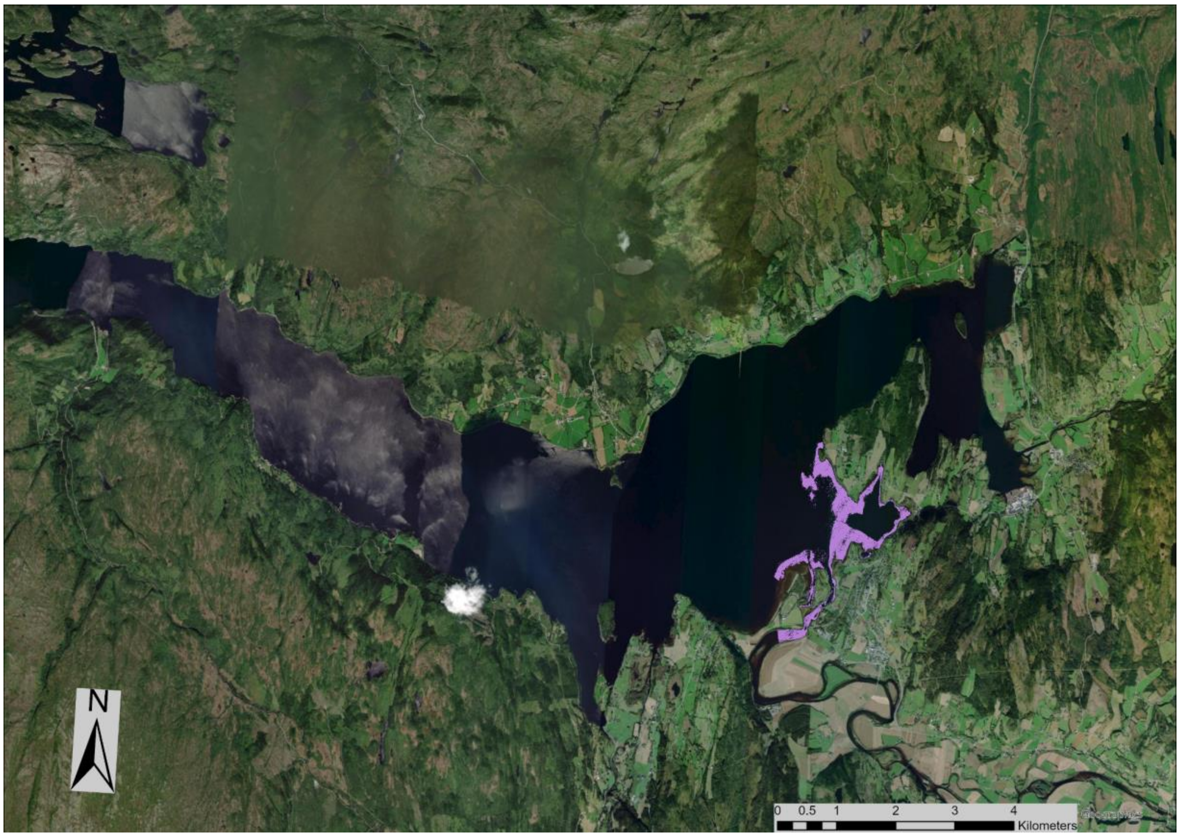

Figure 3. The map shows the coverage of CZMIL in Selbusjøen.

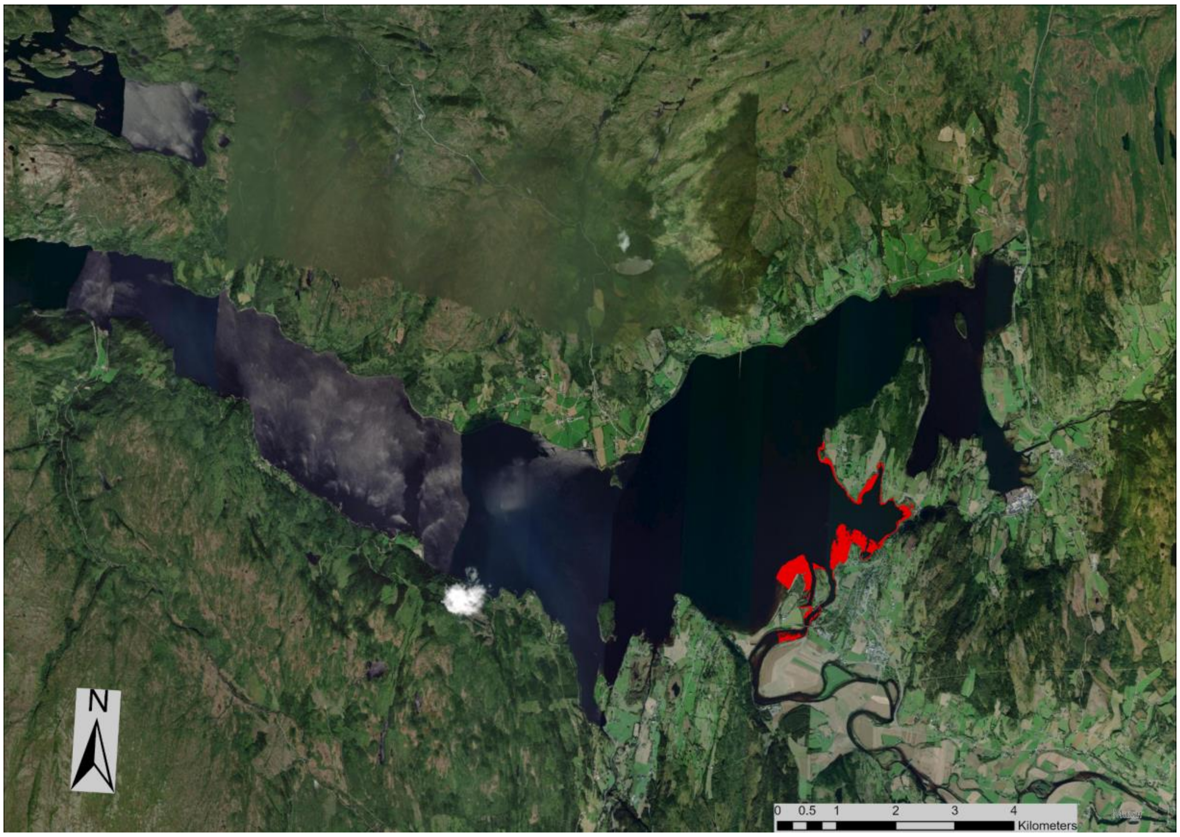

Figure 4. The map shows the coverage of Chiroptera in Selbusjøen.

Figure 5. The map shows the coverage of MBES in Selbusjøen. As MBES data and the measurements with use of Green LiDAR do not overlap, the MBES data is not further included in the comparison.

3.1.1 CZMIL versus Chiroptera

The comparison between the two sensors CZMIL and Chiroptera of the lake bed elevation is shown in Figure 6. As seen in the residual values, the sensors have a relatively higher agreement in areas away from the lake shoreline. In contrast, measurements near the banks have higher absolute residual values reaching up to 2 m. This could be attributed to the differences in physical conditions on the days of the two surveys (the water level was most likely higher during Chiroptera mapping compared to CZMIL). Consequently, some of the shoreline locations were wet on the Chiroptera flight, but dry during the CZMIL flight due to a difference in the water-covered areas. Therefore, the high residuals is to some extent assigned to differences in hydrological conditions (water levels) and are not necessarily related to errors in the measurements.

Although the comparative analysis was carried out for the underwater class only, when the points were transformed from one sensor to another using the nearest distance method, this led to incorrect elevation and outliers, as shown in Figure 7.

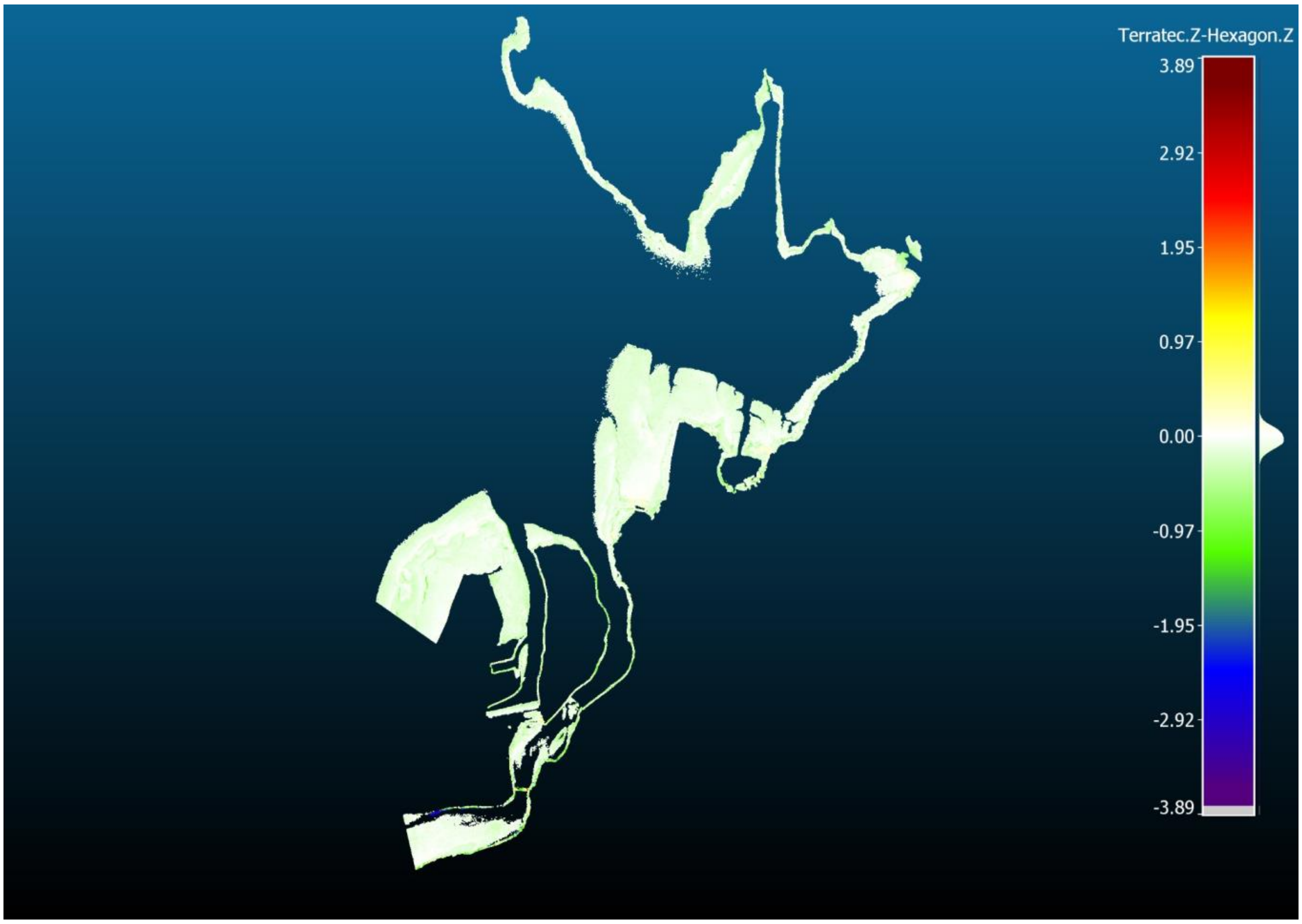

Figure 6. Residual map for the Green LiDAR bed elevations for CZMIL SuperNova against Chiroptera applied in Selbusjøen. The legend refers to residuals between the two sensors in meters.

In deeper parts (but not the deepest), the residuals are very small and distributed around zero. However, outliers were distinguished, and this could be a consequence of the reflection during the Chiroptera flight, where the water surface was calm and reflective, possibly combined with errors coming out of the interpolating of the data. As the water level gets closer to the shoreline, the discrepancies between the sensors are increasing, as shown in also in Figure 7.

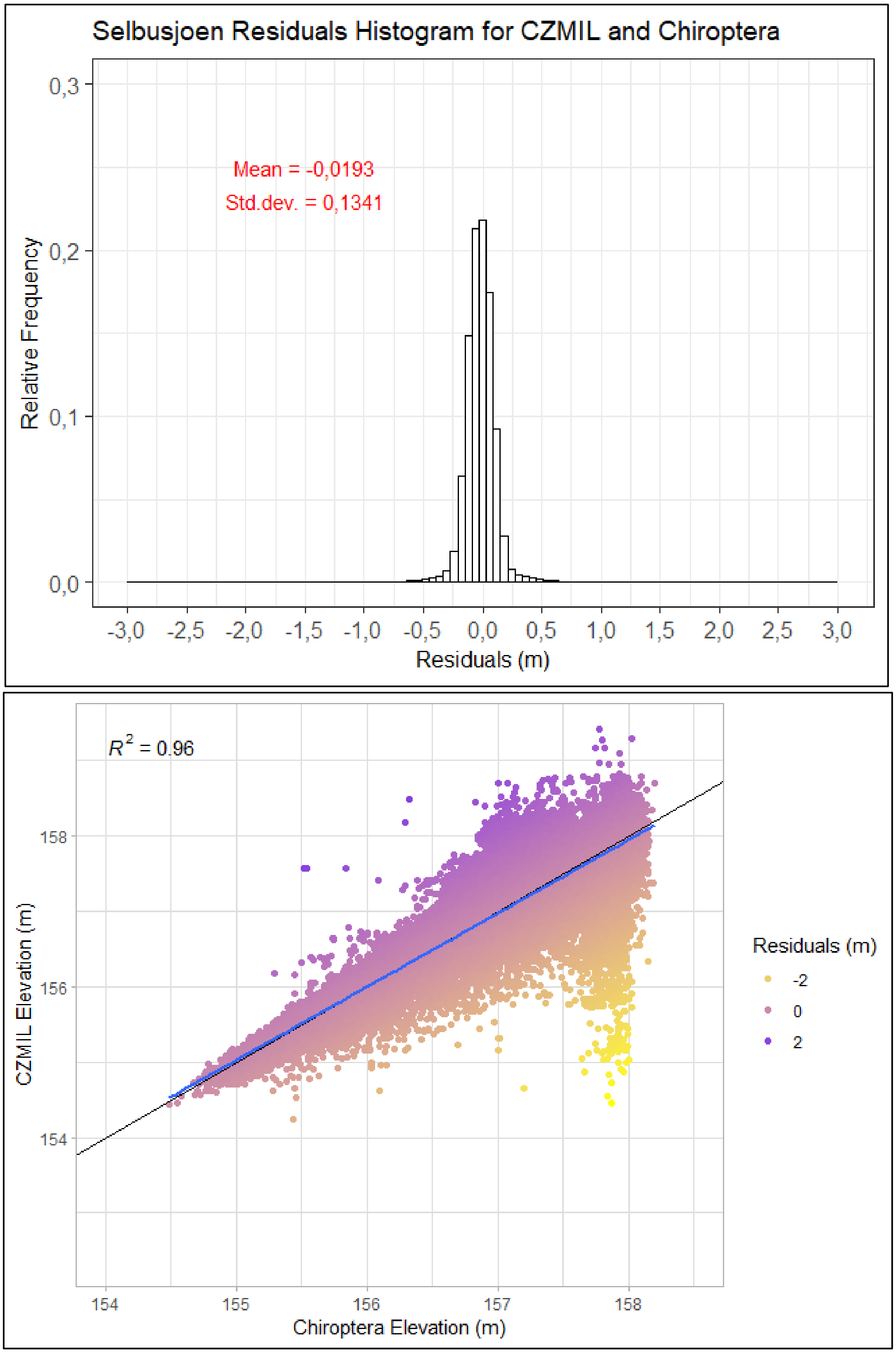

Figure 7. Residuals histogram in meters and the corresponding residuals between Chiroptera and CZMIL applied in Selbusjøen. The elevation in the lower figure refers to the elevation of the bottom of the lake.

Figure 8 shows the residual values between Chiroptera and CZMIL corresponding to the relative frequency of point residual in each elevation range. In relatively deep parts (153 masl), the residual values have fewer points in the sample and a more extensive spread, between -2 to 2 m. As it gets shallower, the two sensors have almost identical bathymetry measurements. For the very shallow elevation (158 masl), the residuals start spreading again due to the difference in water level between the flights with the two sensors.

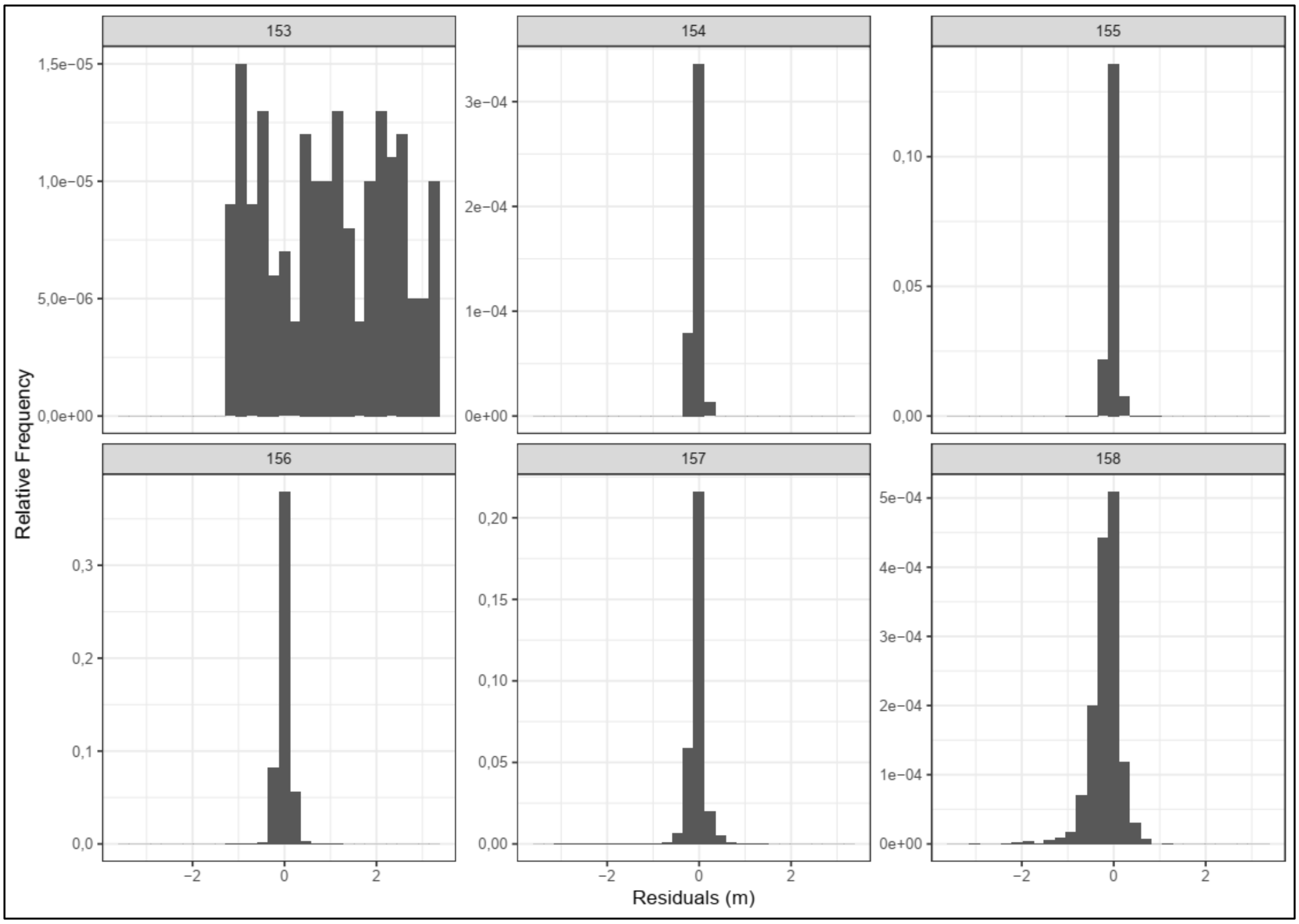

Figure 8. Relative density of residuals for various elevation intervals comparing Chiroptera and CZMIL in Selbusjøen.

Generally, the residuals are high in the very deepest parts of the lake, and to some extent also in the very shallow parts (Figure 8). This comes out of the differences in the penetration depth of the compared sensors, and potentially various challenges in mapping the areas close to the shoreline (different water levels during measurements, vegetation, etc.).

3.2 Krøderen

Krøderen is the most extensively measured lake included in the assessment. MBES, CZMIL, VQ880, and VQ840 sensors have been compared against each other in Krøderen.

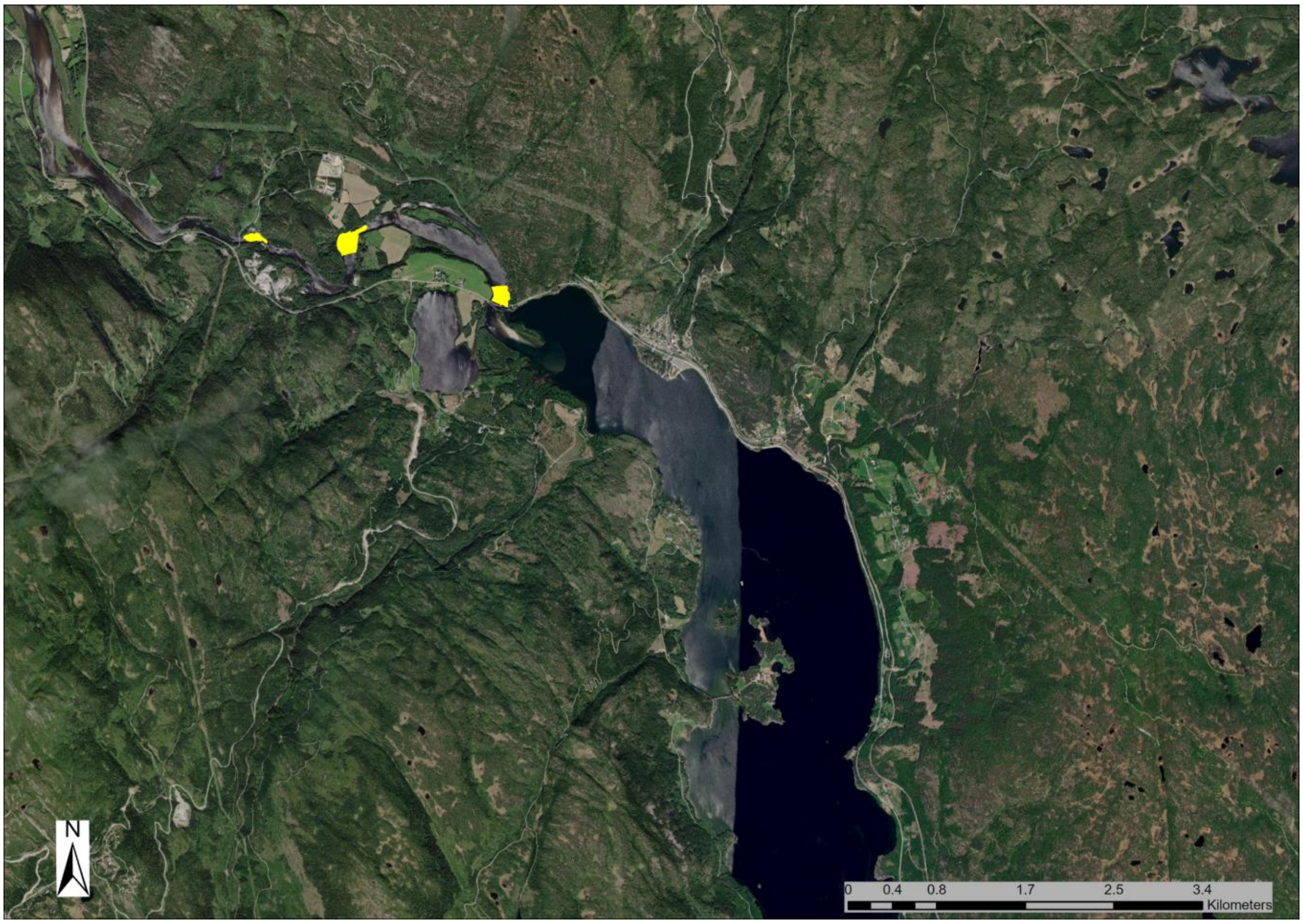

Figure 9. The map shows the coverage of MBES in Krøderen.

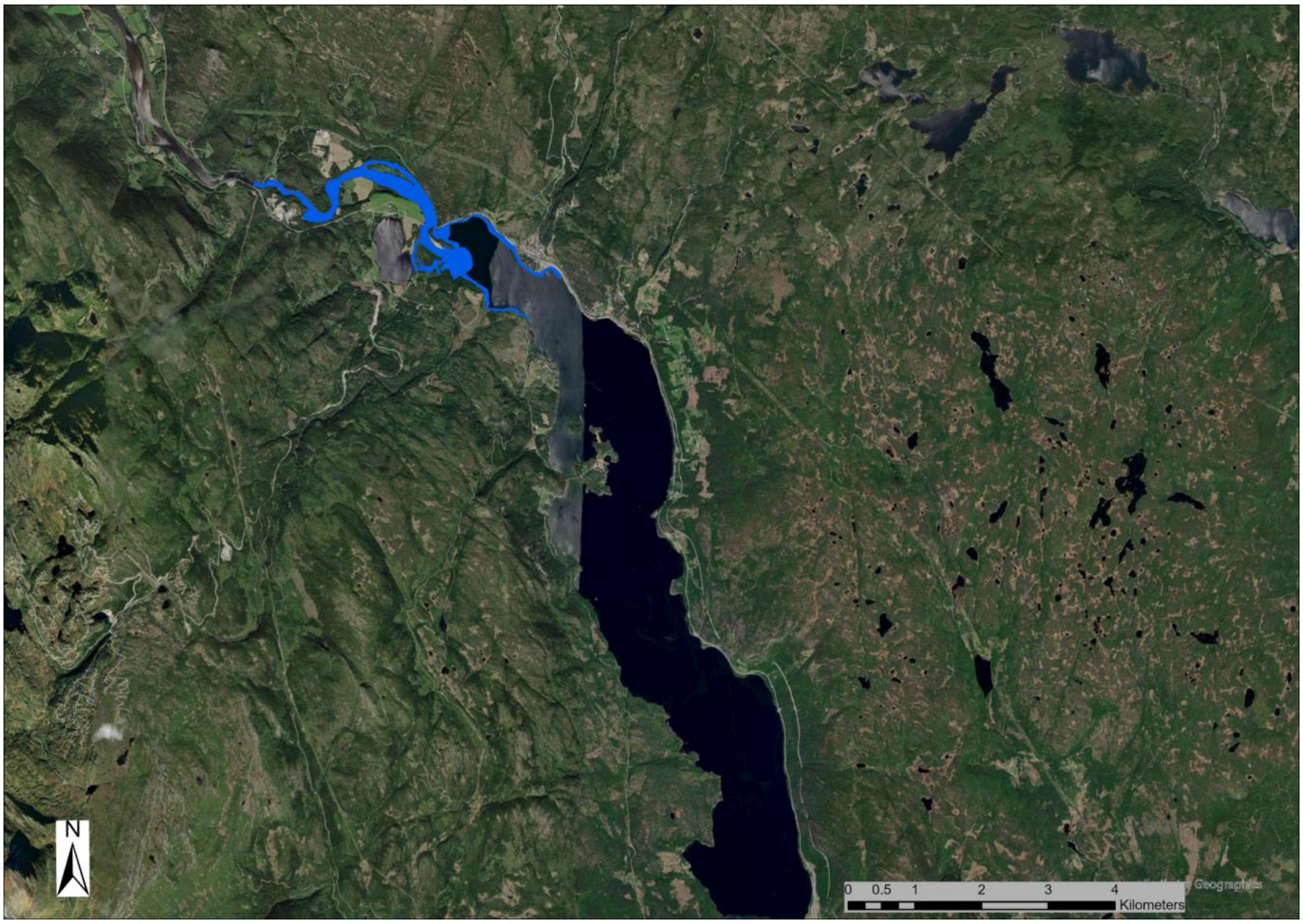

Figure 10. The map shows the coverage of CZMIL in Krøderen.

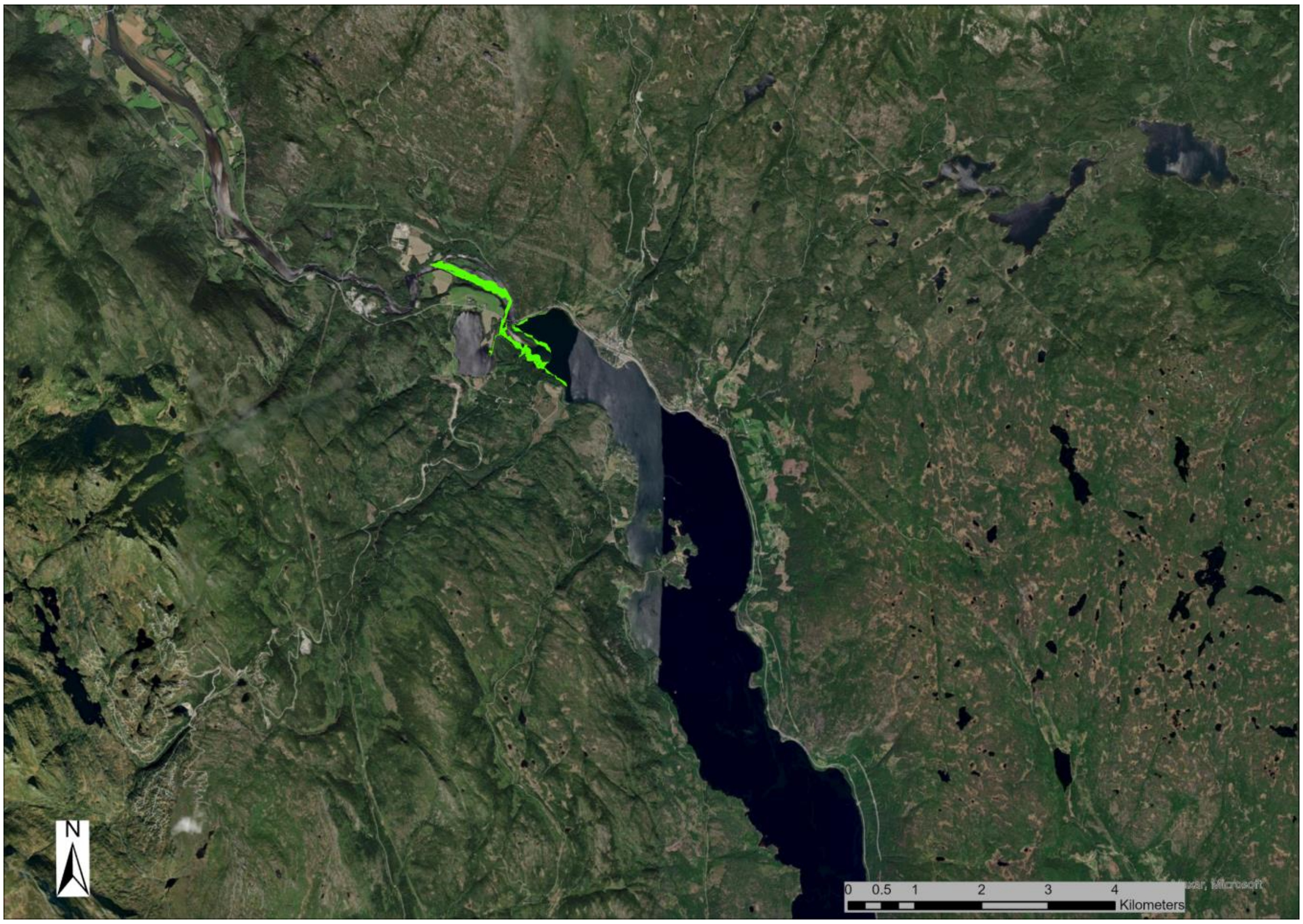

Figure 11. The map shows the coverage of VQ840 in Krøderen.

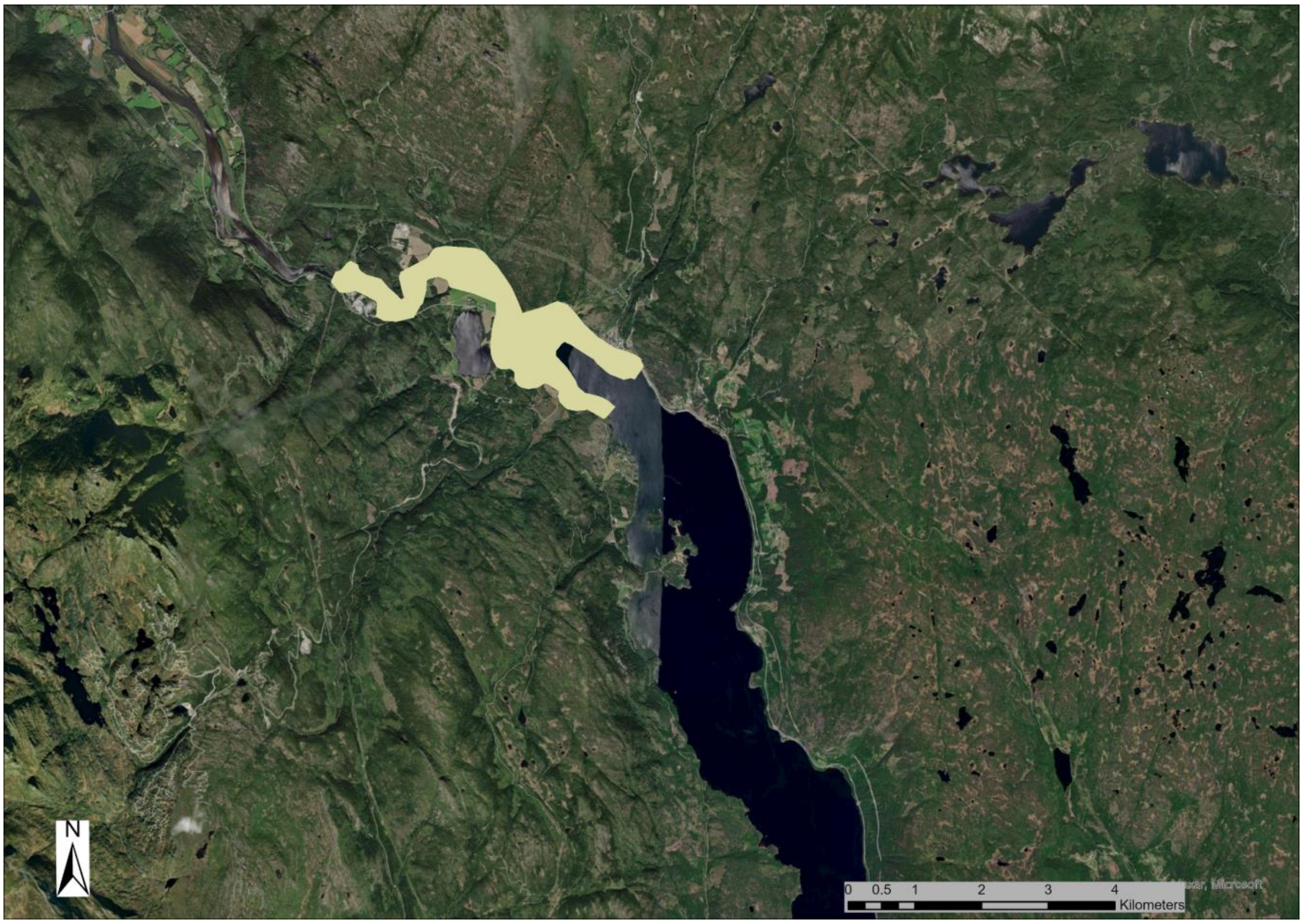

Figure 12. The map shows the coverage of VQ880 in Krøderen.

3.2.1 MBES versus CZMIL

Comparing MBES against CZMIL in Krøderen, the CZMIL measured shallower than MBES in deep parts of the lake. The residuals from comparing MBES against CZMIL are generally small (Figure 14), i.e. typically 3 cm, except for the deeper and the most shallow parts. In the deeper parts MBES is able to measure at elevations deeper than CZMIL can penetrate, i.e. elevations below 126 masl and equivalent to 8 m depth below the water surface. Therefore, significant discrepancies will appear. This explains the considerable noise in dark blue regions in Figure 13. In the more shallow areas, MBES is less suitable and can introduce deviations (Lawrence et al., 2015), which explain the residuals in Figure 13 in the areas presented with intense red color.

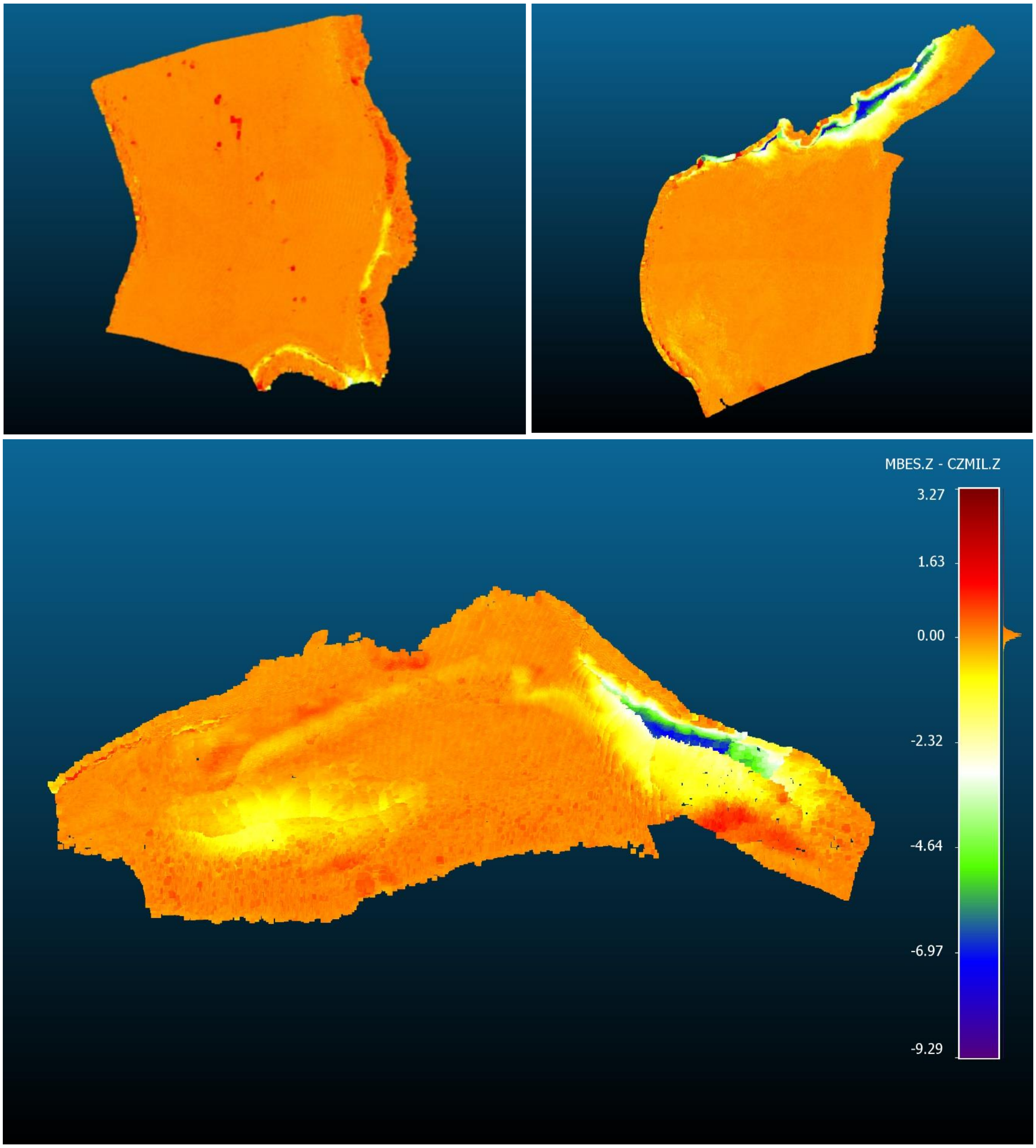

Figure 13. Residual map for the Green LiDAR bed elevations for CZMIL SuperNova against MBES in three different parts of Krøderen.

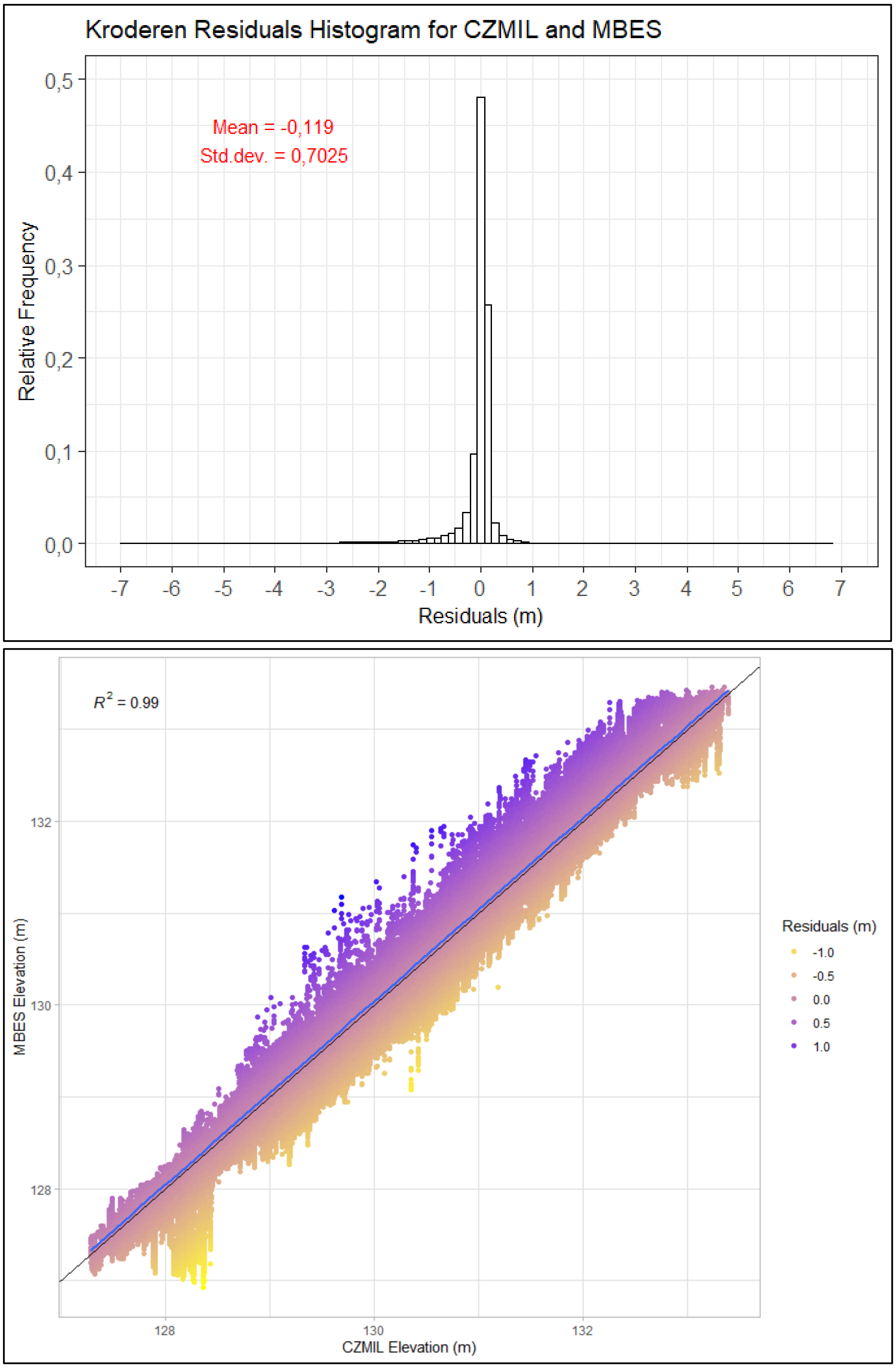

Figure 14. Residuals histogram in meters and the corresponding residuals between MBES and CZMIL applied in Krøderen.

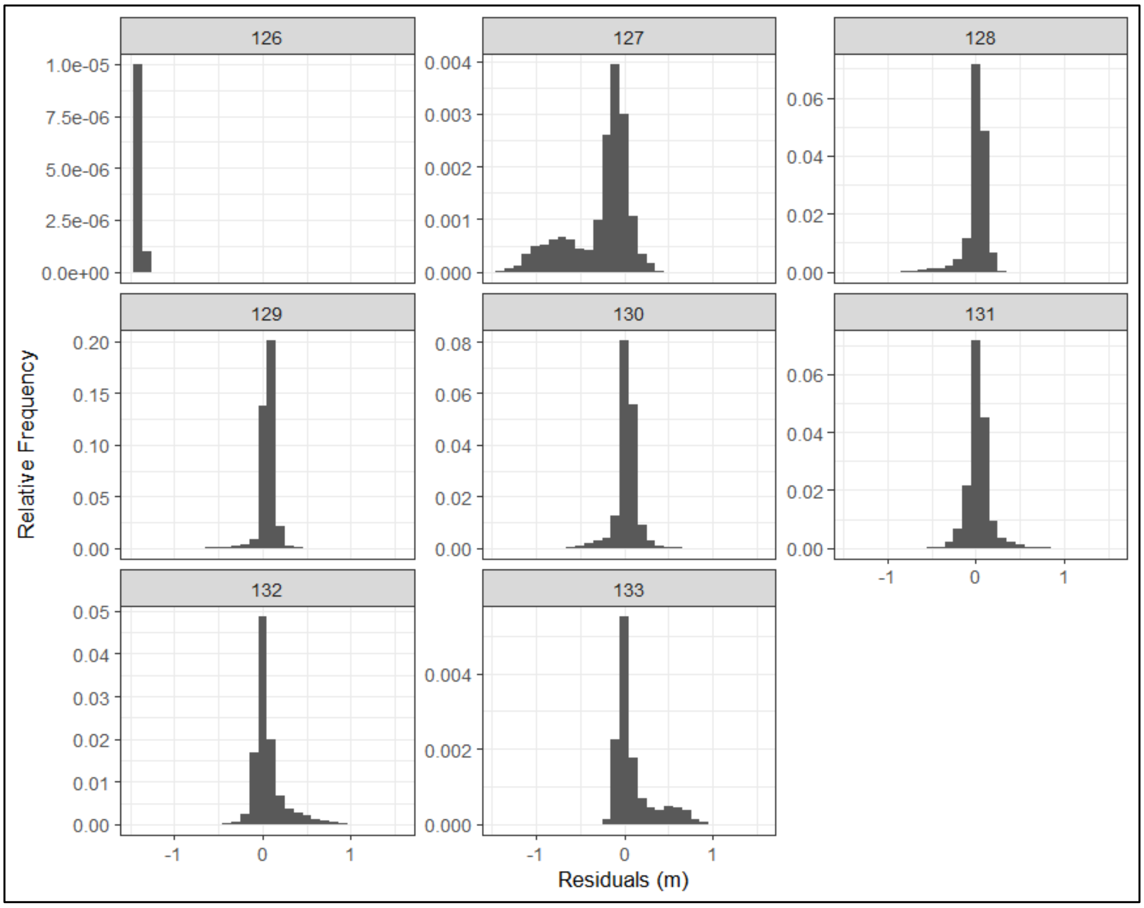

Figure 15. Relative density of residuals for various elevation intervals comparing MBES versus CZMIL in Krøderen.

The histograms presented in Figure 15 confirm the general findings presented earlier in this section of the report; the residuals are largest and with skewness in the most shallow parts of the lakes and in the deepest parts covered by the Green LiDAR, i.e. the upper end of MBES and lower end of CZMIL. This comes out of the differences in the penetration depth of the MBES and CZMIL and the ability to measure shallow areas (MBES is not suitable for depths less than 1 meter).

3.2.2 MBES versus VQ840

In comparing MBES against VQ840, the map overall showed deeper bathymetric elevations of VQ840 than MBES, with 5.6 cm mean and 5 cm median values. The red areas in Figure 16 shows positive residuals near the banks where MBES measures 1.0 m shallower than VQ840.

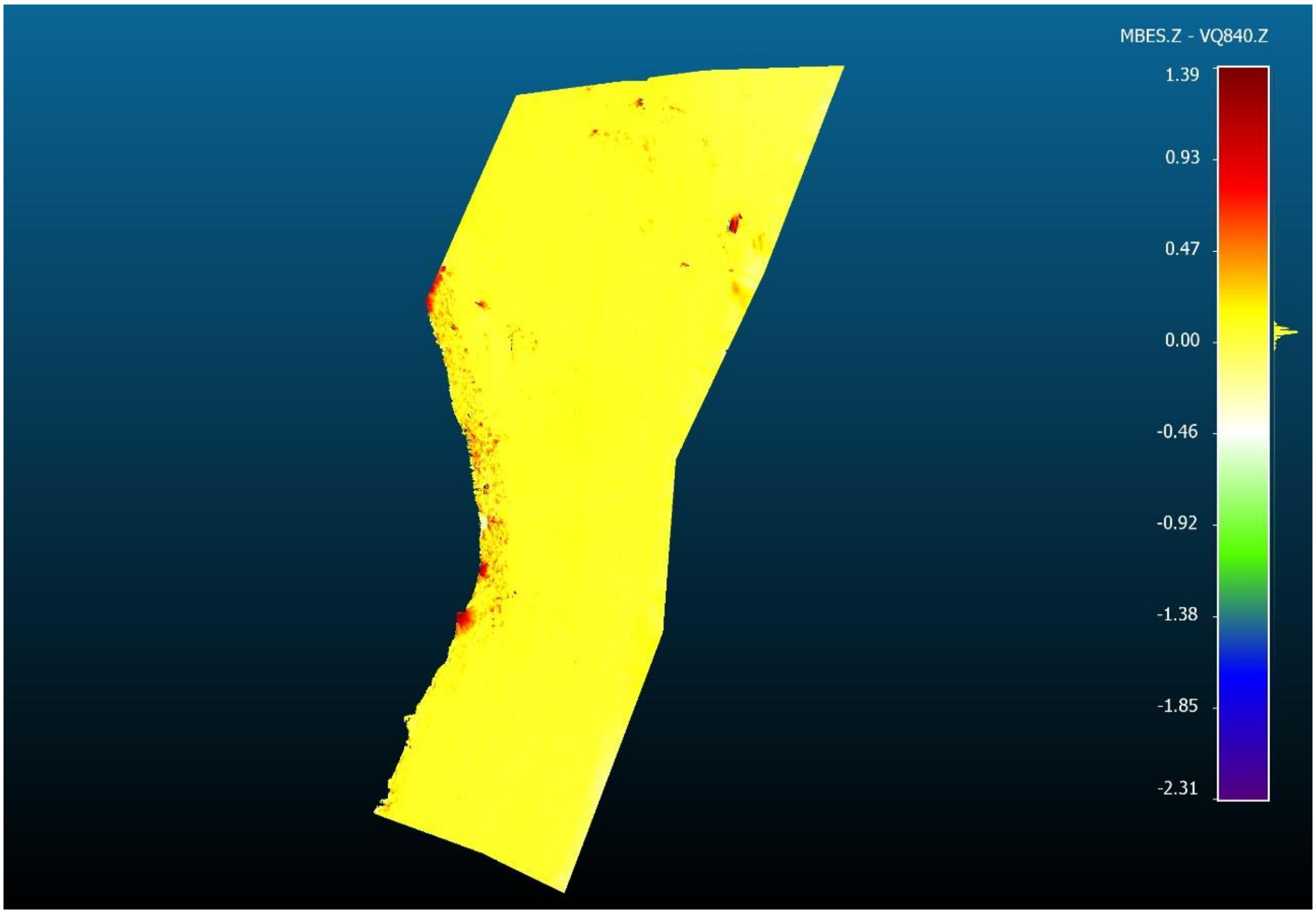

Figure 16. Residual map for the Green LiDAR bed elevations for MBES against Riegl VQ840 applied in Krøderen.

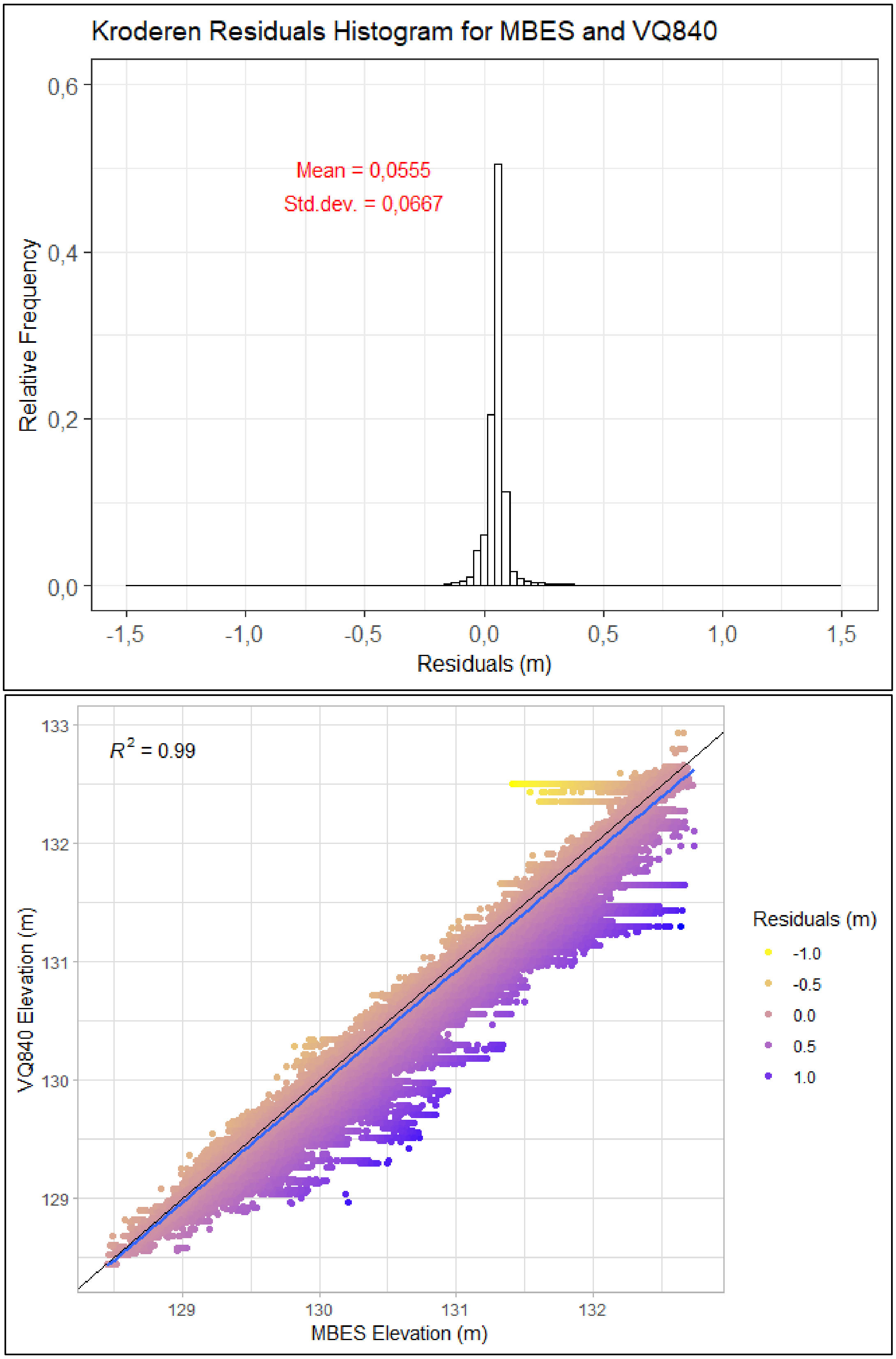

Figure 17. Residuals histogram in meters and the corresponding residuals between MBES and Riegl VQ840 in Krøderen.

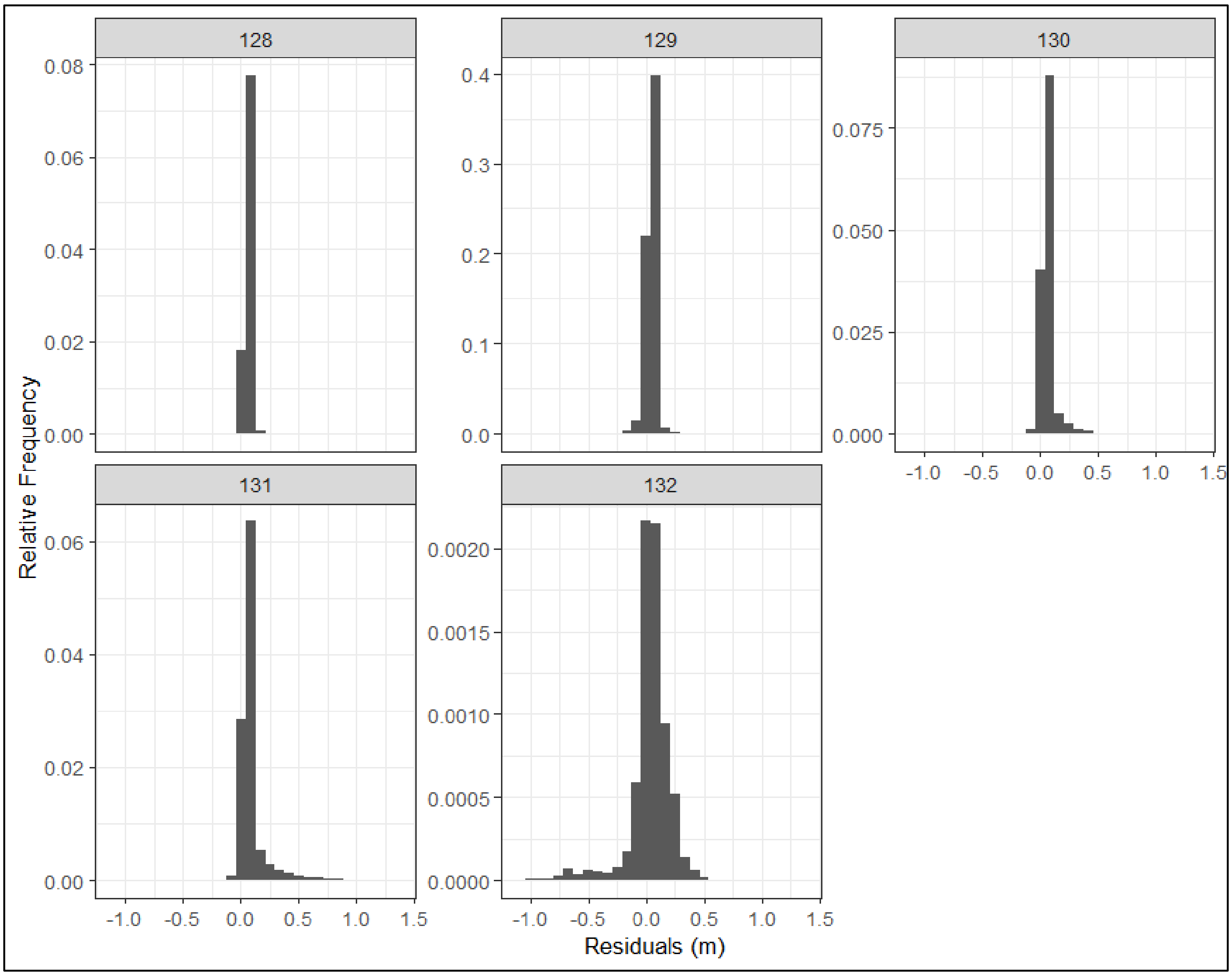

Figure 18. Relative density of residuals for various elevation intervals comparing MBES against Riegl VQ840 in Krøderen.

In Figure 18 it appears that the shallow elevation 132 masl has the largest discrepancies between MBES and VQ840, nevertheless, deeper areas are showing remarkable consistency.

3.2.3 CZMIL versus VQ840

The common scanned area between CZMIL and VQ840 showed minimal residuals of around 0.5 to 1 cm differences. Additionally, more than 50% of the residuals are 0 cm. The residual map overall showed a consistent distribution of the residuals for bathymetric elevations for the two sensors with outliers in the shoreline.

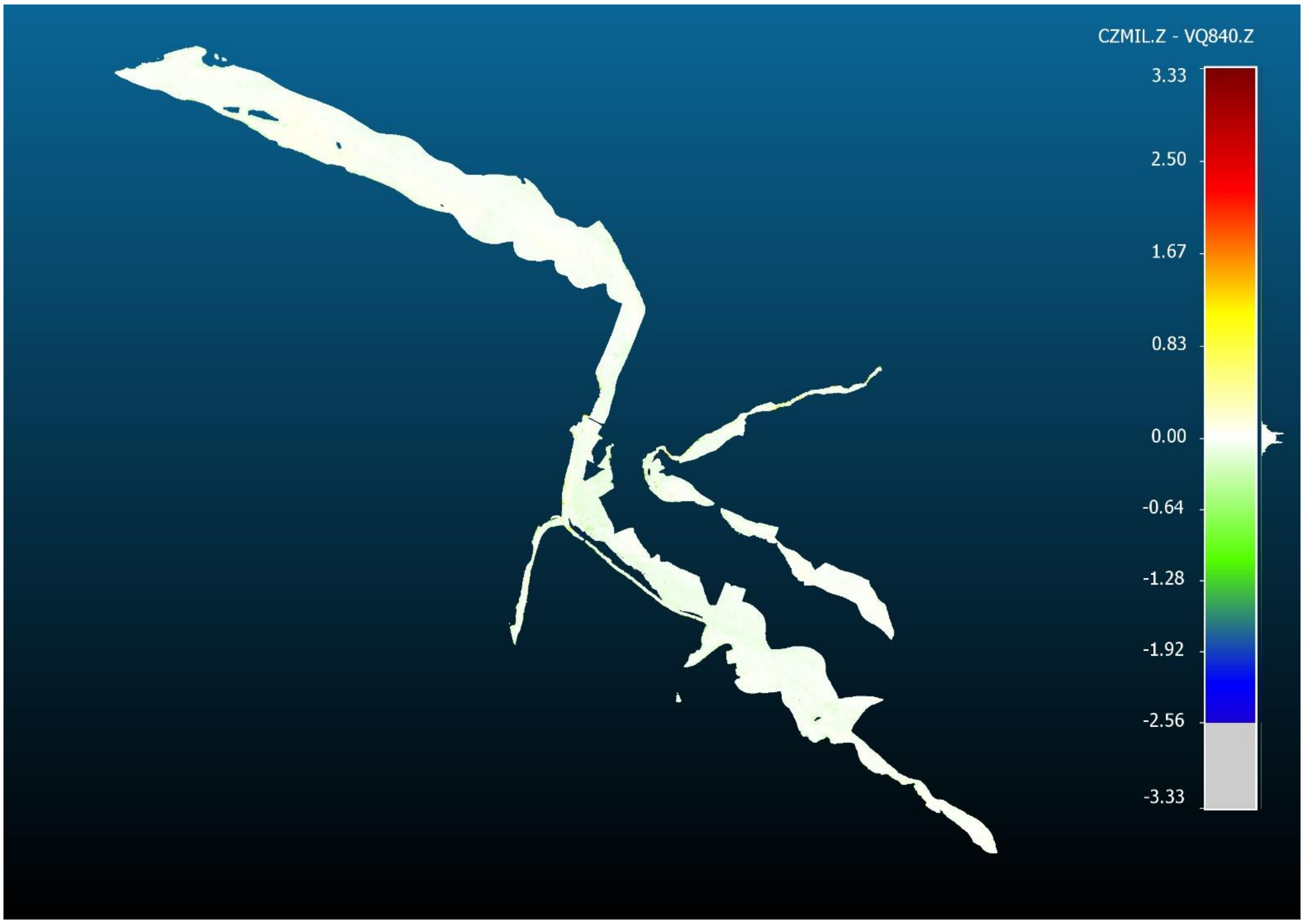

Figure 19. Residual map for the Green LiDAR bed elevations for CZMIL against Riegl VQ840 in Krøderen.

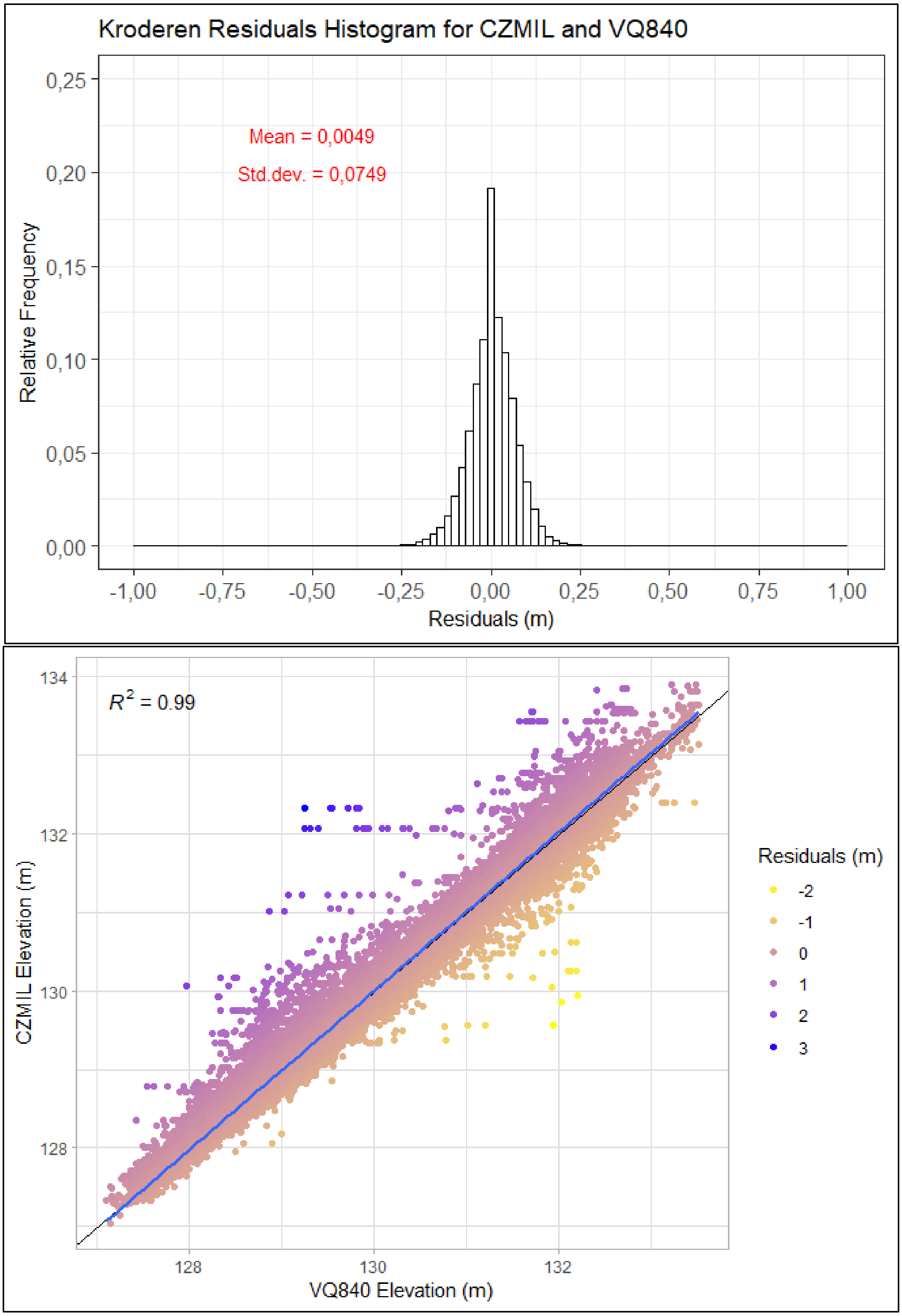

Figure 20. Residuals histogram in meters and the corresponding residuals bewteen CZMIL and Riegl VQ840 in Krøderen.

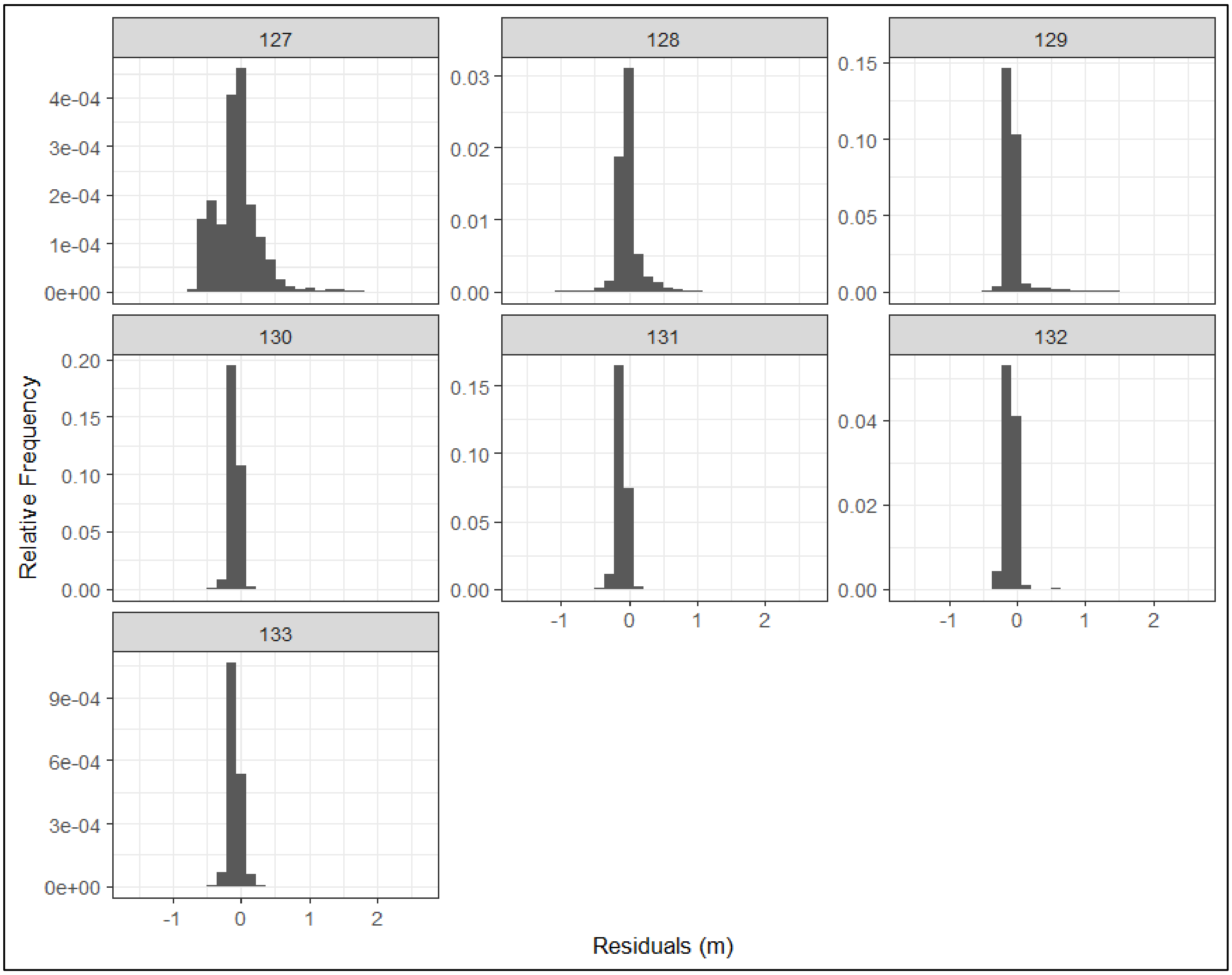

Figure 21. Relative density of residuals for various elevation intervals comparing Riegl VQ880 against CZMIL in Krøderen.

Generally, the residuals are highest in the very deepest parts of the lake (Figure 21) and to a smaller extent the shalow areas. This comes out of the differences in the penetration depth of the compared sensors, and potentially various challenges in mapping the areas close to the shoreline (different water levels during measurements, vegetation, etc.).

3.2.4 VQ880 versus MBES

The results from comparing MBES against VQ880 resulted in generally small residuals, as shown in Figure 22 The mean residual between the two sensors is -10.5 cm. The red areas show large deviations between the two types of mapping. The red areas are areas with very shallow water and the deviations are because MBES are not capable of producing reliable measurements in areas with weater depth less than 1 meter.

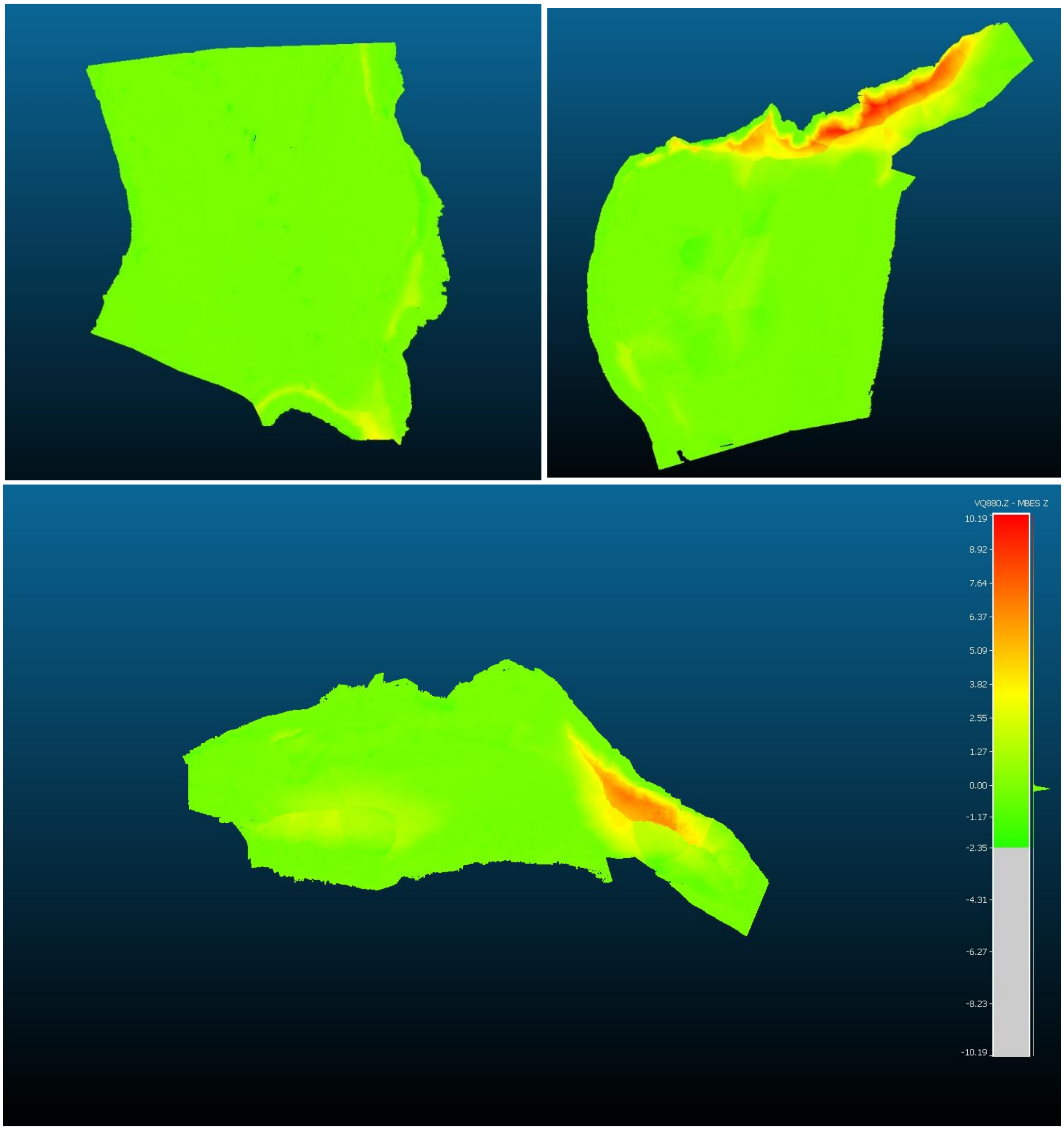

Figure 22. Residual map for the Green LiDAR bed elevations for Riegl VQ880 against MBES in Krøderen.

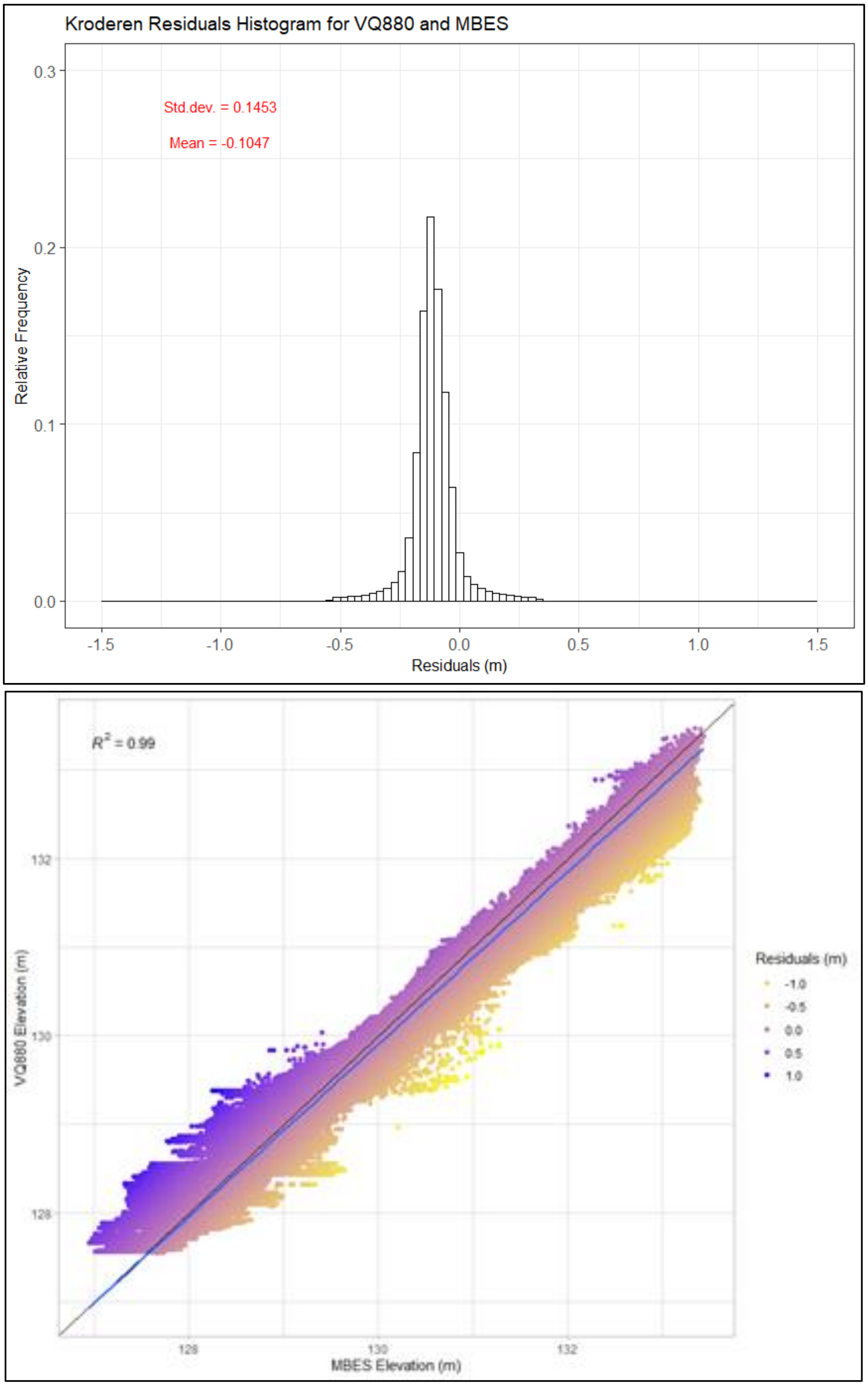

Figure 23. Residuals histogram in meters and the corresponding residuals between Riegl VQ880 and MBES in Krøderen.

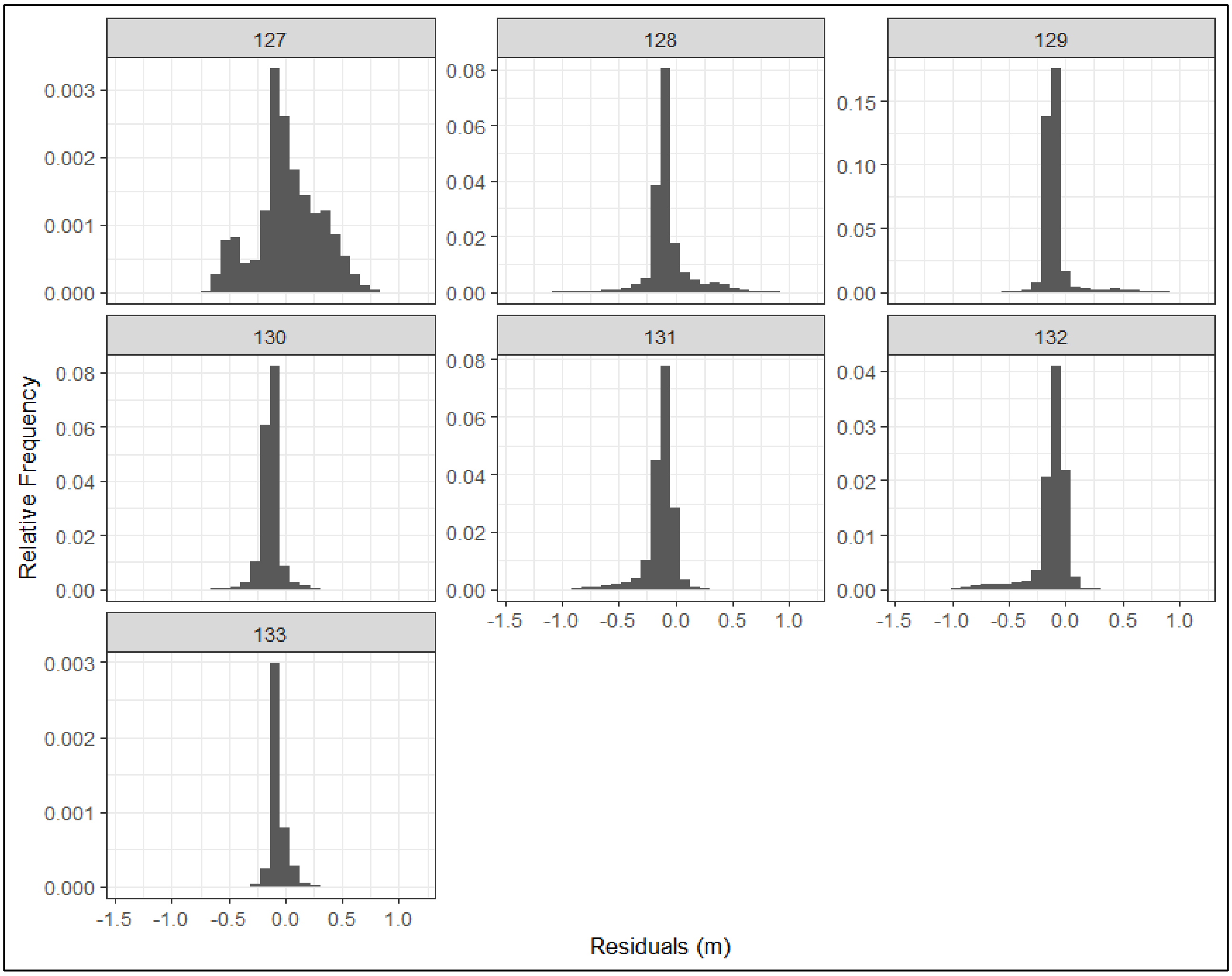

Figure 24. Relative density of residuals for various elevation intervals comparing MBES versus Riegl VQ880 in Krøderen.

Figure 24 confirms the general finding earlier described and presented; the residuals in the deeper parts come out of the difference in penetration depth of MBES and Green LiDAR.

3.2.5 VQ880 versus CZMIL

As can be seen in Figure 24, the residuals from comparing CZMIL to VQ880 were generally low. The green areas indicate significant consistency between the two forms of mapping; the mean residual between the two sensors is -8.0 cm.

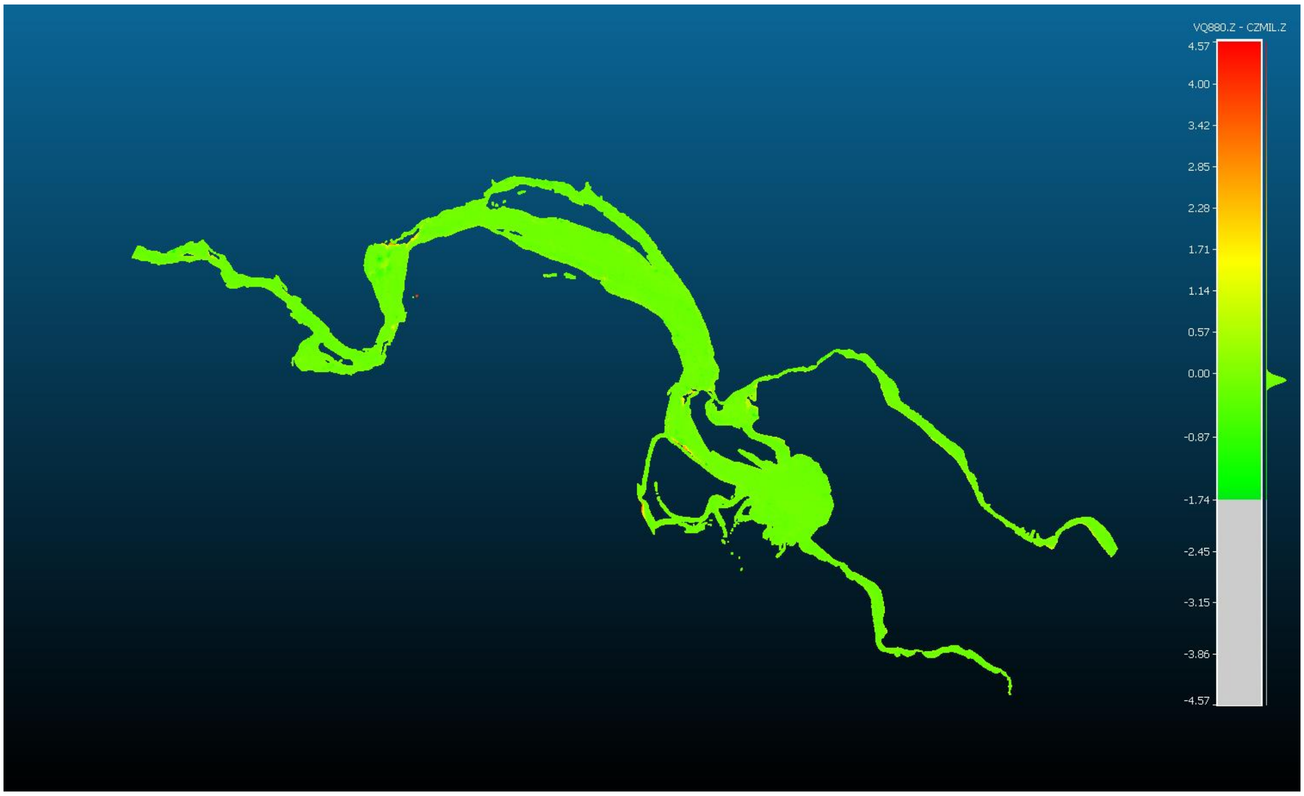

Figure 25. Residual map for the Green LiDAR bed elevations for Riegl VQ880 against CZMIL in Krøderen.

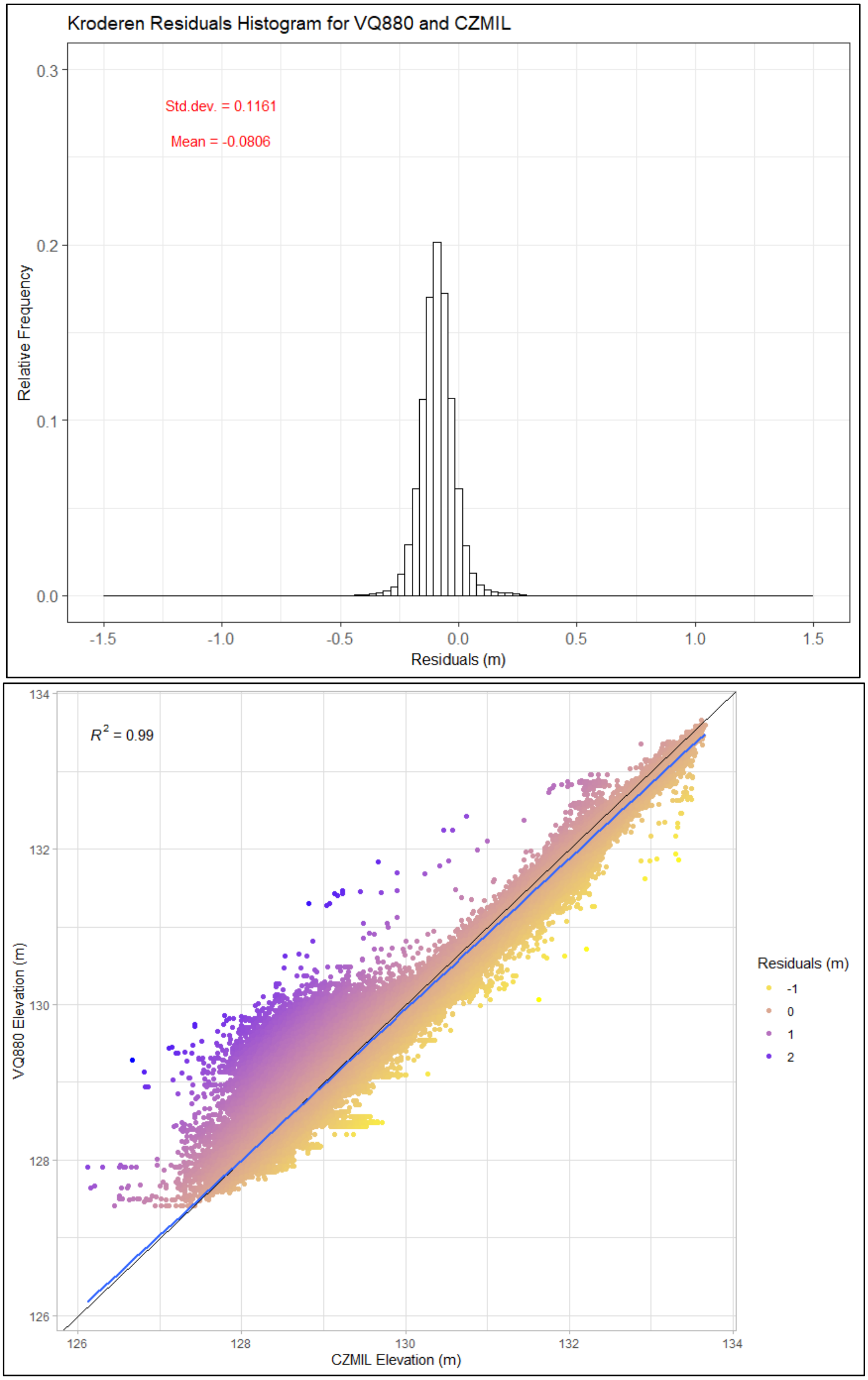

Figure 26. Residuals histogram in meters and the corresponding residuals between Riegl VQ880 and CZMIL in Krøderen.

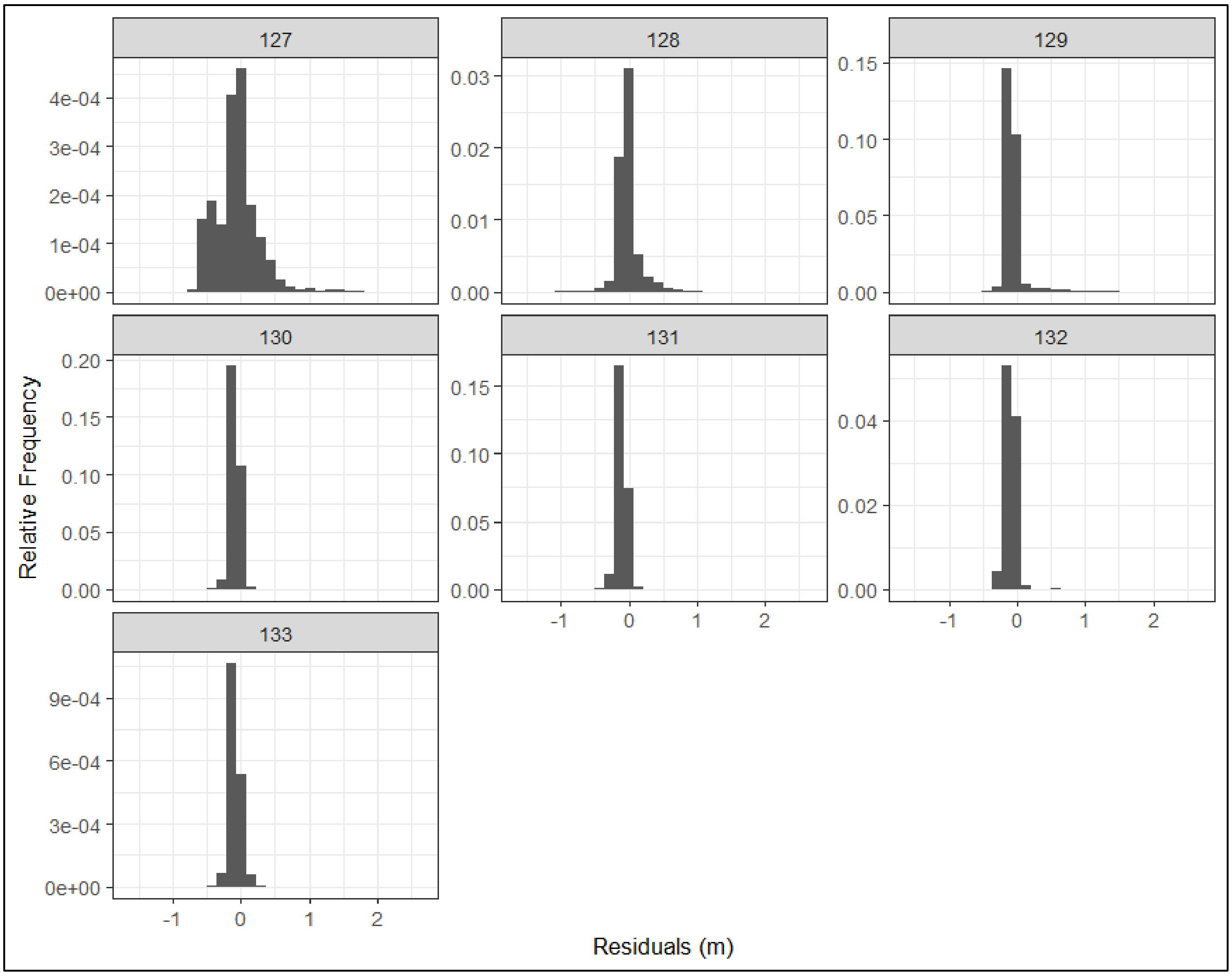

Figure 27. Relative density of residuals for various elevation intervals comparing Riegl VQ880 against CZMIL in Krøderen.

Generally, the residuals are highest in the very deepest parts of the lake (Figure 27). This comes out of the differences in the penetration depth of the compared sensors. The errors in the shallow areas are due to various challenges in mapping the areas close to the shoreline (different water levels during measurements, vegetation, etc.).

3.2.6 VQ880 versus VQ840

The residual maps depict consistency with slight skewness to the negative values where VQ880 measures deeper than VQ840. The mean residual value is -7.8 cm, and -8.8 cm as the median.

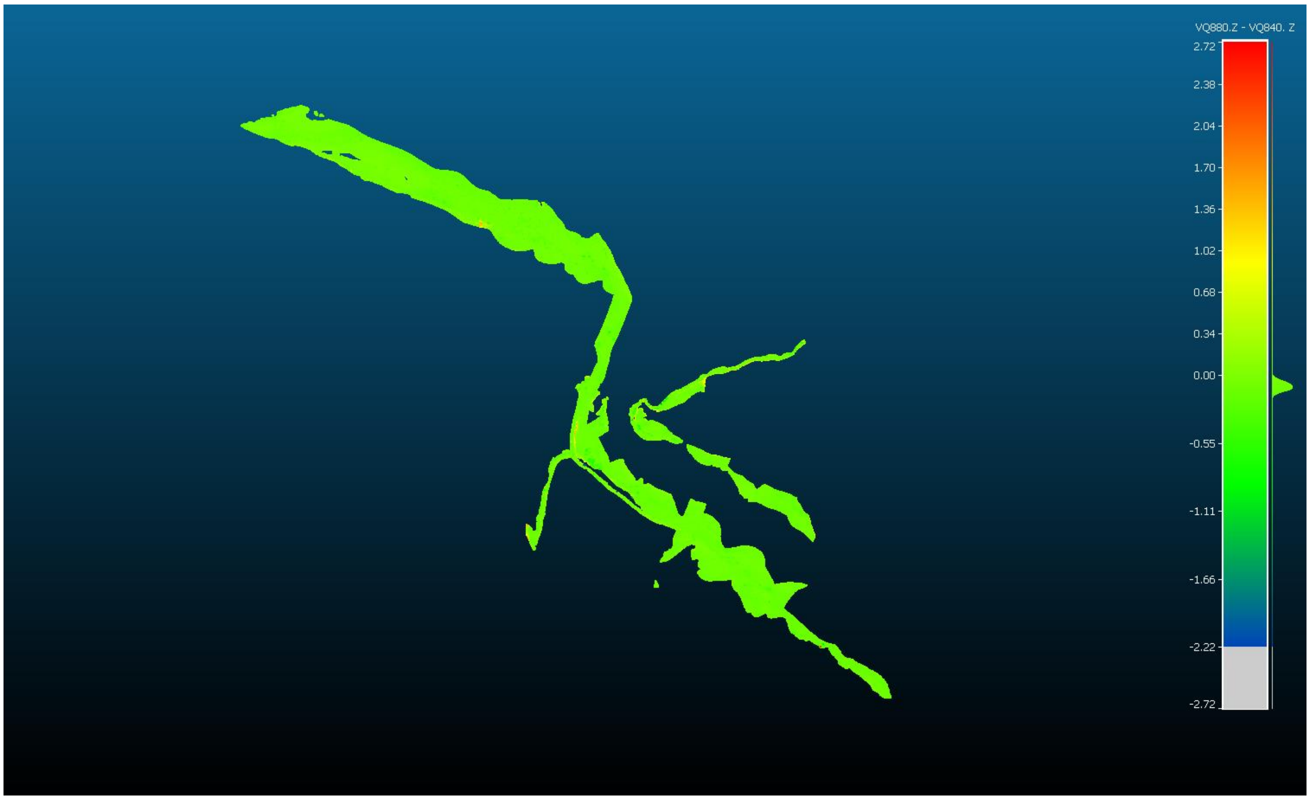

Figure 28. Residual map for the Green LiDAR bed elevations for Riegl VQ880 against Riegl VQ840 in Krøderen.

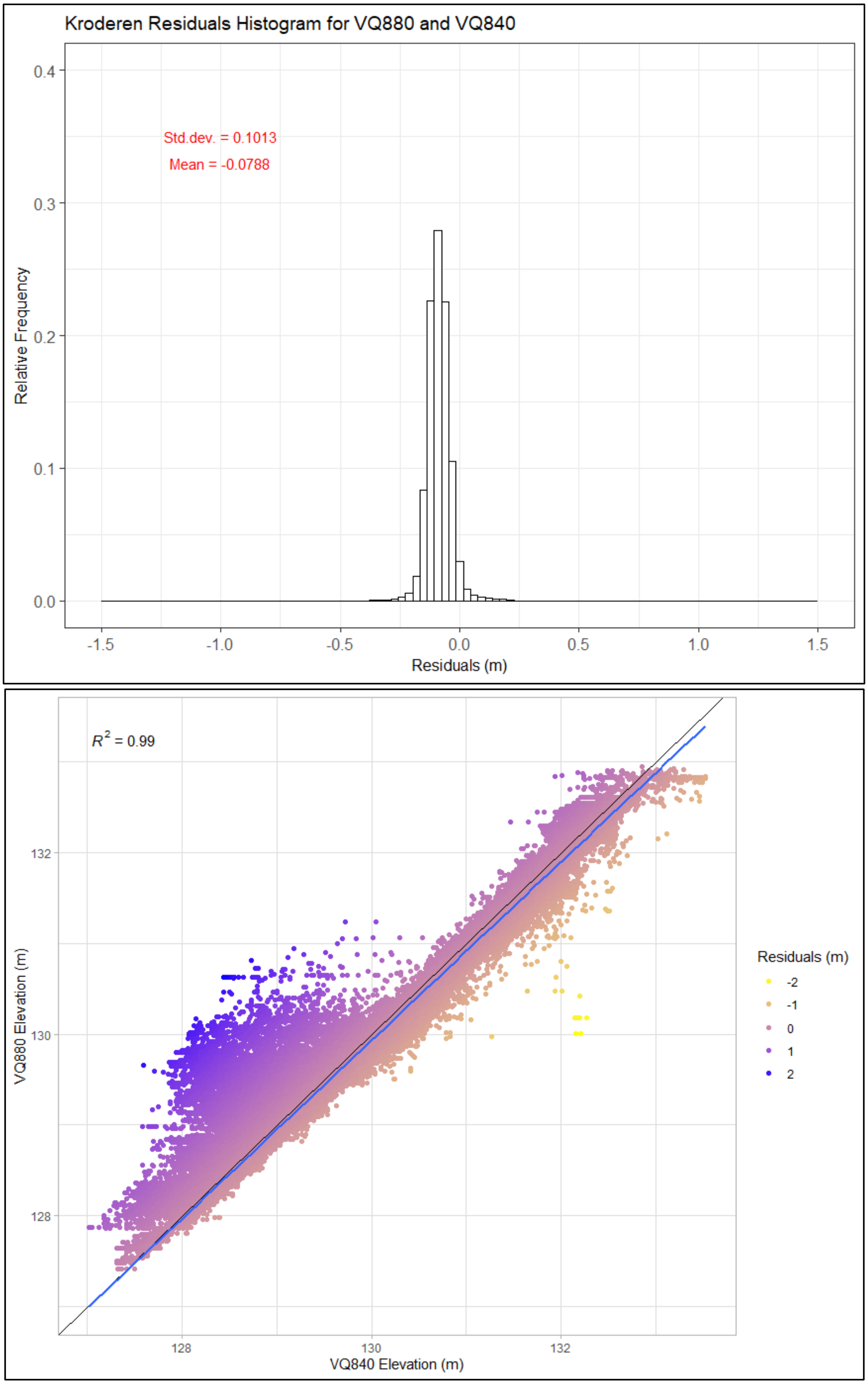

Figure 29. Residuals histogram in meters and the corresponding residuals between Riegl VQ880 and Riegl VQ840 in Krøderen.

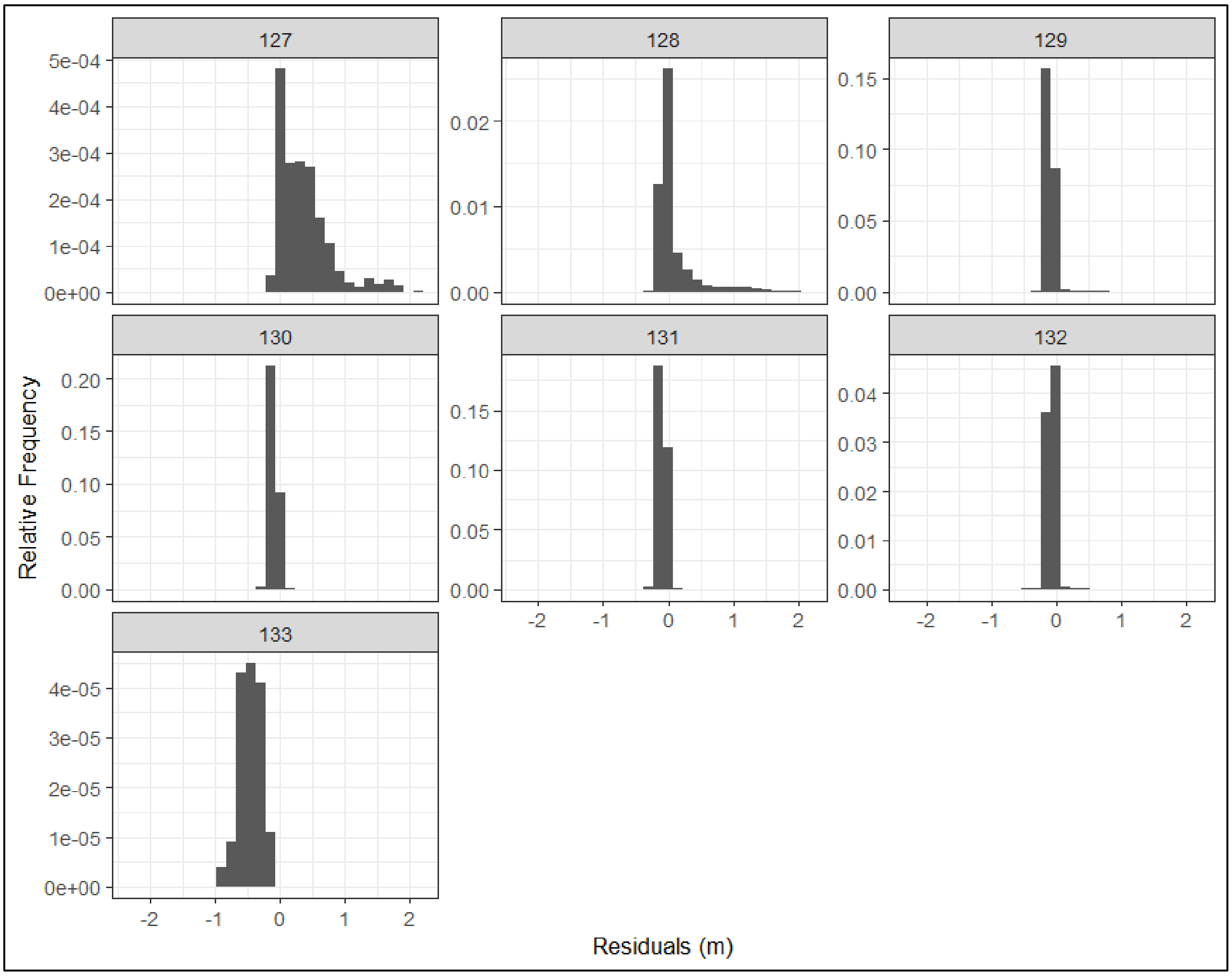

Figure 30. Relative density of residuals for various elevation intervals comparing Riegl VQ880 against Riegl VQ840 in Krøderen.

Figure 29 shows the relative density and the residual value for comparing Riegl sensors in Krøderen. The residuals have larger values as the water depth increases (elevations 127 and 128 masl), as well as in shallow areas. While in the elevation ranges between and 129 and 132 masl, the instruments have similar performance, and the residuals are distributed well around zero.

3.3 Benna

Benna is the smallest lake included in the assessment and is, in contrast to Krøderen and Selbusjøen, not affected by hydropower regulations. As it is much smaller in surface are compared to Selbusjøen and Krøderen, the measurements also cover a larger part of the lake area.

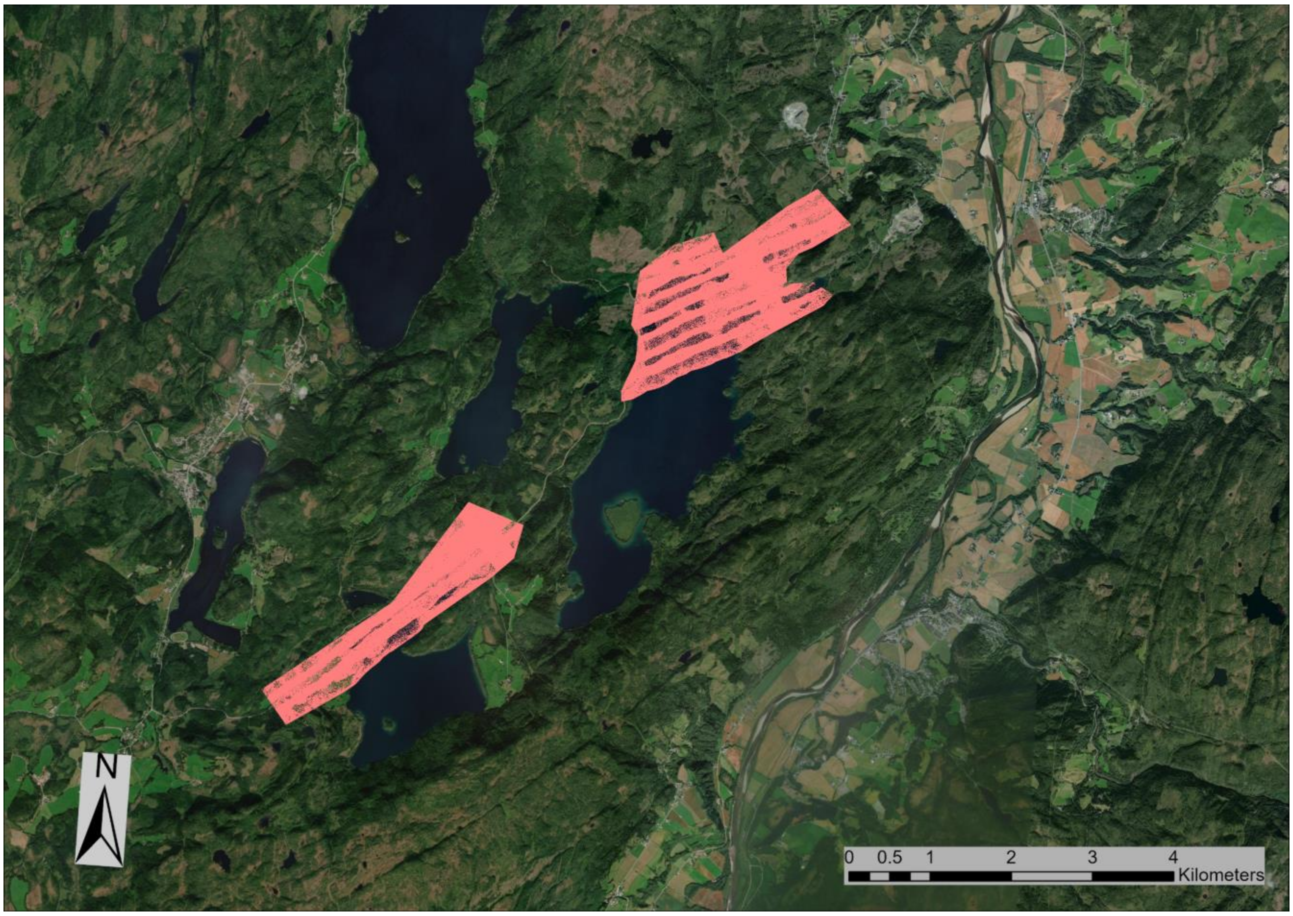

Figure 31. The map shows the coverage of CZMIL as measured in 2018 in Benna.

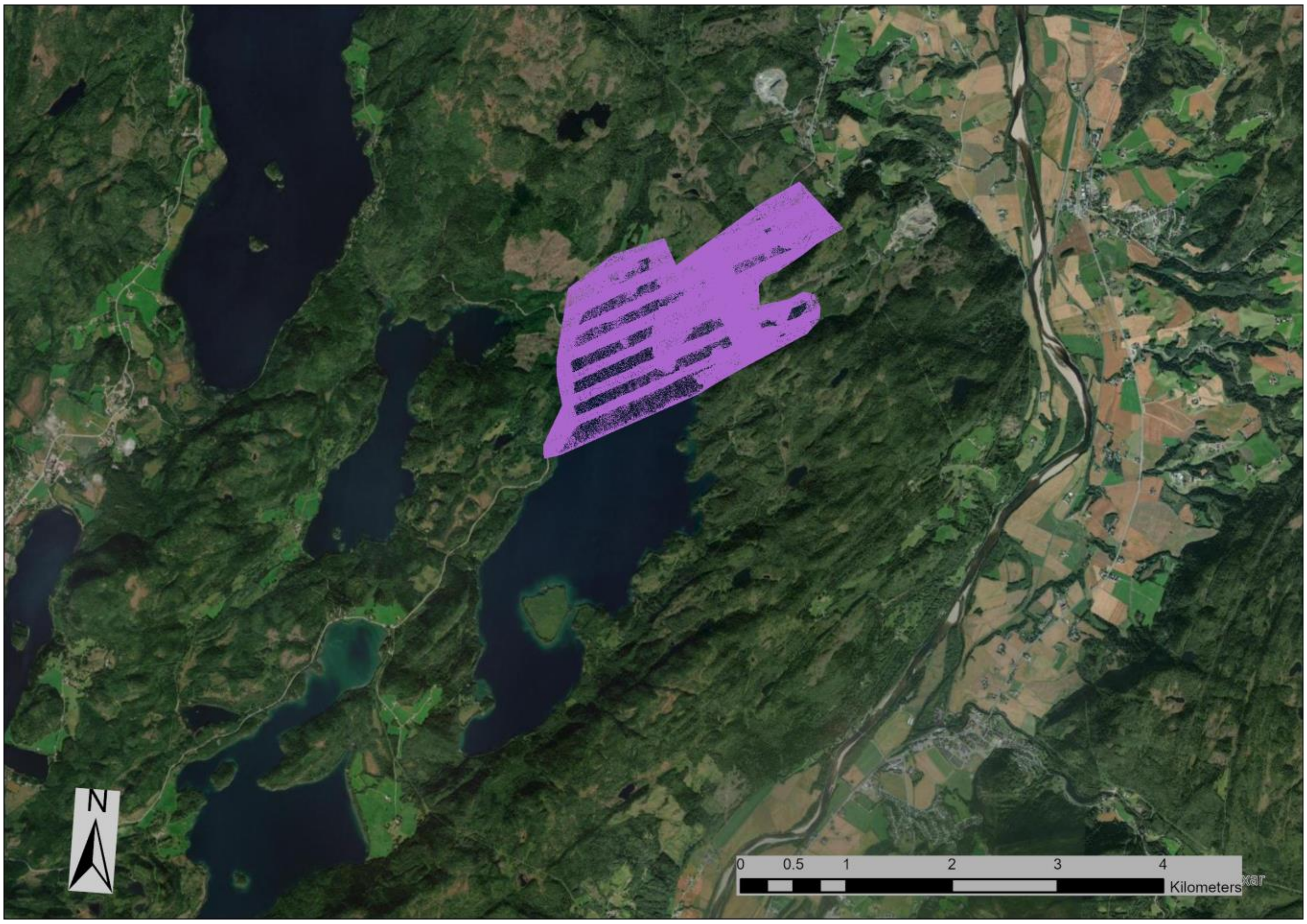

Figure 32. The map shows the coverage of CZMIL as measured in 2020 in Benna.

3.3.1 CZMIL2018_CZMIL2020

In Benna, the same CZMIL sensor was applied with two years in between, i.e. in 2018 and in 2020, named CZMIL2018 and CZMIL2020. As a pre-processing, the segmentation of incomparable parts of the lake was done, as well as filtering noise in the residuals. The CZMIL measurements in 2018 went deeper in some areas than CZMIL 2020. Overall, the comparison showed small residuals of around 3.3 cm on average and a median of 3 cm, which is a very high precision and shows the potential of detecting changes over time, e.g. due to sedimentation or dredging, when the same sensors are repeatedly applied over time.

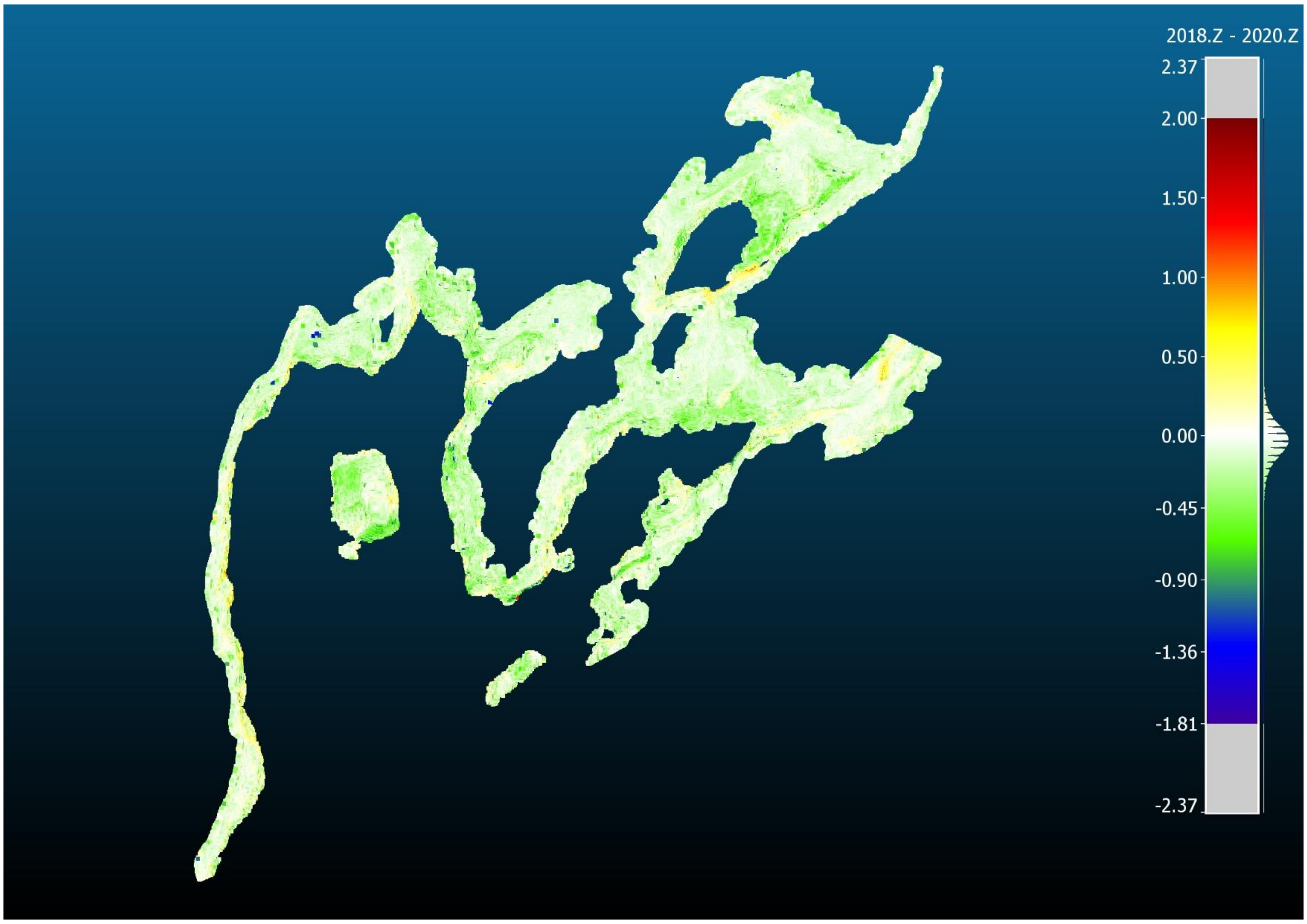

Figure 33. Residual map for the Green LiDAR bed elevations for CZMIL_2018 against CZMIL_2020 in Benna.

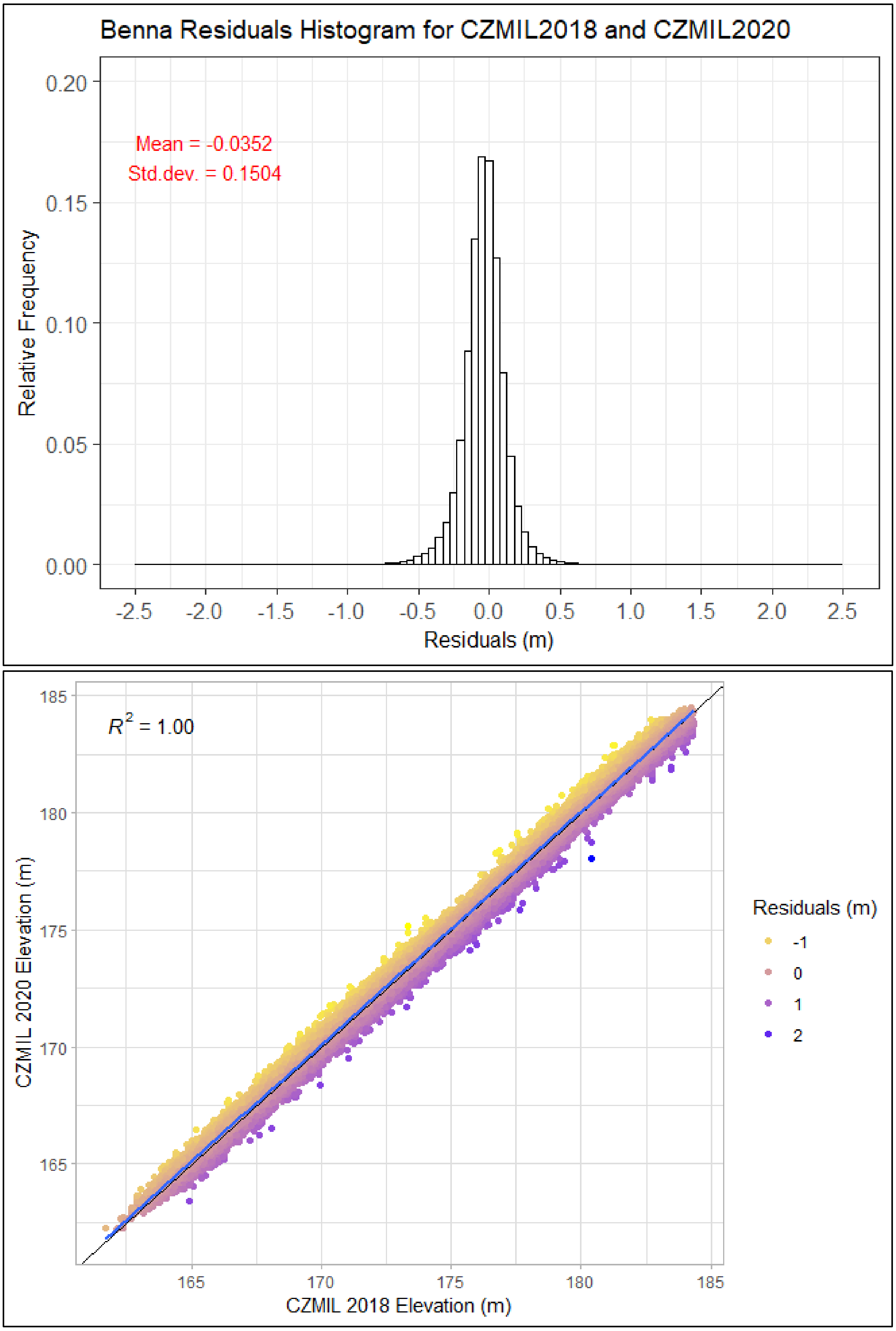

Figure 34. Residuals histogram in meters and the corresponding residuals between CZMIL 2018 and CZMIL 2020 in Benna.

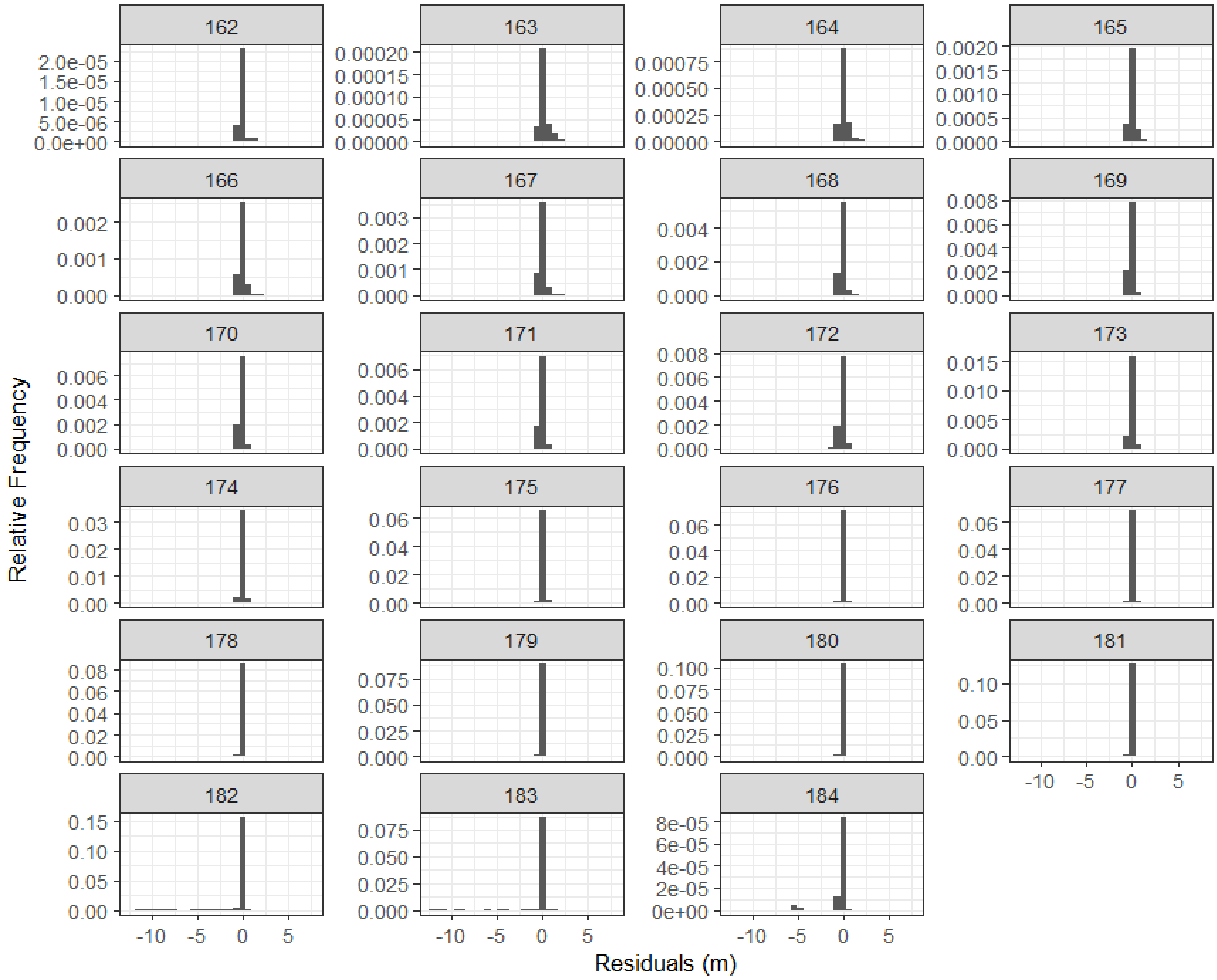

Figure 35. Relative density of residuals for various elevation intervals comparing CZMIL 2018 and CZMIL 2020 in Benna.

3.4 Point densities – sensor penetration

The size and composition of the substrate are considered key factors in shaping the physical habitat in rivers, and extensive research has been carried out to identify substrate of proper characteristics to sustain important life-stages of salmonid fish in rivers. A synthesis of this research has ended into guidelines for 'environmental design in salmon rivers' (Forseth and Harby, 2014), where suitable substrate size and composition for juvenile habitat (Figure 36) and spawning habitat (Figure 37) have been defined. The similar approach for environmental design of lakes and reservoirs is now under development, based on e.g. pilot studies carried out at NTNU (Saulnier, 2021).

To what extent relevant substrate information for the assessment of habitat qualities can be extracted from the Green LiDAR data is given by the precision and density of the point measurements. In order to read out features given in the following figures (Figures 36 & 37), detailed description of the bottom surface will be needed. It is, however, difficult to quantify this by point density requirements, and further research would be needed to study this in more detail.

The sensor penetration, in the meaning how deep the sensor are able to measure, can be read out of the correspondence diagram where two sensors are compared against each other, by assuming that the highest elevation values are close to water surface of the lakes. It is, however, difficult to read out of these plots the point densities of these measurements, i.e. how many points per area unit that are measured over depth. Point densities can, after some data processing, be extracted out of the software (Cludcompare) applied in the analysis.

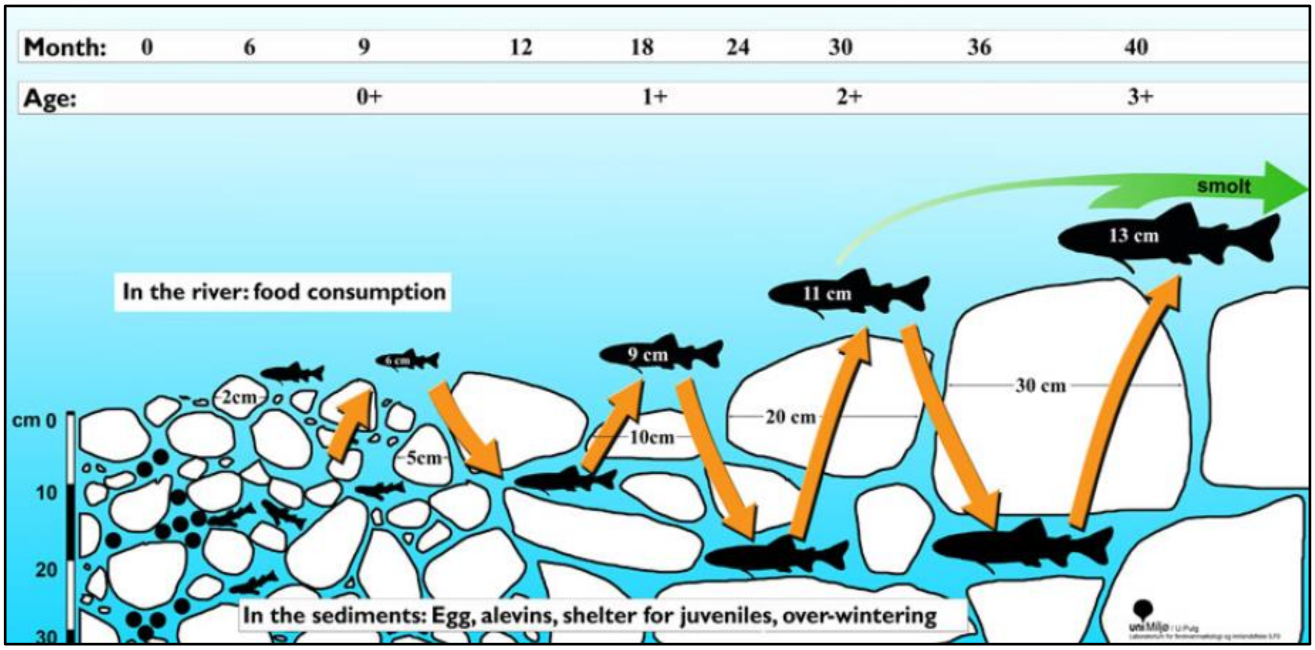

Figure 36. Juvenile salmon habitat during their early development in rivers. Hiding places (holes and crevices) in the sediments are important in order to avoid predation, for overwintering, and for resting (from Forseth and Harby, 2014).

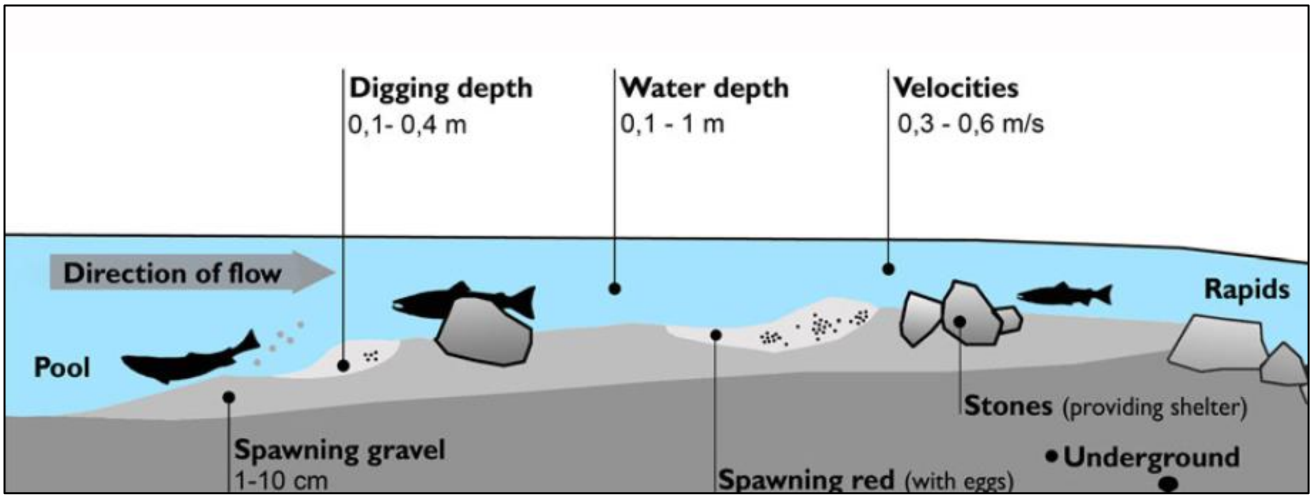

Figure 37. Longitudinal river profile illustrating salmon and brown trout spawning habitat in rivers (from Forseth and Harby, 2014).

In the Figures 38-41 point densities over depth are presented for the three lakes studied. The figures show the number of points in a circle of an area equal to 1 m^2 . Note that the first axis gives the Green LiDAR densities, while MBES is presented on the secondary axis (for lake Krøderen).

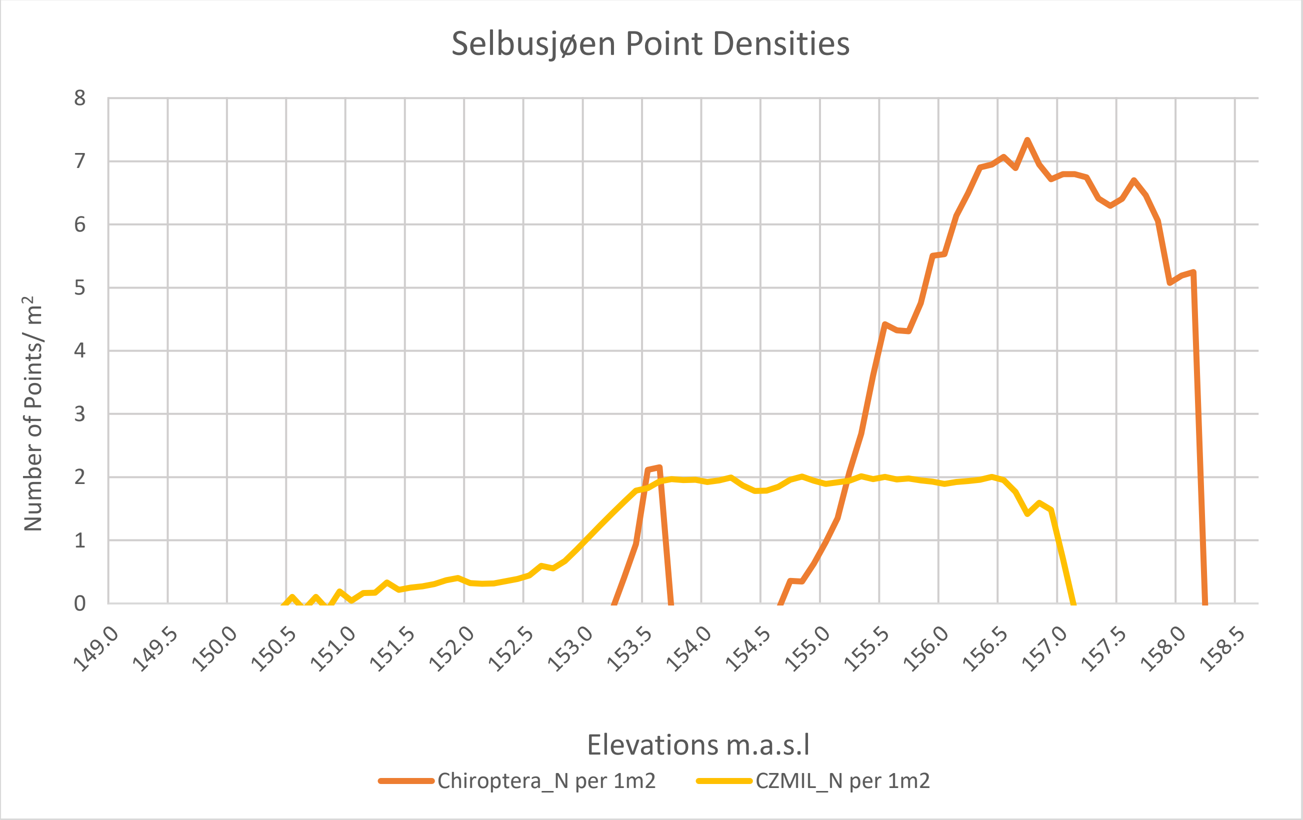

Figure 38. Number of points per 1 meter squared for Chiroptera and CZMIL in Selbusjøen.

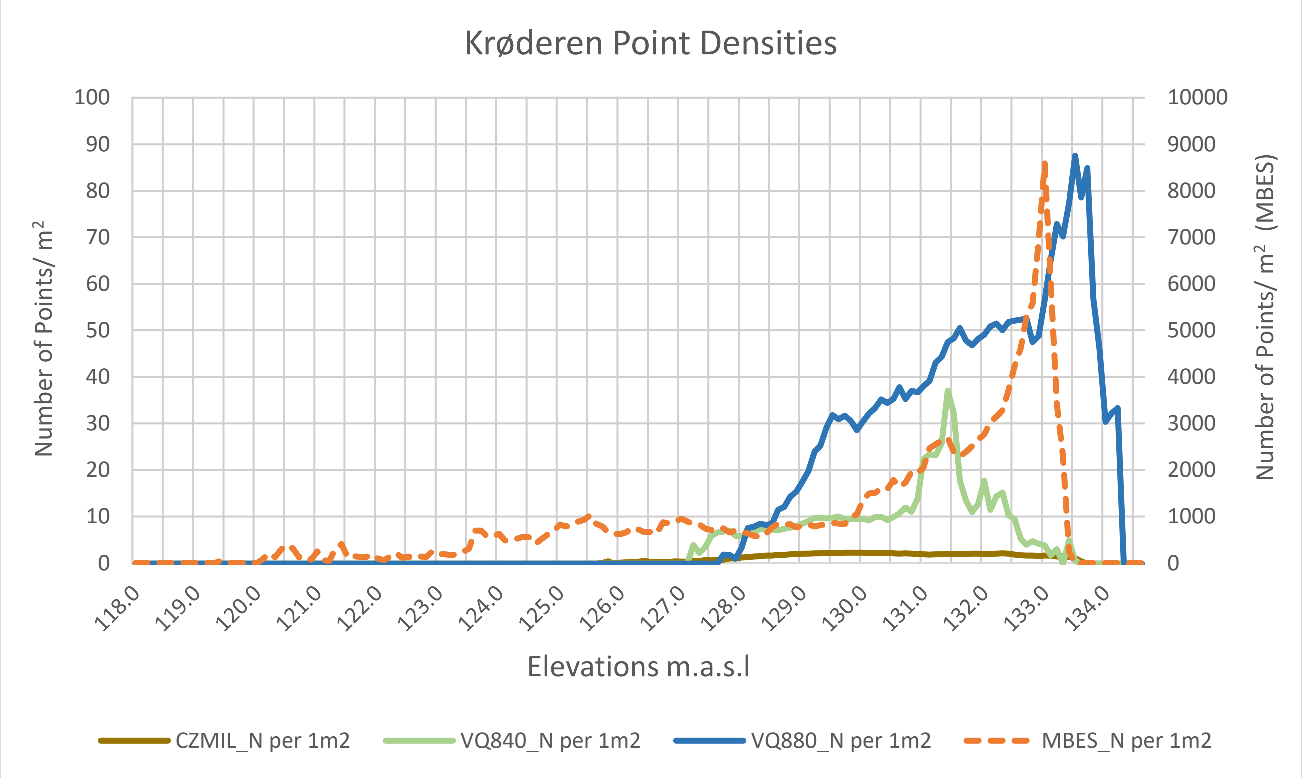

Figure 39. Number of points per 1 meter squared for CZMIL, VQ840, VQ880, and MBES (on the secondary axis) in Krøderen in the full range of the sensors.

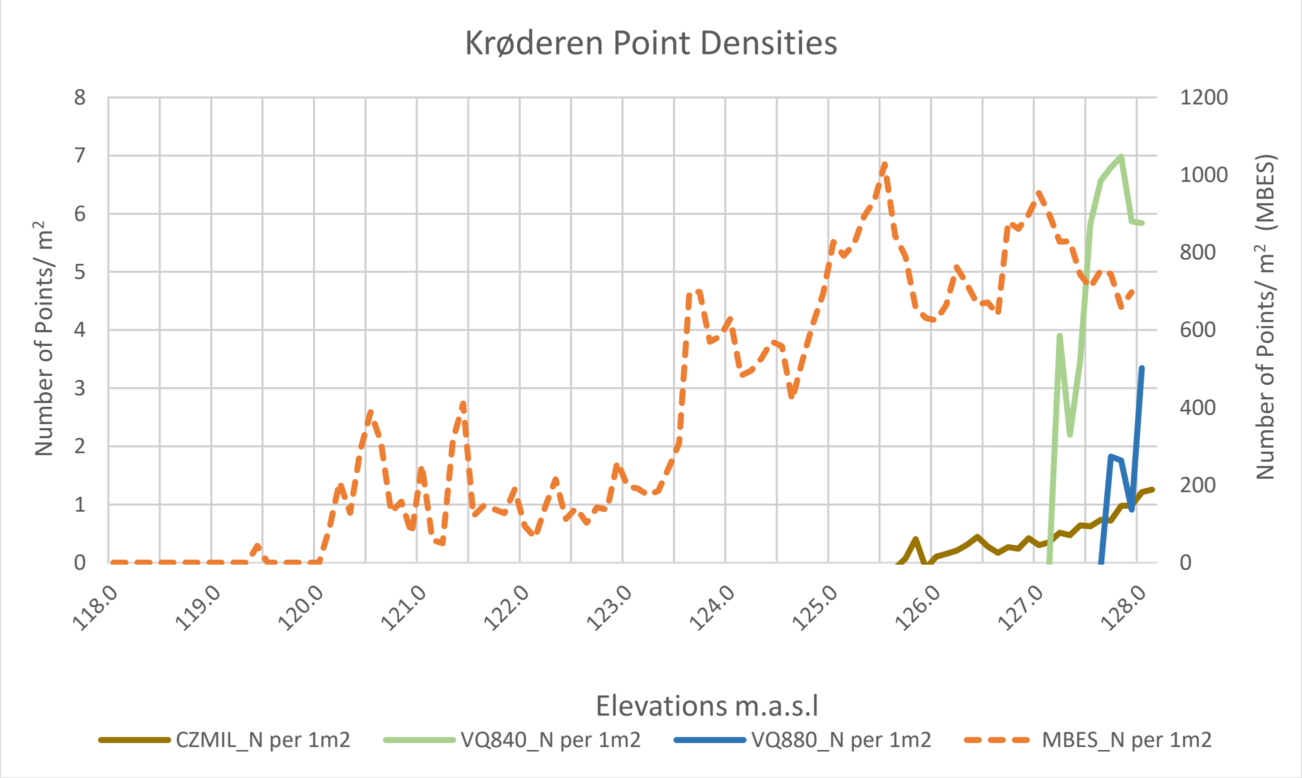

Figure 40. Number of points per 1 meter squared for CZMIL, VQ840, VQ880, and MBES in Krøderen in the elevation range 118 masl – 128 masl of the sensors.

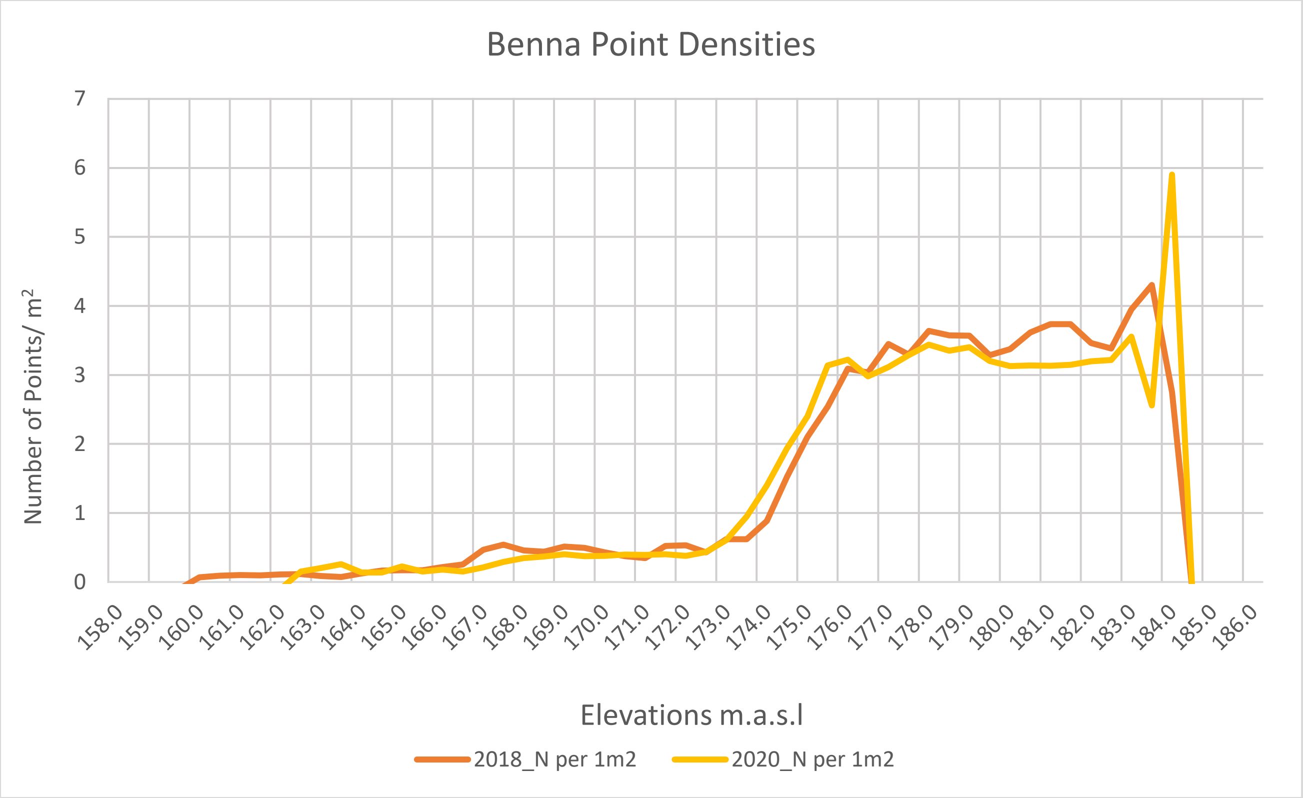

Figure 41. Number of points per 1 meter squared for CZMIL measured in 2018 and 2020 in Benna.

The point densities of Green LiDAR data vary very much over depth. In the very shallow parts of Krøderen VQ880 has point densities at 80 points/m^2, decreasing to around 30-50 points/m^2, before it further decreases towards the maximum penetration depth. Also VQ840 has high point densities (close to 40 points/m^2) in a fairly small range of elevations in the same lake. Except for these sensors in Krøderen, all the Green LiDAR sensors have point densities less than 10 points/m^2, and the densities decline down to less than 2 points/m^2 the last meters before the maximum penetration depth is reached.

MBES has generally much higher point densities than Green LiDAR, but does not cover the most shallow areas as MBES is not capable of measuring depths less than 1 meter for the boat mounted MBES, as applied in this measurement campaigns.

In those elevations ranges point densities are higher than 10 points/m^2, substrate information similar to presented in the Figure 36 and Figure 37 can potentially be extracted. This has, however, not been investigated in this project.

When the point densities are as in the deeper parts covered the Green LiDAR (less than 2 points/m^2), it is most likely difficult to extract detailed substrate qualities (microhabitat data). In the lower half of the penetration depth of the Green LiDAR, properties related to mesohabitat might be possible to extract, such as slope, exposition and larger underwater terrain structures (ridges and depressions).

3.5 Water quality and sensor penetration

It is interesting to investigate the importance of water quality related to the Green LiDAR sensors ability to penetrate the water column. The detection capability of the Green LiDAR is a function of both energy loss in the water column and the seabed's capability to return the photon energy, that can be related to the 'clearness' of the water. In order to do so, we have collected water quality data from the three lakes studied. Data from Krøderen and Selbusjøen are from the national water quality database "Vannmiljø" (https://vannmiljo.miljodirektoratet.no/) and Miljødirektoratet (2022). Water quality data from Benna is taken from the regular monitoring programme of Trondheim municipality (Trondheim kommune, 2018, 2020).

It was not sampled water quality data during the field campaign of the Green LiDAR measurements, which means that there is not water quality data available at the exact time and location when and where the Green LiDAR survey took place (see dates of the surveys given in Table 1). Furthermore, water quality is often sampled in different depths of the water column in lakes, which makes finding representative water quality data to compare with the sensor penetration challenging. This analysis must then be based on the water quality data available and collected for other purposes than our analysis. We have extracted data from nearby sampling locations at times we have found being representative for the conditions when the Green LiDAR measurements were made, and based on our best knowledge, estimated water quality values used in the assessment.

The water quality parameters used for the assessment have been selected based on discussions with the client, as well as own knowledge about water quality analysis. All the water quality parameters selected represent different varieties of measuring the clearness of the water, with slightly different water constituents targeted by the analysis and the analytical methods applied.

Water color number: This water quality parameter is used to map the clearness of the water by the means of the watercolor scale or Platinum-Cobalt color scale. Based on dilutions of 500 parts per million platinum cobalt, it measures the color as an indicator of organic matter such as dissolved humic substances and planktonic algae. The scale ranges from 0 to 500 mg/L Pt, where 0 refers to clear distilled water, while 500 refers to a high watercolor/yellowness value.

For Selbusjøen, the watercolor number differs between the two flights measured. The parameter was 24 mg/l Pt sampled in September 2021, and the watercolor number in July was 15 mg/l Pt. Both samples were measured at 10 m depth beneath surface. Other records were sampled at the Nea River outlet and showed a value of 18 mg/l Pt.

In Krøderen, the watercolor number was 15 mg/l Pt, measured 2 km from the mapped zone. While for Benna, the parameter was 3.15 mg/l Pt at the measurement point closest (Point A) to where the Green LiDAR measurements was done. The value used is the average value of the samples at 5 meter depth at the monitoring point.

Turbidity: Turbidity is a measure of cloudiness caused by particles in the water and is used to determine the concentration of suspended particles in a sample of water. Turbidity is measured by different variants of optical methods applied, e.g. FNU, NTU and FTU. The term FNU stands for Formazine Nephelometric Unit, NTU stands for Nephelometric Turbidity Unit, while the term FTU stands for Foramzine Turbidity Unit. These units represent the same value, but the detection methods can be different from each other, and can give slightly different outcomes.

The turbidity data for Selbusjøen is taken from long-term monitoring programme of Selbusjøen at a sampling location more in the centre of the lake, and hence not spatially covered by the Green LiDAR measurements (that are from the outlet of Nea). The turbidity measurements in Krøderen are from the inlet to Krøderen and coincide spatially well with the areas covered by the Green LiDAR data. The turbidity data from Benna is the average of the values found in 2018 and 2020, at the most Northern location of the lake. Please note that the turbidity data comes from different analytical methods.

<u>Secchi depth:</u> The secchi depth is also a measure of the clearness of the water, but uses another technique than the other two measurements techniques that both involve a chemical analysis. Secchi depth is measured as the depth at which the Secchi disk, a standardized white disc, is no longer visible when lowered into water, and the point at which it reappears after raising it. The secchi depth measurements are simple to take and are therefore often repeated and the average value reported.

The secchi depth value for Selbusjøen is taken from long-term monitoring programme of Selbusjøen, but unfortunately not available from Krøderen and Benna.

Table 3. Time periods for Green LiDAR mapping in the three test lakes and representative water quality values during the same periods. The numbers in bold are used in the Figures 42 and 43. The data are taken from national water quality database "Vannmiljø" (https://vannmiljo.miljodirektoratet.no/), Miljødirektoratet (2022) and Trondheim municipality (2018, 2020).

Lake	**Time period of LiDAR mapping**	**Max. penetration depth [m]**	**Water color [mg Pt/l]**	**Turbidity [FTU/FNU]**	**Secchi depth [m]**
Selbusjøen	16/07 – 02/12/2021	5	18 / **19** i Økostor,2021-rapport)	FNU: **0.43**	6.1
Krøderen	16/07 – 09/11/2021	6.5	**15**	FNU: **0.74**	6
Benna	28/10/2018, 10/08/2020	22	3.0 (2018) / 3.3 (2020) (**3.15**)	FTU: 0.29 (2018) / 0.33 (2020) (**0.31**)	N/A

Figure 42 shows the relationship between the watercolor number and the maximum penetration depth for the Green LiDAR sensors. As the watercolor increases, the penetration depth decreases accordingly for the three different lakes, possibly due to the light scattering or absorption during the mapping. The Green LiDAR maps more than 20 m deep when the water is very clear (Benna). Figure 43 shows the relation between turbidity and maximum penetration depth.

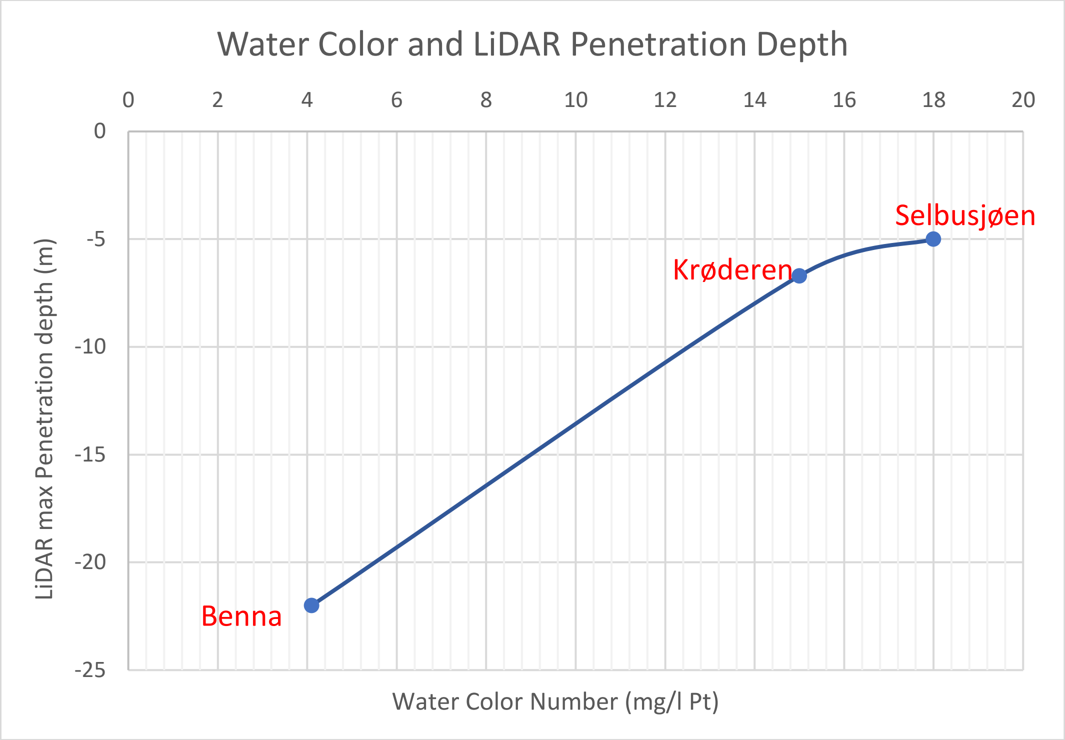

Figure 42. Relation between water color and Green LiDAR penetration depth. The few data points available are from Benna, Krøderen and Selbusjøen. Note that the water quality was not sampled at the exact time of the Green LiDAR mapping and not at points covered by the LiDAR scanning in all lakes.

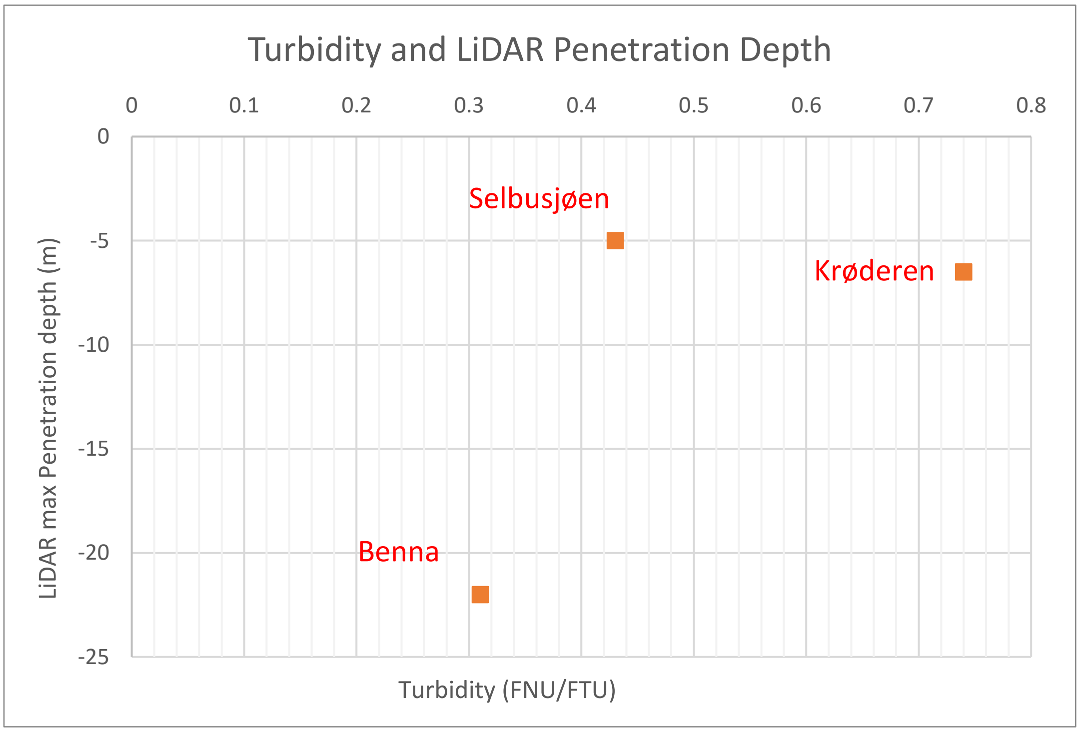

Figure 43. Relation between turbidity and Green LiDAR penetration depth. The few data points available are from Benna, Krøderen and Selbusjøen. Note that the water quality was not sampled at the exact time of the Green LiDAR mapping and not at points covered by the LiDAR scanning in al lakes.

Figure 42 shows are relation between water color and penetration depth as expected, while Figure 43 does not show any meaningful relationship. For the third parameter describing the clearness of water, i.e. secchi depth, sufficient data was not found to draw a similar relationship. Benna is known to be a clear lake (low water color number), while lakes with extensive inflow of humic water or high internal phytoplankton production can have water color numbers even higher than measured in Selbusjøen, probably further reducing the penetration depth. As the water color also can vary over the year, this is also a factor to consider when planning a new Green LiDAR measurement campaign.

Related to the results presented in the Figures 42-43 we would underline the following:

- The number of lakes used in the assessment is very low (only three).
- The Green LiDAR flights and the water quality sampling are not carried out at the same time.
- The water quality samples and the Green LiDAR flights to do not overlap in space (water quality samples are made at a different location than those areas covered by the Green LiDAR).
- The water quality data selected as representatives and plotted in Figures 42-43 has undergone several iterations of averaging (from several replicates, averaged over depths and averaged over season(s)).
- The actual maximum penetration depth is estimated from the graphs in the report, and it should be further investigated what is the correct penetration depth to be used in the analysis. E.g. should the very maximum depth (where one single sample seems to be corrected), or should it be a certain minimum density of points (e.g. minimum 2 points/m^2).

Based on these large methodological uncertainties, limited and uncertain data, the analysis presented in this section should be used with great care and more be seen as a possible approach to investigate the dependencies between water quality and penetration depth more comprehensively.

3.6 Bathymetric maps based on Green LiDAR data

Bathymetric maps can be produced based on the Green LiDAR measurements. In the following figures examples of such products are presented. We will underline that the presented maps show only those parts covered by the Green LiDAR sensors.

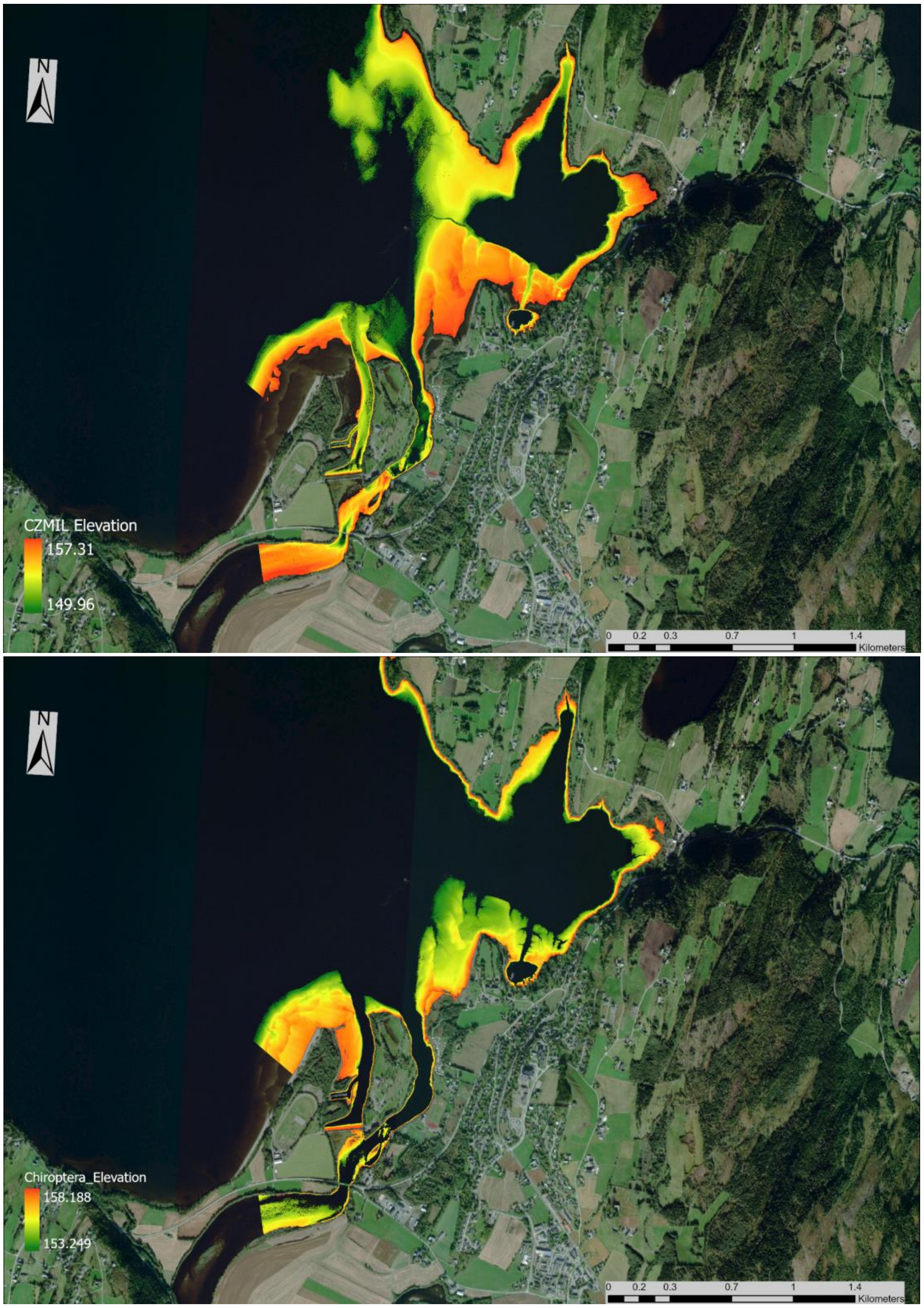

Figure 44. Bathymetric maps of Selbusjøen generated fromGreen LiDAR measurements with the CZMIL sensor (upper part) and the Chiroptera sensor (lower part).

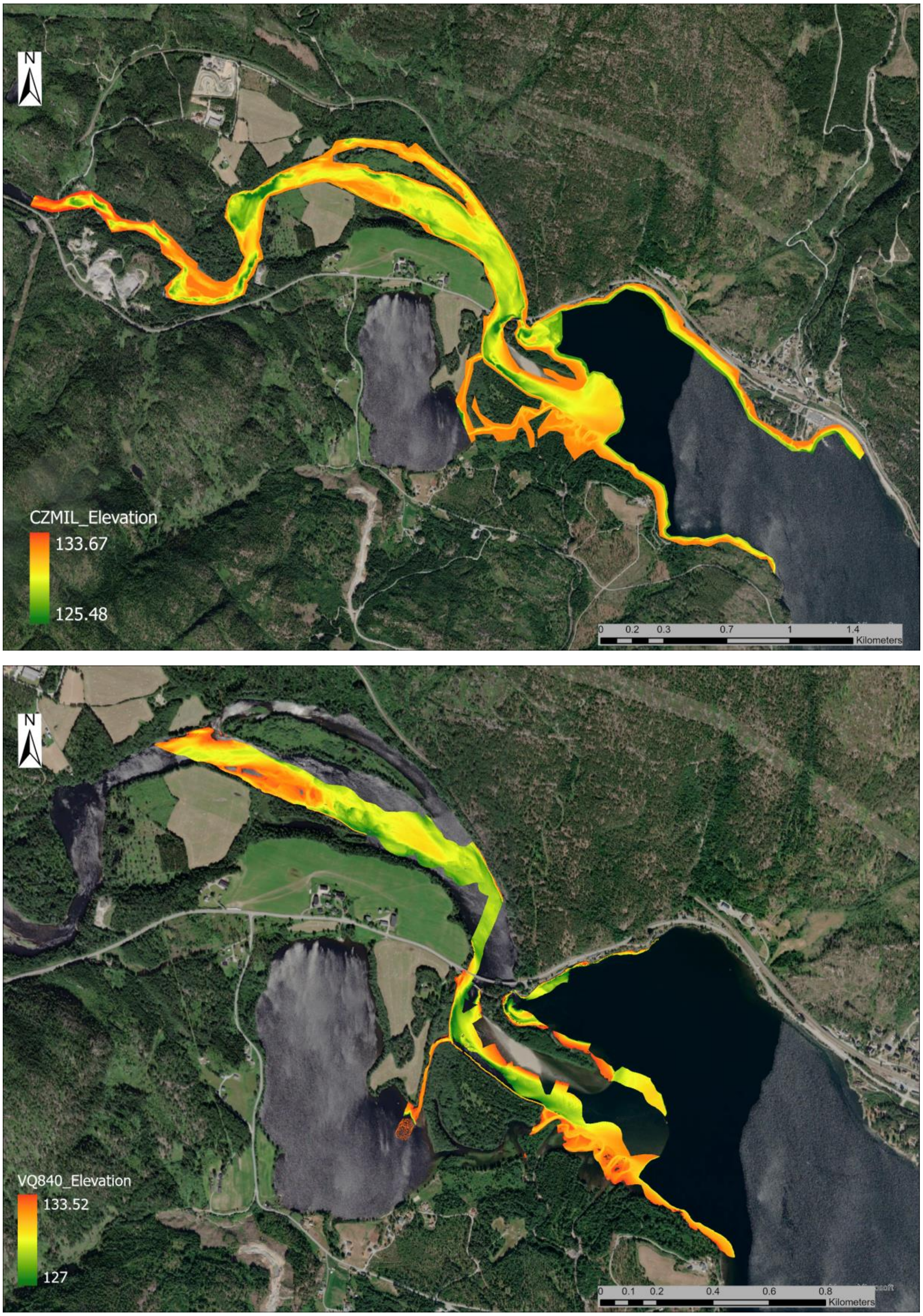

Figure 45. Bathymetric maps of Krøderen generated fromGreen LiDAR measurements with the CZMIL sensor (upper part) and the VQ840 sensor (lower part).

4 Conclusions

Green LiDAR data have been measured in three different lakes with various types of sensors. These datasets have been analyzed and compared against each other, and also been compared with data collected from multibeam echosounders (MBES). Based on this analysis, the following conclusions can be drawn:

- The precision when comparing Green LiDAR and MBES datasets are in general very high, when comparing mean and median residual values.
- When comparing Green LiDAR datasets between each other, the mean and median residual values range from 1 cm or less for some datasets, up to 9 cm as the maximum residual median value.
- When comparing different Green LiDAR sensors, the residual values are generally normally distributed around 0 cm, indicating no systematic error.
- When Green LiDAR datasets are compared against MBES datasets, the residual median values typically range between 3 to 10 cm.
- The outliers in the datasets (large residuals, filtered out in some of the figures) have the highest representation in the outer range of the coverage, i.e. in very shallow water and close to the maximum penetration depth of the sensors.
- Under certain conditions (perfect conditions), Green LiDAR seems capable of measuring down to more than 20 meters below the lake surface as in Lake Benna, while in most lakes probably less than 20 meters.
- Our analysis show that point densities of the Green LiDAR range from 80 points/m^2 (in some smaller parts of one of the lakes) to 30-50 points/m^2 as the depth increases, and decrease to less than 2 points/m^2 the last meters before the maximum penetration depth is reached.
- For the purpose of (micro) habitat mapping, Green LiDAR datasets might be useful in areas with high point densities, but less suitable closer to the penetration depth when the datasets are less rich (low point densities). This needs, however, be further investigated.
- Our experiences find Green LiDAR suitable for mapping shallow to moderately deep parts of lakes, including areas normally covering the littoral zone.
- MBES is suitable for the deeper parts not covered by Green LiDAR data, and areas up to a minimum of 1 meter water depth. As such, there is an overlap where both Green LiDAR and MBES technologies seem both suitable and useful.
- The water quality seems to affect the maximum penetration depth of Green LiDAR, and the correlation with water color gave some insight into how this relationship can be. For the purpose of supporting future studies with better datasets, water quality data should be collected at the time and the place of the LiDAR mapping.
- The results of Green LiDAR scanning of lakes seem to be more than satisfactory for assessing flood levels in lakes and water bodies.
- Green LiDAR and MBES datasets can be complementary to each other to build a seamless and accurate representation of the lake bathymetry used for important applications such as generation of precise volume curves for power plants.
- Mapping reflecting water surface can have a mirror effect on light and introduce noise in the data. It can potentially lead to mismapping some bathymetric ranges.

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