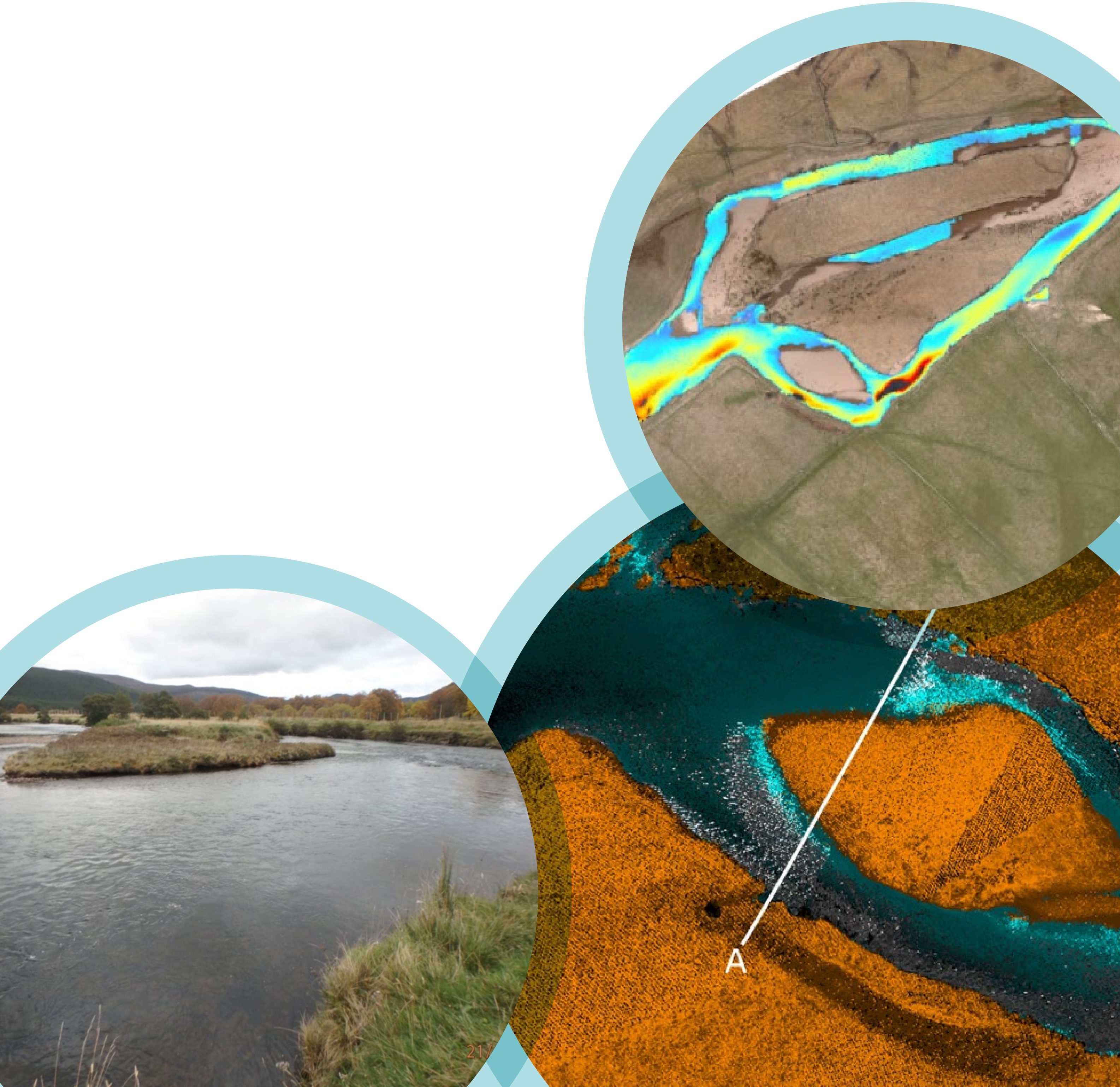
Scotland's centre of expertise for waters

Topo-bathymetric LiDAR in support of hydromorphological assessment, river restoration and flood risk management



Scotland's centre of expertise for waters

Published by CREW – Scotland's Centre of Expertise for Waters. CREW connects research and policy, delivering objective and robust research and expert opinion to support the development and implementation of water policy in Scotland. CREW is a partnership between the James Hutton Institute and all Scottish Higher Education Institutes supported by MASTS. The Centre is funded by the Scottish Government.

This document was produced by:
Dr Pauline E. Miller and Dr Stephen Addy
The James Hutton Institute, Craigiebuckler, Aberdeen. AB15 8QH. UK.

Report Steering Group:
Roberto Martinez (SEPA, Scottish Environment Protection Agency)

Dissemination status: Unrestricted

Research Summary

Background

This project was commissioned by SEPA to investigate the potential of the emerging technique of **topo-bathymetric LiDAR**. The main contribution of this technique is the ability to map submerged regions of rivers – i.e. river channel, including river bed, producing a single seamless digital elevation model (DEM) of channel and floodplain. LiDAR uses an airborne laser scanning approach, by applying a green laser to penetrate water surfaces and record the bathymetry of shallow water bodies. Data were collected for the River Dee (Aberdeenshire) and River Garry (Perth and Kinross) in order to assess performance, and potential for typical management considerations.

Research Questions

- What are the strengths and limitations of topo-bathymetric LiDAR?
- Can this technology be used to improve river typology classification?
- Is it possible to derive detailed hydromorphological assessments?
- What is the potential for supporting 2D hydrodynamic modelling?

Main Findings

- Topo-bathymetric LiDAR worked well for the River Dee where near-complete coverage of the river bed and good coverage of the water surface were achieved. This is likely due to good bed reflectance (gravel bed), combined with favourable water clarity. Due to very low flow conditions at the River Garry, performance was limited. This reinforces the need to evaluate likely success at potential sites prior to survey commission.

- Topo-bathymetric LiDAR was found to offer a similar accuracy and precision to conventional topographic LiDAR, with a mean discrepancy of 0.04 m. The mean error of the water surface and bed points was between 0.04 and 0.07 m.

- Topo-bathymetric LiDAR can provide good coverage of the river bed. For the River Dee, >95 % of the river bed was captured. The measured spatial resolution (point density) of bed points here is 15 points/m^2 (single flightline). This is very similar to the spatial resolution of points over dry terrain.

- Use of a single green laser produces relatively few returns from the water surface compared to the river bed, and the coverage of water surface returns is highly variable. Automated identification of water surface points is still very challenging, particularly for complex topography (e.g. River Garry), but is important in order to enable refraction correction. This is one of the current limiting aspects to a more automated and reliable workflow.

- Depths shallower than approximately 8 cm cannot be measured because the signals from the water surface and river bed cannot be distinguished. This is a fundamental limitation of most commercial LiDAR systems. The Riegl VQ-880-G instrument used here has been designed with a very short laser pulse duration to minimise this effect.

Topo-bathymetric LiDAR can contribute to various river management tasks including assessment of existing morphological typology and identification of hydromorphological features. While this was assessed here in a theoretical manner, it should be achievable through basic interrogation of LiDAR data in combination with expert hydromorphological input. More automated classification is feasible, but the effort required to reliably achieve this should not be underestimated.

- Topo-bathymetric LiDAR offers potential to enhance hydrodynamic models – e.g. for flood risk and meso-habitat modelling. Such models currently rely on field surveyed cross-section data (or approximations) to represent the channel. Provision of a combined channel and floodplain DEM will allow models to be parameterised with more reliable and continuous topographic information.

- It is challenging to coordinate topo-bathymetric LiDAR surveys with 'ideal' flow conditions. Flows which are too low will cause difficulties due to very shallow depths (e.g. River Garry). Conversely, higher flows may produce more turbulent conditions, which present challenges for capturing the water surface and possibly also the bed. 'Average' flow conditions (e.g. Q50 discharge) are most conducive to successful capture.

Research undertaken

This project evaluated topo-bathymetric LiDAR data for the Rivers Dee and Garry by assessing performance in terms of: accuracy; spatial resolution (point density); completeness of data; and measurement of water depth. The research also considered aspects relating to the quality of the provided datasets. This report discusses the outcomes of these investigations and discusses factors influencing the results. In addition, consideration is given to the potential of topo-bathymetric LiDAR for classifying river typology, characterising hydromorphology and for supporting hydrodynamic modelling applications. These are critical activities in terms of water body condition assessment and management.

Recommendations

Topo-bathymetric LiDAR is the preferred option if in-channel morphology is important. Although conventional LiDAR may produce slightly enhanced terrain definition over dry terrain (Mandlburger et al., 2015b), for applications where both floodplain and in-channel morphology are important, topo-bathymetric LiDAR should be considered as a primary choice.

Consideration of site suitability is necessary before commissioning surveys. To appraise the likely suitability of a river for effective topo-bathymetric survey, flow level and nature of the site should be considered, particularly with respect to bed material, water clarity and expected water depths. However, more comparative research needs to be undertaken to appreciate how such factors vary from site to site, and to more fully consider the effects of overhanging vegetation.

Improved deliverables should be requested from LiDAR suppliers. A water surface model (produced as part of the post-processing workflow) should be provided by the LiDAR supplier as a standard deliverable. This would greatly enhance the calculation of depth and identification of bed morphology features. Furthermore, orthorectified aerial imagery should be provided as standard to aid in contextual interpretation.

Additional research is needed to investigate potential insights from repeat surveys. This study considered only a single LiDAR survey. Further investigation should be undertaken to assess the potential of repeat (multi-temporal) surveys for quantifying morphological change, providing insights into river dynamics and sediment budgets.

Increased cost-effectiveness through strategic planning. As with any airborne survey, LiDAR data is relatively costly and the largest cost is associated with mobilising the aircraft. However, costs can be reduced through strategic planning. For example, multiple locations can be surveyed as part of a single job, and by coordinating multiple operational requirements (e.g. flooding, hydromorphology, etc.) efficiencies can be gained.

- **Coordination with other field surveys would enhance overall value.** Depending on project requirements, if LiDAR surveys can be coordinated with other field surveys – e.g. to collect habitat data, pebble counts, etc. at the same time, they can provide a useful topographic baseline from which to assess subsequent morphological or ecological changes or impacts.

- **Integration with modelling.** Consideration should be given as to how existing hydrodynamic models (e.g. flooding, meso-habitat, etc.) can be adapted or developed to handle DEM data from topo-bathymetric LiDAR so that the full benefits of high resolution topography can be exploited to advance process behaviour modelling.

- **Fitness for purpose.** Manned aerial surveys are commonly delayed by weather or technical considerations. Thus, topo-bathymetric LiDAR may not always be appropriate for projects requiring immediate data collection – e.g. following a flood event. Likewise, LiDAR is relatively expensive and costs may not be justifiable for smaller projects, such as river restoration schemes. In such cases, alternative approaches, such as imagery and DEMs collected from unmanned aerial vehicles (UAV or 'drones') should be considered. UAV approaches are suitable for flexible and responsive surveys over smaller extents (e.g. 1 – 3 km) with scope to provide bathymetry through photogrammetric techniques. However, the accuracy and feasibility of UAV approaches should be evaluated in comparison to LiDAR.

Abbreviations

DEM	Digital Elevation Model
LiDAR	Light Detection and Ranging
UAV	Unmanned Aerial Vehicle
WFD	Water Framework Directive
RBMP	River Basin Management Plans
FRMP	Flood Risk Management Plans
GNSS	Global Navigation Satellite Systems
ADCP	Acoustic Doppler Current Profiler
km	Kilometre
m	Metre
OSGB36	Ordnance Survey of Great Britain 1936
DTM	Digital Terrain Model
RTK GNSS	Real Time Kinematic Global Navigation Satellite Systems
σ	Standard deviation
RMSE	Root mean square error
GIS	Geographic Information System
LAS	LASer
3D	Three Dimensional

1 Background

1.1 Introduction

SEPA requires accurate and up-to-date information on the hydromorphology and physical characteristics of rivers. This is necessary to assess the ecological status of rivers, which is a core aspect of the Water Framework Directive (WFD) (European Commission, 2012). This information underpins the design and assessment of activities such as river restoration – including natural flood management – as part of the River Basin Management Plans (RBMP). Additionally, hydromorphology and associated channel and floodplain topography are important for accurate flood risk modelling. This is a key objective of the EC Flood Directive and the Scotland Flood Risk Management Act (2009), with direct relevance to implementing the Flood Risk Management Plans (FRMP).

Currently, the hydromorphological status of rivers is mainly captured through labour-intensive field surveys. Accompanying topographic data is usually also obtained by field survey and thus is sporadic and limited in spatial extent. In some locations, LiDAR data (an airborne laser scanning technique) may be available, but this is only able to map the topography of dry fluvial and floodplain areas. However, knowledge of the submerged in-channel morphology is also important in understanding hydromorphological processes and assessing habitat suitability, flood risk and the impacts of river restoration. Again, this data is only obtainable through field survey (e.g. cross-sections measured by GNSS, levelling or total station), or in some cases, techniques such as acoustic Doppler current profiling (ADCP). However, such data can only feasibly be collected over small areas.

1.2 LiDAR – topographic and bathymetric systems

LiDAR is a remote surveying technique, which uses a scanning laser mounted on an aircraft to map the underlying terrain. This produces a 'point cloud', where each point has a corresponding XYZ position, and can be used to generate a digital elevation model (DEM) of the landscape. The main advantages of LiDAR are:

- High spatial resolution (> 20 points per m² is readily achievable);
- Good elevation accuracy (precision);
- Ability to penetrate vegetation and map the underlying ground surface;
- Rapid capture of large areas.

LiDAR is especially useful for producing 'bare earth' terrain models, and is widely used for flood modelling and morphological analysis. However, conventional LiDAR systems (sometimes called 'topographic LiDAR') use a near-infrared laser, which is useful for mapping the Earth's surface, but is not able to penetrate water. Therefore, water bodies are missing, or only the water surface is captured. As a consequence of these limitations there is growing interest in an emerging LiDAR technology, which is sometimes referred to as 'shallow water LiDAR', 'green LiDAR' or here, as 'topo-bathymetric LiDAR'. This uses the near-infrared laser in combination with a green laser. The near-infrared laser maps the water surface, whilst the green laser passes through the water column and is returned from the seabed. As light is refracted by water, the water surface defines the air-water interface, and can be used to apply a refraction correction to adjust the position of the points in the water column and seabed. Fundamental concepts of bathymetric LiDAR are explained by Guenther et al. (2000), and illustrated in Figure 1.

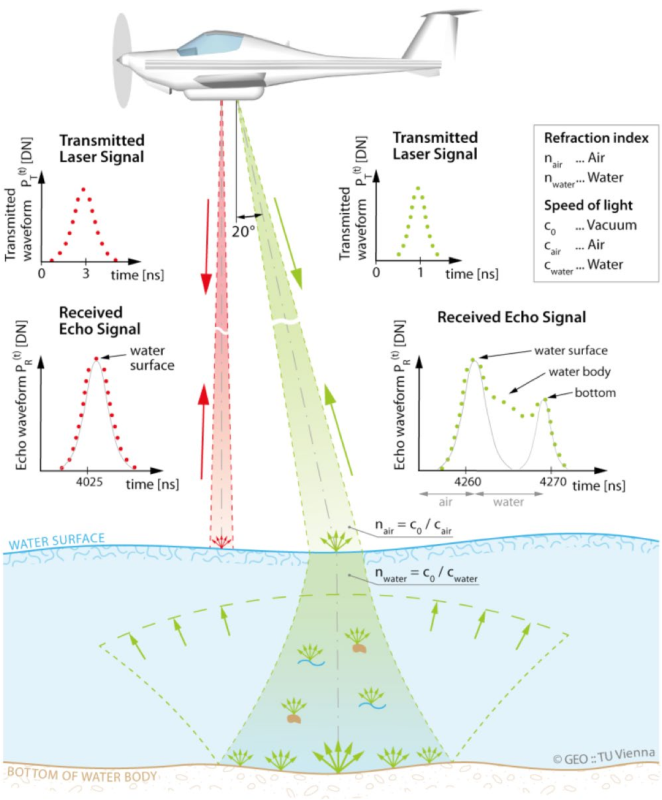


Figure 1 Principle of bathymetric LiDAR using green and near-infrared laser wavelengths (Mandlburger, 2013).

1.3 Topo-bathymetric LiDAR

Bathymetric LiDAR has been used for several decades for mapping near-shore coastal zones, particularly in areas of good water clarity (e.g. Guenther, 1989; Lillycrop et al., 1996; Chust et al., 2010; Eisemann et al., 2018). A small number of studies have also explored the feasibility of coastal bathymetric LiDAR for mapping inland rivers (e.g. Kinzel et al., 2007; Hilldale and Raff, 2008; Bailly et al., 2010). Although these studies noted drawbacks (e.g. low point density, elevation bias), they also highlighted the potential. Over the last decade, systems optimised for shallow water mapping have emerged (Doneus et al., 2015). One such system, the Riegl VQ-880-G, a topo-bathymetric LiDAR system designed for mapping shallow waters, including rivers and the near-shore coastal zone, is assessed in this report (see Riegl, (2016) for further details). The term 'topo-bathymetric' reflects simultaneous capture of both dry terrain (topography) and the submerged (bathymetry) areas. The VQ-880-G employs only a green laser (i.e. no infrared laser). This is understood to be for reasons of manufacturing efficiency.

As noted by Guenther et al. (2000) and Doneus et al. (2015), the ability of bathymetric LiDAR to penetrate water is affected by a combination of system and environmental factors, including:

- energy and length (duration) of laser pulse
- flying height (laser beam divergence and footprint size on the ground)
- atmospheric conditions
- surface turbulence
- water clarity
- bed reflectivity

As several of these factors are environmental, performance will vary between sites. As a rule of thumb, the Secchi depth is often quoted as the maximum penetration depth. This is not a fixed value, but is the depth at which a black and white disc of 20 cm diameter (Secchi disk) is no longer visible to the naked eye in water, and is largely related to water turbidity (Preisendorfer, 1986).

1.4 Outline of study

This study will assess the performance of topo-bathymetric LiDAR (Riegl VQ-880-G) for mapping submerged morphology of rivers and adjacent floodplain, evaluating strengths and limitations. The potential for characterising hydromorphology will be considered, as well as related activities such as classification of river typology and hydrodynamic modelling for assessing habitat suitability and flood risk.

2 OBJECTIVES

SEPA requested CREW to undertake an evaluation of topo-bathymetric LiDAR as a new technology which may have potential to deliver efficiencies to various SEPA activities.

The specific questions are:

1. What are the strengths and limitations of topo-bathymetric LiDAR?
2. Can this technology be used to improve river typology classification?
3. Is it possible to derive detailed hydromorphological assessments?
4. What is the potential for supporting 2D hydrodynamic modelling?

3 METHODS

3.1 Test Sites

In order to evaluate performance under differing conditions, topo-bathymetric LiDAR was collected for two test sites. These sites were selected to provide a variety of hydromorphological and physical conditions, as noted in Table 1, which provides approximate locations in British National Grid Coordinates, with elevations above mean sea level.

Table 1. Overview of test sites, indicating typical characteristics.

Site	Length (km)	Approx. Easting (m)	Approx. Northing (m)	Elevation Range (m)	Bed Type	Channel width (m)	Channel gradient (°)
River Dee	6.5	314,389	791,842	318-327	Gravel bed	30-50	0.5 – 1.0
River Garry	6.0	272,629	770,044	248-334	Alluvial & bedrock	10-20	1.0 – 4.0

The sites are described briefly below, with images of the sites provided in Appendix A1.

3.1.1 River Dee

This surveyed extent is located north and west of Braemar (Aberdeenshire), and includes 6.5 km of the River Dee mainstem, as well as the tributaries, Quoich Water (1.3 km), Clunie Water (0.75 km) and Allt an t-Slugain (2.2. km), as illustrated in Figure 2 and Figure 3. The River Dee test site has the following characteristics:

- Dee mainstem
  - o wandering, gravel bed river upstream of the Quoich Water confluence with extensive bars
  - o passive meandering channel downstream of the Quoich Water confluence with sporadic bars
  - o extensive mid-channel and point bars
  - o locally multi-thread channel with islands
  - o abandoned/back channels
  - o limited riparian vegetation
- Quoich Water
  - o active wandering, gravel bed over alluvial fan
- Clunie Water
  - o plane-riffle
  - o artificial embankments
- Allt an t-Slugain
  - o bedrock (limited), cascade, rapids, plane-riffle and wandering
  - o restoration of lower portion through 2016 embankment removal

The Dee mainstem is bounded to the north by a relatively extensive floodplain (~500 m width) with evidence of historical drainage activities. Part of the site underwent restoration in October 2015 to remove bank reinforcement to encourage natural reconnection to the floodplain (Addy et al., 2016). At midday on the day of the survey, discharge at the SEPA Mar Lodge gauging station (1.7 km to west) was 8.915 m^3/s which is similar to the Mar Lodge Q50 of 8.284 m^3/s.

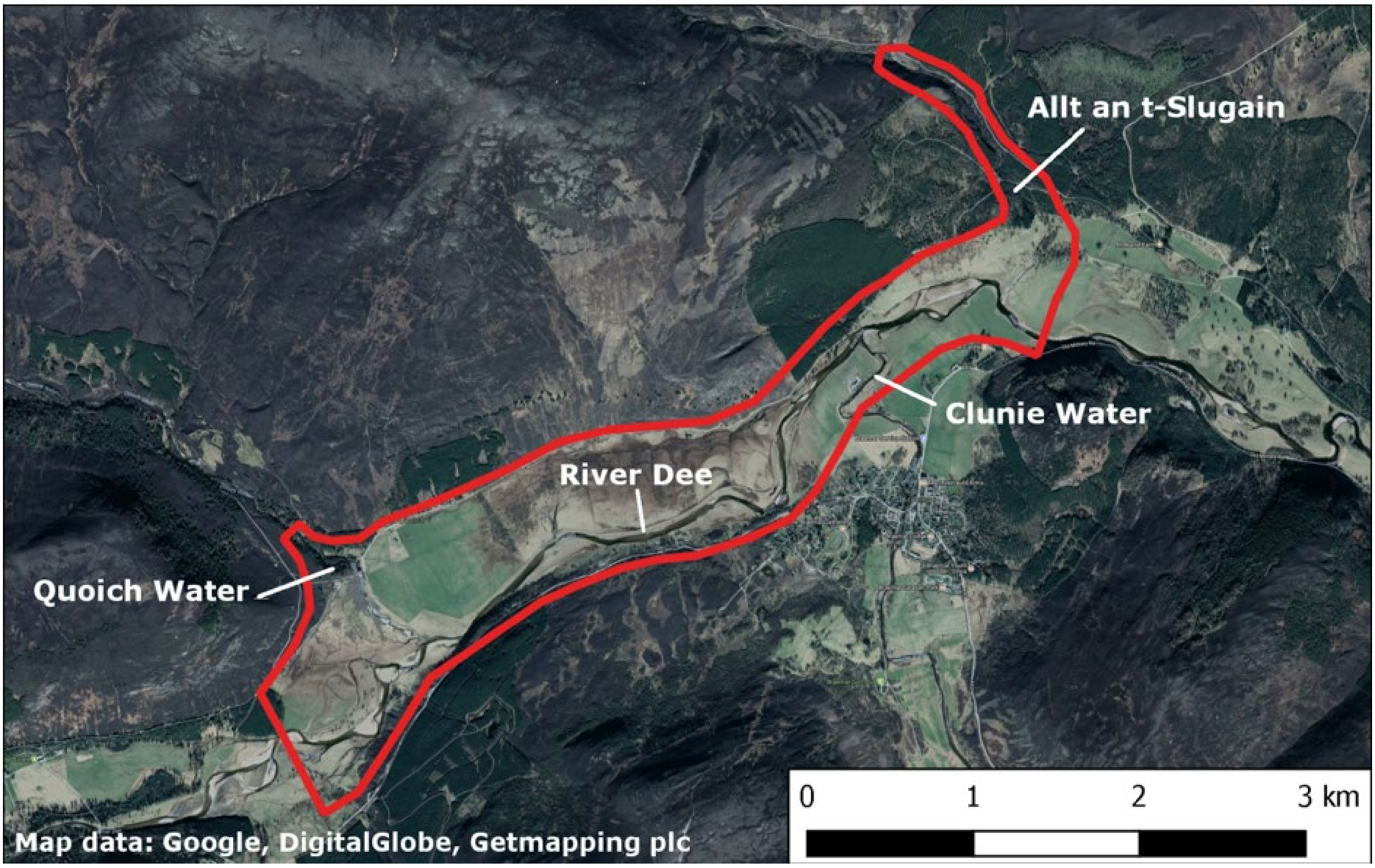


Figure 2 River Dee site overview with imagery backdrop. Red polygon indicates LiDAR survey area.

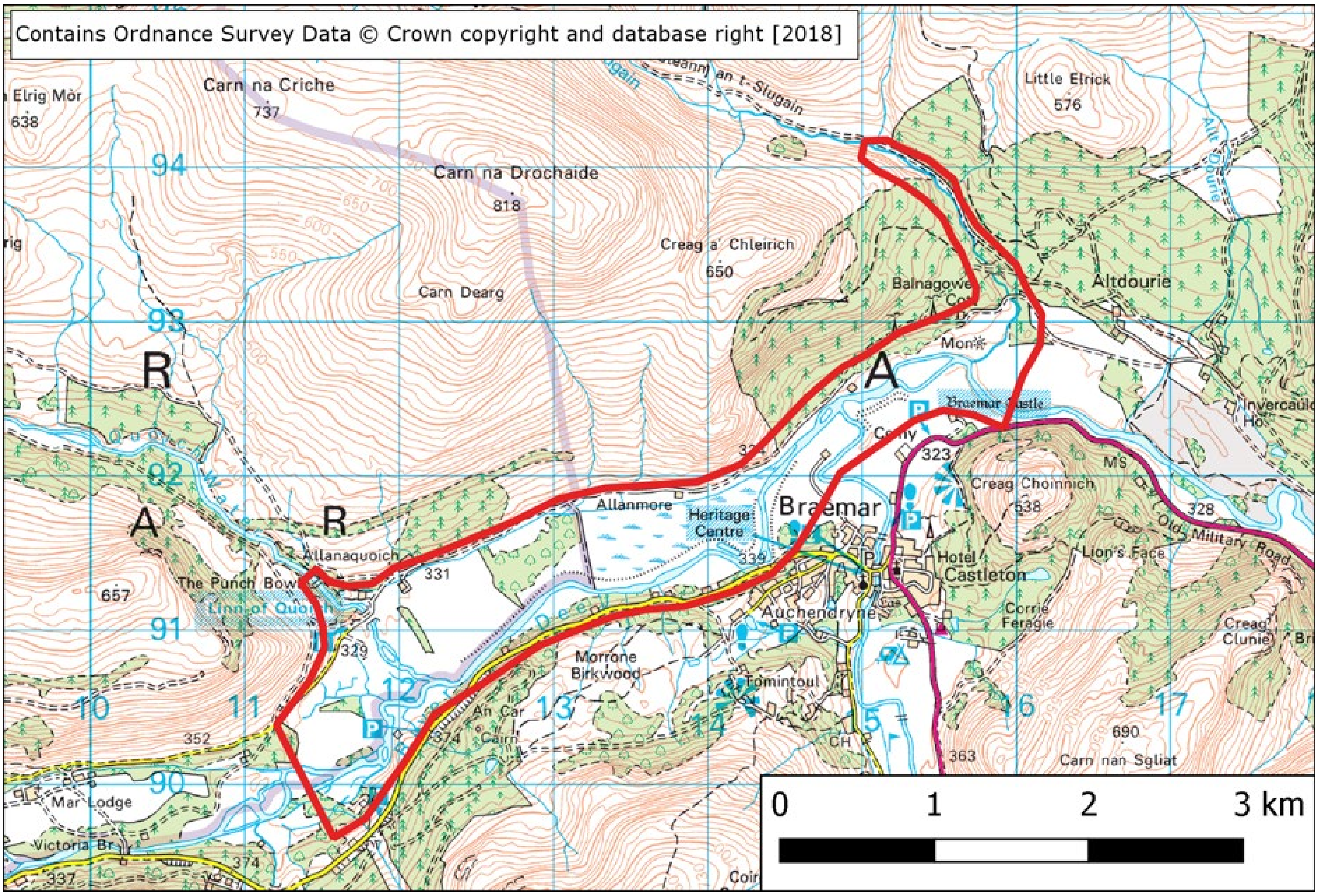


Figure 3 River Dee site overview with map backdrop. Red polygon indicates LiDAR survey area.

3.1.2 River Garry

This site comprises a 6 km extent of the River Garry (Perth and Kinross) in Glen Garry, commencing 7 km downstream of Loch Garry (Figure 4 and Figure 5), and is characterised as follows:

- plane riffle and bedrock, with gravel and cobbles
- sediment-starved due to hydro-power activities
- topographically-confined channel
- limited riparian vegetation

This section of the River Garry has been heavily impacted by hydro-power abstraction since the 1930s, and has been dry, or subject to very low, managed flows. The hydro dam and the lack of sediment management have contributed to sediment discontinuity. In 2017 SEPA, in conjunction with other parties, commenced efforts to increase flows and improve ecological status. However, the LiDAR data was collected prior to the improvement activities, and therefore represents extreme low flow conditions, with discharge on the day of the survey ≤Q99 – i.e. less than 1% of discharges are of this magnitude or lower.

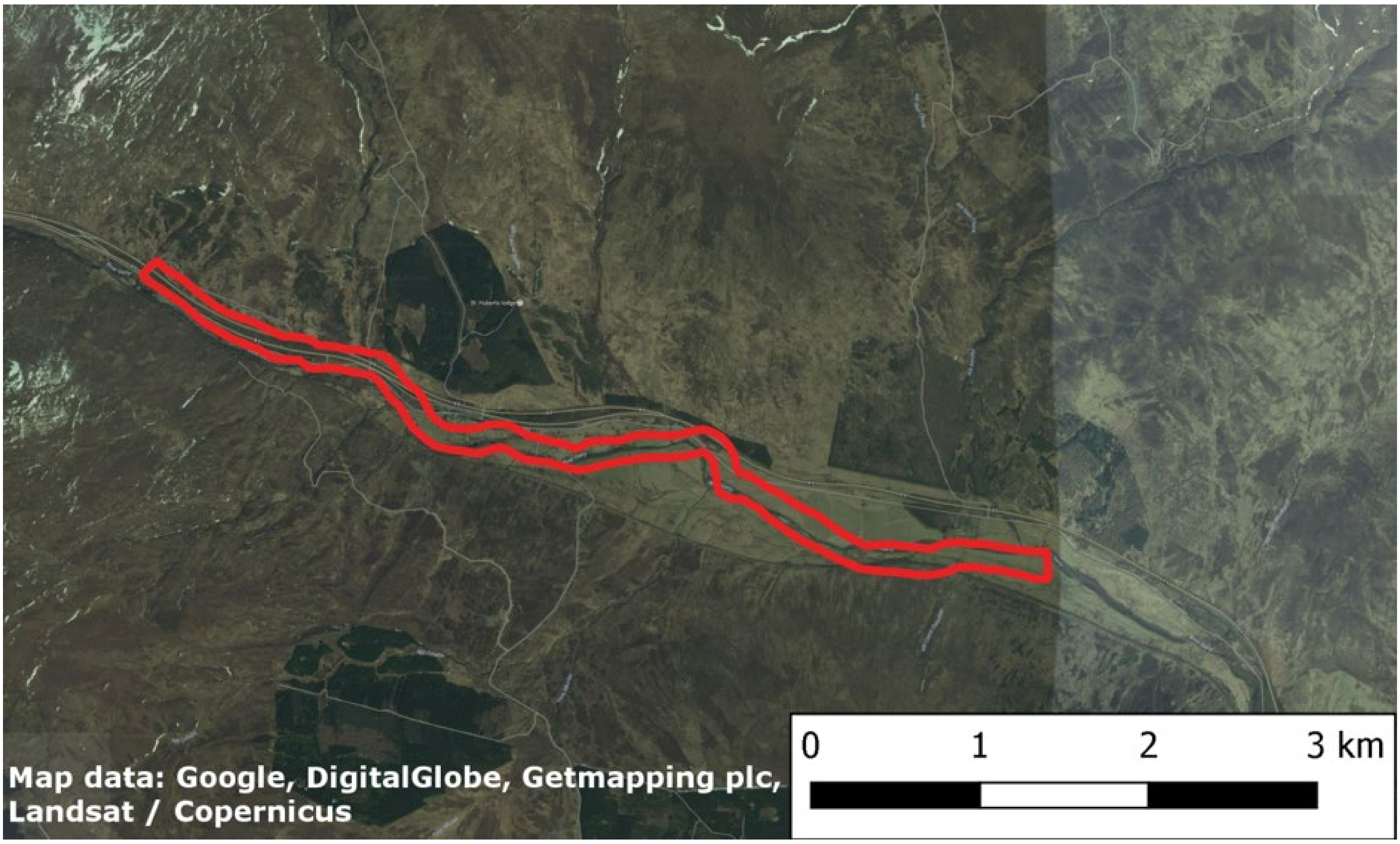


Figure 4 River Garry site overview with imagery backdrop. Red polygon indicates LiDAR survey area.

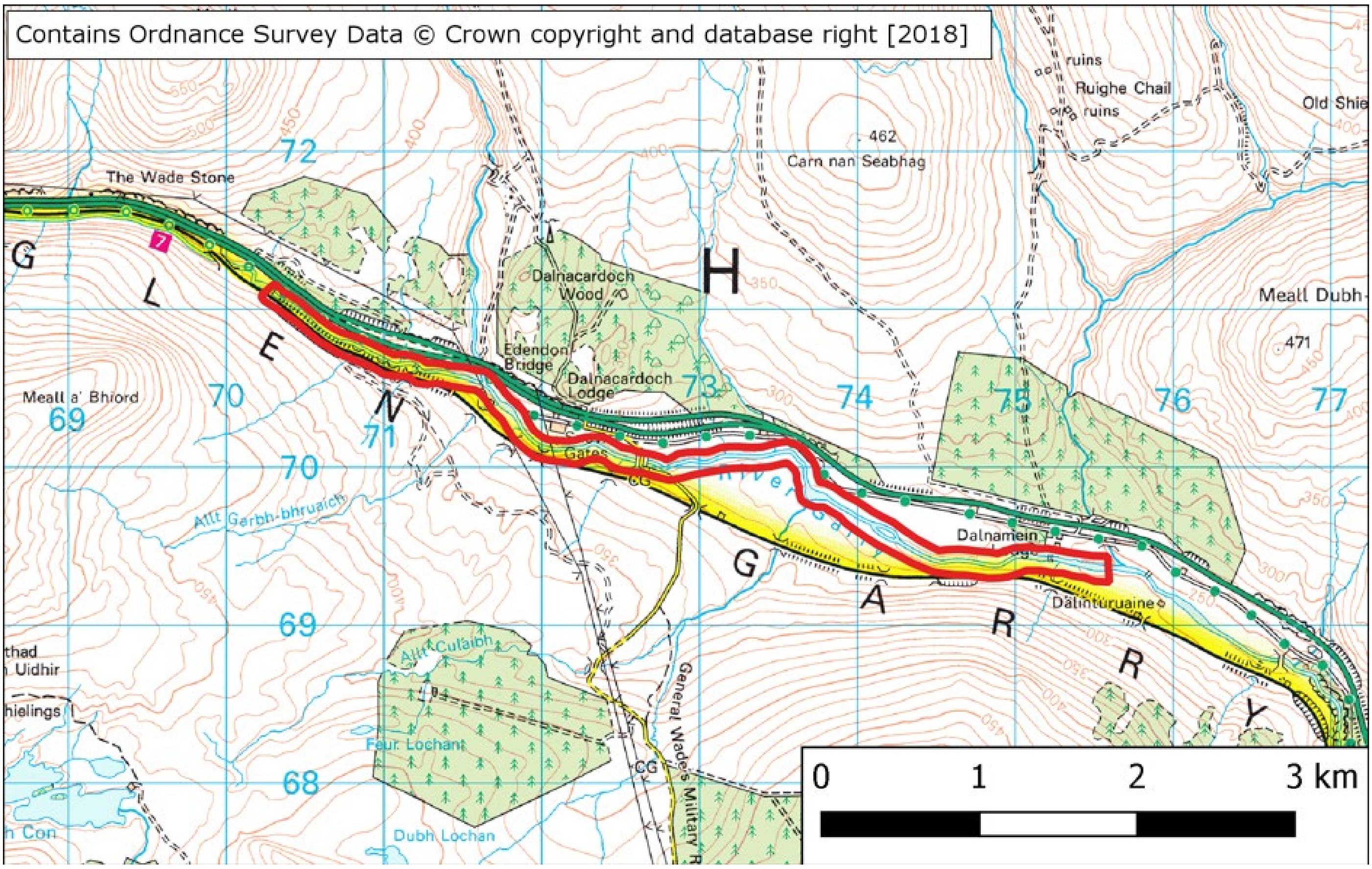


Figure 5 River Garry site overview with map backdrop. Red polygon indicates LiDAR survey area.

3.2 Datasets

3.2.1 Overview

Topo-bathymetric LiDAR was collected for the test sites on 20th October 2016 with the Riegl VQ-880-G mounted on a fixed wing aircraft flown at 600 m above ground level. Multiple overlapping flightlines were flown at each site in order to optimise coverage of the rivers.

The LiDAR supplier undertook initial post-processing. This involved deriving the raw point clouds by combining the laser returns with the on-board position and orientation information; strip adjustment to remove offsets between overlapping flightlines; removal of outliers; and transforming the point clouds from WGS-84 to British National Grid (OSGB36) coordinates, Newlyn datum. Coordinate transformation was undertaken using precisely-surveyed control points of stable features (e.g. road markings, building corners) which were collected following the LiDAR survey. Classification was then carried out using semi-automatic procedures to assign the points to one of the following classes (Figure 6 and Figure 7):

- ground (dry terrain, including exposed areas of riverbed and bars, floodplains, banks, terraces, etc.) **[Dry]**
- water surface **[Water Surface]**
- wetted channel bed **[River Bed]**

For brevity, the above classes are referred to using the terms in square brackets throughout the remainder of this report.

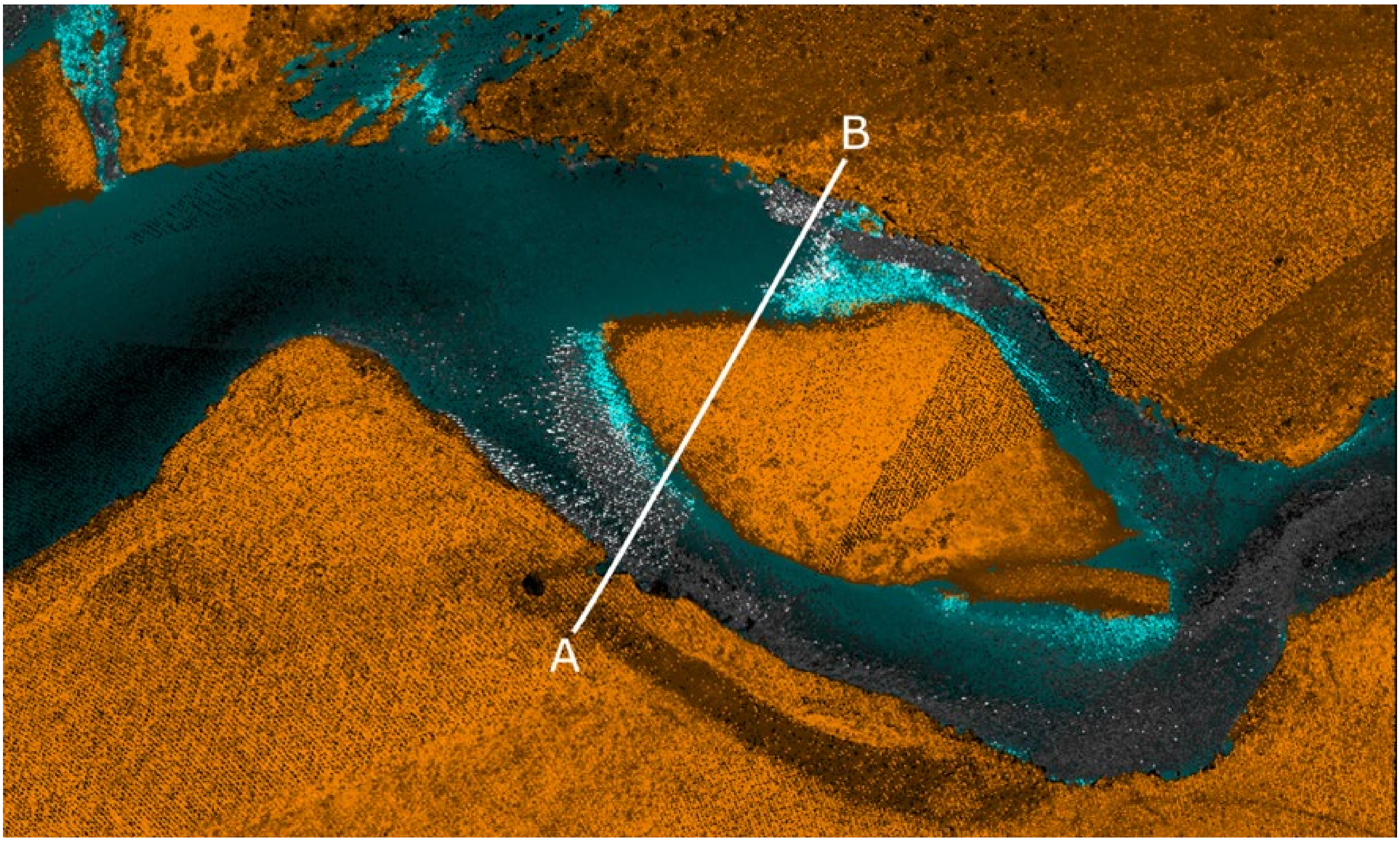


Figure 6 Classified LiDAR points (River Dee) shown with intensity shading. Orange: dry, blue: river bed, white: river surface. Cross-section A-B illustrated in Figure 7 below.

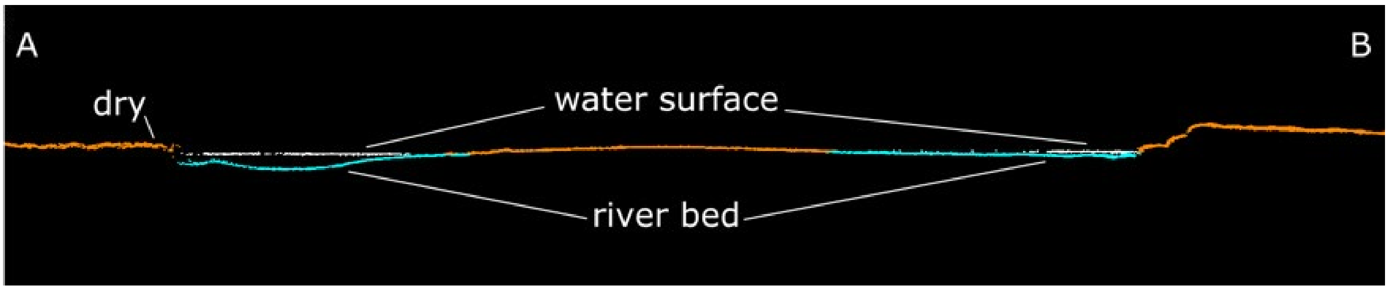


Figure 7 Cross-section A-B illustrating LiDAR point classification.

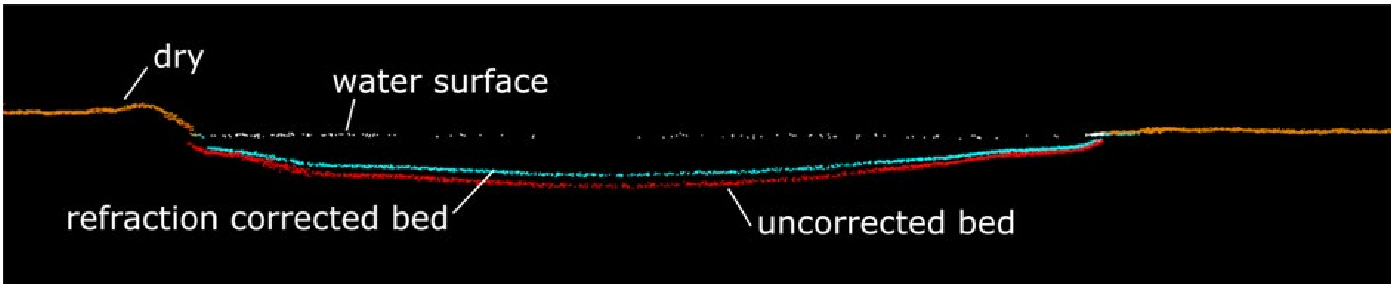


Figure 8 Cross-section of LiDAR points at River Dee, illustrating effect of refraction correction.

The dry point class has been filtered to remove vegetation and other non-ground points and therefore can be considered a digital terrain model (DTM), representing the bare earth points. The LiDAR supplier generated an elevation model of the water surface, and used this to apply the refraction correction to adjust the position of points within the water body. This is illustrated in Figure 8 which shows how the elevations of the corrected points are adjusted upwards.

To assess the accuracy of the data, RTK GNSS check points were measured for two tarmac road sections in the vicinity of the Dee site. Furthermore, in order to assess the accuracy of the LiDAR within the fluvial zone, cross-section data was collected by RTK GNSS (Leica System 1200 GPS). Points were measured on the floodplain, river banks, river bed and water surface. The accuracy of the GNSS measurements is expected to be 1-2 cm in XY (plan) and 2-3 cm in height (Edwards et al., 2010), which should be considered in the context of the results achieved. It was only feasible to acquire validation data at the River Dee, due to the geographical separation of the sites.

It was planned that aerial imagery would be captured alongside the LiDAR data to enhance interpretation. However, due to a fault with the camera, imagery was not acquired. Orthoimagery captured in April 2016 was available for the River Dee, and was useful in providing context, as little morphological change had occurred between April and October 2016. Unfortunately no high resolution imagery was available for the River Garry.

3.2.2 Initial Appraisal of Datasets

Inspection of the Dee and Garry LiDAR datasets revealed that the LiDAR approach appeared to have worked well at the River Dee, but results for the River Garry were poorer. This latter aspect was evident from the disproportionately low number of water surface points for the Garry (only 177,629), and questionable bed point classification in places. This is illustrated in Table 2 and Figure 9.

Table 2. Number of flightlines and LiDAR points for Dee and Garry

Site	No. flightlines	No. Points		
		Dry	Water Surface	River Bed
River Dee	30	405,012,881	4,068,979	34,602,182
River Garry	18	151,089,785	177,629	22,653,856

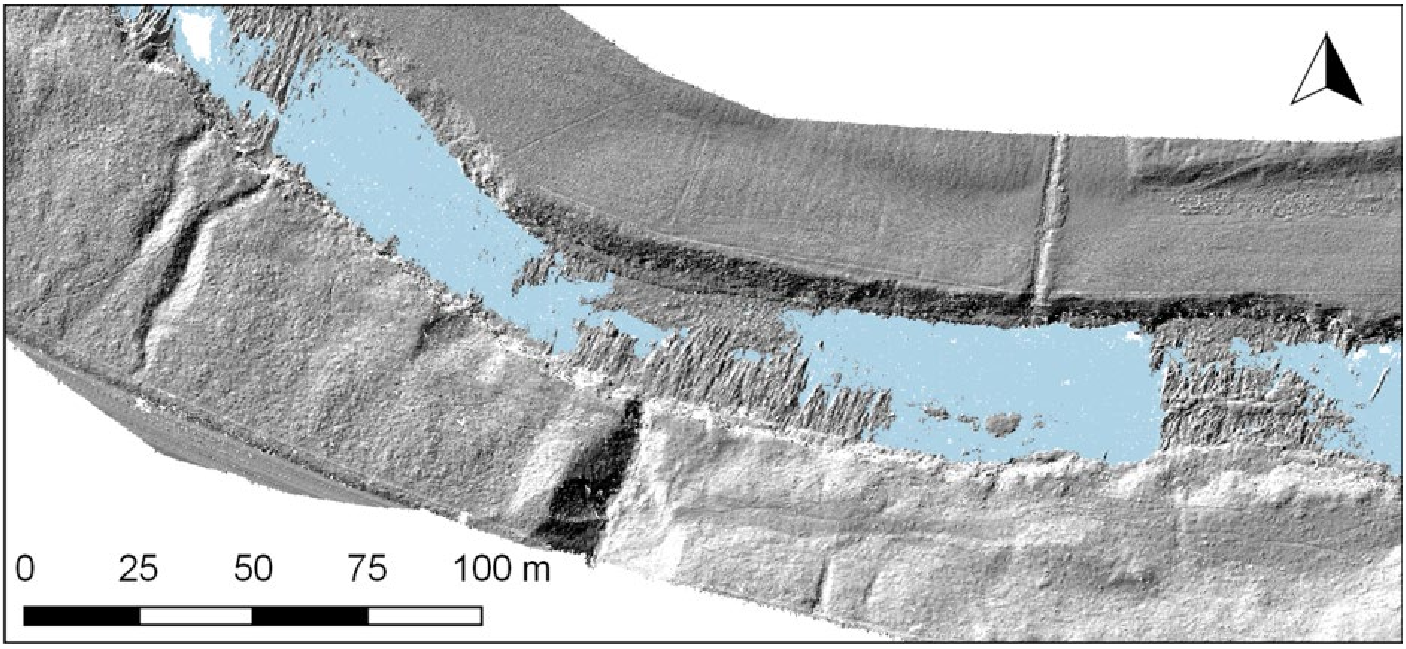


Figure 9 Potential misclassification at the River Garry. River bed point coverage in blue, and dry terrain represented as hillshade.

From close inspection, the issue illustrated in Figure 9 relates to uncertainty as to whether regions of river bed classified as dry bed should in fact be wetted bed. There are two likely reasons for this misclassification:

1. Flows at this site were known to be very low (discharge <Q99), and stretches of the channel were likely also dry. In very shallow water, only a single return is recorded (see Section 4.4.3), and this leads to ambiguity as to whether water is present or not;

2. The channel is very complex with many angular, jutting slabs of bedrock, and large in-stream boulders, leading to adjacent pools at differing elevations. This adds to classification complexity, even when a manual approach is adopted.

Due to the lack of validation data for the Garry, it has not been possible to assess the classification results. While consistent coverage of the bed (wet or dry) was achieved, limited corresponding surface points made it difficult to extract depth. For these reasons, the subsequent analysis and discussion focusses mainly on the findings at the River Dee. Examples of the Garry dataset are provided where relevant.

3.3 Analysis

Analysis was undertaken in order to examine the following aspects of performance:

- accuracy
- point density (spatial resolution)
- effectiveness of capturing submerged terrain
- depth measurement

In addition, potential was assessed with respect to:

- characterising hydromorphology
- contributing to classification of river typology
- enhancing hydrodynamic models

4 ASSESSMENT OF PERFORMANCE

4.1 Accuracy Assessment

The topo-bathymetric LiDAR data were compared to validation data collected by RTK GNSS to examine:

- Overall accuracy of the dataset
- Accuracy of water points

4.1.1 General Accuracy Assessment

The LiDAR data was compared to the check points located on sections of road. The mean difference of +0.04 m (refer to Appendix A2) between the LiDAR and GNSS check points is within the expected accuracy of 3 -5 cm specified by the data provider. The positive mean indicates that the LiDAR points lie slightly *above* the GNSS points.

4.1.2 Fluvial Accuracy Assessment

A total of 12 cross-sections were collected on the Dee and its tributary, Allt an t-Slugain. This includes collection of dry and submerged points on the riverbanks, gravel bars, water surface and river bed, thus providing an evaluation of accuracy within the fluvial zone. It should be noted that measured cross-sections were restricted to safely walkable, shallow zones. Table 3 summarises the cross-section data. Due to a miscommunication of the survey timing from the LiDAR supplier, the cross-sections were surveyed one day after the LiDAR survey (Friday 21st October). Gauging data (Mar Lodge) indicates that the water level fell by 2-5 cm from 20th October (LiDAR) to 21st October (validation survey), which equates to a drop in discharge of 8.915 m^3/s to 6.810 m^3/s. The effects of this would not have been consistent across the study area, and the following results must be considered in the context of this uncertainty.

The results of the accuracy assessment for the combined cross-sections are presented in Table 4 where the GNSS elevations are compared (vertical difference) to a triangulated surface generated from the LiDAR point cloud. A further breakdown, by individual cross-section is presented in Table A-2 and Table A-3 (Appendix). Outliers were removed before calculating the statistics.

The poorest accuracies (mean error) are generally found for dry terrain points. This may be a result of the steep, and sometimes complex, river banks which may not always be adequately captured by airborne survey methods, or well represented by the DEM. Within the Dee mainstem, the river bed points returned the highest accuracies (see Table A-2), of generally < 0.05 m. For the Allt an t-Slugain, the picture is more mixed, but bed points generally returned a mean error of < 0.07 m (Table A-3). The Allt an t-Slugain returned better results for river surface points than the Dee, but there is substantial variation between individual cross-sections.

All cross-sections produce a positive mean, which indicates that all classes of LiDAR points are *above* the cross-section check points. This fits with the context of falling water level between the LiDAR survey and the cross-section measurements, and also corresponds to the findings of Section 4.1.1. As a component of the error is likely due to the falling water level, these results suggest that improved accuracies would have been achieved had the cross-sections been measured at the same time as the LiDAR data. This would also correspond to the findings of Andersen et al. (2017) who assessed the quality of a similar Riegl system in an inter-tidal environment, reporting RMSE errors of less than 0.05 m.

Table 3. Summary of cross-section data for River Dee and Allt an t-Slugain tributary

Location	No. of cross-sections	Combined No. of Points			
		Dry	Water Surface	River Bed	Total
Dee mainstem	6	101	72	99	272
Allt an t-Slugain	6	189	30	65	284

Table 4. Elevation differences (dZ) between LiDAR and cross-section points for Dee.

Location	Class	Elevation differences (LiDAR Z – GPS Z)				
		Mean (m)	σ (m)	RMSE (m)	Min. (m)	Max. (m)
Dee mainstem	Dry	+0.071	0.080	0.107	-0.043	0.321
	Surface	+0.070	0.085	0.110	-0.159	0.176
	Bed	+0.051	0.040	0.064	-0.018	0.170
Allt an t-Slugain	Dry	+0.094	0.063	0.125	-0.162	0.260
	Surface	+0.041	0.055	0.067	-0.083	0.171
	Bed	+0.063	0.035	0.072	-0.009	0.130

4.1.3 Summary of findings

These results can be summarised as:

- Overall accuracy matches expectations for conventional LiDAR
- Within the fluvial zone, actual accuracies are likely to be better than those reported here due to uncertainty arising from the temporal offset of the cross-section measurements
- There is little difference in accuracy between surface and bed points, with mean errors of 0.04 to 0.07 m
- No correlation was found between accuracy and water depth

4.2 Point density

4.2.1 Overview

Point density can be measured as the number of points per square metre (points/m^2). Higher point density results in improved capture of topographic detail. Achieving good point density is especially important for bathymetric LiDAR, as the water will absorb and scatter some of the incident points depending on local water conditions. This affects the completeness of the water surface and bed coverage and influences ability to directly calculate water depth.

Over the last decade, advances in scanning technology have resulted in spatial resolutions of 10-20 points/m^2 becoming readily achievable for topographic LiDAR. Likewise, improvements in the scanning configuration of the Riegl VQ-880-G have also increased point density. This section examines the following:

- Point density over dry terrain, water surface and river bed
- Variability in point density across the test sites

4.2.2 Point density assessment

A LiDAR survey produces a swath of points below the aircraft, which is referred to as a flightline. The flightline width is defined by the scanning angle and the flying height. In order to build up coverage over an area, parallel flightlines, with slight overlaps are flown. In the case of the topo-bathymetric LiDAR surveys, point density has been enhanced by flying multiple flightlines over the river corridors. This is illustrated in Figure 10 and Figure 11 which show how the River Dee has been covered by 30 flightlines, and the River Garry by 18.

Point density was measured for each flightline, and for all flightlines combined, for the two test sites. The results are shown in Table 5 (Dee) and Table 6 (Garry), broken down by class.

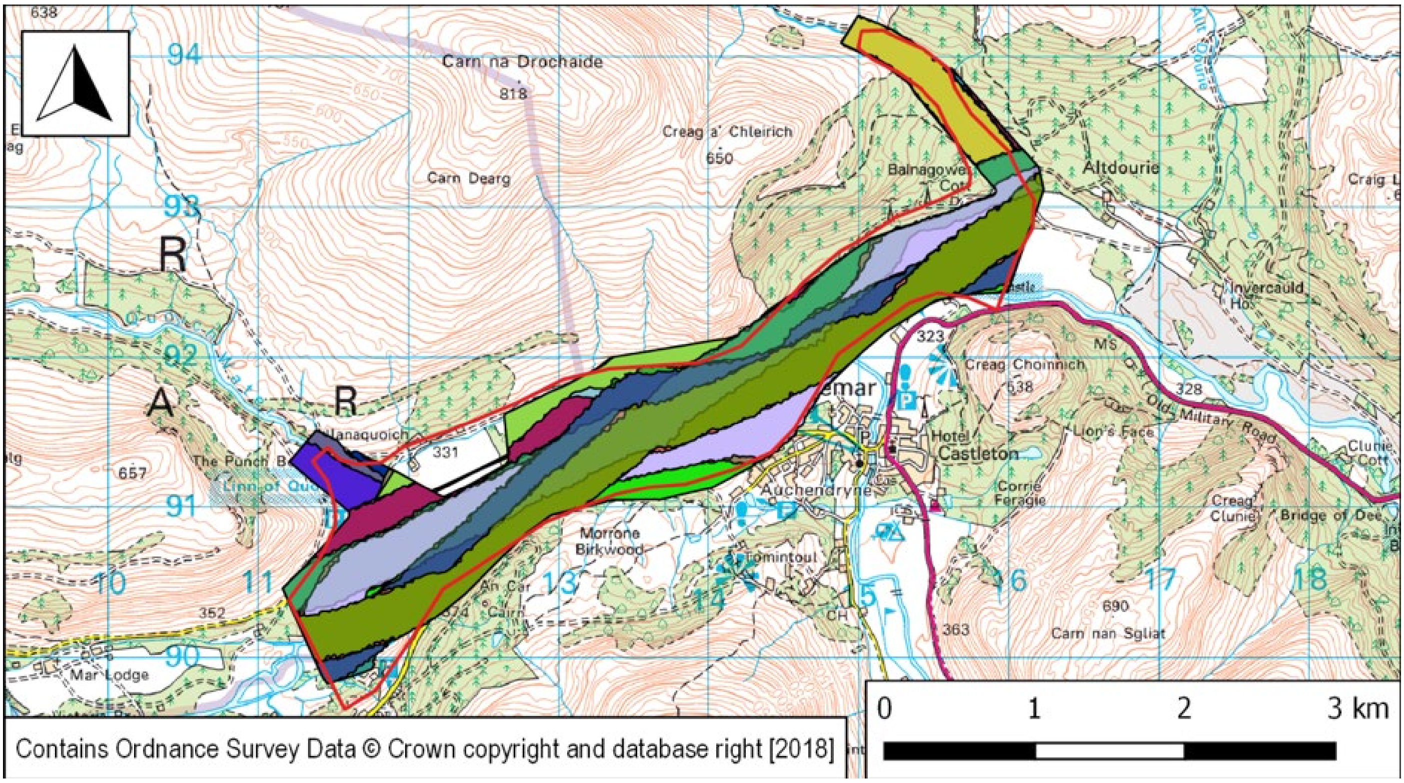


Figure 10 Overlapping flightlines at Dee test site (different colours indicate different flightlines), with red polygon indicating test site boundary.

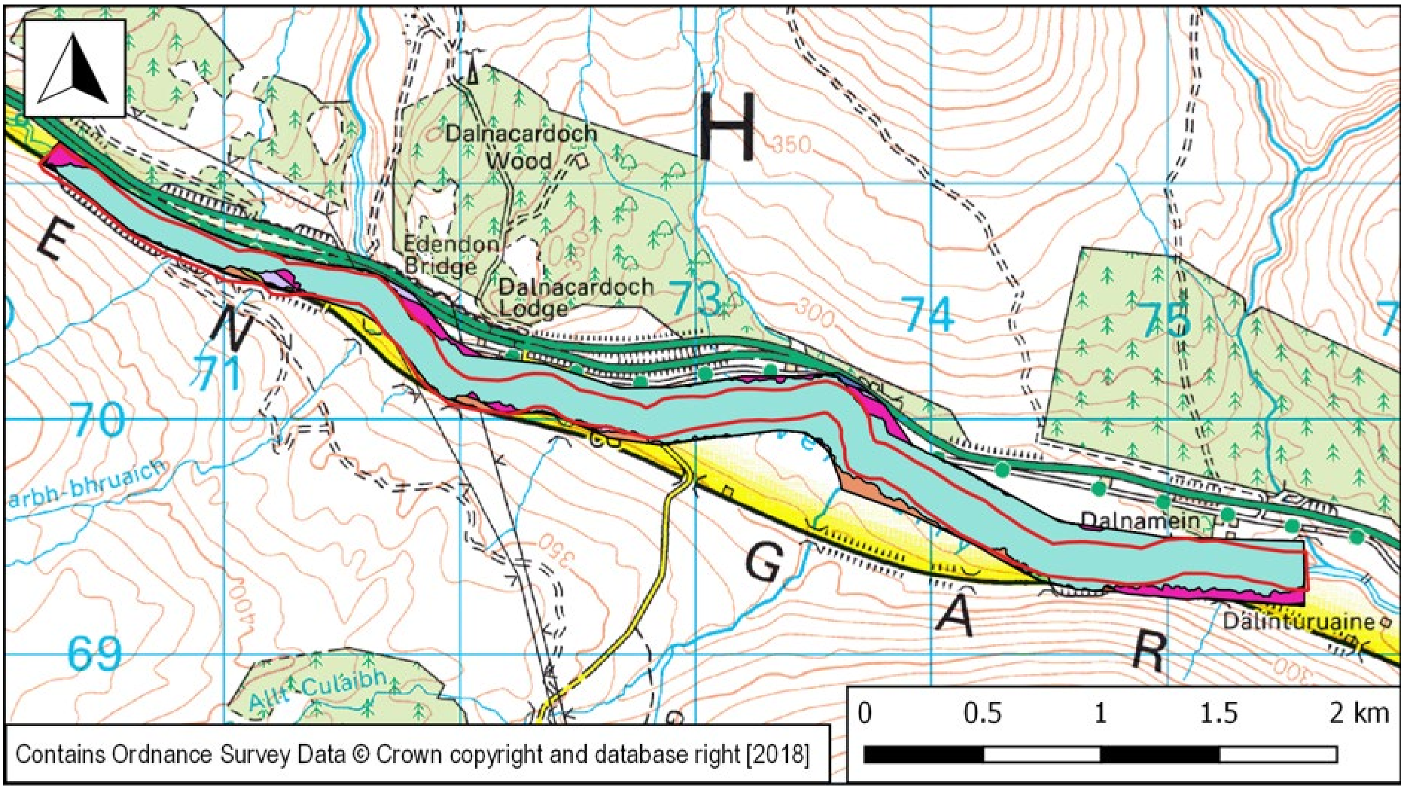


Figure 11 Overlapping flightlines at Garry test site (different colours indicate different flightlines), with red polygon indicating test site boundary.

Table 5. River Dee: median point density for individual flightline and combined (30) flightlines.

	Dry	Water Surface	River Bed
Single flightline (points/m²)	16	3	15
30 combined flightlines (points/m²)	101	7	91

Table 6. River Garry: median point density for individual flightline and combined (18) flightlines.

	Dry	Water Surface	River Bed
Flightline (points/m²)	18	2	13
18 Combined flightlines (points/m²)	202	8	170

The results demonstrate that significantly fewer points are returned from the water surface compared to the river bed – 7 points/m² (surface) compared to 91 points/m² (bed), for the River Dee, considering all flightlines. This is because reflection of the green laser from the water surface is complex and variable, and particularly poor for calm (smooth) areas of water, which leads to challenges in determining the air/water interface (Guenther et al., 2000; Mandlburger et al., 2015a). The point density at the River Garry is around twice that achieved at the River Dee for dry terrain (202 points/m² comparted to 101 points/m²). This is because the Garry is largely a single thread channel whereas the Dee is braided in places and thus the flightlines are more spread out across the river corridor, reducing spatial resolution. While the increased spatial resolution at the Garry is also reflected in the river bed points, the spatial resolution of the water surface returns is similar for the Dee and Garry (8 points/m² for Garry compared to 7 points/m² for Dee), suggesting that increasing spatial resolution does not improve the representation of the water surface.

For both the Dee and Garry, a slightly higher point density is achieved over dry (fluvial and floodplain) areas compared to the river bed. This is to be expected, as attenuation of the signal in the water column will reduce the number of points returned from the bed. However, the reduction in point density is not very substantial. As the dry terrain points have been filtered to remove vegetation and other non-ground points (i.e. a DTM), it is reasonable to conclude that the bed points are of a similar point density to the DTM over dry terrain.

The results indicate that utilising the data from all flightlines significantly improves the spatial resolution, and adds valuable detail to the resultant elevation models. This is illustrated in Figure 12 which shows a hillshade DTM of the same area produced from all flightlines (left), compared to using data from a single flightlines (right), with some gaps in the case of the latter. However, for the river bed (Dee), a single flightline provides 15 points/m^2 which offers detailed representation. As survey effort (and cost) is closely linked to the number of flightlines, it is likely that in practice, optimal resolution could be achieved through two-to-three overlapping flightlines.

4.2.3 Variation in point density

Point density will vary across the survey area, depending on local conditions in the water body, and the number of overlapping flightlines at any one location. This is somewhat complex and unpredictable, and is highlighted in Figure 13 which shows a histogram of point density for all combined flightlines for the river bed class at the Dee. This indicates that point density ranges from a minimum of 1 point/m^2 to a maximum of 1063 points/m^2, with significant variability. At a small number of locations, point density is in excess of 250 points/m^2 (areas with a high number of overlapping flightlines). This is further illustrated in Figure 14 which demonstrates the spatial variability of point density for the river bed class. Note the background orthoimagery was captured in April 2016. Results for the Garry test site are included in Appendix A4.

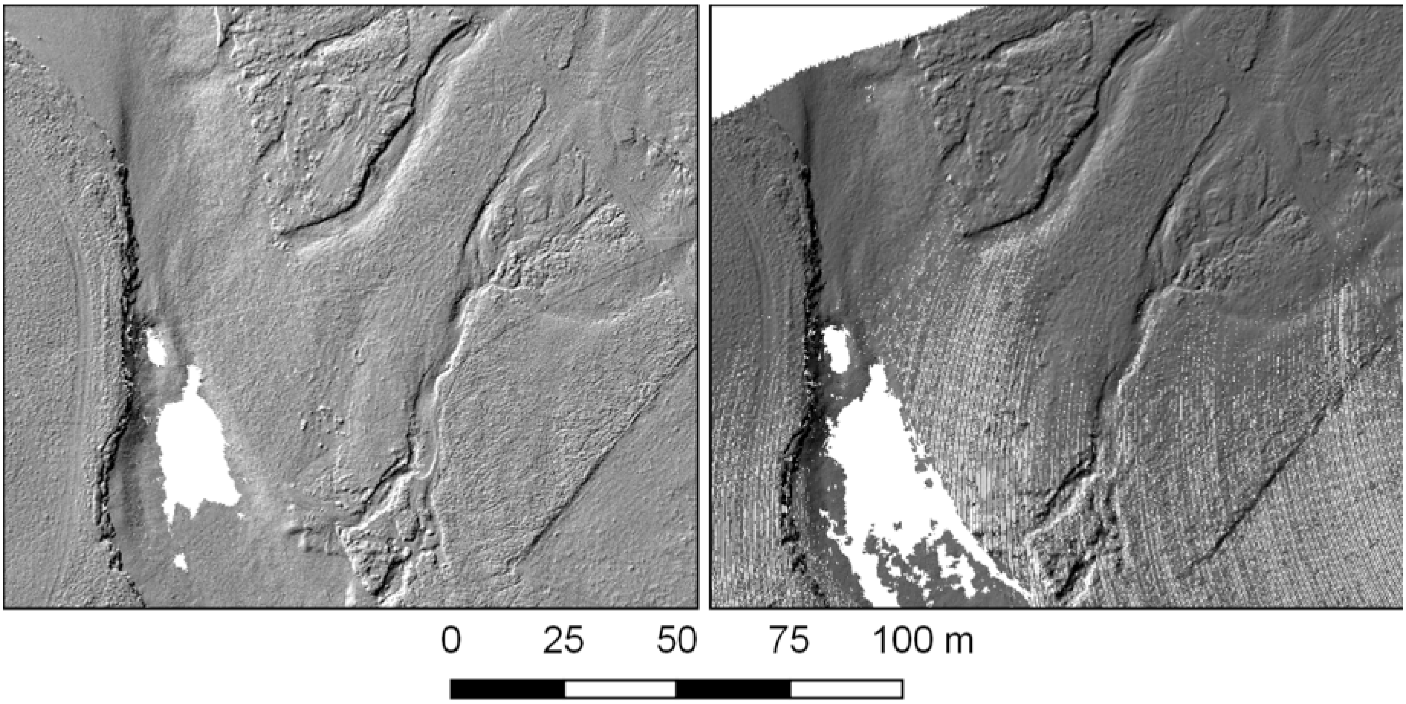


Figure 12 Hillshade produced for part of River Dee (at confluence with Allt an t-Slugain) using points from all flightlines (left) and single flightline (right), 0.1 m spatial resolution.

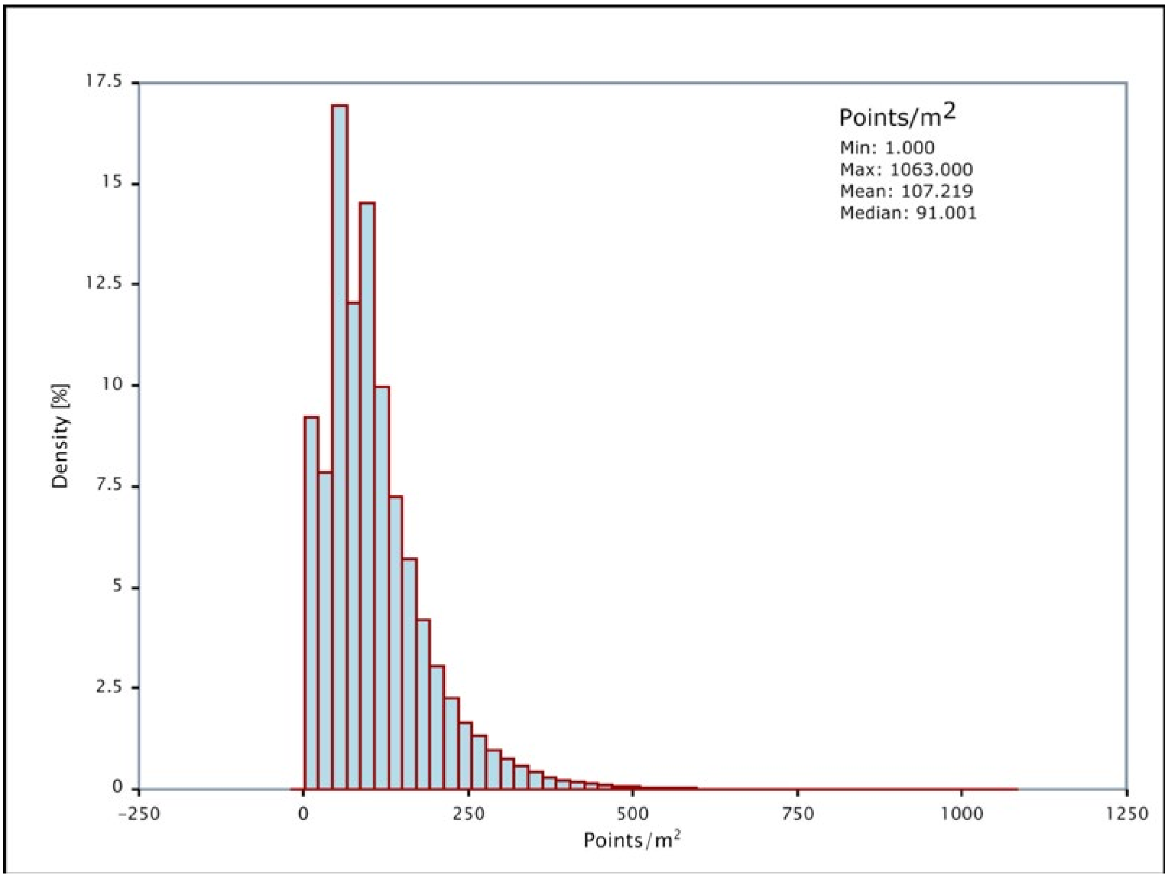


Figure 13 Histogram of point density for river bed class at Dee test site.

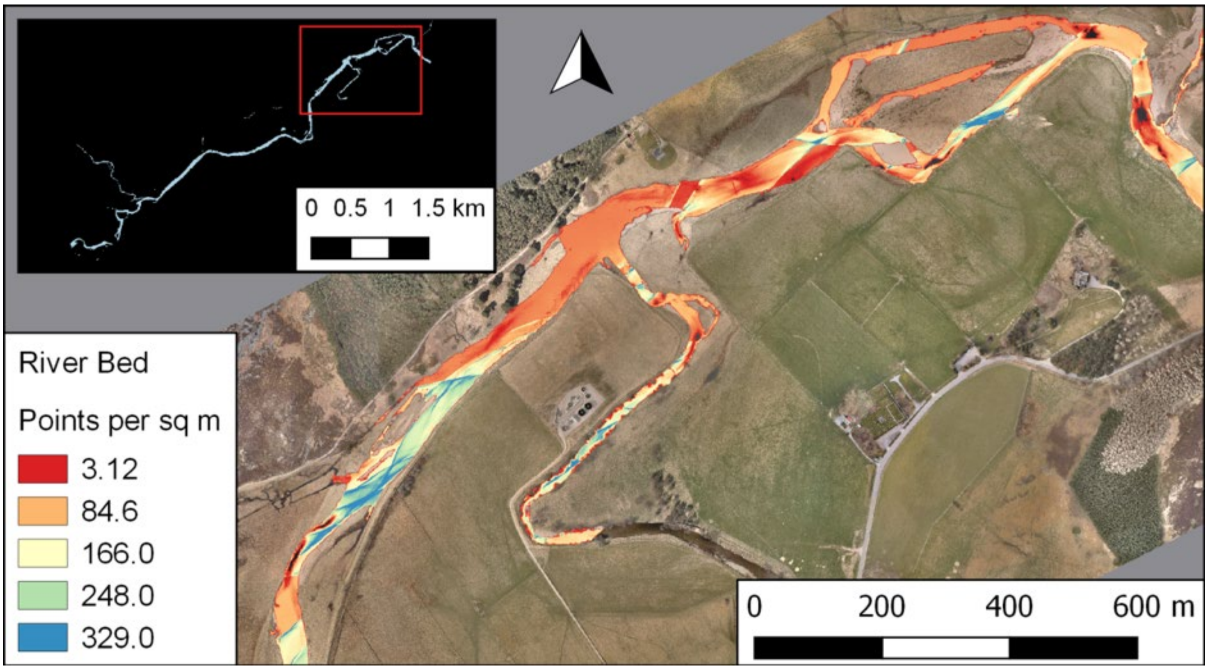


Figure 14 Spatial variability of point density at Dee test site (river bed class).

4.2.4 Influence of vegetation

Due to a general lack of vegetation (both terrestrial and aquatic) at the Dee test site, and the limited number of returns from the Garry, it is difficult to assess the influence of vegetation. Furthermore as the data had already been filtered to remove non-ground points, and there was no accompanying imagery, it has not been possible in this study to assess vegetation influences on aspects such as point density and bathymetric measurement.

4.2.5 Point density findings

The results of the point density assessment show:

- A single flightline can provide reasonable spatial resolution of the river bed, and limited coverage of the water surface, although there is significant local variability
- Multiple overlapping flightlines offer improved spatial resolution, allowing better definition of the water surface and bed morphology
- The optimum number of flightlines depends somewhat on water conditions, and will also be influenced by other parameters (flying height, channel braiding, meanders etc.)
- The combined dry and bed point classes can provide a high resolution seamless DTM of the channel and catchment for applications such as flood modelling, river restoration, etc.

4.3 Data Coverage Completeness

It is not possible to provide coverage of all areas. Water penetration is limited by factors including water clarity and bed reflectivity, and therefore, coverage gaps can be expected. Considered in combination with point density, completeness of coverage gives an indication of how well we can expect submerged terrain to be represented. Data completeness has only been assessed here for the wet areas, as this is of greatest relevance to this study.

4.3.1 Approach

As a first step, the observed 'wetted' area is defined, and then the actual LiDAR coverage is compared to this to assess what percentage of the wetted area has been captured. This is assessed on the basis of water surface and river bed (submerged) points. As no accompanying aerial imagery is available the wetted area has been determined on the basis of the point classification (dry/water surface/river bed) provided by the LiDAR supplier. The dry point class is taken as the reference, and a wet/dry boundary is generated from this. This was achieved by inverting the 'no data' areas from a 0.1 m raster hillshade of the dry terrain points, to produce a reference raster for the wetted areas. Corresponding raster coverages were generated at 0.1 m for the water surface and river bed classes (elevation). The percentage coverage of the water point classes (water surface, river bed) were then calculated in comparison to the wetted area reference. As an extension of this, depth coverage was also compared to the reference. Section 4.4 reports more fully on depth measurement. Completeness assessment was undertaken only for the River Dee site, where the results are broken down by the mainstem and the three tributaries.

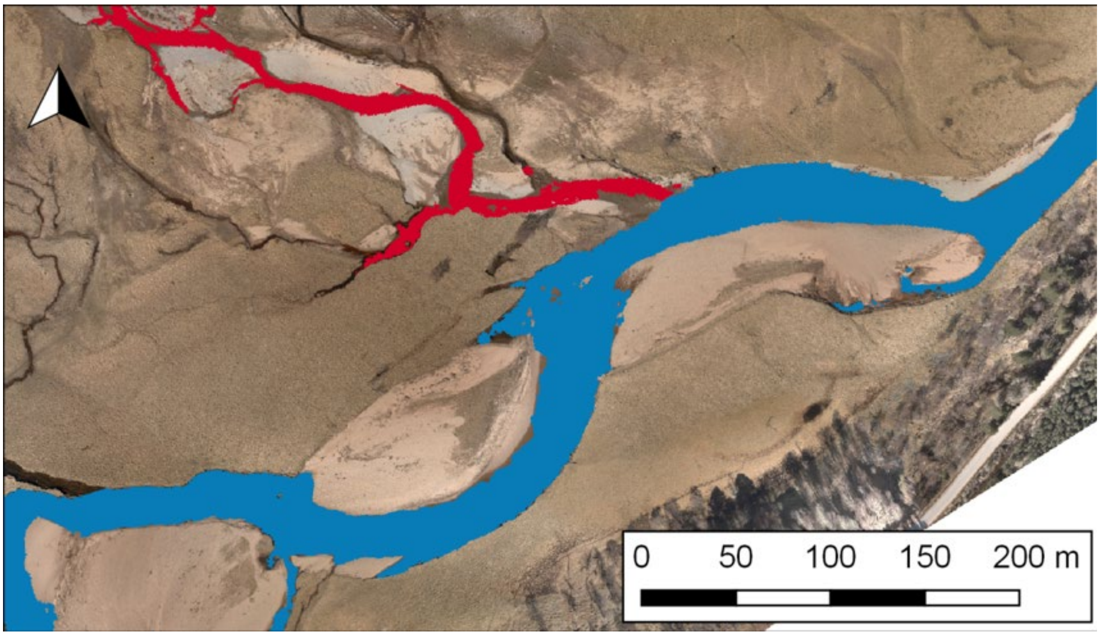


Figure 15 Wetted area masks for Dee (blue) and Quoich Water (red). N.B. background orthoimage is from April 2016 and for reference only.

4.3.2 Coverage Completeness Results

Table 7 shows results for the River Dee and its three tributaries.

Figure 16 illustrates a typical example of coverage for water surface and river bed for a similar area to that shown in Figure 15 (above).

From this, the following can be observed:

- Coverage of the river bed is very good, at >95 %
- Coverage of the water surface is variable, and poorest for Dee mainstem. This may be partially influenced by shallow backwater regions where only a river bed return is recorded
- Calculation of depth requires corresponding surface and bed points, and therefore coverage is similar to the water surface results, but slightly lower

Table 7 Coverage completeness for River Dee and tributaries

River	Wetted area (m^2)	Water surface coverage (m^2)	Water surface coverage (%)	River bed coverage (m^2)	River bed coverage (%)	Water depth coverage (m^2)	Water depth coverage (%)
Dee mainstem	242,361.33	153,956.51	63.52	236,835.11	97.72	149,922.90	61.86
Quoich	13,750.83	10,046.19	73.06	13,703.45	99.66	9,987.99	72.64
Clunie	11,634.70	9,891.57	85.02	11,106.50	95.46	9,643.43	82.89
Allt an t-Slugain	7,019.00	5,617.30	80.03	6,718.68	95.72	5,417.28	77.18

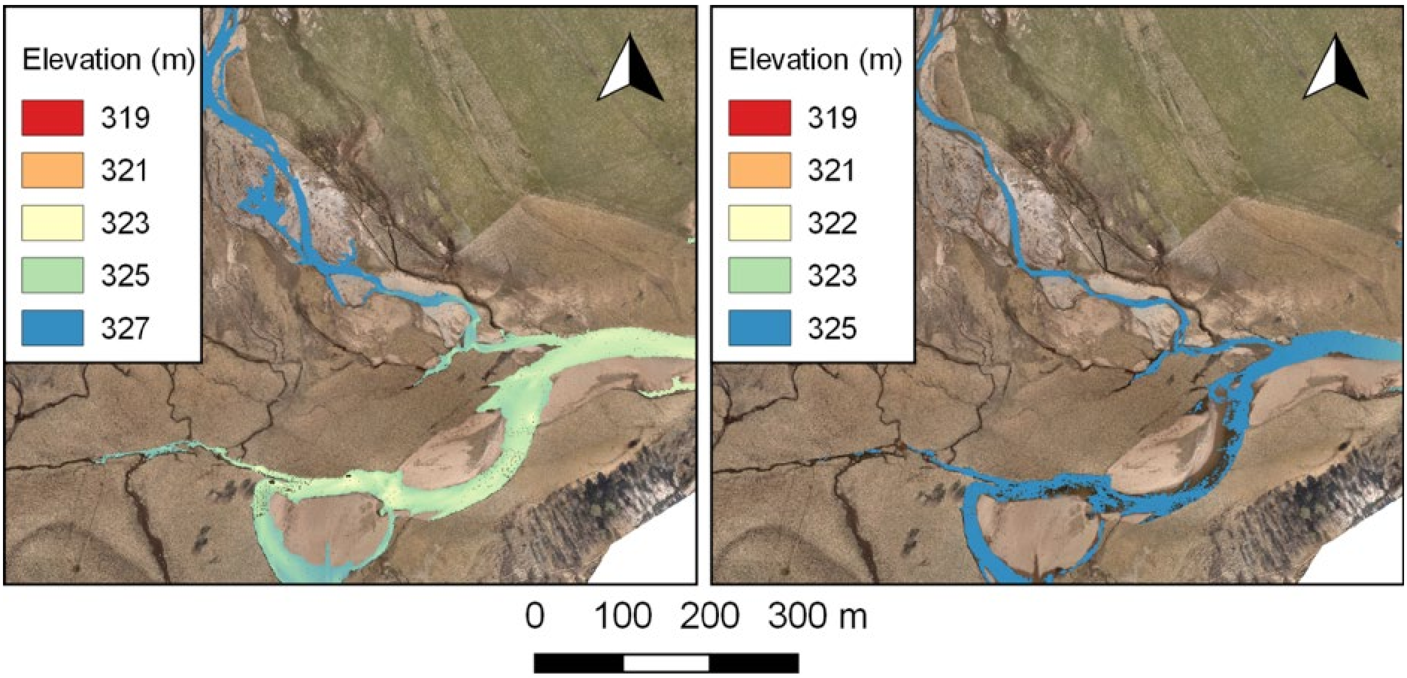


Figure 16 Example coverage of river bed (left) and water surface (right) classes.

4.4 Depth measurement

4.4.1 Approach

Water depth is one of the key deliverables from bathymetric LiDAR, as it aids identification of hydromorphological features such as pools and riffles. Depth, and local variability in depth, has implications for many fluvial processes and habitat assessment. From the LiDAR data, depth can be calculated in a straightforward manner as:

$$Depth = DEM_{SURFACE} - DEM_{BED}$$

A gridded DEM of the water surface and river bed can be produced directly from the classified point cloud. In this study, DEMs with a spatial resolution of 0.1 m were produced for each class. This resolution should preserve much of the fine topographic detail present in the original point cloud. The resultant depth map for the River Dee is shown in Appendix A5. This reveals that relatively complete retrieval of depth is possible at the Dee site.

This study only evaluated the data provided as standard by the LiDAR supplier. However, as part of the refraction correction process, a complete water surface model – effectively a DEM constructed from water surface points – should be produced in order to correct the bed point locations. If this water surface model is available, a more complete depth map can be produced, as demonstrated by Mandlburger et al. (2015a).

4.4.2 Depth results

The main remaining gaps correspond to pools. The maximum depth measured by LiDAR on the Dee mainstem is 2.84 m at the edge of a pool, as shown in Figure 17 and Figure 18. The LiDAR has not returned water bed points at depths greater than this, most likely due to deterioration in water clarity.

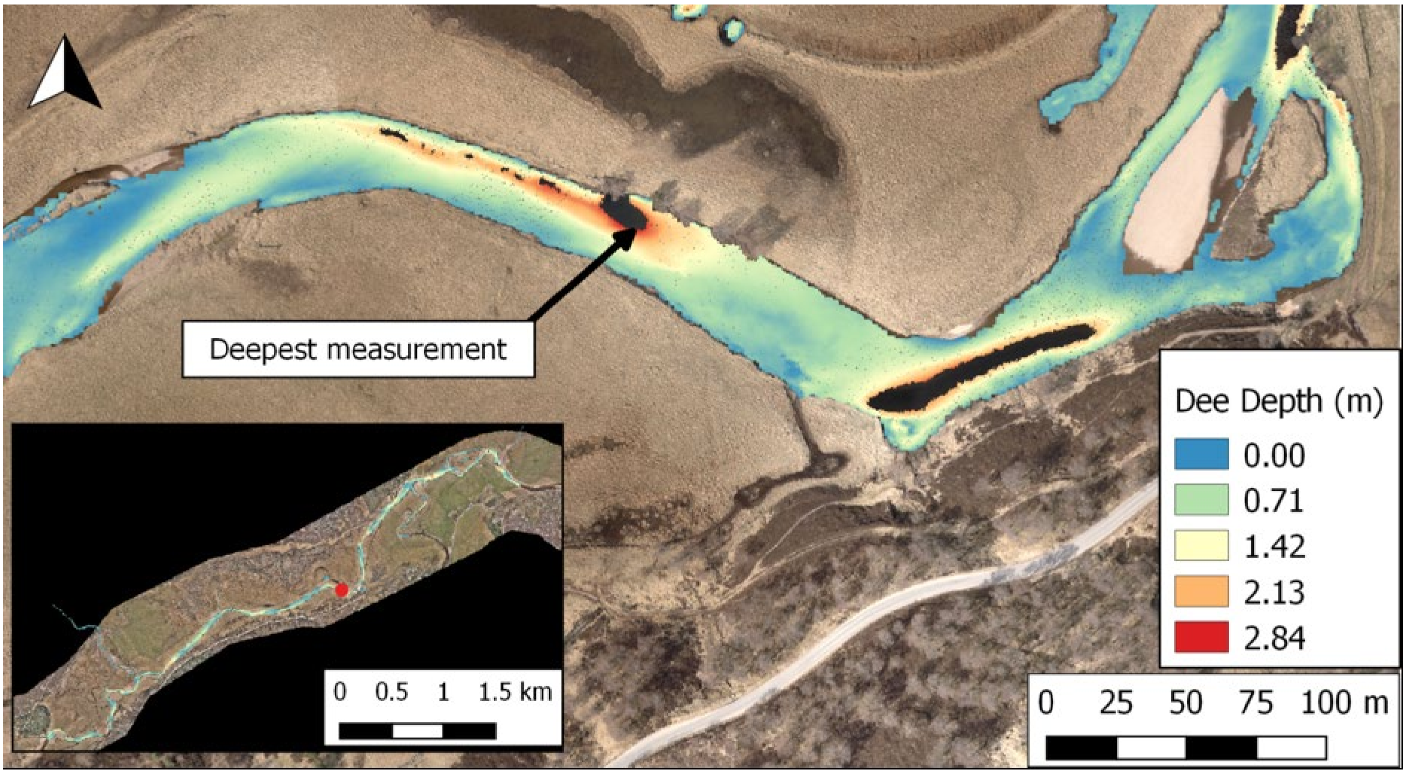


Figure 17 Deepest LiDAR measurement on Dee, with inset map illustrating location.

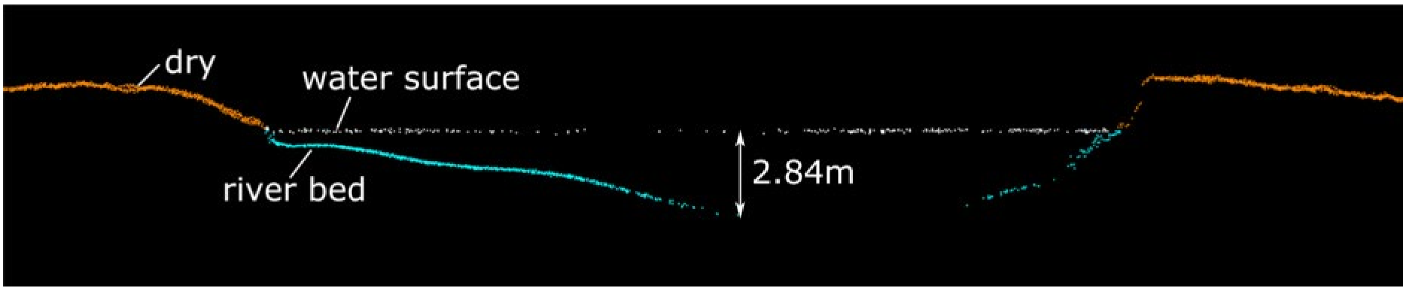


Figure 18 Cross-section corresponding to deepest measurement on Dee.

At the Garry, the deepest measurement was 2.85 m (Figure 19 and Figure 20). Despite the lack of depth data at the Garry (due to lack of surface points), the deepest measurement is almost identical to that found at the Dee.

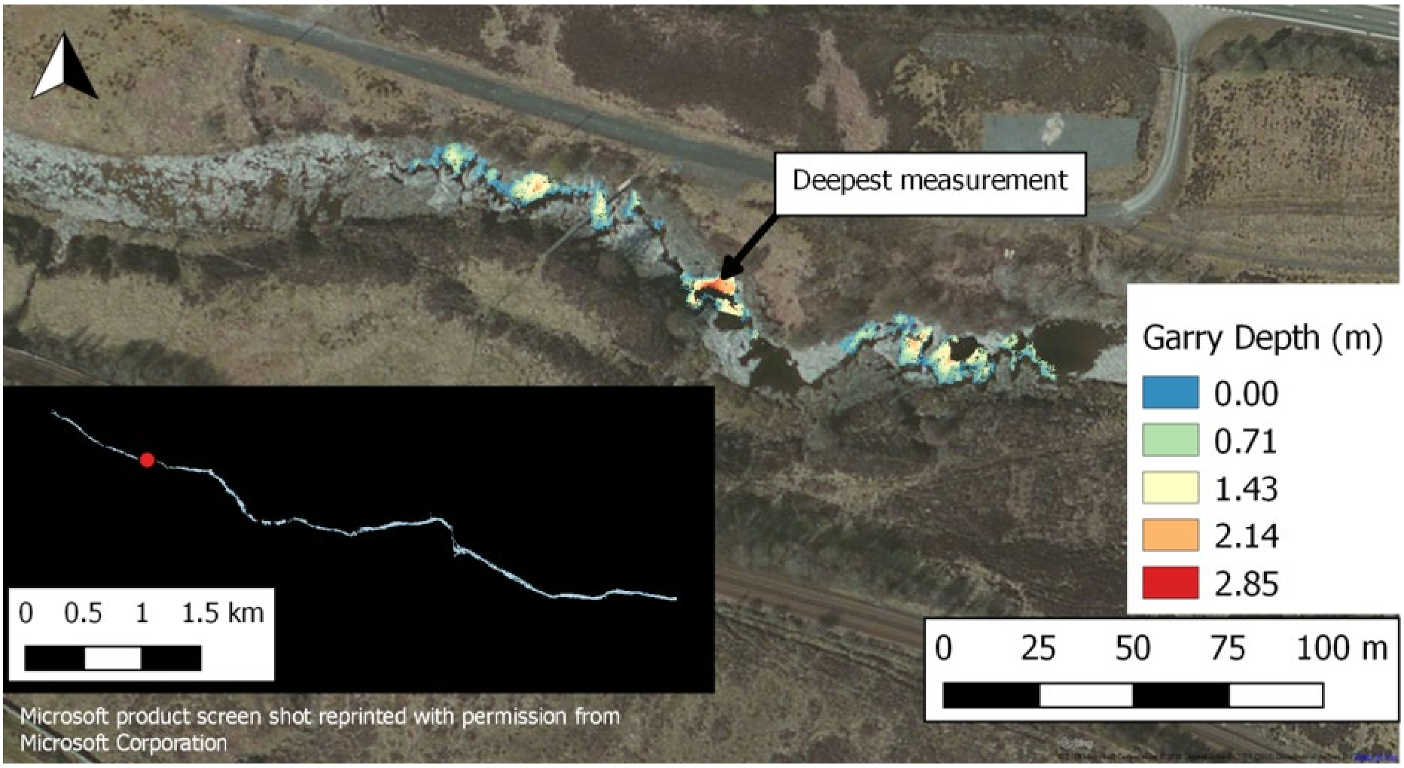


Figure 19 Deepest LiDAR measurement on Garry, with inset map illustrating location.

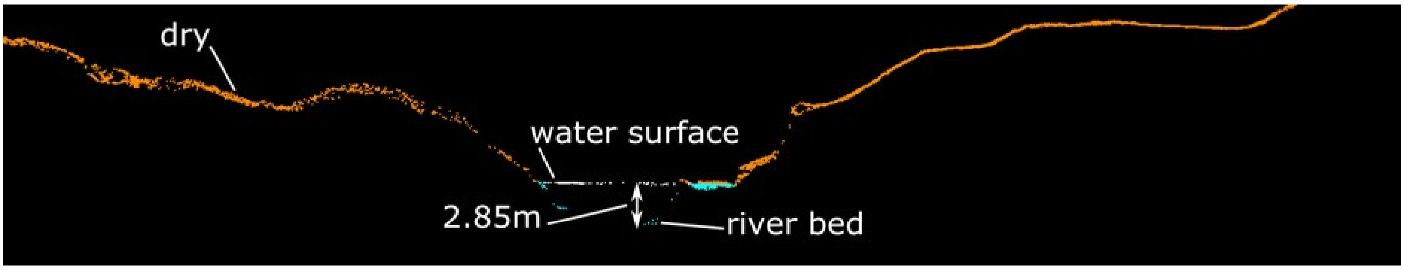


Figure 20 Cross-section corresponding to deepest measurement on Garry.

4.4.3 Depth limitations in shallow water

Bathymetric LiDAR also has limitations in terms of minimum measureable depth. This is directly related to the laser pulse length, which determines whether adjacent targets (e.g. water surface and river bed) can be discriminated as separate returns. In practice, this study has observed that depths shallower than 8 cm are returned as a single point, which will be a convolution of the two targets (surface, bed), but in practice appears to be dominated by the bed return. This results in some potentially submerged regions being classified as dry terrain, with no water surface recorded. The availability of a water surface model (See Section 4.4.1) would possibly help in identifying such misclassifications.

4.4.4 Summary of findings

The main observations from assessment of depth are:

- Depth coverage over the Dee test site is relatively complete, with the main gaps corresponding to pools
- In depths < 8 cm, only a single point is returned, as the water surface and bed cannot be separated. This can lead to misclassification or uncertainty
- For the Dee test site, the maximum depth measured by topo-bathymetric LiDAR is 2.84 m

5 Potential for Management Activities

5.1 River typology

Classification of morphological river typology is an important aspect of SEPA's work, and provides a basis for understanding how rivers will respond in relation to morphological and other pressures. Appendix A6 details the SEPA river typology classification.

Topo-bathymetric lidar can play a role in identifying existing typology. In order to identify and assign typology, it is necessary to consider a number of characteristics at the reach scale, as highlighted in Table 8. Ticks indicate variables which can determined from topo-bathymetric LiDAR.

Table 8 Variables relating to river typology classification (following from SEPA, 2012), and contribution of topo-bathymetric LiDAR as indicated by ticks.

Typology characteristics	
Channel gradient	✓
Channel planform	✓
Bed profile	✓
Bed material type	
Morphology (pools, riffles, bars, etc.)	✓
Floodplain (e.g. extensive/confined)	✓
Riparian zone	✓
Bank status (eroding/stable)	
Dynamic/stable	

Bathymetric LiDAR adds considerable value, as conventional LiDAR would only be able to provide information on planform, vegetation and floodplain. There is potential to automate or semi-automate the extraction of some of these variables, although the steps to achieving this should not be underestimated. Assuming LiDAR has also been collected over the adjacent floodplain, it is likely that the nature of and connection to the floodplain can be determined. Determining whether banks are stable or eroding may be possible from the LiDAR, especially if multi-temporal data is available. This may also assist assessing how dynamic the river is. However, evidence of abandoned channels, backwater environments, etc. (e.g. visible in hillshade model) in combination with an appreciation of the other characteristics above could provide useful evidence where only a single LiDAR survey is available. It is unlikely that type of bed material can be determined directly from bathymetric LiDAR. However, with knowledge of the other variables above, and catchment geology, bed material could likely be assessed. Accompanying aerial imagery would greatly enhance the determination of typology. Expert hydromorphological knowledge would be essential to the above processes.

5.2 Characterisation of hydromorphology

Identification of morphological units (e.g. riffles, pools, etc.) is an important component of determining typology. There is significant potential for LiDAR to contribute to this process and to reduce dependency on field surveys. LiDAR can be used to assess bed profile and measure depth, which in turn enables identification of bedforms. Although, as demonstrated, there are limitations in the depth penetration of LiDAR (deep and shallow extremes), this lack of data, interpreted alongside the depth map can provide useful evidence of the presence of bedforms such as riffles and pools. Andersen et al. (2017) implemented an approach for morphological classification of topo-bathymetric LiDAR data in the inter-tidal zone. This demonstrates the potential for automated classification of fluvial morphology.

5.3 Hydrodynamic modelling

Hydrodynamic modelling requires as input the geometry of the river channel. Such models can be used to assess flood risk (including geomorphological risk) and as a basis for modelling habitat suitability. Usually the geometry of such models will be defined using DEMs (if available) and/or cross-section surveys. Whilst DEMs can provide detail of the floodplain, detailed information on the submerged channel is usually missing. Cross-sections can assist in filling the gaps in the submerged channel zone, but are limited in their spatial coverage (i.e. gaps between sections), which may lead to overly-generalised channel representation. Topo-bathymetric LiDAR provides a means of addressing these issues and providing detailed and complete geometry of the floodplain and submerged channel area in one seamless DEM.

Mandlburger et al. (2015a) successfully demonstrated the potential of topo-bathymetric LiDAR for habitat suitability modelling of a river in Austria, while SEPA have also tested the topo-bathymetric LiDAR data for meso-habitat modelling of the River Garry over a short reach. The extracted bathymetry provided a detailed and suitable basis for 2D modelling of habitat suitability, and further work is being undertaken to validate and optimise the results (R. Martinez, personal communication, 8th March 2018).

5.4 Fitness for Purpose

Although this project does not consider cost-benefit analysis, the relatively high cost of LiDAR should be a consideration in determining whether this technique is appropriate under different scenarios. For example, surveying short sections may not be justifiable, and alternative techniques such as conventional field survey, or unmanned aerial vehicle (UAV) photogrammetric survey may be more appropriate. While UAVs cannot cover the same spatial extents as LiDAR, they offer high spatial resolution imagery at lower cost and with greater flexibility for responding to extreme flows or for repeated (e.g. monitoring) activities. Topo-bathymetric LiDAR and UAV remote sensing may indeed offer complementary approaches whereby certain sites or scenarios may justify one over the other. Alternatively, topo-bathymetric LiDAR could be considered as a baseline survey providing detailed DEMs over wider extents, while UAVs could be used for follow-up monitoring over shorter reaches. LiDAR surveys are usually more cost-effective if several locations in a common geographical area can be coordinated for survey together.

6. Remarks on Data Handling and Management

6.1 Data Maturity

Conventional topographic LiDAR has been commercially available since the late 1990s. The processing workflow is mature, and end-users can expect data which meets established quality measures. Topo-bathymetric LiDAR applies many of the standard LiDAR post-processing routines for tasks such as georeferencing, strip matching, etc. and thus the basic point cloud can be expected to meet quality expectations.

The main challenge relates to classification of the point cloud, and especially discrimination between water/non-water points. For the Dee test site, it was observed that some regions were affected by a classification overlap, with some areas classified both as dry terrain and river bed. This is likely due to the point classification being undertaken on a flightline-by-flightline basis rather than considering all points together and imposing a rule which would prevent this. This also reflects the semi-manual approach which is currently implemented by the LiDAR provider to classify the water surface (a key step to applying the refraction correction to submerged points). Some recent studies have proposed automated water classification approaches (Mandlburger et al., 2017; Zhao et al., 2017), and it is likely that over time, such approaches will become more sophisticated and reliable.

6.2 The Big Data Challenge

While LiDAR facilitates very detailed topographic representation, this provides a challenge in terms of managing and handling very large datasets. The two relatively small river extents presented here comprise more than 618 million points (>2 Gb of computer storage), and this is considering only 'bare earth' DTM points, not the complete point cloud.

From an end-user perspective, it is feasible (though still challenging) to manage topo-bathymetric LiDAR data in a GIS environment by converting the point cloud (typically in LAS data format) to a raster (gridded) model, or by specifying this as a deliverable from the LiDAR supplier. This supports raster-based analysis of DEMs and incorporation in modelling software. Note that if a raster is requested from the data supplier, it is always best practice to also request the point cloud data as this contains significantly more information, and will support more advanced analysis tasks. Increasingly, open source software offers functionality for analysis of LiDAR data (e.g. *QGIS* (QGIS, 2018), *R* (R, 2018)), while *CloudCompare* (CloudCompare, 2018) is able to operate directly on the point cloud.

7. Conclusions

This project has assessed the emerging technique of topo-bathymetric LiDAR. This has been tested at two sites, the River Dee (Aberdeenshire) and the River Garry (Perth and Kinross). Due to exceptionally shallow (or no) flows at the River Garry findings at this site are limited, and most of the presented results relate to the River Dee. The outcomes are summarised as follows.

Accuracy

Topo-bathymetric LiDAR was found to offer similar accuracy to conventional topographic LiDAR over dry areas. The mean error of river bed and water surface points is generally < 0.07 m.

Water Surface Definition

The LiDAR surveys included a large number of overlapping flightlines, which supported high point density of the river bed at the Dee test site, with a combined spatial resolution of around 90 points/m^2. There are fewer returns from the river surface due to limited reflection of the green laser. The spatial resolution of the water surface points is typically 7 points/m^2 considering data from all flightlines. Individual flightlines provide fewer returns (15 and 3 points/m^2 for the bed and surface respectively), but this level of spatial resolution is still valuable. While several studies have explored the reconstruction of the water surface from green laser points (Mandlburger et al., 2013; Mandlburger et al., 2017; Zhao et al., 2017), this is still challenging. Inclusion of an infrared laser (now an option with newer versions of the Riegl VQ-880-G sensor) would likely provide a more straightforward definition of the water surface.

Completeness of Coverage

If the representation of the water surface can be improved through delivery of a water surface model or inclusion of an infrared laser, then completeness of the LiDAR data is principally limited by the depth penetration of the green laser. In water shallower than 8 cm it is not possible to separate the river bed and water surface returns. The maximum depth is primarily dictated by factors such as water clarity and bed reflectivity. The maximum depth measured here was 2.84 m (Dee) and 2.85 m (Garry). This will vary from river to river, and there will likely be data gaps in deeper pools.

Measurement of Depth

Determination of depth is straightforward if the water surface and river bed elevations (DEMs) are available. In this study, the main gaps in the depth maps relate to deeper pools. Depth provides valuable information on the nature of bedforms – pools, riffles, etc. and bed profile. Thus, this is a key variable in assessing the channel hydromorphology.

End-user applications

The real value of topo-bathymetric LiDAR relates to its effectiveness for activities relating to water body management and condition monitoring, as discussed in Section 5. There is significant potential for this technique to contribute to classification of existing river typology, provided this is combined with expert input from fluvial geomorphologists. This would benefit from the additional context provided by aerial imagery, which is normally collected as part of a LiDAR survey.

Additionally, topo-bathymetric LiDAR offers potential for characterising hydromorphology and is well-suited to identifying and assessing the status of riparian vegetation. Although hydromorphological features can be identified from topo-bathymetric LiDAR, or through inspection of depth maps, an automated feature classification approach would be highly desirable, and could substantially reduce the need for current field survey approaches.

Topo-bathymetric LiDAR offers possibilities to enhance the reliability of process models. A seamless DEM which fully captures both the floodplain and the fluvial zone, including the submerged channel, holds significant potential for advancing hydrodynamic models supporting flood risk assessment and habitat suitability mapping.

Topo-bathymetric LiDAR offers significant potential to support and enhance SEPA's fundamental activities, and in particular to reduce and in some cases replace the need for field surveys. However, this technique is not suited to all rivers. Important factors to consider in determining likely suitability are:

- Depth of the river in relation to water clarity;
- Flow status, including turbulence, and scheduling the survey to avoid extremely high and low flow conditions;
- Bed material (reflectivity). Performance is known to be better for gravel bed rivers;
- Significant overhanging vegetation (not assessed here, but likely to introduce limitations).

Acknowledgements

This project was carried out with the assistance of Dr Ina Pohle (James Hutton Institute), who provided fieldwork assistance. Invercauld Estate, Mar Lodge Estate (National Trust for Scotland) and Mar Estate provided access for fieldwork. The Technical University of Vienna kindly provided access to OPALS software for analysis of LiDAR data.

References

Addy, S., Wilkinson, M., Cooksley, S., 2016. Geomorphic changes and hydrological responses to the 2015 'Strom Frank' flood event at a river restoration site on the upper River Dee, 4th British Hydrological Society International Conference, Cranfield University, UK.

Andersen, M.S., Gergely, A., Al-Hamid, Z.K., Steinbacher, F., Larsen, L.R., Ernstsen, V.B., 2017. Processing and performance of topobathymetric lidar data for geomorphometric and morphological classification in a high-energy tidal environment. *Hydrology and Earth System Sciences*, 21 (1): 43-63.

Bailly, J.S., Le Coarer, Y., Languille, P., Stigermark, C.J., Allouis, T., 2010. Geostatistical estimations of bathymetric LiDAR errors on rivers. *Earth Surface Processes and Landforms*, 35 (10): 1199-1210.

Chust, G., Grande, M., Galparsoro, I., Uriarte, A., Borja, Á., 2010. Capabilities of the bathymetric Hawk Eye LiDAR for coastal habitat mapping: A case study within a Basque estuary. *Estuarine, Coastal and Shelf Science*, 89 (3): 200-213.

CloudCompare, Date accessed: 12th June, 3D point cloud and mesh processing software. http://www.danielgm.net/cc/

Doneus, M., Miholjek, I., Mandlburger, G., Doneus, N., Verhoeven, G., Briese, C., Pregesbauer, M., 2015. Airborne laser bathymetry for documentation of submerged archaeological sites in shallow water. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences,* XL-5 (W5): 9 pp.

Edwards, S.J., Clarke, P.J., Penna, N.T., Goebell, S., 2010. An examination of Network RTK GPS services in Great Britain. *Survey Review*, 42 (316): 107-121.

Eisemann, E.R., Wallace, D.J., Buijsman, M.C., Pierce, T., 2018. Response of a vulnerable barrier island to multi-year storm impacts: LiDAR-data-inferred morphodynamic changes on Ship Island, Mississippi, USA. *Geomorphology,* 313 (2018): 58-71.

European Commission, 2012. Report from the Commission on the Implementation of the Water Framework Directive River Basin Management Plans. 14 pp.

Guenther, G.C., 1989. Airborne laser hydrography to chart shallow coastal waters. *Sea Technology*, 30 (3): 55-59.

Guenther, G.C., Cunningham, A.G., LaRocque, P.E., Reid, D.J., 2000. Meeting the accuracy challenge in airborne lidar bathymetry, 20th EARSeL Symposium: Workshop on Lidar Remote Sensing of Land and Sea. EARSeL, Dresden, Germany, 27pp.

Hilldale, R.C., Raff, D., 2008. Assessing the ability of airborne LiDAR to map river bathymetry. *Earth Surface Processes and Landforms*, 33 (5): 773-783.

Kinzel, P.J., Wright, C.W., Nelson, J.M., Burman, A.R., 2007. Evaluation of an experimental LiDAR for surveying a shallow, braided, sand-bedded river. *Journal of Hydraulic Engineering,* 133 (7): 838-842.

Lillycrop, W.J., Parson, W.J., Irish, J.L., 1996. Development and operation of the SHOALS airborne lidar hydrographic survey system, in: Feigels, V.I., Kopilevich, Y.I. (Eds.), Laser remote sensing of natural waters: from theory to practice. SPIE, pp. 26-37.

Mandlburger, G., Hauer, C., Wieser, M., Pfeifer, N., 2015a. Topo-bathymetric LiDAR for monitoring river morphodynamics and instream habitats - a case study at the Pielach River. *Remote Sensing*, 7 (5): 6160-6195.

Mandlburger, G., Pfeifer, N., Soergel, U., 2017. Water surface reconstruction in airborne laser bathymetry from redundant bed observations. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, IV-2 (W4): 8 pp.

Mandlburger, G., Pfennigbauer, M., Pfeifer, N., 2013. Analyzing near water surface penetration in laser bathymetry - a case study at the River Pielach. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, II-5 (W2): 6 pp.

Mandlburger, G., Pfennigbauer, M., Riegl, U., Haring, A., Wieser, M., Glira, P., Winiwarter, L., 2015b. Complementing airborne laser bathymetry with UAV-based lidar for capturing alluvial landscapes, SPIE Remote Sensing. SPIE, 14pp.

Martinez, R., 2018. Personal communication. Email and draft report from R. Martinez to P. Miller, 8th March 2018.

Preisendorfer, R.W., 1986. Secchi disk science: visual optics of natural waters. *Limnology and Oceanography,* 31 (5): 909-926.

QGIS, Date accessed: 12th June 2018, QGIS: A free and open source geographic information system. https://qgis.org/en/site/

R, Date accessed: 12th June 2018, The R project for statistical computing. https://www.r-project.org/

Riegl, Date accessed: 01/03/16, Riegl VQ-880-G. www.riegl.com/nc/products/airborne-scanning/produktdetail/product/scanner/46/

SEPA, 2012. Supporting Guidance (WAT-SG-21): Environmental standards for river morphology, v2.1 ed, 68pp.

Zhao, J., Zhao, X., Zhang, H., Zhou, F., 2017. Shallow water measurements using a single green laser corrected by building a near water surface penetration model. *Remote Sensing*, 9 (426): 18 pp.

APPENDICES

A1 Site Photos

River Dee

Figure A-1 Dee mainstem, looking downstream from south bank at location 314,360 mE, 791,434 mN, close to cross-section A-1/A-2.

Figure A-2 Dee mainstem, looking upstream from location 315,557 mE, 792,777 mN, close to cross-sections E and F.

Figure A-3 Side-channel off Dee mainstem, looking upstream at location 315540 mE, 792750 mN. Surveyor pictured at cross-section D.

Figure A-4 Allt an t-Slugain tributary, looking upstream at location of cross-section K, 315,925 mE, 792,923 mN.

Figure A-5 Allt an t-Slugain tributary, looking downstream towards confluence with Dee, from location 315,794 mE, 792,758 mN. Close to location of cross-section H.

Figure A-6 Allt an t-Slugain, looking upstream from same location (315,794 mE, 792,758 mN) as Fig. A-5.

River Garry

Figure A-7 River Garry, looking upstream from location 271,646 mE, 770,559 mN. Photo credit: SEPA. 20/11/2016

Figure A-8 River Garry, looking south-west from location 271,706 mE, 770,523 mN. Photo credit: SEPA. 20/11/2016

Figure A-9 River Garry, looking upstream from location 271,619 mE, 770,555 mN. Photo credit: SEPA. 20/11/2016

Figure A-10 River Garry, looking downstream from same location (271,619 mE, 770,555 mN) as Fig. A-9. Photo credit: SEPA. 20/11/2016

A2 LiDAR Accuracy Assessment

Table A-1 summarises results for the combined set of 20 check points located on two sections of road (10 points at Area 1 and 10 at Area 2), with locations as illustrated in Figure A-7. There was virtually no difference in the results between the two areas. While a sample of 20 points cannot be considered statistically significant, the low standard deviation (σ) of < 0.01 m suggests the results are in good agreement (high precision), with minimal variation.

Table A-1 Statistics of elevation differences (dZ) between LiDAR and GNSS check points

Number of points	Mean dZ (m)	σ dZ (m)	RMSE dZ (m)	Min. dZ (m)	Max. dZ (m)
20	+0.042	0.008	0.043	+0.028	+0.057

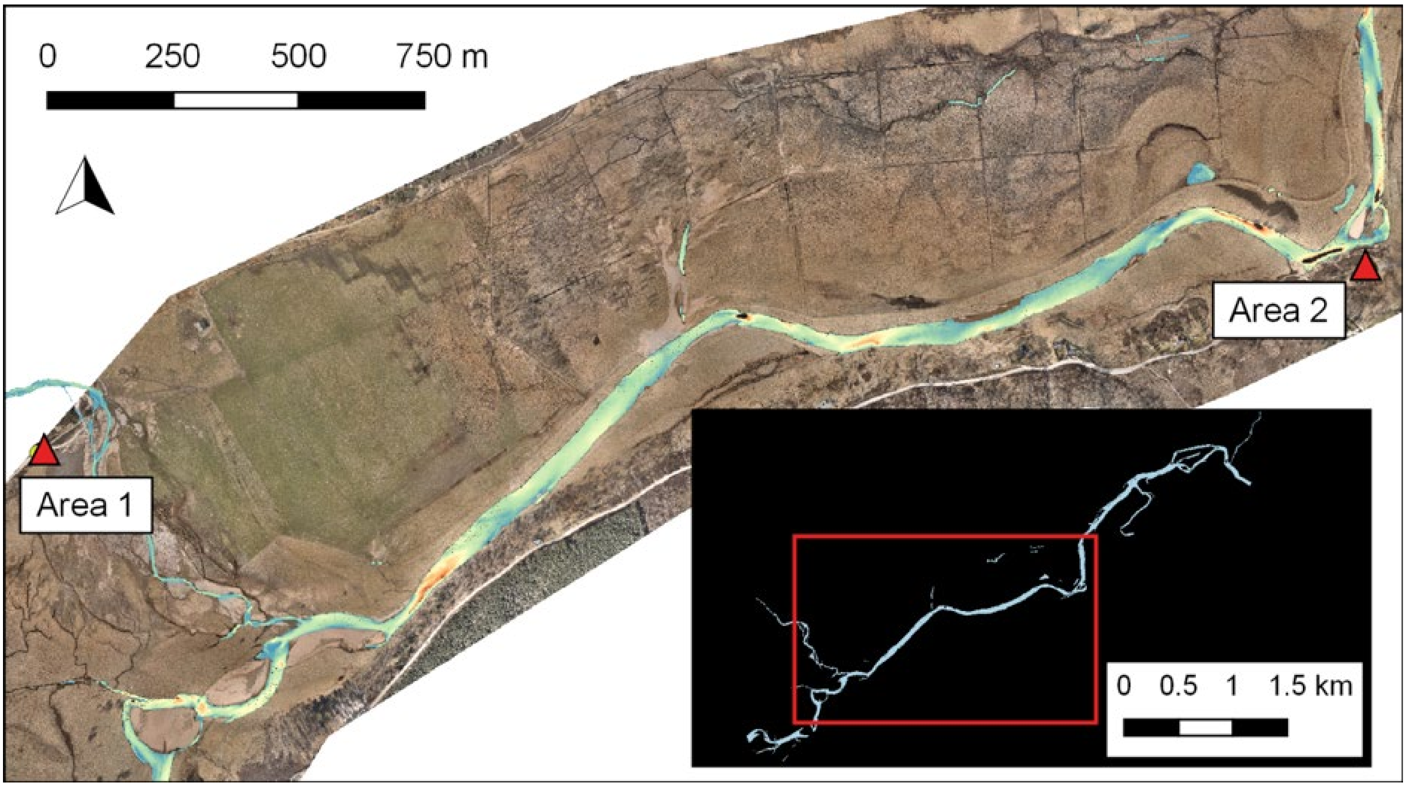


Figure A-11 Road check points areas 1 and 2 at River Dee.

A3 Cross-section Validation Results

Table A-2 Elevation differences between LiDAR and GPS for all River Dee cross-sections.

Section	Class	No. Points	Mean (m)	σ (m)	RMSE (m)	Min. (m)	Max. (m)
A-1	Dry	5	0.274	0.143	0.302	0.127	0.451
	Surface	19	-0.043	0.066	0.077	-0.159	0.071
	Bed	19	0.035	0.037	0.051	0.003	0.170
A-2	Dry	5	0.173	0.064	0.183	0.100	0.268
	Surface	11	0.104	0.067	0.122	-0.062	0.171
	Bed	11	0.065	0.039	0.075	0.027	0.157
B	Dry	23	0.086	0.045	0.097	0.029	0.217
	Surface	27	0.129	0.062	0.142	0.051	0.366
	Bed	36	0.080	0.031	0.086	0.018	0.133
C	Dry	15	0.100	0.132	0.162	0.010	0.421
	Surface	No points returned					
	Bed	11	0.021	0.028	0.034	-0.006	0.096
D	Dry	16	0.079	0.110	0.132	-0.013	0.321
	Surface	No points returned					
	Bed	No points returned					
E	Dry	28	0.054	0.109	0.120	-0.043	0.432
	Surface	8	0.113	0.028	0.116	0.070	0.160
	Bed	12	0.048	0.080	0.090	-0.011	0.292
F	Dry	6	0.219	0.185	0.276	0.028	0.563
	Surface	8	0.085	0.034	0.091	0.030	0.131
	Bed	10	0.021	0.023	0.030	-0.018	0.053

Section	Class	No. Points	Mean (m)	σ (m)	RMSE (m)	Min. (m)	Max. (m)
G	Dry	18	0.093	0.123	0.151	-0.019	0.518
	Surface	4	0.011	0.024	0.023	-0.010	0.045
	Bed	6	0.026	0.031	0.038	-0.009	0.067
H	Dry	29	0.084	0.041	0.093	-0.013	0.164
	Surface	No points returned					
	Bed	9	0.026	0.031	0.038	-0.009	0.067
I	Dry	17	0.094	0.067	0.114	-0.015	0.211
	Surface	5	0.088	0.054	0.101	0.023	0.156
	Bed	13	0.067	0.031	0.073	0.010	0.126
J	Dry	14	0.088	0.093	0.126	-0.162	0.261
	Surface	10	0.074	0.066	0.097	-0.013	0.185
	Bed	15	0.090	0.041	0.099	0.032	0.194
K	Dry	28	0.085	0.058	0.102	-0.044	0.181
	Surface	7	0.023	0.053	0.054	-0.083	0.069
	Bed	5	0.065	0.047	0.077	0.015	0.117
L	Dry	14	0.167	0.054	0.175	0.097	0.270
	Surface	4	-0.007	0.018	0.017	-0.026	0.012
	Bed	6	0.055	0.020	0.058	0.022	0.073

Table A-3 Elevation differences between LiDAR and GPS for all Allt an t-Slugain cross-sections.

For sections C (Dee) and H (Allt an t-Slugain), no surface points were present in the LiDAR data, and for section D (Dee) no bed or surface points were present. In the former case (C, H) this is due to shallow water depth, as discussed in Section 4.4.3. The lack of bed and surface points at section D is likely due to the classification overlap discrepancy, as discussed in Section 6.1.

A4 Point Density

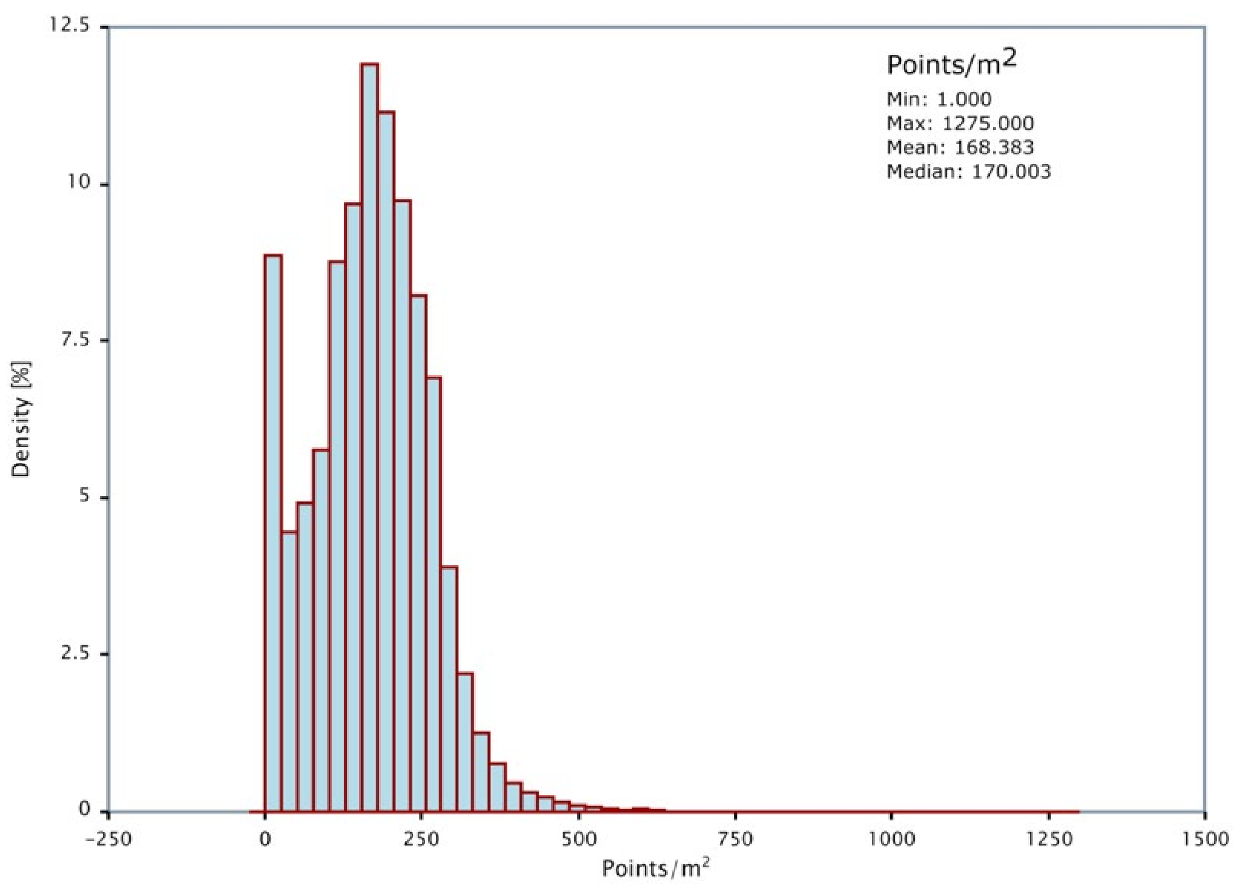


Figure A-12 Histogram of point density for river bed class at Garry test site.

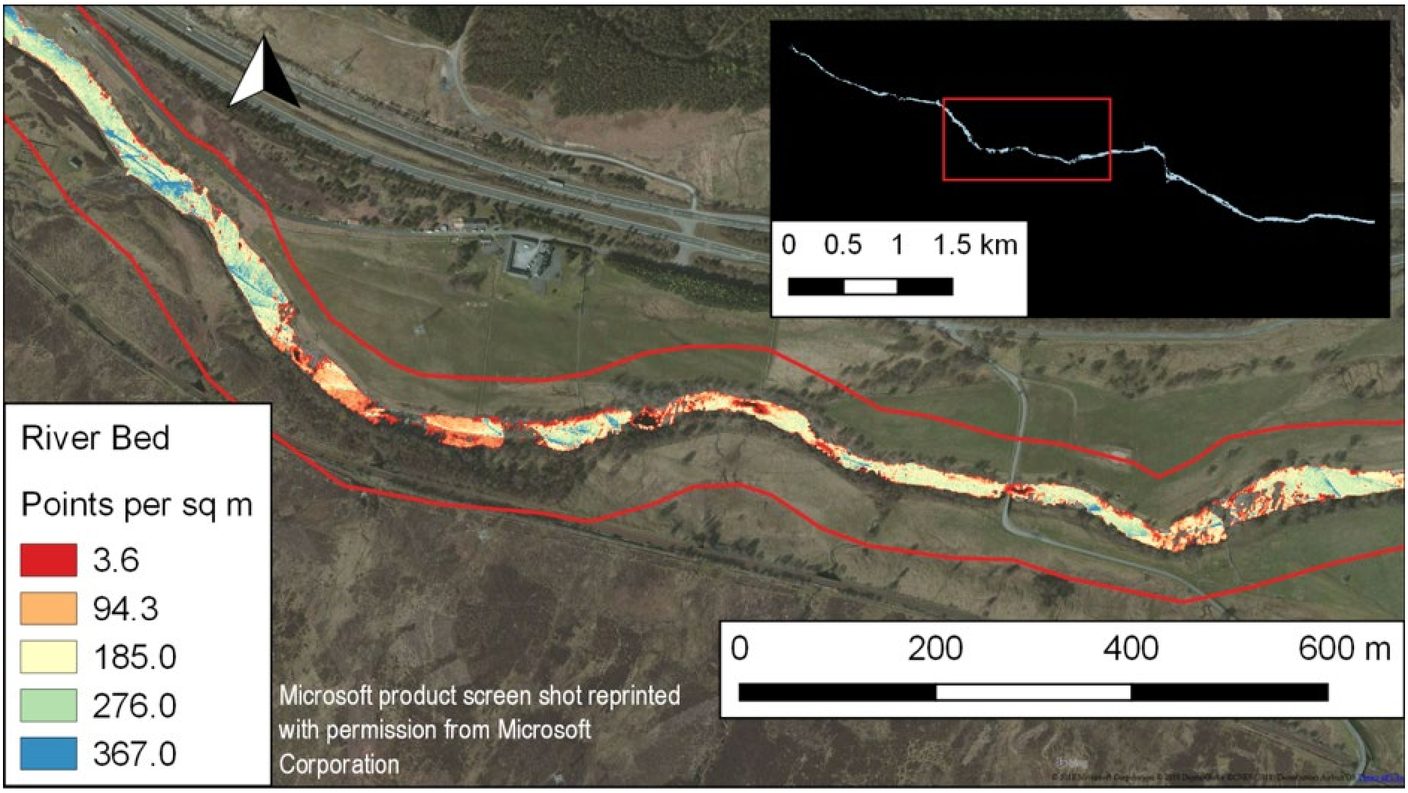


Figure A-13 Spatial variability of point density at Garry test site (river bed class).

A5 Water Depth

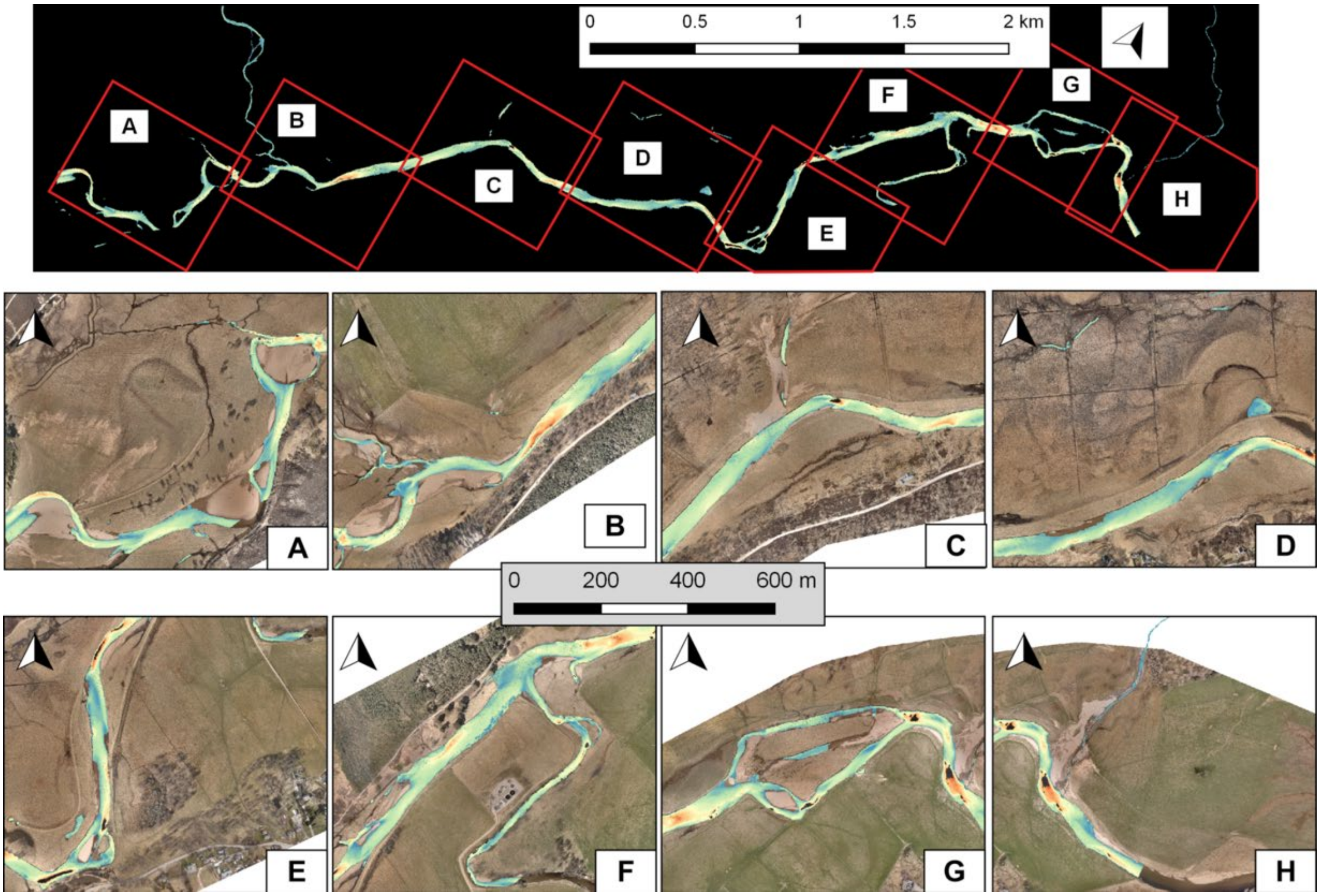


Figure A-14 Complete depth maps for River Dee.

A6 SEPA River Typology

Table A-4 SEPA river typology classification (SEPA, 2012)

SEPA River Type	Sub-Types
A	Bedrock, Cascade
B	Step-pool, Plane bed
C	Plane-riffle, Braided, Wandering
D	Actively meandering
E	Groundwater dominated
F	Low gradient passively meandering

Scotland's centre of expertise for waters

CREW Facilitation Team

James Hutton Institute

Craigiebuckler

Aberdeen AB15 8QH

Scotland UK

Tel: +44 (0)1224 395 395

Email: enquiries@crew.ac.uk

www.crew.ac.uk

CREW is a Scottish Government funded partnership between
the James Hutton Institute and Scottish Universities.